ANL-7130 E.N.P.

ANL-7130

Proceedings of the international conference on weak interactions

October 25-27, 1965

RETURN TO REFERENCE FILE
TECHNICAL PUBLICATIONS
DEPARTMENT

PROPERTY OF
ANL-W Technical Library

ARGONNE
NATIONAL
LABORATORY

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in USA. Price $4.75. Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia

ANL-7130
Physics
(TID-4500, 47th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60440

PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON WEAK INTERACTIONS

October 25-27, 1965

Sponsored by
Argonne National Laboratory and
IUPAP (International Union of
Pure and Applied Physics)

Operated by The University of Chicago
under
Contract W-31-109-eng-38
with the
U. S. Atomic Energy Commission

CONFERENCE STAFF

A. Roberts	Conference Director
K. C. Wali	Associate Conference Director
D. Carlson	Executive Assistant
H. Cramer	Secretary

ADVISORY COMMITTEE

G. Feinberg	Columbia University
V. L. Fitch	Princeton University
W. F. Fry	University of Wisconsin
L. T. Kerth	Lawrence Radiation Laboratory
A. Roberts	Argonne National Laboratory
R. G. Sachs	University of Chicago and Argonne National Laboratory
V. L. Telegdi	University of Chicago
S. B. Treiman	Princeton University
K. C. Wali	Argonne National Laboratory

SCIENTIFIC SECRETARIAT

C. H. Albright	Northwestern University
G. R. Burleson	Northwestern University
N. L. Gelfand	University of Chicago
D. Horn	Argonne National Laboratory
L. G. Hyman	Argonne National Laboratory
R. A. Lundy	Argonne National Laboratory
W. D. McGlinn	University of Notre Dame
D. W. McLeod	Argonne National Laboratory
B. Sakita	Argonne National Laboratory
C. L. Sandler	Argonne National Laboratory
K. C. Wali	Argonne National Laboratory
R. Winston	University of Chicago

PREFACE

The Argonne National Laboratory played host, on October 25-27, 1965, to 415 physicists for an international conference on weak interactions. The first major international meeting in particle physics held at Argonne since the commissioning of Argonne's 12.5 GeV accelerator, the ZGS (zero gradient synchrotron), it was jointly sponsored by Argonne and the International Union for Pure and Applied Physics.

A few words on the organization of the conference may be appropriate. The general plan of the conference was formulated by the advisory committee. The committee's aims were to provide complete and authoritative coverage of all major aspects of the field; to organize the sessions so that discussions could be free and thorough; and to provide access to the conference to as many interested physicists as feasible. It was explicitly agreed that political considerations, such as national representation, would be excluded from the criteria for inviting participants. Most of the physicists invited came; the major disappointment was the inability of any of our invitees from the Soviet Union to accept our invitations.

To achieve these partially conflicting goals, the conference was held in the auditorium of the high-energy physics building, which seats 299. Participants were divided into three classes, called conferees, auditors, and listeners. The attendance was by invitation for conferees and auditors; listeners were admitted ad lib. The conferees, restricted to the number that could be accommodated in the auditorium, included all contributors to the proceedings and discussions. The conference proceedings were transmitted by closed-circuit television monitors to auditors and listeners in two remote auditoria. Auditors partook equally with conferees in all other conference functions; listeners (a category designed primarily for graduate students) were restricted to the televised proceedings. A thoroughly unscientific and non-random sampling of opinion of the participants yields the impression that the aims of the advisory committee were, on the whole, successfully achieved.

Since the pace of high-energy physics is rapid, the conference staff sacrificed many niceties to the overriding need to publish the printed proceedings of the conference in the shortest possible time. Consequently, we have used offset rather than letterpress reproduction.

The proceedings as published differ from a verbatim transcript. The published versions of the invited and contributed papers are those submitted by the authors. The discussions have been transcribed from tape recordings, and edited minimally - just enough to correct trivial mistakes - in an effort to preserve their flavor. The careful reader may note discrepancies between the discussions and the preceding papers; these are due to inevitable differences, sometimes considerable, between published and spoken versions of a given contribution.

Our greatest debt of gratitude is due to the advisory committee, whose considerable effort gave the conference its distinctive format and provided the necessary scientific guidance. An equal debt is due to the scientific secretariat and the editorial staff of the proceedings, for their efforts to provide intelligible edited versions of frequently puzzling transcripts.

Last, we acknowledge with thanks the untiring contributions of the Argonne staff whose efforts helped so much to make the conference operate smoothly. First among these was Mrs. Dorothy Carlson, conference executive assistant; Mrs. Hazel Cramer, secretary; and also Mrs. Frances Dominick, Mrs. Elizabeth Wallis, Mrs. Florence O'Neill, William Rickhoff, and typists Carolyn Hoeflein, Mrs. Jane Kargas, and Mrs. Allene Bachman. The manuscript preparation was ably carried out by Mrs. Joyce Kopta.

A. Roberts

K. C. Wali

SESSION I

October 25, 1965

CP VIOLATIONS

Chairman: P. T. Matthews, Imperial College of Science and Technology

Page

THE TRANSVERSE POLARIZATION OF THE MUON IN THE DECAY $K_L^o \rightarrow \mu^+ + \pi^- + \nu$
D. Bartlett, C. Friedberg, K. Goulianos and D. Hutchinson, Princeton University. . 3

TIME REVERSAL INVARIANCE IN $\Sigma^o \rightarrow \Lambda^o + e^+ + e^-$
R. G. Glasser, B. Kehoe, University of Maryland; P. Engelmann, H. Schneider, University of Heidelberg, Germany; and C. Alff, L. L. Kirsh, Columbia University. 13

EXPERIMENTAL STATUS OF C. P. VIOLATION
James W. Cronin, Princeton University 17

PHENOMENOLOGICAL DESCRIPTION OF K DECAY
C. N. Yang, Institute for Advanced Study. 29

SESSION II

October 25, 1965

EXPERIMENTAL DATA ON K-DECAYS

Chairman: R. H. Dalitz, Oxford University

$K_2^o \rightarrow \pi^+\pi^-\pi^o$ DECAY
P. Guidoni, V. Barnes, H. W. Foelsche, G. R. Kalbfleisch, G. W. London, K. Lai, T. Morris, Y. Oren, M. Webster, W. Willis, Brookhaven National Laboratory; and T. Ferbel, A. Firestone, J. K. Kim, J. Lach, J. Sandweiss, H. D. Taft, Yale University 49

MEASUREMENT OF THE RATE OF K_2^o DECAY INTO THREE PIONS AND TEST OF CP INVARIANCE
L. Behr, V. Brisson, P. Petiau, C. Pascaud, B. Aubert, Ecole Polytechnique, Paris; E. Bellotti, A. Pullia, Istituto di Fisica dell'Universitá, Milano; and M. Baldo-Ceolin, E. Calimani, S. Ciampolillo, H. Huzita, A. Sconza, Istituto di Fisica dell'Universitá, Padova 59

THE DECAY $K_2^o \rightarrow \pi^+\pi^-\pi^o$
H. W. K. Hopkins, T. C. Bacon, Vanderbilt University; and F. R. Eisler, Rutgers University 67

PRELIMINARY RESULTS ON THE CHARGED DECAY MODES OF K_2^o
P. Basile, J. Bingert, J. W. Cronin, B. Thévenet, R. Turley, S. Zylberach, A. Zylberstejn, L.P.C.H.E., C.E.N., France 77

THE ENERGY DEPENDENCE OF THE VECTOR FORM FACTOR IN THE K_{e3}^o DECAY
G. P. Fisher, A. Abashian, R. J. Abrams, D. W. Carpenter, B. M. K. Nefkens, J. H. Smith, and A. Wattenberg, University of Illinois 83

SPARK CHAMBER MEASUREMENT OF THE $K^o_{\mu 3}$ DECAY SPECTRUM
D. W. Carpenter, A. Abashian, R. J. Abrams, G. P. Fisher, B. M. K. Nefkens, and J. H. Smith, University of Illinois 91

K^+_{e2} BRANCHING RATIO
D. R. Bowen, A. K. Mann, W. K. McFarlane, University of Pennsylvania; and A. D. Franklin, E. B. Hughes, R. L. Imlay, G. K. O'Neill, D. H. Reading, Princeton University. 107

K DECAY
George H. Trilling, University of California 115

SESSION III

October 26, 1965

SPECIAL FEATURES OF STRANGE PARTICLE DECAYS
Chairman: R. K. Adair, Yale University

TIME DISTRIBUTION OF K^o LEPTONIC DECAYS
B. Aubert, L. Behr, L. M. Chounet, J. P. Lowys, C. Pascaud, Ecole Polytechnique, Faculté des Sciences Accélérateur Linéaire, France 153

SELECTION RULES IN LEPTONIC DECAY
W. J. Willis, Yale University 159

HYPERON NON-LEPTONIC DECAYS
N. P. Samios, Brookhaven National Laboratory 189

K_1 - K_2 MASS DIFFERENCE AND K^o_1 REGENERATION
Myron L. Good, Institut des Hautes Etudes Scientifiques, France 215

SESSION IV

October 26, 1965

ACCELERATOR NEUTRINOS AND INTERMEDIATE BOSONS
Chairman: M. Schwartz, Columbia University

SEARCH FOR INTERMEDIATE BOSONS IN PROTON-NUCLEON COLLISIONS
R. Burns, E. Hyman, L. M. Lederman, W. Lee, J. Rettberg, J. Sunderland, Columbia University; and G. Danby, Brookhaven National Laboratory 233

SEARCH FOR INTERMEDIATE VECTOR BOSON PRODUCTION IN NUCLEON-NUCLEON COLLISIONS
R. C. Lamb, R. A. Lundy, T. B. Novey, D. D. Yovanovitch, Argonne National Laboratory; and M. L. Good, R. Hartung, M. W. Peters, A. Subramanian, The University of Wisconsin. 247

ν AND $\bar{\nu}$ INTERACTIONS IN A HEAVY LIQUID BUBBLE CHAMBER
J. Bartley, M. M. Block, H. Burmeister, D. C. Cundy, B. Eiben, C. Franzinetti, R. Mollerud, G. Myatt, M. Nikolic, A. Orkin-Lecourtois, M. Patty, D. H. Perkins, C. A. Ramm, K. Schultze, H. Sletten, K. Soop, R. Stump, W. Venus, H. W. Wachsmuth, and H. Yoshiki, CERN Heavy Liquid Bubble Chamber Group, Geneva 257

Session IV (Contd.) Page

HIGH ENERGY NEUTRINO EXPERIMENTS AT ACCELERATORS
D. H. Perkins, Oxford University, England 273

HIGH ENERGY SEMILEPTONIC REACTIONS
Stephen L. Adler, Harvard University 285

SESSION V

October 27, 1965

STRANGENESS--CONSERVING BETA-DECAY
Chairman: R. H. Hildebrand, The University of Chicago

THE MOMENTUM DEPENDENCE OF THE HELICITY OF BETA PARTICLES
J. S. Greenberg and D. M. Lazarus, Yale University. 313

AN APPARENT SMALL ANOMALY IN THE ft VALUE OF A SUPERALLOWED FERMI TRANSITION
Joan M. Freeman, J. G. Jenkin, G. Murray, Atomic Energy Research Establishment, Harwell, England; and W. E. Burcham, University of Birmingham, England . 327

INDICATION OF PARITY MIXING IN AN ELECTROMAGNETIC TRANSITION
G. Scharff-Goldhaber and M. McKeown, Brookhaven National Laboratory 333

WEAK INTERACTIONS OF NON-STRANGE PARTICLES
V. L. Telegdi, The University of Chicago 337

THE CASE-WITWATERSRAND UNDERGROUND NEUTRINO PROGRAM
M. F. Crouch, H. S. Gurr, T. L. Jenkins, W. R. Kropp, F. Reines, G. R. Smith, Case Institute of Technology; and B. Meyer, J. P. F. Sellschop, University of the Witwatersrand, Johannesburg, South Africa 373

COSMIC-RAY NEUTRINOS
J. W. Keuffel, University of Utah. 393

SESSION VI

October 27, 1965

THEORETICAL ASPECTS
Chairman: A. Salam, Imperial College of Science and Technology and International Center for Theoretical Physics

RECENT WORK ON THE RENORMALIZATION OF THE WEAK AXIAL-VECTOR COUPLING CONSTANTS
W. I. Weisberger, Stanford University 409

SU(3) AND NONLEPTONIC WEAK INTERACTIONS
B. W. Lee, University of Pennsylvania 421

THEORETICAL REMARKS ON CP NON-INVARIANCE
T. D. Lee, Columbia University 431

SUMMARY
H. Primakoff, University of Pennsylvania 439

LIST OF ATTENDEES. 445

SESSION I

CP VIOLATIONS

Monday, October 25, 1965

CHAIRMAN: P. T. Matthews
Imperial College of Science and Technology

Scientific Secretaries

D. Horn, Argonne National Laboratory
W. D. McGlinn, University of Notre Dame
C. L. Sandler, Argonne National Laboratory
R. Winston, The University of Chicago

THE TRANSVERSE POLARIZATION OF THE MUON IN THE DECAY $K_L^o \longrightarrow \mu^+ + \pi^- + \nu$ (*

D. Bartlett, C. Friedberg, K. Goulianos and D. Hutchinson

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Paper presented by D. Bartlett)

The discovery[1] of the decay $K_L^o \rightarrow \pi^+ + \pi^-$ has suggested the study of other reactions in which the effect of CP or the related T-violation may be manifested. In particular, if time reversal is violated, it is possible for the muon in $K_{\mu 3}$ decay to be polarized in a direction transverse to the π - μ plane. The polarization might be as large as 20% if there were a "maximal" breakdown of CP invariance in K_o leptonic decays.[2]

We have investigated this polarization in an experiment using plastic scintillator counters. In any given K decay, the degree of transverse polarization will vary as $P_\pi^* X P_\mu^*$, so that an experiment should be sensitive to decays in which the π and μ are emitted with reasonable momenta and at approximately 90° to each other in the K center of mass. If the spin of the μ is monitored by the asymmetry in the direction of its decay electron, it is of course necessary to detect electrons which are emitted in a direction perpendicular to the π - μ plane.

---

*) Work supported by the U. S. Office of Naval Research, Contract No. Nonr-1858(06).

1) J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay Phys. Rev. Letters 13, 138 (64).

2) R. G. Sachs, Phys. Rev. Letters 13, (64)
Brian G. Kenny and Robert G. Sachs, Phys. Rev. 138, B943 (65).

This need to be sensitive to momenta in three mutually perpendicular directions is sufficiently awkward to achieve with scintillator counters that we are fortunate indeed not to be working in the K center of mass, but rather to need a beam of K mesons. As illustrated in figure 1, the apparatus is sensitive to events in which the plane of the decay in the K c.m. system is perpendicular to the K beam direction. In the lab, however, the π and μ are pitched forward but the direction of the μ spin is not drastically altered. In the events of interest, then, all three momenta p_π, p_μ, and p_e are primarily along the beam direction and can conveniently be detected by counters whose planes are perpendicular to the beam.

By using the indicated four quadrants of counters, it is possible to distinguish four types of events:

1) π clockwise from μ, e forward
2) π clockwise from μ, e backward
3) π counterclockwise from μ, e forward
4) π counterclockwise from μ, e backward (illustrated in fig. 1)

A transversely polarized sample of muons yields an asymmetry of the form

$$A = \frac{n_1 + n_4 - n_2 - n_3}{n_1 + n_2 + n_3 + n_4} \neq 0$$

where n_i are the number of events of type i.

Figure 2 shows one of the quadrants in detail. To register a trigger, each of two particles must go through the first three counters (in adjacent quadrants), but not shower in either of the two 3/8 in. slabs of lead. In addition, one particle (presumably a muon) is required to stop between counters 4 and 22 and subsequently an odd and even numbered counter in that quadrant must be activated (hopefully by the electron from muon decay). Naturally, not all such triggers correspond to valid events, so in practice, each counter drives two small light bulbs. These may

be lit only when a trigger has occurred. One light indicates activity during "prompt" time, that is, when the two particles have entered the apparatus, the other shows activity during the delayed 2.7 μ sec interval in which the electron from muon decay is likely to occur. A picture is then taken and recorded on 35 mm film. 120,000 such pictures were taken in an experiment recently completed in the 13° neutral beam of the Princeton-Penn Accelerator. Three-fourths of these have now been scanned for events in which two particles enter the apparatus, one stops and subsequently decays. Of all the pictures taken, one third satisfy our requirements. A sample event is shown in fig. 3.

The 28,000 events so obtained have been analyzed to give a preliminary value for the asymmetry. We find

type	$(p_\mu \times p_\pi) \cdot p_k$	$p_e \cdot p_k$	number
1)	+	+	6955
2)	+	-	7046
3)	-	+	6939
4)	-	-	6937
			27,877

$$A = \frac{n_1 + n_4 - n_2 - n_3}{n_1 + n_2 + n_3 + n_4} = \frac{-93}{27,877} = -0.003 \pm 0.006$$

The error quoted is purely statistical. We believe the symmetry of the apparatus makes us vulnerable to biases only at a level much lower than $1/2\%$. For instance, any instrumental inefficiency which favors a definite sign of $p_\mu \times p_\pi$ for a particular pair of quadrants tends to producing cancelling asymmetries elsewhere so that the asymmetry in the sum over all four quadrants is greatly reduced. Indeed, this asymmetry itself is $\lesssim 1\%$ (compare n_2 and n_4) and consequently has almost no effect on the result since our sample contains nearly equal numbers of forward and backward going decays.

The muon polarization is of course substantially larger than this asymmetry. It may be found by multiplying the experimental asymmetry by a factor, F. Incorporated into this factor are three primary effects:

i) The expected ratio (forward - back)/(forward + back), of the decay electron from completely polarized muons is predicted by a Monte Carlo program to be 0.33 ± 0.02 .

ii) A fraction of the sample consists of events from unpolarized sources, e.g. a π^+ from $K_{\mu 3}$, K_{e3}, or $K_{\pi 3}$ stops, decays into an undetected muon which later yields a decay electron. Another fraction is only partially polarized, as when a muon stops in a scintillator counter rather that in brass. The results of a calibration in a charged beam indicate that because of these effects the polarization is diluted by a factor of 2.8 ± 0.6.

iii) Finally, accidentals and neutron induced events have been found experimentally to account for $23 \pm 6\%$ of the total.

Combining these effects, we find that $F = 11 \pm 3$ and consequently the polarization is -0.03 ± 0.08. Of course, the polarization which one measures in the lab system using only certain of the kinematically allowed decays might be expected to be different from a polarization which is always measured perpendicularly to the decay plane and which uses all possible decay configurations. However, what we lose by not measuring along the optimum direction, we gain by using only decays favorable to seeing a transverse polarization, so that

$$\langle pol \rangle_{\text{all decays}} = -0.03 \pm 0.08$$

or in terms of the customary form factors

$$\mathrm{Im}\,\zeta = \mathrm{Im}\,\frac{f_- - g_-}{f_+ - g_+} = +0.15 \pm 0.40, \text{ assuming } \mathrm{Re}(\zeta) = 0.$$

We are making efforts to improve the sensitivity of our result by excluding some unwanted events such as those where the decaying particle stops in a scintillator, but have not yet been able to make the subtraction in a way which is convincingly free from bias.

We are particularly grateful to Professor Fitch, for suggesting this investigation, and for the continual encouragement he has given. The staff of the PPA were most helpful and made our long stay there enjoyable. Finally, we wish to thank Mrs. Helen Stitely who scanned nearly all our film and Mr. David Perlman who helped in the design and construction of the apparatus. Finally, we benefited from several discussions with Prof. S. W. MacDowell.

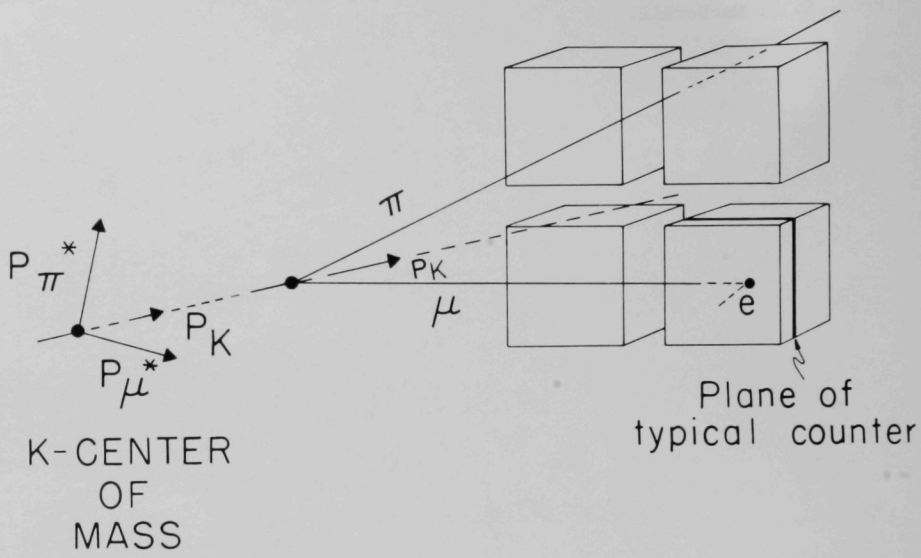


Fig. 1. A Schematic Drawing of the Apparatus

Fig. 2. A Typical Quadrant. The brass plates in which most of the muons stop are 1/8 in. thick. All scintillators (except #22) are 1/4 in. thick, the first three being 15 in. square, the remainder 18 in. square.

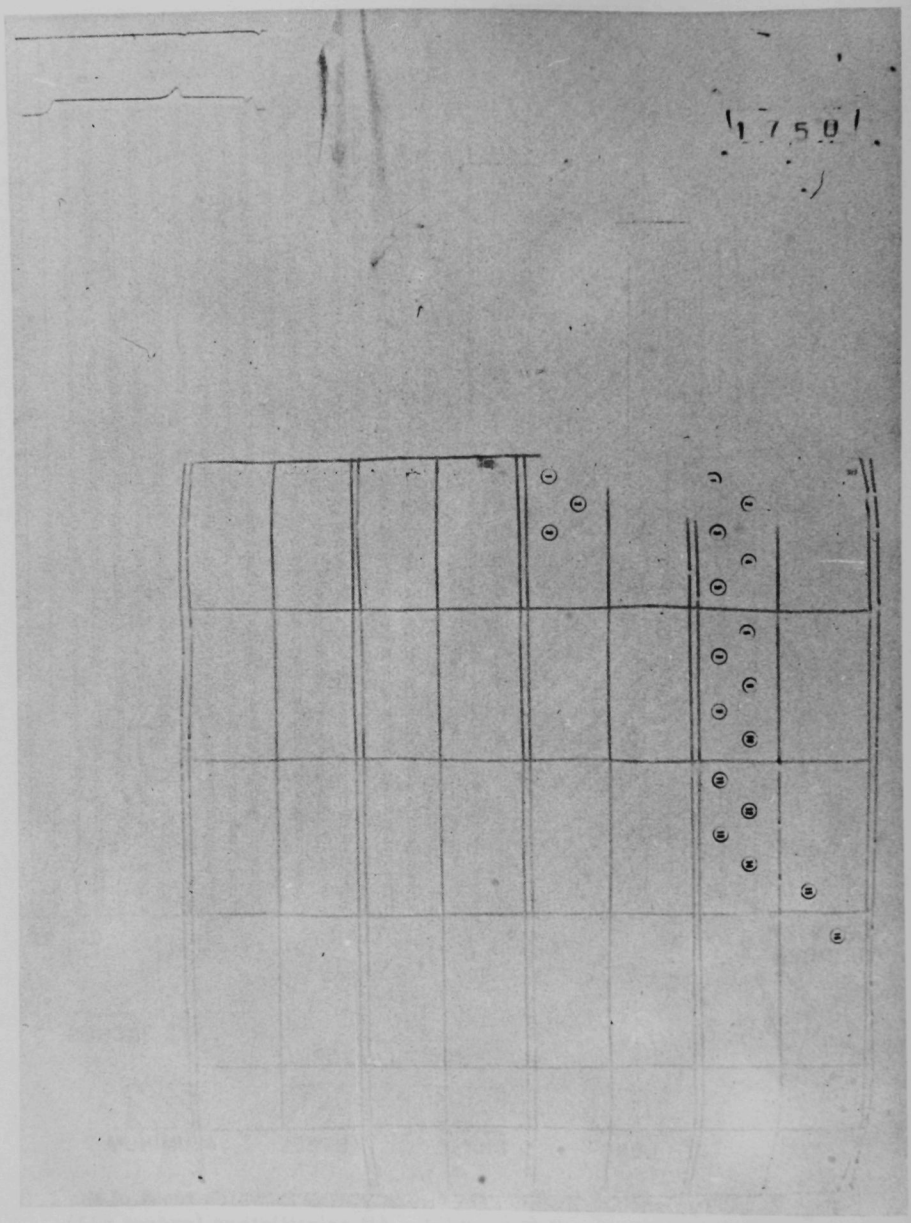


Fig. 3. A Typical Event. Two particles enter the apparatus, one is stopped by the steel wall between counters 3 and 4 and one stops and decays into a forward going electron. Shown on the oscilloscope trace is the time between

DISCUSSION

WATTENBERG (U. of Illinois): There are two questions that I would like to try to understand better. One is that there are probably about three times as many π^+'s as μ^+'s because of other competing reactions. Was there something that you knew which distinguished between the other decay modes, or have you in some way removed this π^+ sample?

BARTLETT: First of all, in certain cases, as for instance in the K_{e3} decay, we made an effort to remove this decay. The first three counters in each quadrant have upper level discriminators on their outputs and lead absorbers between them. Then the electron from the K_{e3} would shower and we could remove it with an efficiency of around 60-70%. In other decays, for instance $K_{\pi 3}$ decay, we weren't so successful. In $K_{\mu 3}$ decay we were not that successful in distinguishing the π from the μ; however, we had one feature going for us, namely, that the π had a good chance of interacting in the 3 to 4 inch steel wall, which was shown on one of my slides. It turns out that π's of the momentum we are interested in interact in the steel wall almost 60% of the time, so that there is suppression because of that.

WATTENBERG: I think it's difficult because your interactions actually include scattering.

BARTLETT: Yes, but the point is that when there is scattering it is quite interesting. We have taken some pictures to look at the scattering. Sometimes the scattering is such that it can produce a π^o because the charge exchange scattering is very likely. In which case, of course, you have effectively removed the contaminating particle, because the π^o would never give you a decay electron. In any event, our dilution factor because of these effects is not as low as we would have liked it to be. It is 2.8, so we have taken into account, just in that one number, a lot of the effects which you have mentioned.

WATTENBERG: The other question is the following. In the decay plane there is a missing particle, namely the neutrino. Now there are a certain fraction of events in which the neutrino goes forward and another fraction in which the neutrino goes backwards. This changes the angle between the π and the μ for a certain fraction of events from an acute angle, as you have shown it, to an

obtuse angle. When this happens the actual direction of the plane changes sign. Do you know what fraction of your events this includes?

BARTLETT: I think that in the center of mass system we are sensitive to events in which the plane of the decay, including the neutrino, is all transverse to the K momentum. So I must admit in that spirit I don't quite understand your question. Of course, there is some slop in the apparatus acceptance, and so the neutrino in the center of mass system appears sometimes to be going backwards, sometimes forward. It doesn't seem from our analysis that we were as close to the threshold as you indicate.

CHAIRMAN: Has someone else any questions to ask?

MAC DOWELL (Yale U.): I would like to ask you a question about how you distinguish μ^+ and μ^- events.

BARTLETT: Basically we use the experimental property of μ^-'s namely, that when they stop in brass, which is our primary stopping material, they will be captured before they decay.

MAC DOWELL: But you still have some contamination.

BARTLETT: We still have some that stop in the scintillator. We have taken that into account.

Time Reversal Invariance in $\Sigma^o \rightarrow \Lambda^o + e^+ + e^-$

R. G. Glasser and B. Kehoe*

University of Maryland, College Park, Maryland

P. Engelmann and H. Schneider

University of Heidelberg, Heidelberg, Germany

C. Alff and Larry L. Kirsh

Columbia University, New York, New York

(Paper presented by R. G. Glasser)

One of the tests suggested by Bernstein, Feinberg, and Lee[1] for time reversal invariance of the electromagnetic interaction was the polarization of Λ in the Dalitz decay of the Σ hyperon:

$$\Sigma^o \rightarrow \Lambda^o + e^+ + e^- \qquad (1)$$

We have looked for the T non-invariant term in events of the type (1) used in our determination of the relative parity of the Σ and Λ[2,3].

Bernstein et al. have given an expression for the amount of Λ polarization along the direction normal to the plane of decay of (1). The positive sense is given by $\underset{\sim}{N} = \hat{p} \times (\hat{K}_+ + \hat{K}_-)$, where $\hat{p}$, $\hat{K}_+$, $\hat{K}_-$ are unit vectors (in the Σ^o rest frame) along the Λ positron and electron directions. Equation (102) of ref. 1 then gives for the polarization along $\underset{\sim}{N}$

$$P = 2A \frac{|\underset{\sim}{K}_+ \times \underset{\sim}{K}_-| \; |T_+ - T_-|}{\Delta[(T_+ - T_-)^2 + (\underset{\sim}{K}_+ + \underset{\sim}{K}_-)^2]} \qquad (2)$$

*Supported by U. S. Atomic Energy Commission

where $\Delta = M_\Sigma - M_\Lambda$, K_+ and K_- are the electron momentum vectors and T_+, T_- are their kinetic energies. A is a dimensionless constant related to the form factors of the transition amplitude for reaction (1). If T is conserved in this decay then A must be zero.

From equation (2) the predicted polarization is small for most examples of reaction (1). The maximum possible value of A can be found from the requirement that the polarization of the Λ must be less than 1 for any configuration. This requires that A is bounded by 2.8. The average value of the coefficient of A in the above expression is .025. Thus an average polarization of at most 7% could be produced.

Using a maximum likelihood method[4] to calculate the value of A for our 910 events we get $\alpha_\Lambda A = 1.8 \pm 0.8$ or $A = -2.7 \pm 1.3$. This two standard deviation effect would be only a marginal test at best. It is rendered somewhat less significant by the fact that almost all the effect comes from the data of one of the three groups. This could of course be an extreme statistical fluctuation, but the possibility of a systematic error which we have been unable to detect is always present.

References

1. J. Bernstein, G. Feinberg and T. D. Lee, Possible C,T Non-Invariance in the Electromagnetic Interaction. Preprint (May, 1965).
2. H. Courant et al Phy. Rev. Letters 10, 409 (1963).
3. Alff, Gelfand, Nauenberg, Nussbaum, Schultz, Steinberger, Beugger, Kirsch, Plano, Berley & Prodell, Phys. Rev. 137, B1105 (1965).
4. M. S. Bartlett, Phil. Mag. 44, 1407 (1953); R. G. Glasser, Data Reduction in Physics, NRL Report 5667, U. S. Naval Research Laboratory (1961).

DISCUSSION

JACOBSOHN (Washington): Although it isn't relevant to the accuracy you can get at present with an experiment like the one you described, Henley and I have been looking into the question of the limitation on the precision of a time reversal invariance test using either real or virtual gamma rays. The standard tests use gamma rays which have a small "final state interaction" and therefore introduce a phase shift in addition to any time reversal non-invariant phase which may be present, thus spoiling the interpretation. With large momentum transfers as in this (Σ, Λ) experiment, this angle is $\sim 10^{-2}$ or 10^{-3} radians. However, in nuclear physics tests using low energy gamma rays, because of retardation factors the angle goes down to 10^{-5} or considerably better depending on the particular experiment one is considering. This sets the limit on the detection of a time reversal non-invariant amplitude in such experiments.

GLASSER: Yes, one should bear in mind that this limit of 2.8 for A is the maximum. The result is $A = -2.7 \pm 1.3$. So the end result is not at all conclusive. That is, this is not really a very sensitive method. The reason is that the average polarization predicted, if A were equal to its maximum value, is 7%. So it's just not terribly sensitive.

SCHWARTZ (Columbia U.): If you break the data into two parts, say the part corresponding to $|T_+ - T_-|$ small, and the part corresponding to $|T_+ - T_-|$ larger, what sort of numbers do you get for these two parts?

GLASSER: The value of A that we have obtained is obtained from a maximum likelihood fit, using the weighting factor of Bernstein, Lee and Feinberg. If you look at all the data and take the average polarization, you get a number which is zero with a large error, just because most of the data is insensitive. We have looked at it using weighted averages and get substantially the same result you get using the maximum likelihood values. You get a slightly worse value if you take just the 15% of the data of high weight, which is effectively what you are suggesting. There are two components that go into high weight,

the asymmetry in the energy and also the opening angle. If we take the events of high weight then we get essentially the same result but with a larger error because there is some weight left in the others.

LEE (Columbia U.): I wish to emphasize that in this sigma to lambda decay, because sigma and lambda belong to the same SU(3) multiplet, this maximum value of 2.8 can be obtained only if the C-violating electromagnetic current of the non-leptons behaves neither like a singlet nor like an octet under SU(3). Otherwise, if the C non-invariant electromagnetic current has behavior similar to the usual C-invariant electromagnetic current, then the maximum one would expect would be about 10% of the 2.8.

CHAIRMAN: Do you want to comment?

GLASSER: No, he said it all.

EXPERIMENTAL STATUS OF C. P. VIOLATION(*

James W. Cronin†

Palmer Physical Laboratory
Princeton University, Princeton, New Jersey

The discovery[1,2] of the decay mode $K_2^o \longrightarrow \pi^+ \pi^-$ is most naturally interpreted as a violation of CP invariance. There have been many proposals for other explanations of the effect. Many of these have now been eliminated by experiments carried out since the original discovery. Figure 1 shows a time distribution of the theoretical and experimental papers published on the subject of CP noninvariance, its interpretations, and implications in other processes. One can see the immediate flood of theoretical ideas to explain the effect. The experimental work which followed shows the delay required to build a new experiment or reanalysis of old experiments in the light of possible CP violation. We are now in the situation where one awaits the answers to a set of rather well defined experiments. Wu and Yang[3] were the first to make a systematic analysis of the experiments required to characterize in a phenomenological way the CP violating effect in $K_2^o \longrightarrow \pi^+ \pi^-$.

In this report I will assume that the data will fit into the framework of this analysis, and take note of any deviations which appear.

---

† A. P. Sloan Foundation Fellow

* Supported by the Office of Naval Research Contract Nonr-1858(06).

The time development of the $K\bar{K}$ is given by

$-i\frac{d\Psi}{dt} = M + i\frac{\Gamma}{2}$ where $\Psi = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$, $a(t)$ and $b(t)$ being the amplitudes of $|K\rangle$ and $|\bar{K}\rangle$ respectively as function of time. If CPT invariance is assumed the matrix is of the form:

$$M = \begin{pmatrix} M_0 & M_R + iM_I \\ M_R - iM_I & M_0 \end{pmatrix}; \quad \Gamma = \begin{pmatrix} \Gamma_0 & \Gamma_R + i\Gamma_I \\ \Gamma_R - i\Gamma_I & \Gamma_0 \end{pmatrix}$$

For CP invariance $M_I = \Gamma_I = 0$.

The wave functions for the status of definite lifetime are the linear combinations

$$|K_1\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}}[p|K\rangle + q|\bar{K}\rangle]$$

$$|K_2\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}}[p|K\rangle - q|\bar{K}\rangle]$$

If $p = q$, then CP is conserved. One measure of the violation of CP is given by $\varepsilon = \frac{p-q}{p+q}$. For $p \approx q$ one finds ε is given by

$$\epsilon = \frac{iM_I - \frac{\Gamma_I}{2}}{\lambda_1 - \lambda_2}$$

where $\lambda_1 - \lambda_2 = (M_1 - M_2) + \frac{i}{2}(\Gamma_1 - \Gamma_2)$. Here M_1 and M_2 are the masses of K_1 and K_2 and Γ_1 and Γ_2 are the total decay rates of K_1 and K_2.

The Γ_I is a sum of imaginary parts of on-the-mass-shell matrix elements connecting $|K\rangle$ and $|\bar{K}.\rangle$ Upper limits on these values can be given from known decay rates for the various final states.

The ratio of the decay amplitudes of K_2 to K_1 to $\pi^+\pi^-$ and $\pi^o\pi^o$ is given by:

$$\eta_{+-} = \varepsilon + \frac{i}{\sqrt{2}} \frac{\mathrm{Im}\, A_2}{A_o} e^{i(\delta_2 - \delta_o)}$$

$$\eta_{oo} = \varepsilon - i\sqrt{2} \frac{\mathrm{Im}\, A_2}{A_o} e^{i(\delta_2 - \delta_o)}$$

where A_o is the amplitude of $|K> \rightarrow \pi\pi$, $I = 0$ and A_2 is the amplitude for $|K> \rightarrow \pi\pi$ $I = 2$. The phase of $|K>$ and $|\bar{K}>$ is chosen so A_o is real. The factor $e^{i(\delta_2 - \delta_o)}$ comes from the difference of the $I = 0$ and $I = 2$ scattering phase shifts. A measurement of η_{+-} and η_{oo} and their phases can yield the phase and magnitude of ε.

At the present $|\eta^{+-}|$ has been measured in four experiments.[1,4,5,6] The experiments give directly $R = (K_2^o \rightarrow \pi^+\pi^- / K_2^o \rightarrow$ charged modes). If the effect is due to a true CP violation, then one finds that $|\eta^{+-}|$ cannot depend either on the laboratory energy of the K_2^o or on the distance from the target measured in mean lives of the K_2^o or on the amount of absorption material placed in the beam. Table I gives the results of the four experiments, along with the conditions that could possibly influence the results. There is no evidence of a variation of the branching ratio for the various conditions. In fact the agreement between the various independent experiments is better than one has a right to expect. The weighted mean value is $(2.04 \pm 0.14) \times 10^{-3}$.

Drawn in figure 2 for comparison is a curve γ^2 which would be the result of the splitting in energy of $|K>$ and $|\bar{K}>$ by a long range vector field.[7,8] The variation with laboratory energy can be

characterized by $R = R_o \gamma^{\eta}$ where $\eta = 0.06 \pm .18$. Figure 2 shows a plot of R vs. γ. A γ^2 dependence is shown for comparison.[7,8]

The possible variation of the branching ratio with distance from the target can be characterized by a ratio of lifetimes:

$$R = R_o \frac{e^{-\lambda_{2\pi} t}}{e^{-\lambda_2 t}} = R_o e^{-\delta\lambda t}$$

where $\delta\lambda = (\lambda_{2\pi} - \lambda_L)$. Fitting the four experimental branching ratios to the form above one finds $\frac{\delta\lambda}{\lambda_2} = 0.27 \pm 0.75$. In fact the experiment of Fitch, Roth, Russ, and Vernon[6] ranges from .3 to 1.0 K_2^o mean lines from the target. Computing δ from this data alone gives $\delta\lambda/\lambda_2 = -0.05 \pm 0.45$.

A second very important experiment has been carried out and published[9] by the group of Fitch at Princeton. They have discovered that constructive interference exists between the $\pi^+\pi^-$ decays of K_2 and $\pi^+\pi^-$ decays of regenerated K_1 in a diffuse beryllium generator. The very fact that interference exists between these two kinds of π decay indicates that the two final states are identical and that their sources are coherent as expected for a true CP violation.

If the K^o beam passes through a material medium there is an energy shift due to the potential created by the strong interactions of $|K\rangle$ and $|\bar{K}\rangle$ in the medium. The diagonal elements of the mass matrix become:

$$M_0 + \frac{2\pi}{K} f \beta \gamma cN + \frac{i}{2} \Gamma_0$$

$$M_0 + \frac{2\pi}{K} \bar{f} \beta \gamma cN + \frac{i}{2} \Gamma_0$$

where K is the laboratory wave number, N the density of nuclei /cm^3 in the medium and f and $\bar{f}$ are the forward scattering amplitudes of $|K\rangle$ and $|\bar{K}\rangle$ respectively for the nuclei of the medium. Passing through the calculation of the two pion decay rate again, one finds;

$$\eta'_{+-} = \eta_{+-} + a_r \,, \; a_r = \frac{N\lambda \Lambda f_{21}}{\lambda_1 - \lambda_2} \Gamma_s, \text{ and } f_{21} = \frac{f-\bar{f}}{2}$$

Thus by knowledge of the phase of f_{21}, one can measure the phase of η_{+-}, since $|\eta_{+-}|$ is known from the decay rate without the regenerator. In the Princeton experiment the magnitude of f_{21} was measured with solid beryllium where the interference effects are negligible. Then the beryllium density was chosen to be .1 gm/cm^2 to make $|a_r| \approx |\eta_{+-}|$. The low density beryllium was simulated by thin sheets spaced to give the average density. The result gave approximately four times the intensity of the $|\eta_{+-}|$ term alone, indicating that η_{+-} and f_{21} have the same phase.

The conclusion is somewhat uncertain because of its dependence on the $K_1 - K_2$ mass difference. The same group has carried out an improved experiment which is independent of the mass difference. The qualitative conclusion of large constructive interference is unaltered by this new experiment. The measurements were carried out at a mean momentum of 1.5 BeV/c. At this energy the real parts of the forward scattering amplitudes are probably small (although there is no direct measurement of this fact). In this case f_{21} is

very nearly imaginary with the consequence that η_{+-} lies along a line making an angle of 45° with respect to the imaginary axis.

To illustrate the importance of this experiment when combined with other experiments, consider the following possible set of circumstances. Suppose one finds that $\mathrm{Im}\, A_2 \cong 0$. Such a result would be strongly suggested by $|\eta_{oo}| \cong |\eta_{+-}|$. For this case $\eta_{+-} \cong \varepsilon$. Remembering the form of

$$\varepsilon = \frac{iM_I - \frac{1}{2}\Gamma_I}{\lambda_1 - \lambda_2}$$

and comparing with a_R, one can see that a pure imaginary f_{21} would imply the CP violation comes entirely from the off the mass shell contributions to the mass matrix. Experiments are also now under way at CERN to measure the phase of η_{+-} by means which hope to avoid the uncertainty in the regenerative phase. There are experiments to measure the rate $K_2^{o} \longrightarrow \pi^{o}\pi^{o}$ in preparation or under way at CERN, Princeton, and Berkeley. There have been a number of experiments which have searched for CP violations in the leptonic decay modes of K^{+} and K^{o}. To observe a violation requires the interference of <u>two</u> amplitudes which have a relative imaginary part. In $K^{+} \longrightarrow \pi^{o}\mu^{+}\nu$ there are two form factors f_{+} and f_{-} whose ratio $\frac{f_{+}}{f_{-}}$ is ξ. An imaginary part of ξ indicates a violation of CP. The best limit that has been placed on $I_m\, \xi$ for K^{+} decay has been given by Camerini et al.[10] Using the observed spectra and longitudinal polarization of the decay muons, they have found $I_m\, \xi = 0.0 \pm 0.85$.

The polarization of the muon in $K^{+} \longrightarrow \pi\mu\nu$ transverse to

the decay plane is given by $\approx -0.2\ I_m\ \xi$. The transverse polarization found by Camerini et al. was 0.04 ± 0.35, not giving a more significant limit. A new measurement of transverse μ polarization in K_2^o decay has been presented to this conference by Bartlett, Friedberg, Goulianos, and Hutchinson. They find that $I_m\ \xi = 0.15 \pm 0.40$.

In K_{e3}^+ decay there is no handle to observe CP violation since only the f^+ form factor contributes. However if $\Delta Q = -\Delta S$ transitions exist as well as $\Delta Q = +\Delta S$ transitions, then for K_{e3}^o decay the amplitudes for the two types of transition can have a relative imaginary part. If f is the amplitude for $\Delta Q = \Delta S$ transitions and g is the amplitude for $\Delta Q = -\Delta S$ transitions one measures $x = |x|\, e^{i\theta} = \frac{g}{f}$. Study of the time rate of decay of $K^o \longrightarrow e^+ \pi^- \nu$ and $e^- \pi^+ r$ beginning with pure K^o give a measure of x. The values of $R_e\ x$ and $I_m\ x$ obtained in recent experiments,[11,12,13] are given in Table II. Although there is a suggestion of an imaginary value of x, more accurate experiments are needed to verify this conclusion. All other experiments which test for $\Delta Q = -\Delta S$ transitions seem to yield agreement with the $\Delta Q/\Delta S$ rule.

Although the experiments in progress will characterize the CP violation for the 2π decay of K_2^o in terms of the mass matrix elements which contribute to the violation, it is not certain that these experiments will reveal the source of the violation. The source of the violation can be in principle either in the strong, electromagnetic or weak interactions. A super weak $\Delta S = 2$

interaction is also a possibility.[14] In order to pin down the interaction responsible for the violation it may be necessary to find it in some other reaction. If this is the case, the job of the experimentalist will be difficult, since other systems with the extreme sensitivity of the $K_1 - K_2$ system do not seem to exist.

References

1. J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay, Phys. Rev. Letters 13, 138 (1964)

2. A. Abashian, R.J. Abrams, D.W. Carpenter, G.P. Fischer, B.M.K. Nefkins, and J. H. Smith, Phys. Rev. Letters 13, 243 (1964)

3. T. T. Wu and C. N. Yang, Phys. Rev. Letters 13, 180 (1964)

4. X. de Bouard, D. Dekkers, B. Jordan, R. Mermod, P. Scharff, L. Valentin, M. Vivargent. M. Bott-Bodenhausen, Physics Letters 5, 58 (1965).

5. W. Galbraith, G. Manning, A. E. Taylor, B. D. Jones, J. Malos, A. Astbury, N. H. Lipman, and T. G. Walker, Phys. Rev. Letters 14, 383 (1965).

6. V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon, Princeton University, to be published.

7. J. S. Bell and J. K. Perring, Phys. Rev. Letters 13, 348 (1964).

8. J. Bernstein, N. Cabibbo, and T. D. Lee, Physics Letters 12, 146 (1964).

9. V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon, Phys. Rev. Letters 15, 73 (1965).

10. U. Camerini, R. L. Hantman, R. H. March, D. Murphree, G. Gidal, G. E. Kalmus, W. M. Powell, R. T. Pu, C. L. Sandler, S. Natali, and M. Villani, Phys. Rev. Letters 14, 989 (1965).

11. P. Franzini, L. Kirsch, P. Schmidt, J. Steinberger, and R. J. Plano, Phys. Rev. 140, 127 (1965); quoted by J. Steinberger at Oxford International Conference on Elementary Particles, 1965.

12. B. Aubert, L. Behr, F. L. Canavan, L. M. Choumet, J. P. Lowys, P. Mittner, C. Pascaud, Phys. Letters 17, 59 (1965).

13. M. Baldo-Ceolin, E. Colimani, S. Ciampolillo, C. Fillipi-Filosofo, H. Huzila, F. Mattioli, and G. Miari, Nuovo Cimento 38, 684 (1965).

14. T. D. Lee and L. Wolfenstein, Phys. Rev. 138, [illegible]

TABLE I

Data on $K_2^o \longrightarrow \pi^+ \pi^-$ Branching Ratio

Experiment	Reference	Medium	Momentum	γ^2	Distance from Target	Material in Beam	Ratio($K_2^o \longrightarrow \pi^+\pi^-/K_2^o$ changed)
Princeton I	(1)	Helium	1.1	5.5	.52	45 gm/cm^2 Pb	$2.0 \pm 0.4 \times 10^{-3}$
CERN*	(4)	Vacuum	10.7	460	.14	55 gm/cm^2 Pb	$2.24 \pm 0.23 \times 10^{-3}$ ± 10 % systematic
Rutherford	(5)	Vacuum	3.15	39	.37	55 gm/cm^2 Pb	$2.08 \pm 0.35 \times 10^{-3}$
Princeton II	(6)	Vacuum	1.5	10	.53	45 gm/cm^2 Pb	$1.97 \pm 0.18 \times 10^{-3}$

* Decay products identified as strongly interacting

Weighted avg. $(2.04 \pm 0.14) \times 10^{-3}$

$|\eta_{+-}|$ $(2.02 \pm .10) \times 10^{-3}$

TABLE II

$\Delta Q = \Delta S$ Rule Experiments

Group	Reference	Re X	Im X	$\lvert\Delta M\rvert$
Columbia	9	$0.00 \pm .20$	-0.07 ± 0.2	0.5 (constrained)
Paris	10	$0.04 \pm .12$	$0.21 \pm {}^{.15}_{.11}$	0.47 ± 0.2
Padua	11	$0.06 \pm .25$	$0.43 \pm .25$	$0.15 {}^{+.35}_{-.50}$

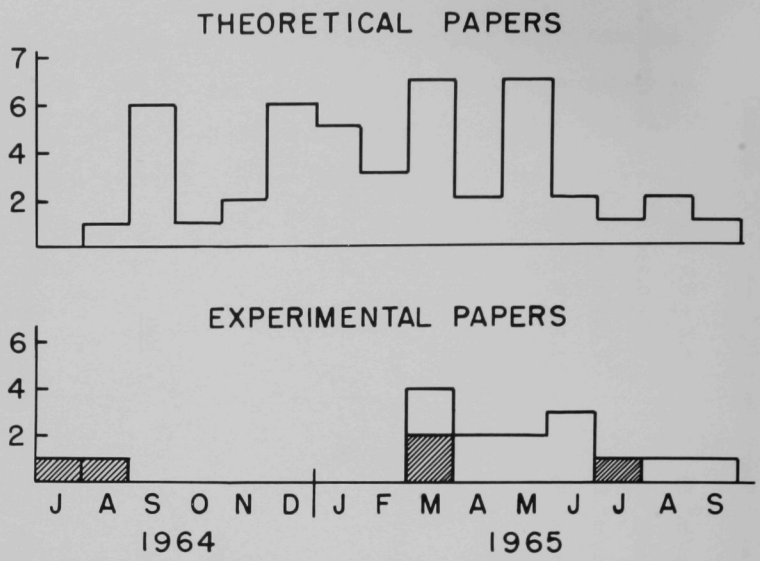


Fig. 1. Time Distribution of Theoretical and Experimental Papers on CP Violation. Cross hatched experiments are those specifically measuring $K_2^\circ \to 2\pi$.

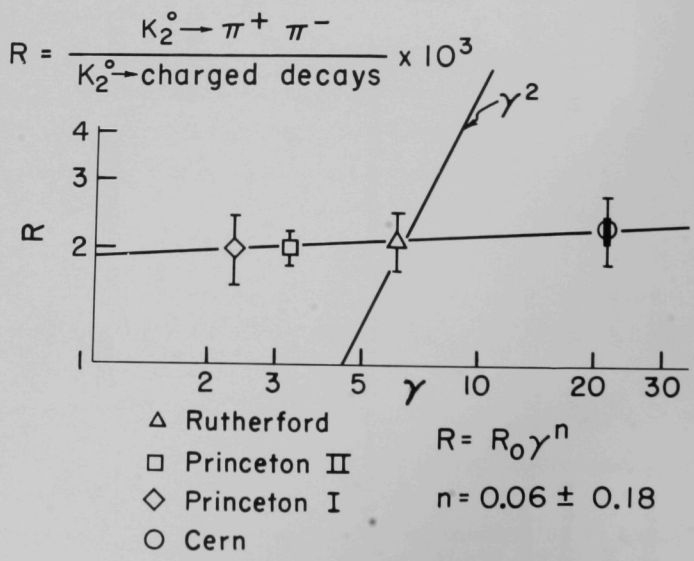


Fig. 2. Plot of R = ($K_2^\circ \to \pi^+ \pi^-/K_2^\circ \to$ all charged) as a Function of Total Energy γ.

DISCUSSION

TELEGDI (U. of Chicago): Inasmuch as so much weight is being put on these two standard deviations in the imaginary part of x, I wonder what the imaginary part of the number would become if you impose $\Delta m = 0.5$?

CRONIN: I wonder if somebody here could answer that. I could not find it in the published report.

CHAIRMAN: Can anyone answer that question?

CRONIN: I have the result of the Paris work. If you do that of course it obviously doesn't change much, expect to perhaps reduce the error a little bit.

TRUONG (Brown U.): I would like to make a remark about the parameter $\xi = f_-/f_+$. If you take the viewpoint of dynamical calculation like that of MacDowell, then f_- is related directly to f_+. In the K^* model $f_-/f_+ = -.3$, a real number. So if there is a CP-violating phase, it should cancel out and you don't expect any polarization.

CRONIN: Well, maybe that would be found experimentally also.

MARSHAK (U. of Rochester): While you are talking about masses and so on, could you answer two questions? One, can you understand the difference between this $\Delta m = 0.5$ value that you continue to get from some of the higher values? And, secondly, what are the chances of getting a decent measurement of the actual sign of the mass difference?

CRONIN: Well, I can direct you to the people to talk to. As far as the measurement of sign is concerned, I am aware of one experiment that is being carried out, by Fry and his group at Wisconsin. With respect to the first question, maybe the best thing for us to do would be to wait and hear what Bud Good has to say this afternoon. The results on the mass difference seem to be converging to a value considerably lower than the old one. There are a series of values which were measured with regeneration as a function of thickness, not by the method of two separate absorbers of variable distance, which tends to give values of Δm around 1.8. Whether that is significantly different or not I think it is hard to say. I tend to believe not. I tend to believe the result of Fitch on

the interference experiment, which turned around, says that it is very difficult to see how the mass difference can be much greater than 0.5.

YANG (Institute for Advanced Study): You mentioned an Illinois experiment with an upper limit of 8×10^{-3}. Could we ask the Illinois group to tell us what exactly is 8×10^{-3}?

FRAUENFELDER (U. of Illinois): The experiment really looked for $K_2^o \rightarrow \gamma + \gamma$. If you assume that the two gammas we are seeing are two of the four gammas you expect from $K_2^o \rightarrow \pi^o + \pi^o$, then you get an upper limit on the branching ratio for $K_2^o \rightarrow \pi^o + \pi^o / K_2^o \rightarrow$ all modes $\leqslant 9 \times 10^{-4}$. We cannot distinguish at the present time whether the two gammas we are seeing are really two gammas or two out of four. They are not six. If we ascribe them all to two gammas from the π^o, then the upper limit for the branching ratio is 8×10^{-3}. This assignment is unlikely; it is likely that most of these gammas are from the true two-gamma decay.

PHENOMENOLOGICAL DESCRIPTION OF K DECAY

C. N. Yang
Institute for Advanced Study
Princeton, New Jersey

The enormously important experiment of Christenson, Cronin, Fitch and Turlay[1] led to many papers, both theoretical and experimental, in the past year. Much of the theoretical discussions concerning the mechanism for the decay $K_L \to \pi\pi$ have been reviewed at the recent Oxford conference.[2] My discussion this morning will be concerned with the phenomenological aspect of the decay of the K-$\bar{K}$ complex. (We shall make no attempt to include a complete list of references here. Such a list can be found in reference 11.) We assume the CPT theorem and assume C, P and T invariance for strong and electromagnetic interactions.

1. General Description of K-$\bar{K}$ Decay

In the nineteen thirties Weisskopf and Wigner[3] formulated a theory of line widths. Breit and Lowen[4] were the first to discuss the problem of two neighboring resonant states interfering with each other. In 1957 the method of Weiskopf-Wigner was applied[5] to the K^o-$\bar{K}^o$ problem. Later on other formulations appeared[6] giving the same result. After the CP experiment of last year, the consideration of reference 5 was extended to a description of the K-$\bar{K}$ decay systems with CP noninvariance. Our discussions today will follow the notation of references 5 and 7. Except to emphasize a few points, we shall not here repeat the discussions of reference 7.

The decay properties of the K-$\bar{K}$ system is described by the elements of the matrix $\Gamma + iM$ where

$$\Gamma = \Gamma_o + \Gamma_2 + \Gamma_\ell + \Gamma_{3\pi} \tag{1}$$

$$M = M_o + M_2 + M_\ell + M_{3\pi} + \cdots \tag{2}$$

are sums of contributions from various modes. The elements of Γ_o, Γ_2 Γ_ℓ, $\Gamma_{3\pi}$ and of M <u>can all be measured</u>, at least in principle. But to

measure the off-diagonal elements of the Γ's, it is usually necessary to measure interference effects between K_S and K_L which is difficult. Experimentally, however, M cannot be decomposed into its component parts M_o, M_2, etc.

An important parameter in the problem is

$$\epsilon = 1 - \frac{q}{p} \tag{3}$$

which enters into the physical problem because

$$\begin{aligned} K^S &= \text{const.}\ [\, K^o + (1-\epsilon)\bar{K}^o] \quad , \\ K^L &= \text{const.}\ [\, K^o - (1-\epsilon)\bar{K}^o] \quad . \end{aligned} \tag{4}$$

One of the central problems is to measure this small complex number ϵ. Several possibilities are discussed in later sections.

2. 2π Decays

In 2π decays the quantities of immediate experimental significance are η_{+-} and η_{oo}

$$\eta_{+-} = a^L_{+-}/a^S_{+-} \quad , \qquad \eta_{oo} = a^L_{oo}/a^S_{oo}$$

representing the ratios of the decay amplitudes of K_L and K_S into $\pi^+\pi^-$ and $\pi^o\pi^o$ modes. These parameters are[7] related to ϵ through

$$\begin{aligned} \eta_{+-} &= \tfrac{1}{2}\,[\epsilon + (2)^{\frac{1}{2}} iF \operatorname{Im} A_2/A_o] \quad , \\ \eta_{oo} &= \tfrac{1}{2}\,[\epsilon - 2(2)^{\frac{1}{2}} iF \operatorname{Im} A_2/A_o] \quad . \end{aligned} \tag{5}$$

Also

$$\epsilon = \frac{1}{D}\,[\,-M_i + iy_\ell + iy_{3\pi}] \quad , \tag{6}$$

$$D = A_o^2 + i(m_S - m_L) \quad . \tag{7}$$

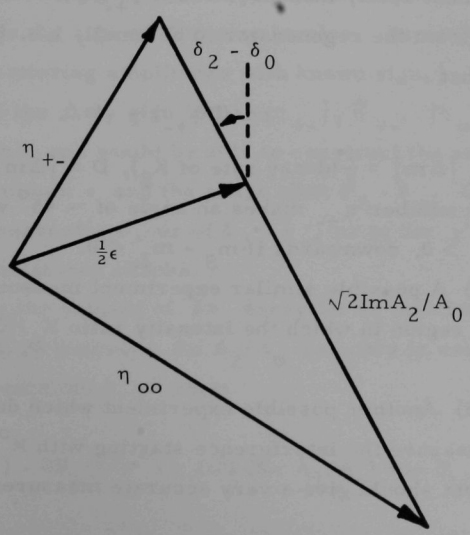
Thus

$$\eta_{+-} = \frac{-M_i}{2D} + \frac{iy_\ell}{2D} + \frac{iy_{3\pi}}{2D} + \frac{iF}{\sqrt{2}} \operatorname{Im} \frac{A_2}{A_o} \quad . \tag{8}$$

One can interpret (8) as follows. CP noninvariance implies T noninvariance which usually is exhibited as an interference effect. Now in K-$\bar{K}$ decay

the dominant mode is the $\pi\pi$ (I = 0) mode. The second, third and fourth terms on the right-hand side of (8) represent respectively the interference effect between this mode and the lepton mode, the 3π mode and the $\pi\pi$ (I = 2) modes. The first term in this formula represents an off-energy-shell interference effect. (The possibility of this term was first suggested by Sachs and Treiman.[8]) If CP invariance holds, each of these four terms is zero. (But the converse of this statement is not true. E.g., if $M_i = 0$, $y_{3\pi} = 0$, Im $A_2 = 0$, and furthermore $\Delta Q = \Delta S$, then also $y_\ell = 0$. But there could still be CP nonconservation in $K_{\mu 3}$ decays, as exhibited in the perpendicular polarization $P_\perp$. See Sec. 3 below.)

It is convenient to introduce a graph of the complex numbers η_{+-}, ϵ and η_{oo} as exhibited in reference 7 and reproduced below. The magnitude $|\eta_{+-}|$ has been measured.[1,9] Its value is, according to Professor Cronin's report we just heard: $|\eta_{+-}| = (1.83 \pm .18) \times 10^{-3}$. I understand the measurement of $|\eta_{oo}|$ is in progress.



To measure the angle $\hat{\eta}_{+-}$, there are several possible experiments. (i) One of them measures the interference between $K_L \to \pi^+\pi^-$ and $K_S \to \pi^+\pi^-$, with the K_S regenerated from K_L in a dilute uniform distribution of matter. A preliminary report of a successful experiment of this type has already been made by Fitch and collaborators.[10] The relevant formula for such an experiment is

$$R^L_{+-} = R^S_{+-}\,(\text{vacuum})\left|\eta_{+-} + \frac{\xi}{D}\frac{v}{\sqrt{1-v^2}}\right|^2 ,$$

$$R^L_{oo} = R^S_{oo}\,(\text{vacuum})\left|\eta_{oo} + \frac{\xi}{D}\frac{v}{\sqrt{1-v^2}}\right|^2 .$$

$$D = A_o^2 + i(m_S - m_L)\,,\quad A_o^2 = \tfrac{1}{2}(K_S \text{ decay rate})$$

v = velocity of K in medium

$$\xi = \frac{N}{4}\left[\sigma(K^o) - \sigma(\bar{K}^o)\right] + i\,\frac{\pi N}{k}\,\mathrm{Re}\left[A(0) - \bar{A}(0)\right]$$

k = c. of m. momentum

N = no. of nuclei/c. c. in medium

The experiment really measures $\cos(D\hat{\eta}_{+-}/\xi)$. Assuming the real scattering amplitudes from the regenerator to be small, i.e. ξ = Real < 0, reference 10 concluded that

$$\cos(D\eta_{+-}) \cong -1 \quad .$$

If one takes $|\Delta m| = \frac{1}{2}$(decay rate of K_S), $D = |\Delta m|\,(1 \pm i)$. This means that the complex number η_{+-} makes an angle of $\sim 45^o$ with the real axis, upwards if $m_S - m_L > 0$, downwards if $m_S - m_L < 0$.

(ii) A possible similar experiment measures the interference effect in a transit region in which the intensity ratio K_S/K_L varies from point to point.

(iii) Another possible experiment which does not depend on regeneration is to measure the interference starting with K^o particles. This last type of experiment should give a very accurate measurement of $|\Delta m|$, and some

information on $\hat{\eta}_{+-}$. It is independent of assumptions concerning the phase of the regeneration parameter ξ, and measures directly $\cos \hat{\eta}_{+-}$ and the sign of $(\sin \hat{\eta}_{+-})/\Delta m$.

In principle, similar experiments could be done on $|\eta_{oo}|$ and $\hat{\eta}_{oo}$.

Discussion of Possible Ambiguities

The experiments referred to above are subject to two kinds of ambiguities due to the existence of multi-solutions. For example, the experiment of reference 10 yields

$$\cos(D\hat{\eta}_{+-}/\xi).$$

Unless this number is ± 1, there are in general two solutions possible for the angle $D\hat{\eta}_{+-}/\xi$. Such ambiguities can be eliminated by doing several experiments with difference phases for ξ, such as a combination of experiments (i) and (ii).

Experiment (iii) does not suffer from such an ambiguity. But all of these experiments together still would contain another ambiguity; the unknown sign of $\Delta m = m_S - m_L$, unless either an additional experiment is performed to measure this sign, or some experiment (i) or (ii) is done with a real part of the scattering amplitude not negligible and of a known sign. [The proposed experiments to measure the sign of Δm also involve, basically, the same use of a real part of scattering amplitudes with known sign.]

Assuming that the Δm, sign (Δm), $|\eta_{+-}|$, $\hat{\eta}_{+-}$, $|\eta_{oo}|$ and $\hat{\eta}_{oo}$ experiments are all done, one would be able to construct the vector diagram yielding the complex number ϵ and the phase shift $\delta_2 - \delta_o$. Of course, if any other methods of measuring ϵ, or of $\delta_2 - \delta_o$, or of the y's prove successful, one would have consistency checks.

Before leaving the subject of 2π decay let us mention that the only experimental possibility to measure $\mathrm{Re}\, A_2/A_o$ consists in using[7] the difference of the $\pi^+\pi^-$ rate and twice the $\pi^o\pi^o$ rate:

$$R_S(\pi^+\pi^-) - 2R_S(\pi^o\pi^o) = 2\sqrt{2}\,(\mathrm{Re}\, A_2/A_o)\cos(\delta_2 - \delta_o). \qquad (9)$$

3. Leptonic Modes

For the leptonic modes K_{e3}, $K_{\mu 3}$ the decay matrix Γ_ℓ is conveniently further split into

$$\Gamma_\ell = \Gamma(e^+) + \Gamma(e^-) + \Gamma(\mu^+) + \Gamma(\mu^-) \ . \tag{10}$$

We shall use the notation

$$\Gamma(e^+) = \begin{Vmatrix} \alpha(e^+) & x(e^+) + iy(e^+) \\ x(e^+) - iy(e^+) & \beta(e^+) \end{Vmatrix} \text{ etc.} \tag{11}$$

where α, β, x and y are real numbers satisfying

$$\alpha\beta \geqq x^2 + y^2 \text{ (for each mode } e^+, e^-, \mu^+ \text{ or } \mu^-) \tag{11a}$$

(since Γ is positive definite or semidefinite).

CPT invariance leads to[11]

$$\alpha(e^+) = \beta(e^-) \ , \ \alpha(e^-) = \beta(e^+), \ x(e^+) = x(e^-) \ , \ y(e^+) = y(e^-) \ , \text{ etc.} \tag{12}$$

$$y(e^\pm) = y(e^+) + y(e^-) = 2y(e^+) \ .$$

There has been three published[12] measurements of these parameters, all analysed under the assumption

$$\alpha(e^+)\,\beta(e^+) = [x(e^+)]^2 + [y(e^+)]^2 \quad \text{etc.} \tag{13}$$

The results are given in different notations from the one used here. Roughly one obtains

$$\Gamma(e^+) \cong \begin{Vmatrix} 8 & .3 + i2 \\ .3 - i2 & .4 \end{Vmatrix} \times 10^6 \text{ sec}^{-1} \tag{14}$$

(assuming $m_S - m_L > 0$)

with large errors especially for the off-diagonal elements. Now (13) is not exactly correct.* It is true if one assumes the ratio of the form factors to be constants for the decay. It may be useful to analyse the data without (13), to

*Dr. Frank Crawford informed me that this had b
memorandum to the Paris and Padua group

check (13), but more importantly, the confidence level to be accorded the nonvanishing value of $y(e^+)$ for the matrix $\Gamma(e^+)$. Since this matrix is of fundamental importance in the question of $\Delta Q \neq -\Delta S$ and of CP invariance, additional experiments in this direction would be desirable.

We notice that the value of $y(e^\pm)$ as displayed in (14) would give only a small contribution (about 20%) to η_{+-} in (8). In fact it was already concluded (from the positive definiteness of Γ) in reference 7 that the dominant contribution in (8) must derive from M_i and/or $\mathrm{Im}\, A_2$.

The spectrum, decay rate, polarization and perpendicular polarization $P_\perp$ in the decays K_{e3} and $K_{\mu 3}$ have been discussed in some detail in the literature. (See e.g. reference 11.) The experiments are not yet accurate enough to allow definite conclusions to be drawn concerning whether the decays $K^+_{\ell 3}$ and $K^o_{\ell 3}$ give complex matrix elements indicating CP noninvariance.

The implications of the CPT theorem for the decay products of $K^+_{\mu 3} K^-_{\mu 3}$ and $K^o_{\mu 3} \bar{K}^o_{\mu 3}$, etc. have also been discussed. (See e.g. reference 11.) In particular (12) shows that

$$\Gamma(\ell^+) - \Gamma(\ell^-) = [\, a(\ell^+) - a(\ell^-)] \begin{Vmatrix} 1 & 0 \\ 0 & -1 \end{Vmatrix} .$$

Thus by (4)

$$R_L(\ell^+) - R_L(\ell^-) = [\, a(\ell^+) - a(\ell^-)]\ \mathrm{Re}\, \varepsilon . \tag{15}$$

This equation allows[13] for a measurement of $\mathrm{Re}\, \varepsilon$.

4. 3π Modes

CP noninvariance allows for a slight difference in the decay rates $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^+\pi^-\pi^-$.[14] It also allows for a small difference between the Dalitz plots for these two decays.[14] We mention also the following points:[11]

(a) The 3π decays are dominated by the $|\Delta I| = \frac{1}{2}$, $I = 1$ final states, with symmetrical space wave functions for the three pions. For such states with and without CP invariance one has

$$R_S(000) + R_L(000) = \frac{3}{4}(1.57)\, R_+(++-) = 5.5 \times 10^6 \text{ sec}^{-1} \quad , \tag{16}$$

$$R_S(000)/R_S(+-0) = R_L(000)/R_L(+-0) = \frac{3}{2}\,\frac{1.57}{1.34} = 1.8 \quad . \tag{17}$$

(b) If $K^o \to 3\pi^o$ amplitudes do not violate CP invariance [i.e. $K^o \to 3\pi^o$ taken together with $K^o \to \pi\pi\,(I = 0)$, $\bar{K}^o \to \pi\pi(I = 0)$ amplitudes do not violate CP invariance], then the decay $K_S \to 3\pi^o$ must come from the combination $K^o - \bar{K}^o$, and not at all from $K^o + \bar{K}^o$. Thus by (4),

$$\frac{R_S(000)}{R_L(000)} = \left|\frac{\epsilon}{2}\right|^2 \quad . \tag{18}$$

This leads to an extremely small value for $R_S(000)$. Unless the Wolfenstein model (see the next section) gives the correct description of CP noninvariance, it is very unlikely that $R_S(000)$ would be actually that small.[11]

(c) It is convenient to analyse the 3π modes in the same language as the other modes.

$$\Gamma_{3\pi} = \Gamma(+-0) + \Gamma(000) \quad ,$$

$$\Gamma(+-0) = \begin{Vmatrix} \alpha(+-0) & x(+-0) + iy(+-0) \\ x(+-0) - iy(+-0) & \beta(+-0) \end{Vmatrix} \quad \text{etc.}$$

Equation (11a) also holds here. CPT invariance asserts[11] that

$$\alpha(+-0) + \alpha(000) = \beta(+-0) + \beta(000) \quad .$$

The decay rate into any state, say (+-0), from any normalized ψ is

$$\text{Rate} = \psi^\dagger\, \Gamma(+-0)\psi \quad .$$

5. Further Remarks

(a) It has oftentimes been emphasized that $\eta \cong 2 \times 10^{-3}$ seems to introduce a new order of magnitude for a new type of weak interaction. To analyse this statement let us remember that in K decay CP violation manifests

itself through the interference between one dominant mode ($\pi\pi$ I = 0) and several much weaker modes. Such interference effects are necessarily small. More quantitatively we see from (8) that the weak strengths of the lepton, 3π and 2π (I = 2) modes limit the magnitudes of the last three terms easily to $\sim 10^{-3}$. The term $M_i/2D$ depends on the variation of the phase of the off-diagonal matrix element with energy and with the different channels. To calculate this term one is beset with divergence difficulties. Thus we are really only entitled to conclude that M_i/M_r is small.

(b) If it should turn out that $y_{lep} = y_{3\pi} = 0$, $\mathrm{Im}A_2 = 0$, the CP noninvariance effects would seem to derive only from the M_i term. The CP nonconservation effects on the mass shell are then all zero. While this is possible, it seems in general highly accidental (why should on-the-mass-shell effects vanish?). Under such circumstances the model of Wolfenstein[15] would seem the most natural. In this model the usual interactions (strong electromagnetic and weak) are proposed to be CP invariant. But an additional CP noninvariant $\Delta S = 2$ superweak interaction is introduced. This additional interaction gives the M_i term, without doing much else.

References

[1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

[2] See the talks by J. S. Bell, T. D. Lee, J. Prentki and J. Steinberger in the Oxford Conference Report (to be published).

[3] V. F. Weisskopf and E. P. Wigner, Z. Physik 63, 54 (1930); 65, 18 (1930).

[4] G. Breit and I. S. Lowan, Phys. Rev. 46, 590 (1934).

[5] T. D. Lee, R. Oehme and C. N. Yang, Phys. Rev. 106, 340 (1957).

[6] See the review article by R. G. Sachs, Ann. Phys. 22, 239 (1963).

[7] T. T. Wu and C. N. Yang, Phys. Rev. Letters 13, 180 (1964).

[8] R. G. Sachs and S. B. Treiman, Phys. Rev. Letters 8, 137 (1962).

[9] A. Abashian, R. J. Abrams, D. W. Carpenter, G. P. Fisher, B. M. K. Nefkens and J. H. Smith, Phys. Rev. Letters 13, 243 (1964); N. Galbraith, G. Manning, A. E. Taylor, B. D. Jones, J. Malos, A. Astbury, N. H. Lipman, and T. G. Walker, Phys. Rev. Letters 14, 383 (1965); X. de Bouard, D. Dekkers, B. Jordan, R. Mumod, P. Scharff, L. Valentin, M. Vivargent, M. Bott-Bodenlausen, Phys. Letters 5, 58 (1965).

[10] V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon, Phys. Rev. Letters 15, 73 (1965).

[11] N. Byers, S. W. MacDowell and C. N. Yang, Proceedings of the Seminar on High Energy Physics and Elementary Particles (1965), the International Centre for Theoretical Physics, Trieste (to be published).

[12] B. Aubert, L. Behr, F. L. Canavan, L. M. Choumet, J. P. Lowys, P. Mittner, C. Pascaud, Phys. Letters 17, 59 (1965); M. Baldo-Ceolin, E. Calimani, S. Ciampolillo, C. Fillipi-Filosofo, H. Huzita, F. Mattioli, and G. Miari, Nuovo Cimento 38, 684 (1965); P. Franzini, L. Kirsch, P. Schmidt, J. Steinberger and R. J. Plano, Phys. Rev. 140, B127 (1965).

[13] See reference 11. The same remark has been made independently by J. Kaplan (to be published).

[14] G. Lüders and B. Zumino, Phys. Rev. 106, 385 (1957).

[15] L. Wolfenstein, Phys. Rev. Letters 13, 562 (1964); T. D. Lee and L. Wolfenstein, Phys. Rev. 138, B1490 (1965).

DISCUSSION

WOLFENSTEIN (Carnegie Tech.): The answer to the question of what one can conclude if one finds that the last three terms are small, depends somewhat on how small. If one finds that in η_{+-} the dominant contribution comes from M_i, then there is no large CP violation in y_ℓ or $y_{3\pi}$. As long as the CP violation in y_ℓ and $y_{3\pi}$ corresponds to, e.g., a CP violation of 1%, its contribution to η_{+-} will be very small. This was the major point in the paper of Wu and Yang. It would therefore be reasonable to expect that in fact y_ℓ and $y_{3\pi}$ make very small contributions. So the question entirely involves the imaginary part of A_2.

Now, if one makes the assumption that the $\Delta I = 1/2$ rule is reasonably good for CP-violating interactions, let us say at least as good for CP-violating interactions as it is for CP conserving, then the last term will also make a small contribution. This would not, of course, be zero but it could easily be in the 10^{-4} rather than in the 10^{-3} region. In that case, η_{+-} is essentially dominated by the M_i term, without necessarily concluding that one has to deal with a super weak interaction.

There are other theories besides the super weak interaction which also predict that the imaginary part of A_2 should vanish. This is true of the Sachs model. The Sachs model, of course, taken literally makes the assumption that y_ℓ should not be zero, but in fact that it should be very large. We know that y_ℓ is not as large as Sachs' original model. But again it is possible to modify Sachs' model by saying that there is a $\Delta Q = -\Delta S$ amplitude (in fact, if one accepts it there might be some evidence for this) which makes a very small contribution to y_ℓ, but could make a still larger contribution to M_i, since the virtual contributions due to the leptonic intermediate states can be much larger than the real contribution because there is no effective cutoff when we go to the virtual leptons. That means that, while the real leptonic transitions may be small, due to the high virtual momenta of the virtual leptons, M_i can be quite large. So again, a modified form of the Sachs model would give essentially the same result.

Finally, if you make a model of a small CP violation, let us say, in the parity-conserving, rather than parity-violating non-leptonic decays, then again because it is parity-conserving, it doesn't make contributions to imaginary A_2. It makes a contribution to 3π decays, of course, but if this again is a CP violation of the order of a percent or so, it will be a very long time before one sees that kind of effects in the 3π decay and its major effect could then come again from virtual contribution from 3π's or from the pion pole in M_i. There seem to be a number of ways in which one can get the conclusion that to the experimental accuracy, at least of the kind you expect to see in the next few years, the dominant contribution will come from M_i. The only way to distinguish the different possible proposals, in particularly the super-weak proposal from others, is to do rather accurate experiments looking for CP violations in some other channels.

YANG: Could I make a comment on that? I hope you agree that the relevant quantities, from the theoretical viewpoint, really are $\mathrm{Re}\,A_2/|A_2|$, y_ℓ/α_ℓ and $y_{3\pi}/\alpha_{3\pi}$. If all these quantities turn out to be small, say just a few percent, one would end in a situation in which, I think, your model is the most attractive one.

MARSHAK (U. of Rochester): Since we are enjoying speculations about what the experimentalists might get, I would like to turn around completely. Suppose it turns out that the ratio of $K_L^o \to \pi^+\pi^- / K_L^o \to \pi^o\pi^o$ is not equal to 2, so that the M_i explanation is not good. As far as I understand Cronin's talk, the evidence on the phase tends to disfavor the y_ℓ and $y_{3\pi}$ not being equal to zero, and tends to favor more the first and the fourth terms because he had an i in the phase. At the moment, we must decide between M_i and the $\mathrm{Im}A_2$ not being equal to zero. The crucial test there will be this ratio of $\pi^+\pi^-$ to the $2\pi^o$, and suppose it turns out to be not equal to 2. Is there any other explanation that can account for such as presumed results, other than the one essentially proposed by Truong and others that we consider the CP violation in the $\Delta I = 3/2$ amplitude? Let me put my position this way: It seems to me that there could be rather an undramatic explanation of this whole CP violation

problem in the sense that it is connected with non-leptonic decays. Suppose that in the 27 representation we have a CP = -1 contribution to the non-leptonic decays in addition to the contribution from the CP = +1 octet. This would, at the same time, explain the K^+ decay going to $\pi^+\pi^o$ without any parity violation in that process. One can easily cook up models which would give the opposite CP value in the 27 representation. I think I can do that. Is there any alternative if experimental results turn out that way?

YANG : I'm not the person to answer that. My impression is that there are theoretical papers to fit every description. So, I don't know whether there exists any really attractive possibility which deals with that particular eventuality.

MARSHAK : Other than the one which would be indicated by Im A_2 not being zero?

YANG : Well, let me quote an example. There are speculations both by Truong, and by Wu and myself, in which it was assumed that only in the $\Delta I = 1/2$ amplitude you have strict CP conservation and otherwise non-strict CP conservation; but these are extremely speculative and I do not want to comment on that.

MARSHAK : But I would like to press this a moment because there is another piece of data, namely the K^+ decay; isn't it true that you can, in a sense, get an independent check of whether that theory has any possiblity at all?

YANG : That then relates to the real part of A_2 and one has not enough information.

NAUENBERG (SLAC): I wonder if you would comment on what modifications in you analysis would have to be made, if there is a CPT violation; or, if not, what experimental reason is there for not considering this possibility?

YANG: Well, to be very honest, I do not know what exactly I would propose to write down if I was told that CPT invariance is not valid and I were required to write a theory or a description concerning the phenomena under such a state of affairs. Now, experimentally, for the CPT theorem, if you

accept C conservation in the strong interactions, I think the most accurate data concerns the lifetime of charge conjugate particles, like π^+, π^- and μ^+, μ^-. I think the μ^+, μ^- data is the most accurate. There have been in the literature discussions of what happens when CPT invariance is not valid. Let us agree that that is different than the question: what are the consequences of CPT invariance?

SACHS (Argonne): I think I'd like to make a statement in answer to this question which is not in contradiction with what Professor Yang has said. It is true that it is quite a different statement to ask, "What would the consequences be if CPT is violated?", and, on the other hand, to ask "What is the consequence of CPT conservation?" However, there is one very simple statement one can make, and that is that CPT conservation tells you that the diagonal elements of this mass matrix which has been written down here a number of times, are equal. If these diagonal elements were not equal, that would have a very direct effect on the magnitude of the $K_L \to 2\pi$ rate. As we've seen the measurement of $K_L \to 2\pi$ rate depends on two parameters assuming CPT invariance. One of these parameters is ϵ, and the other Im A_2. Now, if you give up CPT invariance, you introduce a third parameter and, of course, the whole effect that you are seeing could in principle be due to the fact that this third parameter which is essentially proportional to the difference between the diagonal elements of the mass matrix, is different from zero, and all the other effects we have been talking about are zero. So, once one starts giving up CPT, one tangles up the problem thoroughly. It is so hard to conceive of a way in which to write down a theory violating CPT that it hardly seems worthwhile to complicate the analysis at this stage of the game, but it should certainly be kept in mind.

WOLFENSTEIN: First, in respect to what Sachs says, it is possible to introduce the CP violation solely by making the diagonal terms different, which would correspond to CPT violation; for example, in the strong interactions. The result, however, is to give you a phase of η_{+-} which is just 90° different from the phase that is given if you just take the first term in

that equation. Now, the result of Fitch is that the phase is essentially in agreement with the first term in that equation. This presumably rules out the possibility of 90° out of phase and at lease rules out the simplest example of CPT violation, namely, in which all the effect is solely due to different diagonal elements of the mass matrix. I may also comment on what Marshak said. Suppose one finds out that η_{+-} has a large class of models. One possible model clearly is that the non-leptonic hamiltonian does have a CP violating part which is $\Delta I = 3/2$. A similar result could, of course, be expected if CP were violated in the electromagnetic interaction, as a number of people, particularly Professor Lee, suggested. Since the electromagnetic interaction does violate the $\Delta I = 1/2$ rule, and thus would be expected to yield the size of the value for Im A_2, if one makes the extreme assumption that the $\Delta I = 1/2$ part is exactly CP conserving and that all the CP violation is $\Delta I = 3/2$, then of course you expect that M_i would be quite small, since then the contribution comes only from the virtual $I = 2$ state which enters quadratically in M_i. Therefore, you would expect that most of the explanations would have to come from the imaginary part of A_2. Then you would expect a very large difference between η_{oo} and η_{+-}.

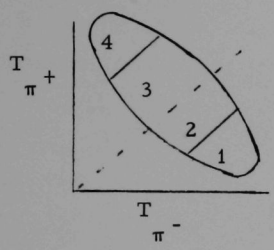
TRUONG (Brown U.): I would like to ask Professor Yang about his assumption that the $\Delta I = 1/2$ rule is valid for 3π decays. As far as I know, this rule has not been tested very accurately. It is only tested accurately in $K^+ \to \pi^+ \pi^o$, but not in the 3π decays, so it is not impossible that one has a detectably large $\Delta I = 3/2$; in other words, that the 3π state can be $I = 2$. It is possible that you have this configuration in the decay $K_2 \to \pi^+ + \pi^- + \pi^o$, and that the CP violation effect can be detected by looking at the asymmetry in the momentum distribution of π^+ and π^-. I would like to ask if we have any data concerning this asymmetry?

YANG: I presume you mean K_L decay.

TRUONG: If we start from purely K_L decay, then the detection of momentum asymmetry in the 3π mode implies that there is a CP violation in 3π modes. This I think would be a sensitive experiment to do.

YANG: Well, I don't know whether anybody really has looked into this data.

NEFKENS (U. of Illinois): We have a sample of about 1,200 K_L decays going into $\pi^-\pi^+\pi^o$ and I have measured the asymmetry. We have 655 events where the π^- energy exceeded that of the π^+, and 606 where the π^+ energy was larger than the π^- energy. This means a ratio of $1.08 \pm .06$. One can split up the Dalitz plot into four bins (see figure) and find the ratios $N(2) : N(3) = 1.03 \pm .08$ $N(1): N(4) = 1.15 \pm .09$



Bin	$T_{\pi^-} > T_{\pi^+}$	$T_{\pi^-} < T_{\pi^+}$
1 and 4	312	273
2 and 3	343	333

OKUBO (U. of Rochester): I want to make a comment based on work done in collaboration with Dr. Y. Ueda. If we use the $\Delta I = 1/2$ selection rule together with the linear-energy approximation, then we should not expect any asymmetry in the π^+ and π^- energy spectrum in $K_2^o \to \pi^+\pi^-\pi^o$ decay, even though we may have CP violations. Similarly, we have proved that if there is no $I = 3$ final state in $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$ decays, then the τ and the τ' decay modes in $K^\pm \to 3\pi$ decays should have the same decay rates in the linear approximation. To test the CP violation in $K^\pm$ decay, we, therefore, have to compare the energy spectra of unlike pions. We have computed it by a generalized Khuri-Treiman method by taking account of CP violation. There is a possibility of a maximal CP violation present in these decays.

SESSION II

EXPERIMENTAL DATA ON K-DECAYS

Monday, October 25, 1965

CHAIRMAN: R. H. Dalitz
Oxford University

Scientific Secretaries

N. L. Gelfand, The University of Chicago
L. G. Hyman, Argonne National Laboratory

$K_2^o \rightarrow \pi^+\pi^-\pi^o$ Decay*

P. Guidoni,† V. Barnes, H. W. Foelsche, G. R. Kalbfleisch, G. W. London, K. Lai, T. Morris, Y. Oren,‡ M. Webster and W. Willis§

Brookhaven National Laboratory
Upton, Long Island, New York

and

T. Ferbel,| A. Firestone, J. K. Kim, J. Lach, J. Sandweiss, and H. D. Taft
Yale University

(Paper presented by P. Guidoni)

The BNL 80-inch hydrogen bubble chamber was exposed to a K_2^o meson beam, produced by 7 GeV π^- incident on an aluminum target. Five inches of lead reduced the gamma ray background to a tolerable level. The shape of the K^o momentum spectrum is shown in Fig. 1, as obtained from 49 $K_2^o \rightarrow \pi^+\pi^-\pi^o$ decays where both the gamma rays from π^o decay convert in the 1.5 radiation length tantalum plate, at the bottom of the chamber. The shape is much better determined than the errors in the figure would indicate, since it has been checked against Monte Carlo predictions based on the visible momentum spectrum and the distribution of fitted beam momenta (two solutions per event). 190,000 pictures have been taken, with an average of 4 to 5 K_2^o per picture. The results reported here refer to about one half of the available data.

* Worked performed under the auspices of the U.S. Atomic Energy Commission.

† On leave of absence from Instituto Nazionale Di Fisica Nucleare, Rome, Italy, and the University of Roma, Rome, Italy.

‡ Presently at Lawrence Radiation Laboratory, Berkeley, California

§ Presently at Yale University, New Haven, Conn.

| Presently at University of Rochester, Rochester, New York

All the neutral Vees, not obviously electron pairs at the scanning table, have been measured. Vees possibly associated with n (=1 to 9) -prong interactions have been discarded by different but consistent procedures at the two Laboratories. A fiducial region in the chamber has been defined. To completely suppress the major source of background, i.e. high energy electron pairs, all the events have been discarded with effective mass, in the $e^+ - e^-$ interpretation, less than 30 MeV (cut#1). Furthermore, events have been discarded if the effective mass was compatible with the Λ mass, in the π^--p interpretation (cut#2). Finally, the following cut (#3) has been applied (corresponding to a similar scanning-table rule): if the projected momentum of one prong of the Vee was less than 120 MeV, then the momentum of the other would be more than 550 MeV. This was intended to reduce the low energy electron pair contamination. A total of 3505 events survived these cuts.

These events contain a large fraction of all the K_2^o 3-body decays, with a small amount of background. The decay

$$K_2^o \rightarrow \pi^+ + \pi^- + \pi^o \qquad (1)$$

is normally analyzed in terms of a spectrum in T_o, the c.m. kinetic energy of the π^o. The symmetry between the π^+ and the π^- (1) in the final state and the small phase space available allow the matrix

element for the transition to depend mainly on T_o [2]. This is an invariant, dependent only on the (effective mass)^2 of the two charged particles. Fig. 2 shows the (effective mass)^2 distribution for all events, in the $\pi^+\pi^-$ interpretation. Apart from the big peak at the K^o mass (due mainly to regeneration of the K_1 in the window and hydrogen, and to undetected single proton recoils), the contribution of reaction (1) is clearly visible above the leptonic background. A Monte Carlo computation of this background, normalized in the region $(14.4-22.1)10^4$ MeV^2, allows for a subtraction to get the (effective mass)^2 spectrum for the 3π charged decay, together with the total rate. (In the Monte Carlo program, pure V interaction has been assumed for both K_{e3} and $K_{\mu 3}$ decays, with $R_L = \Gamma(K_{\mu 3})/\Gamma(K_{e3}) = .73$ [3]. The results are, however, not too sensitive to these assumptions). This method offers the simplest way to take into account the experimental resolution as determined from the K^o peak. The region of the spectrum at $T_o \simeq 0$ (maximum effective mass) is indeed strongly dependent on resolution corrections. The branching ratio for the charged three-pion decay is given by:

$$R = \frac{\Gamma(\pi^+\pi^-\pi^o)}{\Gamma(\text{charged})} = \frac{n(1+\alpha_1)}{N[R(1+\alpha_1) + r_2(1+\alpha_2) + r_3(1+\alpha_3)](1-\epsilon)}$$

where:

n is the number (566) of decays (1), as determined by the subtraction;

N is the total number (2995) of events, after subtraction of 510 K_1 decays;

$r_{2,3}$ are the ratios $^{(3)}\Gamma(\pi e\nu)/\Gamma(\text{charged})$ and $\Gamma(\mu e\nu)/\Gamma(\text{charged})$;

$\alpha_{1,2,3}$ are the corrections determined by a Monte Carlo program and needed to account for the effect of the cuts described above on the 3-body decays. These corrections are different for the 3 channels, and vary between 2 and 13%.

ε is a correction for the estimated background (5.5%).

No correction is applied for scanning efficiency since an independent rescan of a fraction of the film indicated no relative bias in events compatible with 3π decay. (The overall scanning efficiency was about 87%). With all these corrections taken into account, we get

$$R = 0.178 \pm 0.017,$$

where the error is purely statistical, and does not take into account possible systematic uncertainties.

In Fig. 3 the spectrum in T_o is shown, after division by a phase-space factor $\phi(T_o)$. If we assume a transition rate of the form $dW/dT_o = K\,(1 + \alpha\, T_o/M_K)\,\phi\,(T_o)$, we get from a best fit (keeping the total rate constant as determined):

$$\alpha = -5.8 \pm 1.4$$

with a 92% χ^2 probability.

Our results for the branching ratio and the spectrum of $K_2^o \to \pi^+\pi^-\pi^o$ decay are in agreement with the previous experimental work on this decay. For completeness, we list the previous results:[4]

R	α	Experiment
0.16 ± 0.03	-7.2 ± 1.8	(3)
0.15 ± 0.02	-8.3 ± 1.4	(5)
0.159 ± 0.015	-7.1 ± 1.0	(6)

The $|\Delta\vec{T}| = 1/2$ rule relates the absolute rate of reaction (1) to the τ' decay, $K^+ \to \pi^+\pi^o\pi^o$. From Clebsch-Gordan coefficients in the decay amplitudes, and the ratio of the available phase space[3], one gets the prediction,

$$\Gamma(K_2^o \to \pi^+\pi^-\pi^o) = 2 \times 1.032\ \Gamma(\tau') = (2.92 \pm 0.18) \times 10^6\ \text{sec}^{-1}$$

(The right side is obtained from $\tau(K^+) = (1.229 \pm 0.008)\times 10^{-8}$ sec.[7], and $\Gamma(K^+ \to \pi^+\pi^o\pi^o)/\Gamma(K^+) = 0.0173 \pm 0.011$, as an average of the world results[8]. From the absolute rate[9] $\Gamma(K_2^o \to 3\text{-body charged}) = (15.8 \pm 1.9) \times 10^6\ \text{sec}^{-1}$, and our value for the branching ratio, we get the rate

$$\Gamma(K_2^o \to \pi^+\pi^-\pi^o) = (2.82 \pm .43) \times 10^6\ \text{sec}^{-1},$$

in good agreement with the expected result.

With no final state interactions, the $|\Delta\vec{T}| = 1/2$ rule would predict the same spectrum for the unlike pion in the τ'

and $K_2^o \to \pi^+\pi^-\pi^o$ decays. Even with final state interactions, however, substantially identical spectra are expected[10], the decay rate being unaffected. From Fig.3, it is clear that the spectrum deviates from phase space rather sharply. The data give good a good phenomenological fit to a straight line, with a slope compatible with the one obtained from τ' decay[4]:

$\alpha(\tau')$	Experiment
-9.2 ± 0.6	(11)
-6.6 ± 0.7	(12)
-7.6 ± 0.8	(13)

A fit up the second order in T_o could in principle detect the presence of different transition amplitudes, as well as the presence of contributions from terms in $(T_1-T_2)^2$. Similarly, the presence of the "σ" resonance in this final state has been suggested[14]. Given our experimental data, it is clear that neither T_o^2 terms nor the presence of the "σ" resonance is required.

REFERENCES

1. We have checked this symmetry by comparing all the experimental quantities for the two charged pions and find no significant asymmetry.

2. S. Weinberg, Phys. Rev. Letters 4, 87, 585 (1960).

3. D. Luers et al., Phys. Rev. 133, B1276 (1964).

4. To make a consistent comparison, we have fitted all data using the same procedure.

5. R. Adair and L. Leipuner, Phys. Letters 12, 67 (1964).

6. P. Astbury et al., Phys. Letters 18, 175 (1965).

7. A. H. Rosenfeld et al., (compilation), UCRL 8030, March 1965 edition, unpublished.

8. F. S. Shaklee et al., Phys. Rev. 136, B1423 (1964).

9. L. Auerbach et al., Phys. Rev. Letters 14, 192 (1965).

10. R. F. Sawyer and K. C. Wali, Nuovo Cimento 17, 938 (1960).

11. G. Giacomelli et al., Phys. Letters 3, 346 (1963).

12. G. E. Kalmus et al., Phys. Rev. Letters 13, 99 (1964).

13. V. Bisi et al., Nuovo Cimento 35, 768 (1965).

14. L. M. Brown and P. Singer, Phys. Rev. 133, B812 (1964).

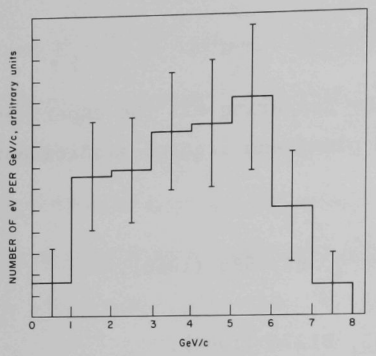


Fig. 1

Momentum Spectrum of the K_2^0 Beam as Determined by 49 $K_2^0 \rightarrow \pi^+ \pi^- \pi^0$ Decays with Both Gamma Rays Converting in the Plate

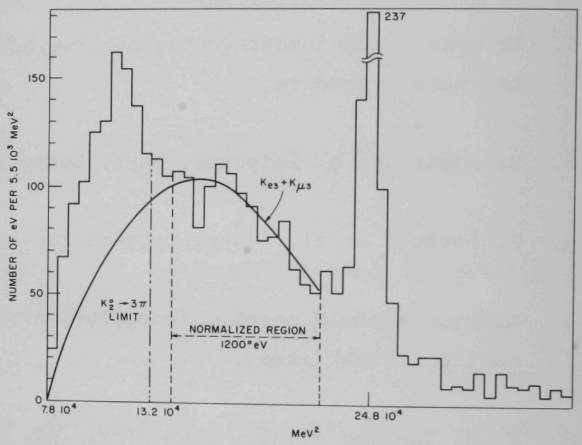


Fig. 2

Spectrum of the (effective mass)^2 of the Charged Prongs Assumed to Be Pions. The background from leptonic decays is given by the continuous curve.

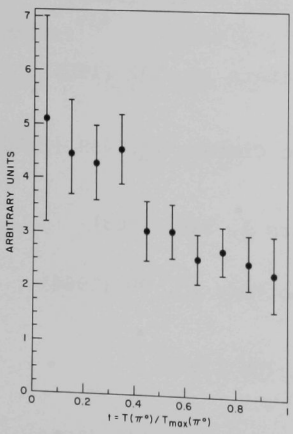


Fig. 3

Spectrum of T_0 (c.m., kinetic energy of π^0), after Division by Phase Space and Correction for Resolution

DISCUSSION

SCHULTZ (Columbia): I have a question concerning that result of the ratio of amplitudes. As I understand it, it is an upper limit. If I were to regard that as an upper limit, I would say that the ratio would be less than .05 with a confidence level of 63%. Is that right?

GUIDONI: The way this result is obtained is as follows: The required ratio is given by $(2\Gamma(\pi^+\pi^0\pi^0) - \Gamma(\pi^+\pi^-\pi^0))/\sqrt{2}\,(4\Gamma(\pi^+\pi^0\pi^0) + \Gamma(\pi^+\pi^-\pi^0))$. The number $.01 \pm .04$ is obtained by putting in experimental numbers and their errors.

MARCH (Wisconsin): I'm sorry, I didn't catch what you assumed for the charged to total rate for K_2.

GUIDONI: I assumed the number $(15 \pm 1.9)10^6$ given by Auerbach et al. for the decay rate of K_2^0 going into the charged modes $-\pi^+\pi^-\pi^0$, $\pi^\pm e^+\nu$, $\pi^\pm\mu^\mp\nu$.

MARCH: You must have assumed some form for the $K_{\mu 3}$ spectrum in doing your subtraction; it appears to vary quite rapidly down there in the low energy region.

GUIDONI: The results are relatively independent of what we assume for the leptonic decays. Anyhow, I assume pure V interaction and I assume that the $K_{\mu 3}/K_{e3} = 0.73$ as determined by you and other people.

MARCH: What is the value of ξ for the $K\mu_3$ spectrum?

GUIDONI: It is consistent with zero.

FRANZINI (Columbia): The ratio that you gave is for the intensity, not for the amplitude. Is it not?

GUIDONI: Yes.

NEFKENS (Illinois): Since you measured the π^0 spectrum from the measurement of the momentum and direction of the π^-, π^+, how well do you know the magnetic field in the bubble chamber?

GUIDONI: I do not understand the meaning of the question.

NEFKENS: To be very specific, I also analysed the π^0 spectrum in the events I reported this morning. I found an appreciable effect on the spectrum if I varied the magnetic field by 1%.

GUIDONI: I did not investigate this question and I do not know at this moment how well the magnetic field is known in the chamber. I can say that the K_1 peak is in the right position, but I do not know what you can conclude from that as to how well we know the magnetic field.

LONDON (BNL): One point you forgot to mention was that in doing the fit you kept the rate constant, that is to say, it was a one parameter fit, and not a 2 parameter fit.

GUIDONI: Well, we fit the slope with one parameter keeping the rate constant as we have determined it. This is rather important when one wants to compare different results from different experiments, because sometimes people speak in terms of 2 parameter fit and sometimes 1 parameter fit. This fit is really a 1 parameter one if the total rate is kept constant.

Measurement of the rate of K_2^o decay into three pions and test of CP invariance

L.Behr, V.Brisson, P.Petiau, C.Pascaud, B.Aubert
Ecole Polytechnique, Paris

E.Bellotti, A.Pullia
Istituto di Fisica dell'Università, Milano
Istituto Nazionale di Fisica Nucleare, Sezione di Milano

M.Baldo-Ceolin, E.Calimani, S.Ciampolillo, H.Huzita, A.Sconza
Istituto di Fisica dell'Università, Padova
Istituto Nazionale di Fisica Nucleare, Sezione di Padova

(Paper presented by M. Baldo-Ceolin)

The three pion decay modes of the K_2^o have been investigated for the determination of the absolute rates $\Gamma_2(+-0)$ and $\Gamma_2(000)$.

The experiment has been performed with a K^+ beam from the CERN PS in the Ecole Polytechnique Heavy Liquid Bubble Chamber. Three samples of pictures were taken and the experimental conditions are summarized in the following table:

		1st experiment	2nd experiment	3rd experiment
Beam		800 MeV/c K^+	800 MeV/c K^+	800 MeV/c K^+
Liquid		$C_3H_8+CF_3Br$	$C_2F_5Cl+CF_3B_r$	CF_3Br
Radiation length		22 cm	17 cm	11 cm
Nb of picture for	$\pi^+\pi^-\pi^o$	145,550	189,000	110,700
	$\pi^o\pi^o\pi^o$	/	170,000	103,000

The K_2^o's are produced through the reactions:

$$K^+ + n \rightarrow K^o + p(+\pi^o) \qquad\qquad K^+ + p \rightarrow K^o + p + \pi^+$$

The decay rates are given by $\Gamma_2(+-0) = \frac{N(\pi^+\pi^-\pi^o)}{T}$ and $\Gamma_2(000) = \frac{N(\pi^o\pi^o\pi^o)}{T}$ where $N(3\pi)$ is the number of observed events corrected for detection and scanning efficiency and T is the total observable time of flight of all K_2^o's inside the fiducial volume taking into account the attenuation of the K_2^o flux by decay and interaction.

Identification of the events.

a) $\pi^+\pi^-\pi^o$.

The $K_2^o \to \pi^+\pi^-\pi^o$ mode is detected by the presence of a V and one or two e^+e^- pairs pointing towards its vertex. Suitable cut-offs have been made to eliminate most of the background. For each event, the three following hypotheses have been tested:

$$K^o \to \pi^+\pi^-, \qquad K^o \to \pi^+\pi^-\gamma, \qquad K^o \to \pi^+\pi^-\pi^o$$

130 events have been retained. For 3 events, there was an ambiguity between the two last hypotheses. Those events have been weighted taking into account the probability given by the χ^2 for each hypothesis and the a priori probability.

b) $\pi^o\pi^o\pi^o$.

The $K_2^o \to 3\pi^o$ mode is observed by the materialisation of 5 or 6 γ's from the three π^o's. All the events with 5 and 6 γ rays which could possibly come from the same neutral vertex have been retained at the scanning stage. Cut-offs have been applied to avoid the two main backgrounds, i.e. $K_1^o \to \pi^o\pi^o$ with Bremsstrahlung products of the electrons from the γ rays conversion, and $K_1^o \to \pi^o\pi^o$ produced in association with a π^o. After a kinematical analysis, 49 events have been retained, among which 6 events have six materialized γ rays inside the fiducial volume.

Evaluation of the decay rate.

A few thousands of K_1^o's have been measured, which allowed to estimate the total number of K_1^o in the experiment and to calculate the total observable time of flight of the K_2^o's. Starting from this sample, a Monte-Carlo calculation generated

events of the type $K^o \to \pi^+\pi^-\pi^o$. Along the line of flight of each K_2^o, the detection probability of the events is computed, as well as the amplitude for the K_2^o wave as a function of the time. Then, by integration of the product of these quantities between the limits of the observation time, we calculate the potential time corrected for the detection efficiency and the K_2^o attenuation.

Assuming CP conservation, and a negligible rate for $K_1^o \to \pi^+\pi^-\pi^o$, the decay rates are:

$$\Gamma_2(+-0) = (2,57 \pm 0,31)\ 10^6\ s^{-1}$$

$$\Gamma_2(000) = (5,30 \pm 0,97)\ 10^6\ s^{-1}$$

Comparison with the theoretical predictions.

These results are to be compared with the values predicted from the K^+ decay rates by the $\Delta I = \frac{1}{2}$ rule:

$$\Gamma_2(+-0) = (2,78 \pm 0,16)\ 10^6\ s^{-1}$$

$$\Gamma_2(000) = (4,83 \pm 0,16)\ 10^6\ s^{-1}.$$

Our results are in agreement with these values.

We can now try to check the presence of $\Delta I = 5/2$ and $\Delta I = 3/2$ transitions.

The comparison between the absolute decay rates $\Gamma_2(000)$ and $\Gamma_2(+-0)$ allows to check the isotopic spin state of the final three pion system. Assuming CP invariance, the final state is restricted to odd isotopic values I=1 and I=3. If there is only I=1 symmetric state and no I=3 admixture (i.e. no $\Delta I = 5/2$ transition), the ratio $\Gamma_2(000)/\Gamma_2(+-0)$ has a determined value:

$$\frac{\Gamma_2(000)}{\Gamma_2(+-0)} = 1,83.$$

We find

$$\frac{\Gamma_2(000)}{\Gamma_2(+-0)} = 1,94 \pm 0.40$$

So we conclude that there is no or very little I=3 admixture and then no $\Delta I=5/2$ transition, in agreement with the results on K^+ rates.

The K_2^o decay in I=1 state of three π's can occur through both $\Delta I=\frac{1}{2}$ and $\Delta I=3/2$ transitions, and we can compute the ratio of the amplitudes $S_1(\Delta I=\frac{1}{2})$ and $S_3(\Delta I=3/2)$ using the relation:

$$\frac{\Gamma_2(+-0)}{\Gamma_+(+00)} = 1,96 \left|\frac{S_1+S_3}{S_1-\frac{1}{2}S_3}\right|^2$$

We get: $Re(S_3/S_1) = -0,026 \pm 0,03$.

Another test of the $\Delta I=\frac{1}{2}$ rule is the comparison of the matrix elements for $K_2^o \to \pi^+\pi^-\pi^o$ decay and $K^+ \to \pi^+\pi^o\pi^o$ decay. Assuming a linear dependence on the unlike pion energy of the squared matrix element:

$$|M|^2 = 1-\alpha T(\pi^o)/M(K^o)$$

where $T(\pi^o)$ is the kinetic energy of the unlike pion, we get for

$$\alpha_{+-0} = 7,65 \begin{smallmatrix} +0,95 \\ -1,25 \end{smallmatrix}$$

This value is to be compared with the value found for $K^+ \to \pi^+\pi^o\pi^o$

$$\alpha_{+00} = 10,0 \pm 1,0.$$

Test of CP invariance.

If CP is violated, the amplitude a_1 for $K_1^o \to \pi^+\pi^-\pi^o$ may be comparable to the amplitude a_2 for $K_2^o \to \pi^+\pi^-\pi^o$.

The expected time distribution is:

$$N(T) = \text{const}\left(|X|^2 e^{-\lambda_1 t} + e^{-\lambda_2 t} + 2|X| e^{-\frac{\lambda_1+\lambda_2}{2} t} \cos(\Delta m t + \theta)\right)$$

where $X=|X|e^{i\theta}$ is the complex ratio between the two amplitudes a_1 and a_2. CP invariance requires X=0.

The histogram shows the experimental time distribution. The dotted curve corresponds to X=0.

Agreement with CP conservation within 80% has been found by a χ^2 test.

Because this test can be based on the time distribution only, it is difficult at this stage to rule out a possible violation. In fact, for some values of X even remarkably different from X=0, the time distribution is hardly distinguishable from that for X=0.

- - -

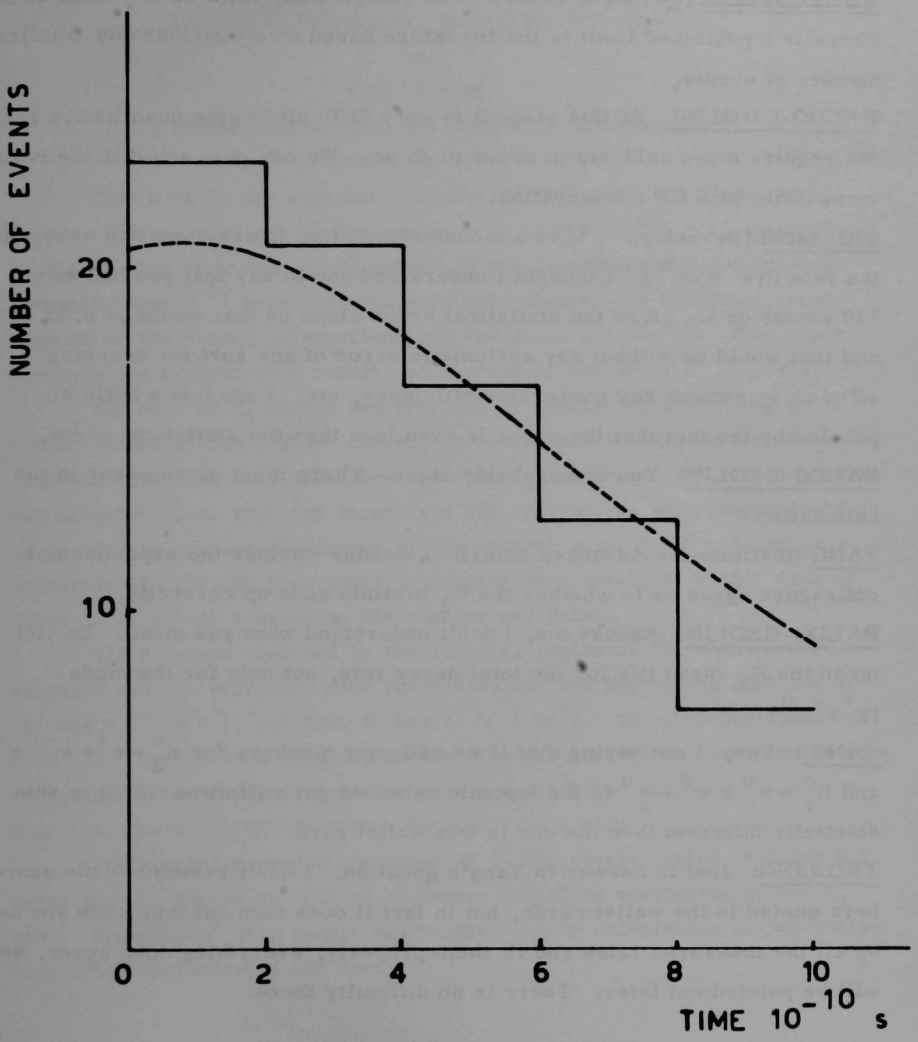


Fig. 1.

DISCUSSION

WOLFENSTEIN (Carnegie Tech.): Can you give any limit on the value of x? There is a published limit in the literature based on a considerably smaller number of events.

BALDO-CEOLIN: At this stage it is very difficult to give quantitative result We require more analysis in order to do so. We can only say that the result compatible with CP conservation.

TRILLING (Berkeley): I have a technical question to ask about the error on the rate $\Gamma(\pi^+\pi^-\pi^o)$. I thought I understood you to say that you had some 130 events or so. Now the statistical error alone on that would be 0.23 and that would be without any systematic error of any sort for scanning efficiency, gamma ray conversion efficiency, etc. I am just a little bit puzzled by the fact that the error is even less than the statistical error.

BALDO-CEOLIN: You are probably right. There must be an error in the calculation.

YANG (Institute for Advanced Study): I wonder whether the experimental colleagues agree as to whether the K_2 lifetime adds up correctly.

BALDO-CEOLIN: Excuse me, I don't understand what you mean. Do you mean the K_2 mean life for the total decay rate, not only for the mode $(\pi^+\pi^-\pi^o)$?

YANG: Yes, I am saying that if we add your numbers for $K_2^o \to \pi^+ + \pi^- + \pi^o$ and $K_1^o \to \pi^o + \pi^o + \pi^o$ to the leptonic rates we get a lifetime which is substantially different than the one in this wallet card.

TRILLING: Just in answer to Yang's question. I don't remember the numbers quoted in the wallet cards, but in fact it does turn out that when you add up all the measured rates and fit them properly, everything does agree, as will be pointed out later. There is no difficulty there.

The Decay $K_2^o \rightarrow \pi^+\pi^-\pi^o$ *

H.W.K. Hopkins and T. C. Bacon
Vanderbilt University, Nashville, Tennessee
and
F. R. Eisler
Rutgers University, New Brunswick, New Jersey
(Paper presented by H. W. K. Hopkins)

This work is the continuation of a general study of K_2^o decays and interactions carried out by the exposure of the BNL 14" liquid hydrogen bubble chamber to a beam of K_2^o mesons at the Brookhaven A.G.S. Previous communications(1-6) based on this work have studied the Ke3 decay, some aspects of the strong interactions and the decay $K_2^o \rightarrow \pi^+\pi^-$. This paper presents the experimental results of a study of the decay $K_2^o \rightarrow \pi^+\pi^-\pi^o$.

The beam of K_2^o mesons was prepared by scattering at 21° off an internal target at the A.G.S. Charged particles and γ rays were removed from the beam with lead absorbers and sweeping magnets. The bubble chamber was situated 25 m. from the target and the collimators were proportioned so as to give an angular divergence of the neutral beam of $\pm$ 4 milliradians. Approximately 150,000 good quality pictures were obtained, with a flux of about 30 K_2^o mesons traversing the chamber per pulse.

All V decays observed in the fiducial region of the chamber were measured and the effective mass calculated on the hypothesis that the decay was a K^o $(\pi^+\pi^-)$, and that it was a Λ $(p\pi^-)$. Those events consistent with Λ decays were examined on the film for ionization, and removed from the study if the ionization of the positive track was at least twice minimum, and consistent with a proton but not with a pion.

The remaining events consisted of 14,986 decays, which included all three body K_2^o decays as well as K_1^o decays following scattering of the K_2^o beam. Analysis of this sample was carried out by calculation of two variables which characterize the decay:

---

* Research carried out under the auspices of the U.S. Atomic Energy Commission.

(1) Q, the apparent Q value of the charged decay products assuming each to be a pion (2) $\bar{p}$, the vector visible momentum in the decay. Figs. 1 (b) and (c) show the distribution in $\bar{p}$ and Q, together with the incoming beam spectrum (fig 1 (a)) derived by comparison of $\bar{p}$ with the results of a Monte Carlo calculation of the experiment. The points in 1 (b) and 1 (c) are the results of the Monte Carlo calculation.

For the study of the decay $K_2^o \to \pi^+\pi^-\pi^o$, a subsample of those decays with Q < 90 MeV were selected. This subsample contains all the decays, with a background of the other K_2^o three body decay modes. The quantity

$$(p_o^1)^2 = \frac{(M_K^2 - M_o^2 - M_{12}^2)^2 - 4(M_o^2 M_{12}^2 + p_t^2 M_K^2)}{4(p_t^2 + M_{12}^2)}$$

was calculated for each decay, where $M_K = K_2^o$ mass, $M_o = \pi^o$ mass, M_{12} = effective mass of$(\pi^+\pi^-)$, and p_t = transverse momentum. This quantity has the property of discriminating further between the τ' decays, and the K μ 3 and Ke3 decays, and is an invariant in the sense that it is independent of the incoming beam momentum [7]. Fig (2) shows the experimental distribution in $(p_o^1)^2$, together with a smooth curve calculated using the Monte-Carlo method.

In the Monte Carlo distribution the leptonic decay modes were generated with a vector interaction, the form factor ratio being described by $= \frac{f^-}{f^+} = 0.33$. In the distribution of the τ' decays over phase space, a π^o spectrum of the form $dW/d\phi = (1 - 8\ To/M_k)$ was used.

A least squares fit of the Monte Carlo generated curves to the data of Fig 2, allowing the ratio K μ 3: Ke3: τ' to vary, yielded a total of 1729 τ' decays. The total number of three body K_2^o charged decays in the fiducial region was 12,046. Hence

$$R = \frac{N(K_2^o \to \pi^+\pi^-\pi^o)}{N(K_2^o \to \text{all charged})} = 0.144 \pm .004$$

(The error in this ratio is calculated from the least squares fitting procedure).

Previous measurements have been

$R = 0.157 \pm .03$ [7]
$R = 0.151 \pm .02$ [8]

The Dalitz plot for those events with $(p_o^1)^2 > -5000\ (\mathrm{MeV/c})^2$ is shown in Fig. 3. On this plot each event has been plotted twice, corresponding to the ambiguity in the zero constraint calculation, except when both solutions were physically unacceptable. The π^o kinetic energy is determined uniquely so that the two solutions lie on a horizontal line.

No structure can be discerned within this plot except for the decrease in population with increasing To. Comparison of the spectra of the π^+ and π^- shows no statistically significant difference between the two.

The kinetic energy spectrum of the π^o is shown in Fig. 4 (a). Subtraction of the calculated leptonic background and division by phase space yields Fig. 4 (b). Here the straight line is a least squares fit, whilst the curve was calculated from the theory of Brown and Singer[10] for a σ meson with mass = 400 MeV, Γ = 75 MeV. Characterizing the straight line by an expression of the form

$$\frac{dW}{d\phi} = 1 + \frac{b\ T_o}{M_K}$$

gives the parameter $b = -7.9 \pm 0.9$.

This may be compared with previous measurements of

-7.3 ± 1.6 [7]
-7.3 ± 1.7 [8]
-7.9 ± 1.0 [9]

Acknowledgements

We wish to thank the operating staff of the Brookhaven A.G.S., and members of the B.N.L. bubble chamber group, for their generous assistance. In particular we wish to thank the scanning team and data analysis aides of the B.N.L. nuclear interactions group for exceptional and invaluable services performed.

References

1. F. R. Eisler, T. C. Bacon, H.W.K. Hopkins, Bull. Am. Phys. Soc. 8, 21.
2. F. R. Eisler, H.W.K. Hopkins, T. C. Bacon, Bull. Am. Phys. Soc. 8, 348.
3. F. R. Eisler, T. C. Bacon, H.W.K. Hopkins, Proceedings Ohio Conf. on Newly discovered resonant states 114 (1963).
4. F. R. Eisler, T. C. Bacon, H.W.K. Hopkins, Proceedings B.N.L. Weak Interactions Conference (BNL 837,82).
5. F. R. Eisler, T. C. Bacon, H.W.K. Hopkins, Bull. Am. Phys. Soc. 9, 35.
6. F. R. Eisler, T. C. Bacon, H.W.K. Hopkins, Bull. Am. Phys. Soc. 9, 443.
7. D. Luers, I. S. Mittra, W. J. Willis, and S. S. Yamamoto, Phys. Rev. 133 (1963), 1276.
8. R. K. Adair and L. B. Leipuner, Physics Letters 12 (1964), 67.
9. B. Aubert, L. Behr, V. Brisson, C. Pascaud, P. Petiau, E. Bellotti, A. Pullia, M. Baldo-Ceolin, E. Calimani, S. Ciampolillo, H. Hugita, A. Sconza. Oxford International Conference in Elementary Particles 1965, A114.
10. L. M. Brown and P. Singer, Phys. Rev. 133, B812

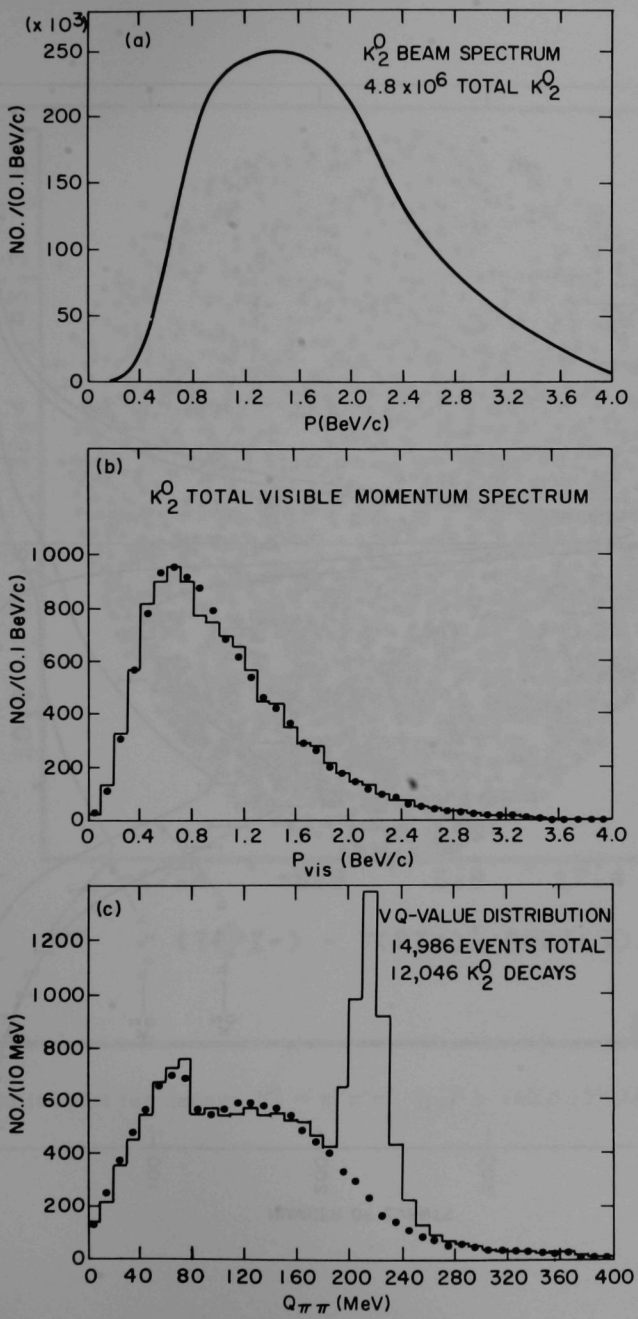

(x 10³)
(a)
K⁰₂ BEAM SPECTRUM
4.8 x 10⁶ TOTAL K⁰₂
NO./(0.1 BeV/c)
P(BeV/c)
(b)
K⁰₂ TOTAL VISIBLE MOMENTUM SPECTRUM
NO./(0.1 BeV/c)
P_vis (BeV/c)
(c)
V Q-VALUE DISTRIBUTION
14,986 EVENTS TOTAL
12,046 K⁰₂ DECAYS
NO./(10 MeV)
Q_ππ (MeV)

Fig. 1.

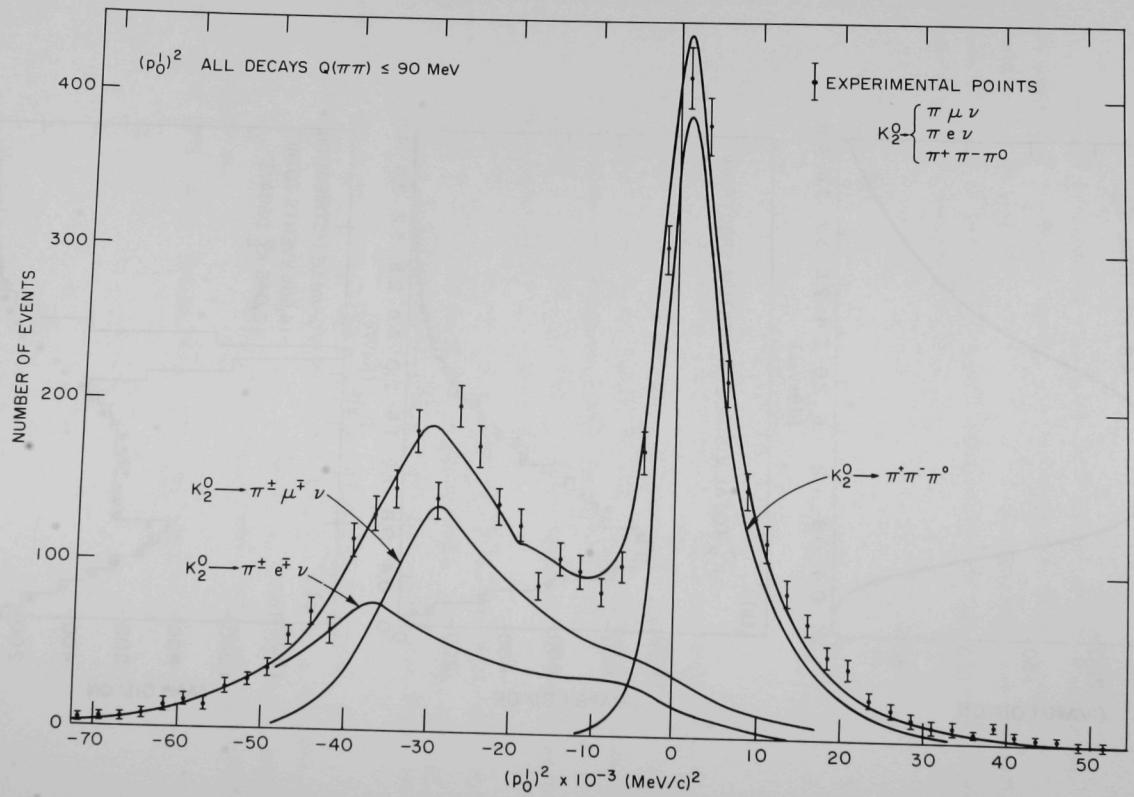


Fig. 2. Smooth Curve: Monte-Carlo Calculation

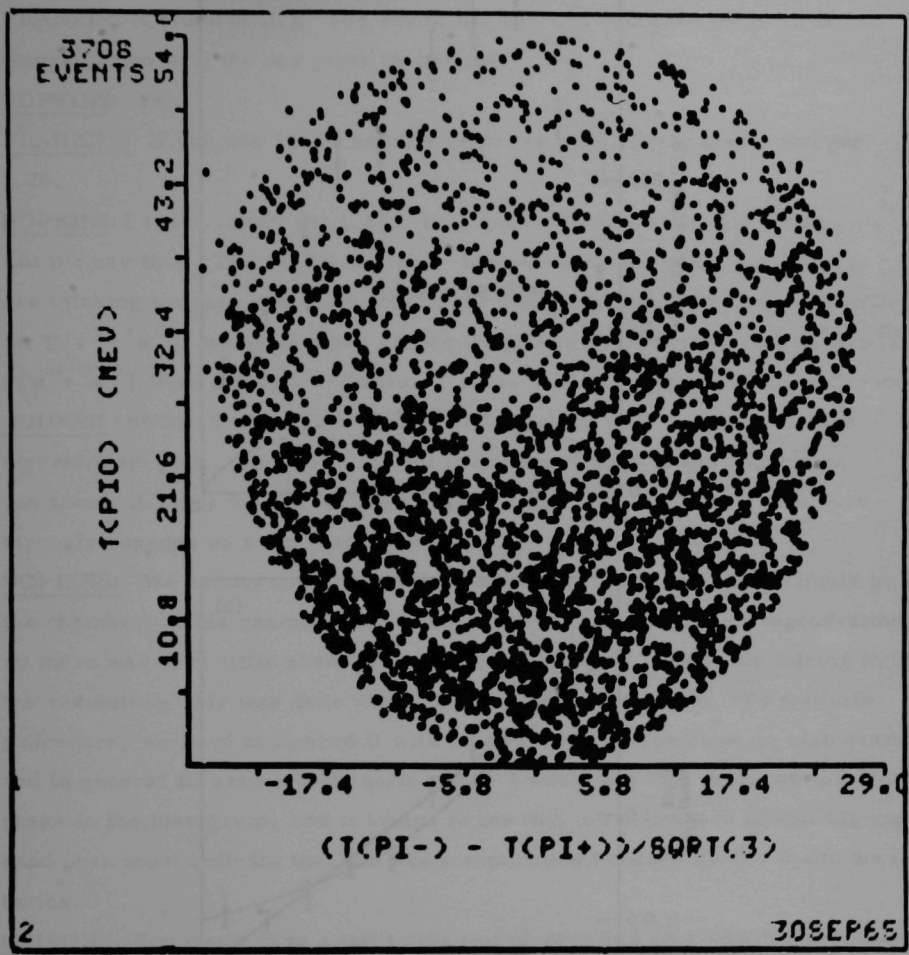


Fig. 3. Dalitz plot for decays $K_2^\circ \rightarrow \pi^+\pi^-\pi^\circ$, $(p_0')^2 > -10.0.10^3$ $(MeV/c)^2$

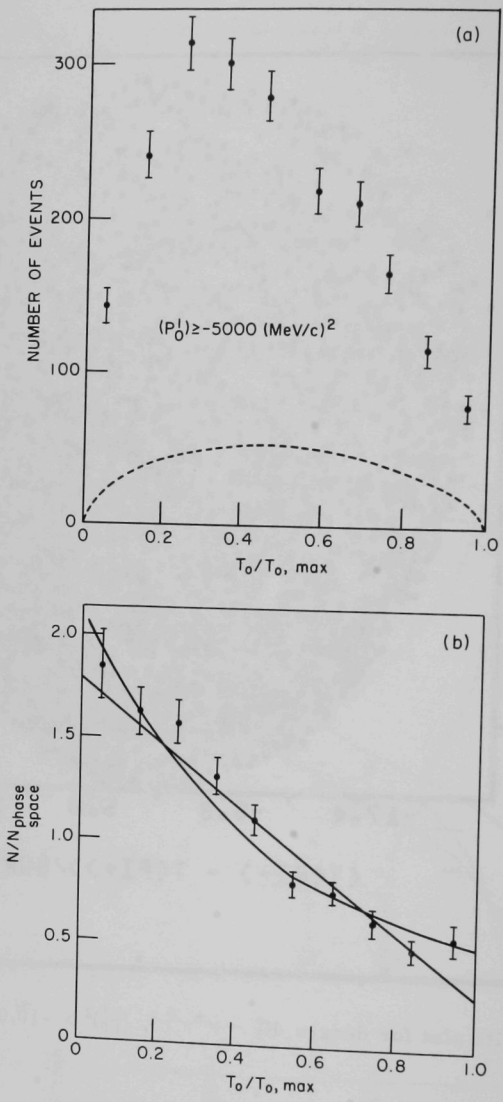


Fig. 4. K_2^0 τ' Decay
π^0 Kinetic Energy Spectrum

DISCUSSION

FRANZINI (Columbia U.): The result for $\Gamma(+ - 0)$ you have obtained is in contradiction with the one given by Samios.

HOPKINS: Yes.

FRANZINI: If you use 14.4% and the ratio $\Gamma(+ - 0) / \Gamma(\text{charged})$, you get 2.26.

HOPKINS: I see ... and I get 1.88. It is quite possible I did this wrong. Let me say this: The 14.4% is right. It may not be the same number you are thinking because you must remember that I took the experimental number for $\Gamma(\pi^+\pi^-\pi^0)$, whereas other people frequently use the ratio of $\Gamma(\pi^+\pi^-\pi^0) / \Gamma(\pi^0\pi^0\pi^0)$ from the $\Delta I = 1/2$ rule. I agree still that there is a big difference.

GUIDONI (BNL): I would like to know if you folded your resolution in the discriminant plot. The discriminant is quite sensitive to the resolution you take. In other words, what you get on the left of 0 for the 3 pion decay strongly depends on your resolution.

HOPKINS: We had no absorber in the beam, apart from the actual liquid in the chamber. This chamber was designed to look at things like regeneration, so there was very little absorber in front of the beam. As to the folding in of the resolution, this was done with a Monte-Carlo calculation. To test this procedure, we have compared it with many different experimental histograms, and in general fit seems to be quite good. I would say that there were 2 clear peaks in the histogram, and it seems to me that the occurence of that big right hand peak must indicate that one has a separation between the + - 0 and the leptonics.

GUIDONI: You could have a tail to the left of zero and so a smaller branching ratio.

HOPKINS: I see your point. However, we believe our resolution and thus believe the separation is effected without serious error.

PRELIMINARY RESULTS ON THE CHARGED DECAY MODES OF K_2^o

P.Basile,* J.Bingert,J.W.Cronin,** B.Thevenet,R.Turlay,S.Zylberach,A.Zylberstejn

L.P.C.H.E., C.E.N. Saclay, France

(Paper presented by R. Turlay)

We present here some very preliminary results of an experiment now being analysed at Saclay . We have observed the charged decay modes $\pi e \nu$, $\pi \mu \nu$, $\pi^+ \pi^- \pi^o$, $\pi^+ \pi^-$ of the K_2^o .

The K_2^o are produced in a uranium target placed in a curved section of Saturne , and a neutral beam at 90° to the incident proton direction is defined by collimators and sweeping magnets . The decays take place in a thin foil spark chamber filled with helium , placed 7 meters from the target . The momentum of the decay products is measured by 2 magnets of 150 x 30 cm aperture placed parallel to the beam and followed by thin foil spark chambers . Figure 1 shows a view of the apparatus . The particles are identified by their range in aluminum and brass spark chambers . The K_2^o spectrum extends from 100 to 700 Mev/c with a peak at 275 Mev/c . The kinematic reconstruction allows in general 2 solutions for the K momentum . The low energy of the K_2^o's and the geometrical selectivity of the apparatus give center of mass energies (E_1,E_2) which differ in general by less than 10 Mev between the two kinematic solutions .

We have taken $2x10^5$ pictures , which correspond to $5x10^4$ K_2^o decays . We give preliminary results for 2730 events which are distributed in the following categories .

1070 K_{e3}
810 $K_{\mu 3}$
200 $K_{\pi 3}$
13 $K \rightarrow \pi^+ \pi^-$

In addition there are 630 not yet identified . 320 events appear with ranges which are too short . The majority of these appear to be K_{e3} for which the electron develops a shower very rapidly .(In general the electrons are identified by having a range too long for a π or μ of the given momentum). 310 events appear with ranges which are too long , corresponding to $\pi^+ \rightarrow \mu^+ \rightarrow e^+$decays or $\mu^+ \rightarrow e^+$ decays which occur during the 300 ns required to trigger the chambers .

---

* On leave of absence from C.N.R.S. , Marseille

** A P.Sloan Foundation Fellow and N.S.F. Senior Postdoctorate Fellow

16 events are identified as $\pi^+ \pi^-$ decays . The range of the secondaries is consistent with pions .(Either exactly as predicted , or too short because of interaction). The mass of the events lies between 480 and 520 Mev and $\cos \theta > .999$. Of these 16 events , 3 correspond to a background from K_{e3} events with the range of the electron too short . We observe 13 events $(\pi^+\pi^-)$ in 2730 charged decays . Taking account of the relative efficiencies of the various decay modes by Monte Carlo techniques , we obtain a ratio

$$\frac{K_2^o \longrightarrow 2\pi}{K_2^o \longrightarrow \text{charged modes}} = (1.5 \pm 0.6) \times 10^{-3}$$

The average momentum of these events is 300 Mev/c , and they are.65 mean lives from the target .

The electron and pion spectra obtained for the K_{e3} events are given in figure 2 . We have compared these spectra by means of the Monte Carlo method with pure scalar,vector or tensor interactions with constant form factors . The best agreement is with the vector interaction . No firm conclusion can be drawn at this time because a large number of ambiguous events come from K_{e3} .

The muon and pion spectra for $K_{\mu 3}$ are shown in figure 3 . The data do not agree with a pure or tensor interaction , but fit the vector interaction very well . A χ^2 calculation indicates that $\xi = f_+/ f_-$ lies between the limits - 2.0 and + 0.5 . These fits have been made with constant form factors .

The $K_2^o \longrightarrow \pi^+\pi^-\pi^o$ events are selected by two criteria , the range of the pions , and the fact that the effective mass must be less than 365 Mev . The spectrum of the π^o's shows a depopulation at low energy that we cannot explain by an experimental bias . In figure 4 we have plotted the spectrum of the π^o divided by phase space and corrected for the efficiency of our apparatus . On the graph we have plotted a line $A (1 + \alpha T_\pi / M_K)$ representing the form of the spectrum suggested by Weinberg [3] . The value $\alpha = - 7.3$ represents the fit of Astbury et al.[4] . Other groups have also observed a similar disagreement with the linear spectrum at low π^o energy [1,2] .

References

1) A.Abashian et al.,Dubna International Conference , 1964 .

2) D.Luers et al., Phys. Rev. 133 , B1276 , 1964 .

3) S.Weinberg, Phys. Rev. Letters 4 , 87 , 1960 .

4) P.Astbury et al., Phys. Letters 18 , 175 , 1965 .

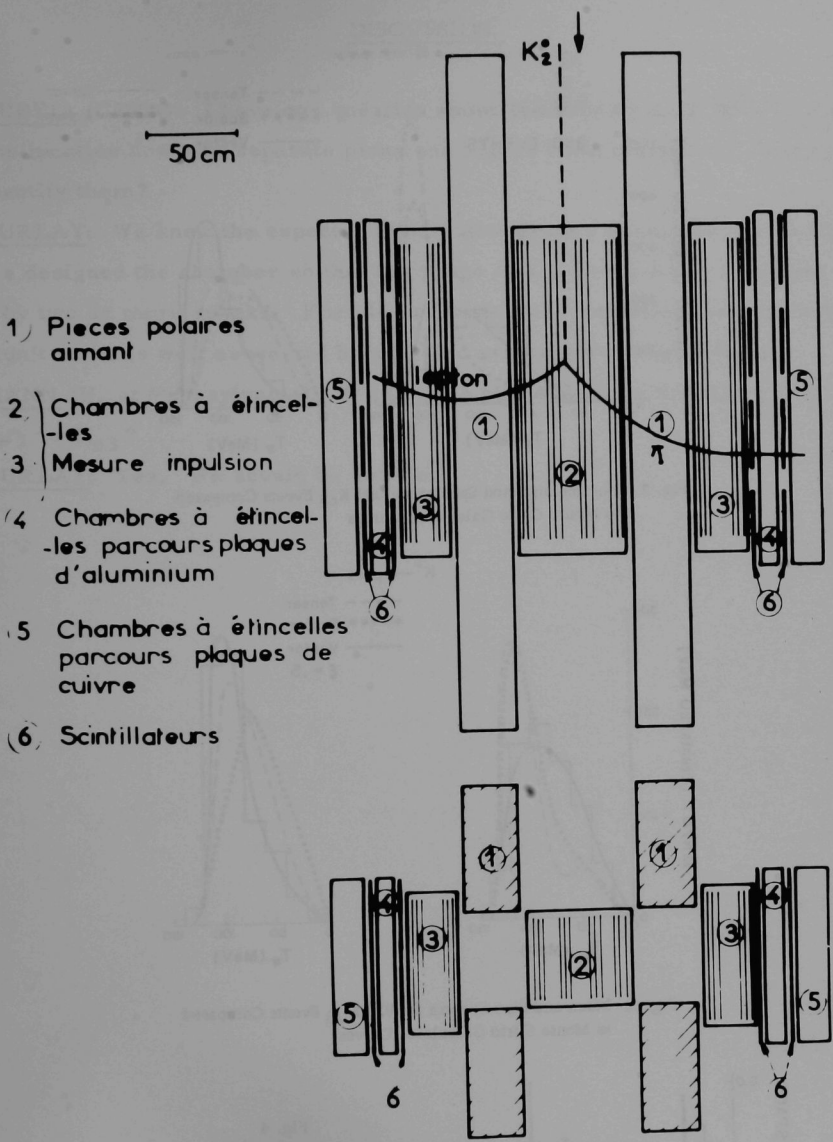


Fig. 1. Experimental Setup

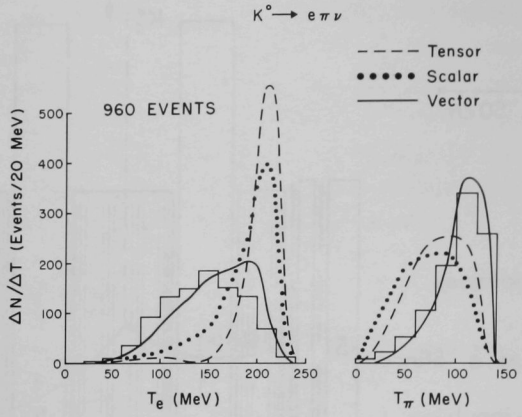


Fig. 2. Electron and Pion Spectra for 960 K_{e3} Events Compared to Monte Carlo Calculated Curves

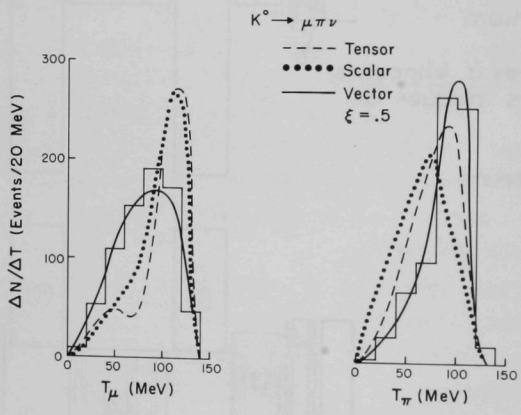


Fig. 3. Muon and Pion Spectra for 810 $K_{\mu 3}$ Events Compared to Monte Carlo Calculated Curves

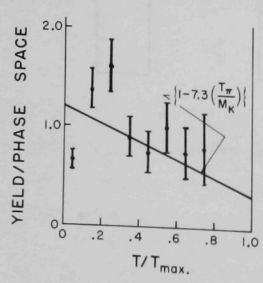


Fig. 4

Spectrum of the π^0 c.m.s. Kinetic Energy. The straight line is not fitted to this spectrum, but the coefficient α is obtained from reference 4.

DISCUSSION

RUBBIA (CERN): I have one question about the experimental detail. Could you mention how you separate pions and muons from electrons? How do you identify them?

TURLAY: We knew the expected distribution from a Monte-Carlo calculation. We designed the chamber so that the range of a μ would differ from that of a π by two or more sparks. For electrons we were expecting showers but it didn't work as well as we had hoped. We are still working on that.

MANN (U. of Pennsylvania): Will you be able to get the branching ratio of $K_{\mu 3}$ to K_{e3}?

TURLAY: Yes. We should be able to.

The Energy Dependence of the Vector Form Factor in the K°_{e3} Decay*

by

G. P. Fisher, A. Abashian, R. J. Abrams, D. W. Carpenter,
B. M. K. Nefkens, J. H. Smith, and A. Wattenberg
Physics Department
University of Illinois
Urbana, Illinois

(Paper Presented by A. Wattenberg)

Before I report the results of experiments on K°_{e3} decays I would like to spend three minutes discussing the fact that one expects the form factors of the vector part of the weak interactions to have an energy dependence. In the theory of Feynman and Gell-Mann it is assumed that the vector part of the weak interaction is the same as the electromagnetic interaction. An example of this is that in the neutrino experiments one expects that the vector part of the form factor will be the same as the form factors observed in electron scattering on protons, namely that at the strong vertex there will be the same form factor for p-p and e-e scattering as there is for P-N and ν-e. The analysis of the experiments seems to bear this out, although there is the complication that there is also an axial vector form factor about which we have no information from electromagnetic scattering. The vector octet containing the ρ, ω, and ϕ were actually predicted from the analyses of the early measurements of electromagnetic form factors.

* This work was supported in part by the U. S. Atomic Energy Commission and the Office of Naval Research.

Cabbibo[1] extended the ideas of Feynman and Gell-Mann to the strangeness changing decays and one might expect that the K^* would enter into the form factors for strangeness changing decays in the same way as the other members of the octet are supposed to enter. Specifically, in our experiment we are looking at the form factor in the reaction $K^{\circ}_{e3} \rightarrow \pi^{\pm} + e^{+} + \nu$. There have been theoretical papers published on this, the first by MacDowell and Acioli,[2] later ones by Jackson and Schult[3] and by Dennery and Primakoff.[4] One would expect in this case that f_+ would have a form

$$f_+(q^2) = C \frac{M_{K^*}^2}{M_{K^*}^2 - q^2}$$

where q is the sum of the four momenta of the leptons $q^2 = M_K^2 + m_\pi^2 - 2M_K E_\pi$. If other particles beside the K^* contribute, we get a multi-parameter expression for the form factors. The form factor that one would like to compare this to in electromagnetic interactions is that of the π-e scattering. More precise experiments like those of Leipuner et al.[5] are necessary before a comparison can be made.

I would now like to describe the experiment that was performed at the Brookhaven National Laboratory. The first slide (Fig. 1) shows the spark chamber array that was 67 feet from the AGS target. The K°_2 mesons decayed inside the vacuum pipe. The vacuum pipe was inside a magnetic field and the momentum of the decay particles was measured in the spark chambers inside this magnet. The electrons were identified in shower spark chambers. The next slide (Fig. 2) shows why we believe we are dealing predominantly with a vector type interaction in this decay. This slide shows a cut through the Dalitz plot at a constant energy of

the neutrino. The next slide (Fig. 3) shows the energy dependence of the form factor we obtained in this experiment. What is plotted here is actually the form factor which is the square root of the density in a Dalitz plot divided by the theoretical expectations with a form factor that is independent of energy.

There have been several other experiments on K_2^0 decays. One of the earliest was that by Luers et al.[6] and the next slide (Fig. 4) shows their results. In this slide the square of the form factor is plotted, but one sees again that there is an increase in the density of points at lower π energies. I, unfortunately, do not have a slide of the results of N. Petrov et al.[7] performed at the Dubna machine. Approximately the same energy dependence fits the data for $K^{\bullet}_{\mu 3}$ decay which is reported by Carpenter et al.[8]

To be quantitative we have made a maximum likelihood fit of the data using a single mass parameter. We obtained $M = 480^{+100}_{-30}$ Mev from statistics alone. The limits are where the maximum likelihood curve goes to 1%. We have naturally been concerned about the possibilities of systematic errors, some effects which are of the order of 5% still need further investigation. However, one of the things we have done to get an idea of the effect of systematic errors is to add a uniform background of 17% and this shifts the mass parameter to 460 Mev. If we subtract a uniform background of events of 17% the mass becomes 530 Mev. If one adds the statistical error, to this range of values one finds that the mass is between approximately 430 and 660 Mev. We are using this as an example of the effect of systematic errors. I do not believe there are systematic errors of this magnitude.

As a final word I would like to say that it is very disconcerting that the form factor measured for the K^+ (the charged K) by Jensen, Shacklee, Roe and Sinclair[9] seems to be independent of energy; their statistical error converted into mass units corresponds to a mass of over 1000 Mev.

References

1. N. Cabibbo, Phys. Rev. Letters 10, 531 (1963).
2. S. W. MacDowell and J. Acioli, Nuovo Cimento 24, 606 (1962).
3. J. D. Jackson and R. Schult, University of Illinois Technical Report.
4. P. Dennery and H. Primakoff, Phys. Rev. 131, 1334 (1963).
5. L. Leipuner (Private Communcation).
6. D. Luers, I. S. Mittra, W. J. Willis, and S. S. Yamamoto, Phys. Rev. 133, B1276 (1964).
7. N. Petrov et al., Report at International Conference on High Energy Physics (Dubna 1964).
8. Report by A. Abashian at this conference, also D. Carpenter et al. submitted to Phys. Rev.
9. G. L. Jensen, F. S. Shaklee, B. P. Roe, and D. Sinclair, Phys. Rev. 136, B1431 (1965).

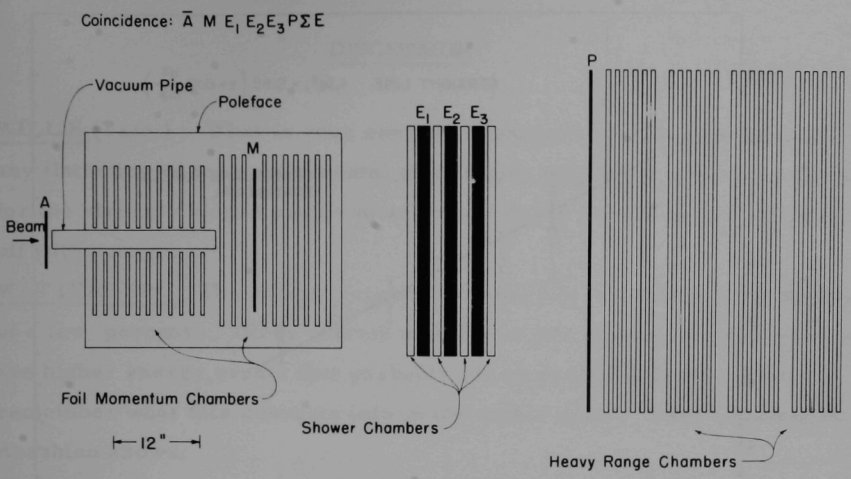


Fig. 1. K_2^0 Detection System

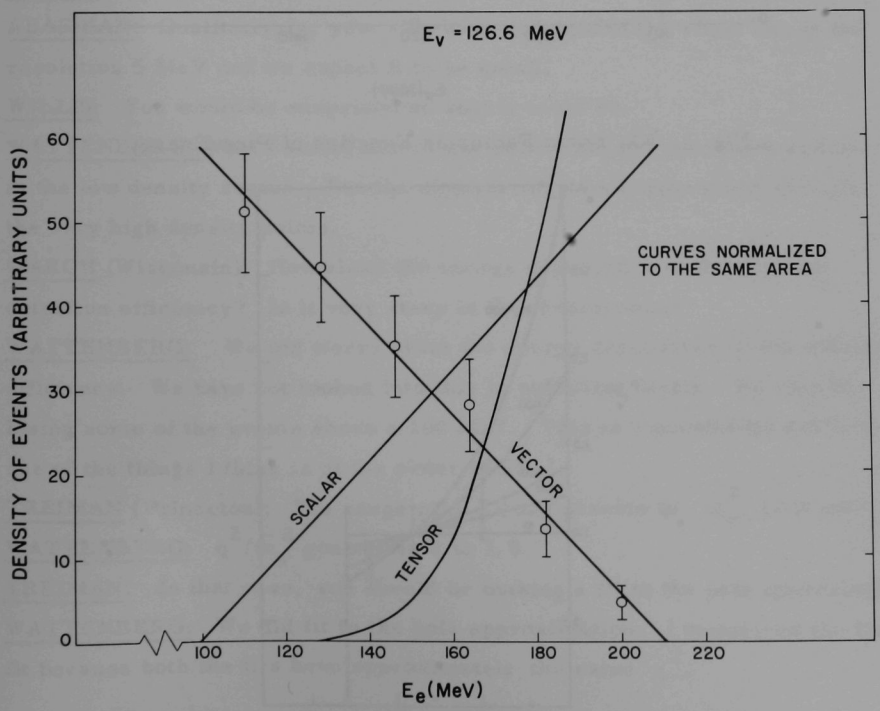


Fig. 2. Density of Events (Corrected for Efficiencies) as a Function of E_e with Constant E_v

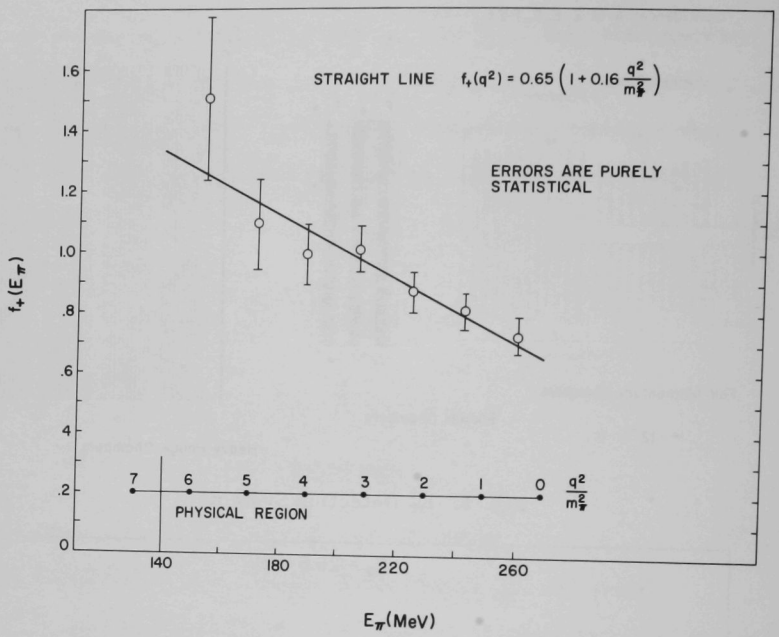


Fig. 3. K^0_{e3} Form Factor as Function of Pion Energy

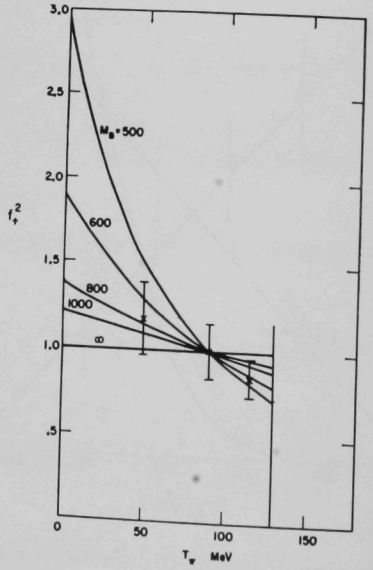


Fig. 4

DISCUSSION

WILLIS (Yale) : What is your energy resolution? The reason I ask is that any flattening of the experimental distribution will (when divided by the shape for the strongly sloped vector interaction) shows a form factor which falls off with energy.

WATTENBERG: The energy resolution in the lab, I would say, is the order of a few percent. Three percent would be a fair statement. Certainly there are higher energy events that probably get up to 5%. I do not, off-hand, remember what this converts into in the center mass. I don't know if Al Abashian knows.

ABASHIAN (Illinois): Typically it is less than about 5 MeV.

WILLIS: Have you considered this effect?

ABASHIAN: Qualitatively, yes. We have considered the effect due to the resolution 5 MeV and we expect it to be small.

WILLIS: You would be surprised at what it could do.

WATTENBERG: What I would like to say is that you get enormous effects in the low density region. But the slope is very well determined with just the very high density points.

MARCH (Wisconsin): How about the energy dependence of the electron detection efficiency? Is it very steep in this experiment?

WATTENBERG: We did worry about the energy dependence of the electron efficiency. We have not looked into this in sufficient detail. We may be losing some of the events above a 100 MeV. This is a possibility and it's one of the things I think is of the order of 5%.

TREIMAN (Princeton): The range of q^2 is comparable to m_π^2, is it not?

WATTENBERG: q^2/m_π^2 goes from 0 to 7.0.

TREIMAN: In that case, you should be making a fit to the pole approximation.

WATTENBERG: We did fit to the pole approximation. I mentioned the linear fit because both the fits have approximately the same χ^2.

CHILTON (ANL): I'm just finishing some work on the electromagnetic form factors of the nucleon. Our results suggest that the reason that the ρ seems to have a mass which is too low when you use a single pole expression is due to the fact that there is a non-negligible nonresonant background, and also there is a second pole. I would suggest, in fact, that the mass in the form factor here should be lower than the K* mass. Although, frankly, I don't understand why it can be that much lower than the K* mass, even with a nonresonant background.

WATTENBERG: We have to wait and see. At present the indications are that the mass is in the range of 430 - 660 MeV.

MCDOWEL (Yale U.): There seems to be a much stronger slope in this K^o decay than in the K^+ decay. How do you explain this?

WATTENBERG: The explanations are all very odious, I think.

Spark Chamber Measurement of the $K_{\mu 3}^{0}$ Decay Spectrum*

D. W. Carpenter, A. Abashian, R. J. Abrams,
G. P. Fisher, B. M. K. Nefkens, and J. H. Smith

Physics Department, University of Illinois, Urbana, Illinois

(Paper presented by A. Abashian)

I. Experimental Details

The detection system is shown in Fig. 1. The useful K_2^o decays occurred in a vacuum pipe which was surrounded by a set of 1 mil aluminum foil spark chambers. The entire assembly was placed into a magnetic field of 10.2 kilogauss. Beyond the magnet was a system of counters, 10" lead absorber, and heavy plate spark chambers which were used for particle identification. In order for a particle to be identified as a μ meson, it was necessary for it to come to rest in the range chambers at a location consistent with the momentum measurement made in the magnet. The triggering scheme was given by $ME_1E_2E_3P$ coincidence in anti-coincidence with A. About 1400 $K_{\mu 3}^{0}$ events were finally accepted in the analysis.

II. Analysis

A. Type of Interaction

Under the assumption of a local bilinear coupling of the μ meson and neutrino, the transition rates for decay via scaler S, vector V, and tensor T, interactions are given respectively by

$$dW_S \propto f_S^2 \, (q^2)\,(W-E_\pi)\,dE_\mu dE_\nu \tag{1}$$

$$dW_V \propto \{[2M_K E_\mu E_\nu - M_K^2\,(W-E_\pi)]f_+^2 - M_\mu^2 E_\nu (f_+-f_-) + \frac{M_\mu^2}{4}$$

$$(W-E_\pi)\,(f_+-f_-)\}^2 \; dE_\mu dE_\nu \tag{2}$$

$$dW_T \propto f_T^2(q^2)\{[E_\mu-E_\nu)^2 - M_\mu^2](W-E_\pi)M_K + 2M_\mu^2 E_\nu^2\}dE_\mu dE_\nu \tag{3}$$

where W = maximum E_π .

q is the K-π momentum transfer. E_π, E_μ, and E_ν are the total energies of the particles π, μ, and ν and the f's are form factors which are functions of the pion energy only.

The distinction between S, V, and T interactions can be made by comparing the data for constant E_π with theory. Fig. 2 shows this comparison for three separate E_π bins. Each of the three bins is treated separately from the others in fitting data and theory. The fits to tensor and scalar interactions are poor whereas the vector fits for ξ = f-/f+ between -2.0 and +2.0 are quite good.

If the form factors are assumed to be linearly varying with q^2, we find that the best fit to the scalar interaction is given by $f_s = 1-0.129 \frac{q^2}{M_\pi^2}$ with χ^2/D.F. = 3.27 for 53 degrees of freedom. The vector interaction, on the other hand, gives a fit which is more probable statistically by a factor of about 10^6. The conclusion reached is that the interaction is predominantly vector.

B. Fit to Constant Form Factors

We now assume the interaction to be solely vector and attempt to make a one parameter fit to the data. The parameter $\xi = \frac{f_-}{f_+}$ is varied but is assumed to be constant throughout the Dalitz plot. The top graph of Fig. 3 shows the χ^2 and maximum likelihood fits to the data, obtained by comparing the number of points in 53 separate bins in the Dalitz plot with the number expected as a function of ξ. The best fit is given for $\xi = 1.3 \pm 0.4$ with a χ^2/D.F. = 0.99. The errors are based on counting statistics only. After correction for events where a π may have been misidentified as a μ and taking into account uncertainties in the magnetic field, K_2^o spectrum and triggering efficiencies, we arrive at a most probable value for ξ of

$$\xi = 1.2 \pm 0.8$$

With the assumption of μ-e universality; namely, that f_+ is the same in both $K_{\mu 3}$ and K_{e3} decay, ξ can also be determined from the ratio R of the total decay rates,

$\frac{K_2^o \to K_{\mu 3}}{K_2^o \to K_{e3}}$. In that case, $R = 0.65 \pm 0.124\ \xi + 0.019\,\xi^2$.

Combining the data of Luers et al. with that of Adair and Leipuner[2], we calculate $\xi = 0.8 \pm 0.8$ or -7.4 ± 0.8. Our result is in excellent agreement with the first value.

C. Fit to J = 1 Intermediate State

Assuming that the strong part of the interaction is dominated by a sharp K-π resonance or intermediate state, one can use dispersion theory to calculate the form factors in terms of the mass (M) of the resonant state. For a J = 1 state, the relations are:[3]

$$f_+(q^2) = \frac{f_+(0)}{(M^2-q^2)} \tag{4}$$

$$f_-(q^2) = -f_+(q^2)\ \frac{(M_K^2 - M_\pi^2)}{M^2} \tag{5}$$

The data were fitted with M as a free parameter. The results are shown in Fig. 4. The best fit occurs at $M = 530^{+50}_{-40}$ MeV, with $\chi^2/DF = 1.11$. The χ^2 percentile is 73%, a reasonable fit.

The pion contamination is estimated to contribute an error in M of $-(10^{+50}_{-40})$ MeV. (A 16% uniform background subtraction raises M by 10 MeV.) The efficiency, field, and beam spectrum uncertainties each contribute errors of about $\pm$ 20 MeV. Thus we find:

$$M = 540^{+140}_{-\ 70}$$

The mass of 540 MeV for the K-π intermediate state is lower than one might expect. The known K-π resonances occur at 891 MeV (J = 1) and 725 MeV (J unknown), both too high for the observed effect. The discrepancy could mean that a single sharp resonance does not dominate the interaction as assumed in (4) and (5). The data can be fit well with a combination of the two resonances or with either mass combined with a very high mass.

D. Fit to Linearly Varying Form Factors

If we let both form factors vary linearly with q^2, we may specify the theory in terms of three parameters: ξ_o, A_+ and A_-:

$$f_+ (q^2) = 1 + A_+(q^2/M_\pi+^2) \tag{6}$$

$$f_- (q^2) = \xi_o + A_- (q^2/M_\pi+^2) \tag{7}$$

Here, $\xi_o = f_-(0)/f_+(0)$, while A_+ and A_- give the rate of variation of f_+ and f_-.

Fig. 5. displays the results of the three parameter fit. For various values of A_+, curves are drawn along lines at which the combination of A_+, A_- and ξ_o gives $\chi^2/DF = 1.50$ (DF = 51), and are intended to represent reasonable error limits for the various values of A_+. The best fit occurs at $\xi_o = 5.6$, $A_+ = -0.01$, and $A_- = -0.6$ with $\chi^2/DF = 0.92$ (36%). These values should not be taken too seriously as deviations are large and strongly correlated.

The measured value of $R(K_{\mu 3}/K_{e3})$ restricts the values of the parameters allowed in Fig. 5. The shaded areas are the regions allowed by $R = .77 \pm .12$, based on the calculations of Jackson and Schult.[4]

E. Investigation of Charge Asymmetry

To look at possible CP violations, the equality of the Dalitz plots of $K_2^o \rightarrow \pi^+ + \mu^- + \nu^-$ with that of $K_2^o \rightarrow \pi^- + \mu^+ + \nu$ is examined. Because the magnet has the tendency to cause all particles of a given sign to be swept in one direction, we found that at the entrance to the range chambers, almost all particles of a given sign were on one side of the beam line. If the counters to the left of the beam are not equally efficient with the counters to the right, asymmetries develop in the μ^+/μ^- rate. We find that such biases do exist if we calculate μ^+/μ^- for each sign of the magnetic field and sum over all the counters. This ratio is 1.02 for one field orientation and 1.20 for the other orientation. To eliminate possible counter inefficiencies, misalignments, and biases, we chose to compare μ^+ mesons with magnetic field up with μ^- mesons with magnetic field down and vice versa.

The raw data plotted in this fashion is shown in Fig. 6. Qualitatively, it appears as if the agreement between the μ^+ and μ^- Dalitz plots is not striking. Integrating over μ meson energies, we get π meson energy spectra as shown

in Fig. 7. We see that both counters give very much the same spectrum for π^+ and also independently for π^-. If we compute a ratio $S = \frac{\mu^+}{\mu^+ + \mu^-}$ for each counter alone, we find $S = 0.525 \pm 0.021$ for the first counter and $S = 0.522 \pm 0.021$ for the second.

To arrive at a quantitative measure of equality of the spectra, we have computed the value of S for each counter separately and for pion energy bins of 20 MeV. The weighted average of the values of S for the two counters was made and plotted as a function of T_π as shown in Fig. 8. We assumed that $S = 0.500$, and a least squares analysis was made to this hypothesis. The χ^2 calculated was 14.2 for six degrees of freedom indicating a 2% probability for the goodness of fit to the assumptions of equality. In doing further analyses by varying bin width or doing a Monte Carlo program to look for the sign of the closest neighbor to a point in the Dalitz plot, we found the χ^2 to change up to a probability of 10%. We, therefore, choose to state the result by saying there is probability of less than 10% that the μ^+ and μ^- spectra are identical. The results indicate that further work of appreciably higher statistics is necessary before the question of equality and CP conservation can be answered.

F. Search for Neutral Currents

We examine here another apparent phenomenological rule, the prohibition of neutral leptonic currents. This rule prohibits the decays $K_2^\circ \rightarrow \mu^+ + \mu^-$, $e^+ + e^-$, and $\mu^\pm + e^\mp$. Among the events of both the $K_{\mu 3}$ run and the accompanying K_{e3} experiment, we find:

0 candidates for e^+e^-
1 candidate for $\mu^+\mu^-$
3 candidates for $\mu^\pm e^\mp$.

In each case, the event satisfies the decay kinematics. The reconstructed K mass is between 480 and 520 MeV and the K direction is within 20 miliradians of the beam direction. In each case, the given identity of the products cannot be ruled out, but in no case, are both products identified by their behavior in the shower or range chambers. The upper limit on the branching ratio we obtained is

$$B = \frac{K_2^\circ \rightarrow ee,\ \mu\mu,\ \text{or}\ \mu e}{K_2^\circ \rightarrow \text{charged modes}} \approx 10^{-4} .$$

REFERENCES

1. D. Luers, I. S. Mittra, W. J. Willis, and S. S. Yamamoto, Phys.Rev. 133, B1276 (1964).
2. R. K. Adair and L. B. Leipuner, Phys.Letters 12, 67 (1964).
3. J. L. Acioli and S. W. MacDowell, Nuovo Cimento 24, 606 (1962).
4. J.D. Jackson and R. L. Schult, Technical Report No. 43, Physics Department, University of Illinois, (1962).

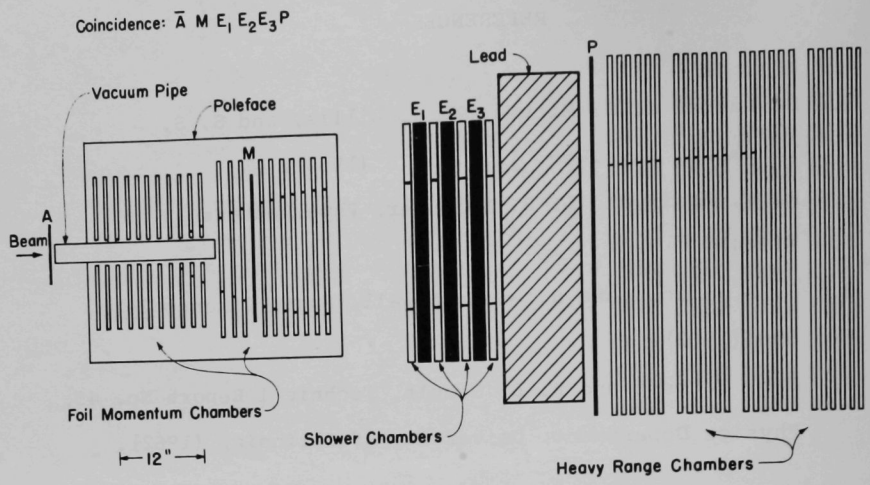


Fig. 1. K_2^0 Detection System

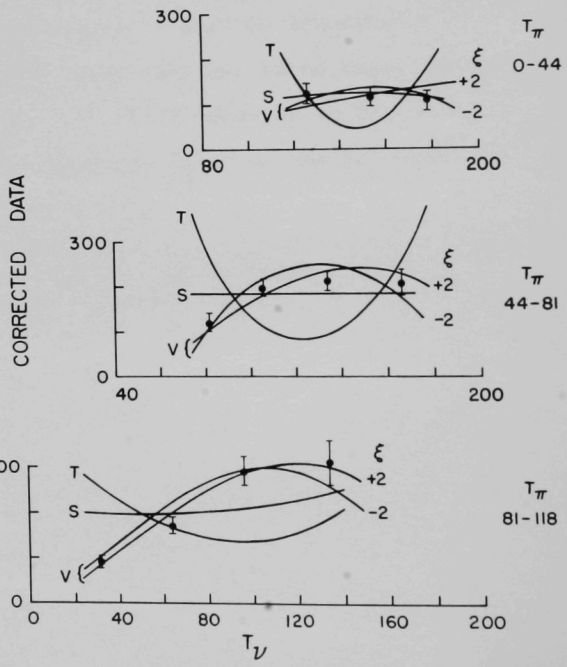


Fig. 2. Comparison of S, V, and T Curves with Data

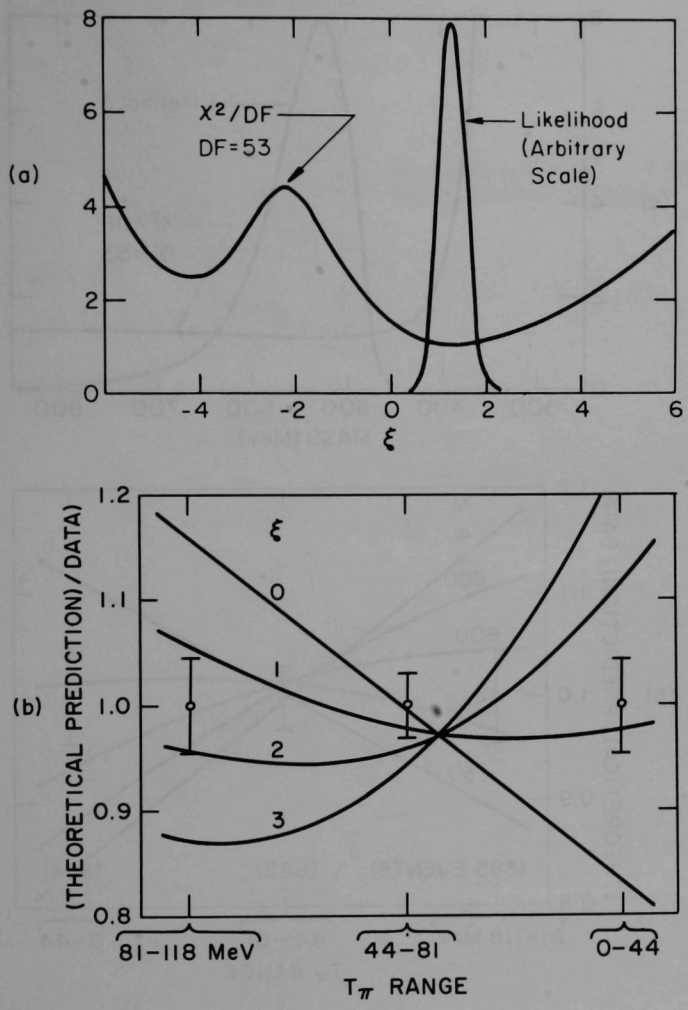


Fig. 3. Fit with Constant Form Factors

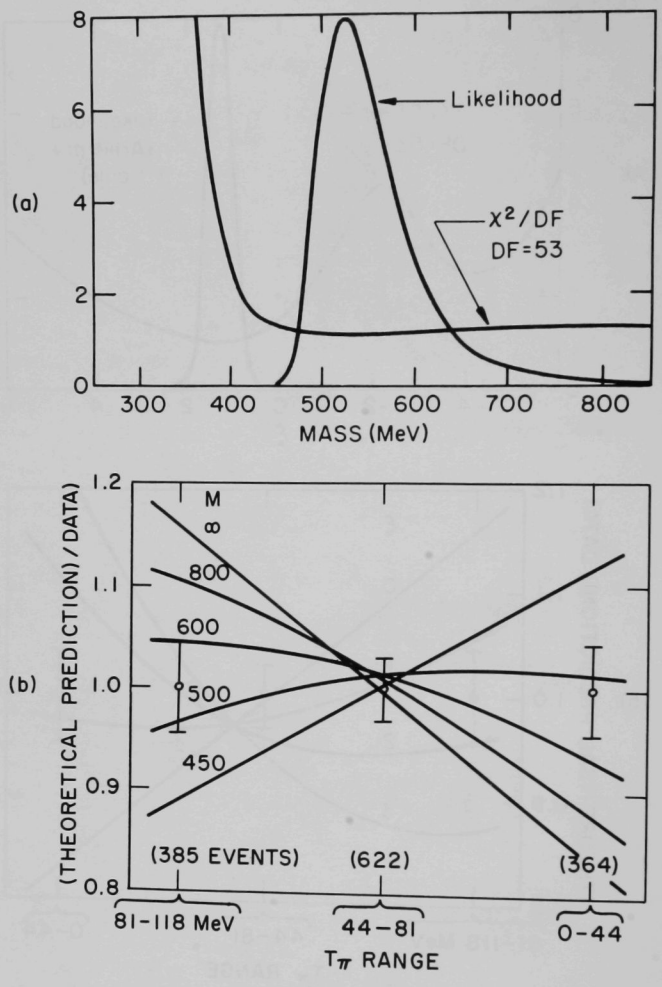


Fig. 4. Fit with Spin I Intermediate State

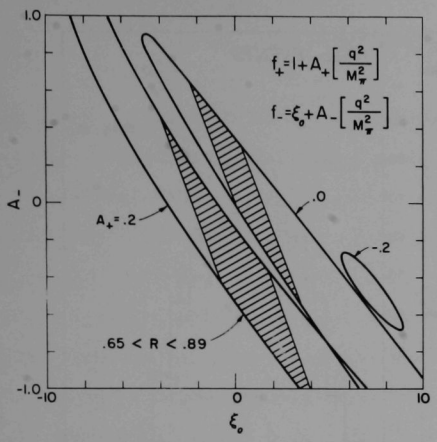


Fig. 5

Three Parameter Fit with Linearly Varying Form Factors

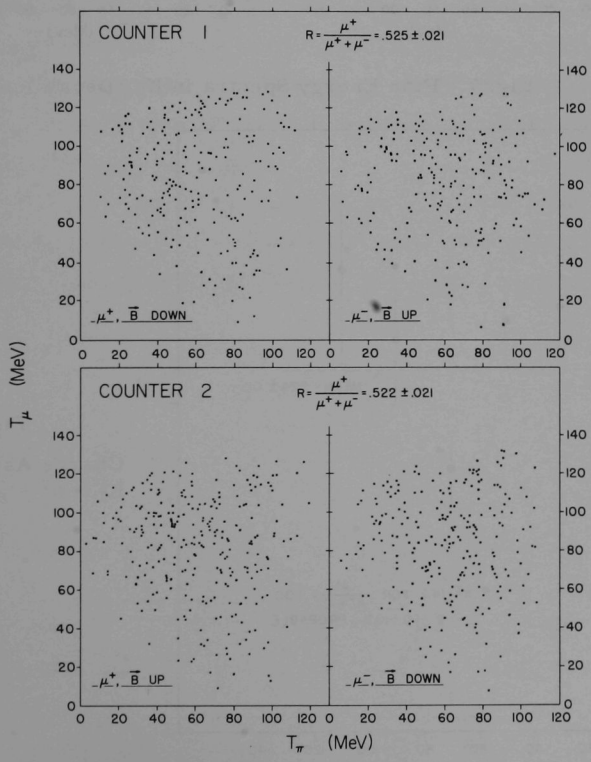


Fig. 6. $K\mu_3$ Dalitz Plots, 30 BeV

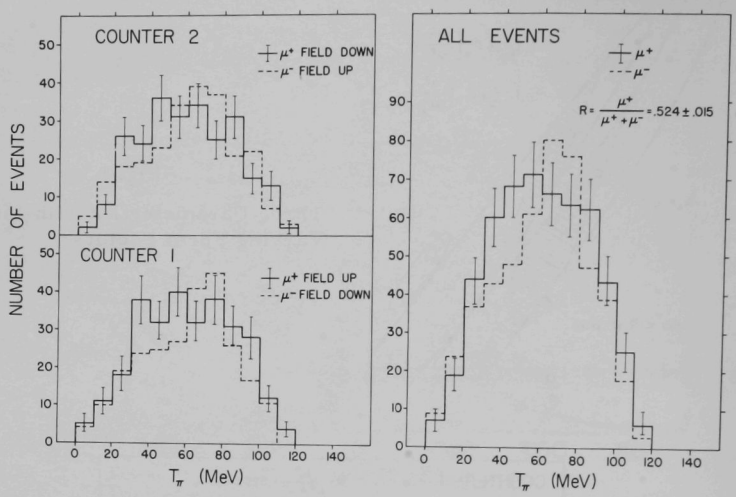


Fig. 7. Pion Energy Spectra in $K\mu_3$ Decay

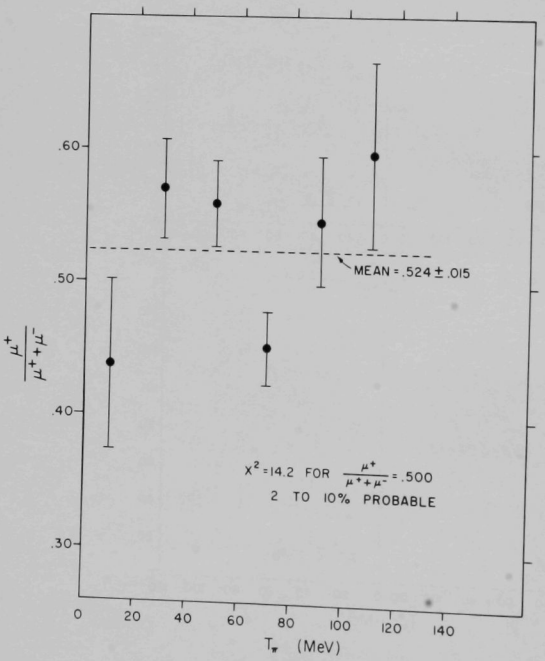


Fig. 8

Charge Asymmetry in $K_2^0 \rightarrow \pi^{\pm} + \mu^{\mp} + \nu$ Decay

DISCUSSION

MARSHAK (Rochester): In writing down the expression for f_-, for which you deduce this low value of m, I should point out that the standard procedure to estimate the f_+ and f_- on the basis of pole approximation, is to say that f_+ is dominated by K*. For f_- one assumes a Goldberger-Treiman type relation for the divergence of the strangeness violating vector current. This, you can argue, is determined by a scalar pole. If you identify the scalar meson pole with $\kappa(725)$ then the value that one obtains for ζ-parameter is -0.14. In general, therefore, one should consider contributions from two poles -- symbolically a vector meson K* and a scalar meson κ. If the K* mas is larger than the κ mass (as is the case if we identify the mesons as K*(888) and $\kappa(725)$), then you get a negative value for ζ. If, however, the effective mass of K* is less than κ, which is what Wattenberg was saying, then you get a positive value. If it gets very close to κ you can make it substantially bigger than 0.1 or so. All the numbers so far have been going in the direction of positive values of ζ, I believe. They are small positive values. Anyway, I do want to point out that you have to consider another pole in f_-.

K^+_{e2} BRANCHING RATIO*

D. R. Bowen, A. K. Mann, and W. K. McFarlane

University of Pennsylvania

A. D. Franklin, E. B. Hughes, R. L. Imlay,
G. K. O'Neill, and D. H. Reading

Princeton University
(Paper presented by W. K. McFarlane)

An attempt has been made to detect the $K^+ \rightarrow e^+ + \nu$ (K^+_{e2}) decay mode using spark chamber and counter techniques. The pure leptonic decays of the charged π and K mesons provide stringent tests of the (V-A) theory of weak interactions. Thus the agreement between the predicted ratio of rates for the decays $\pi^+ \rightarrow e^+ + \nu$ and $\pi^+ \rightarrow \mu^+ + \nu$ and the observed ratio represents one of the highlights of the Universal Fermi Interaction theory. The analogous decays for the kaon, $K^+ \rightarrow e^+ + \nu$ and $K^+ \rightarrow \mu^+ + \nu$, involve a change of strangeness and much higher relative momenta of the leptons. Assuming the kaon to be pseudoscalar, pure axial vector (A) coupling predicts the ratio $K^+_{e2}/K^+_{\mu 2} = 2.6 \times 10^{-5}$ (without radiative corrections), while a pure pseudoscalar (P) interaction predicts 1.02 for the same ratio. A small admixture of pseudoscalar coupling in a predominantly axial vector interaction greatly increases the calculated K^+_{e2} rate. For example, if the P and A amplitudes are in the ratio of 10^{-3}, the K^+_{e2} rate is 4 times the pure A value. Clearly even a rough measurement of the K^+_{e2} rate is of interest in detecting the presence of a P amplitude in the weak interaction of kaons.

---

* Work performed under the auspices of the U.S. Atomic Energy Commission.

The experimental arrangement is shown in Fig. 1. A stopping K^+ beam was set up at the Princeton-Pennsylvania Accelerator which yielded 500 stopped, identified K^+ mesons per second. Particles which left the stopping region at right angles to the incident beam passed through a series of thin plate spark chambers situated in a magnetic field about 2 ft. long, which permitted measurement of the particle momentum with a standard deviation of 2 percent. The spark chambers were photographed in a 90 degree stereo system. A threshold gas Cerenkov counter, set to detect only high momentum electrons, was placed behind the magnetic field region, and fixed the relative solid angle at 0.7×10^{-2}. This counter had a measured efficiency greater than 95 percent for electrons of about 250 MeV/c and about 0.3 percent for other particles of comparable momentum. Finally, a thick plate spark chamber was placed behind the Cerenkov counter to permit observation of the particles emerging from that counter and measurement of their total range.

For much of the experiment counters which detected gamma rays were used to suppress events accompanied by a π^o, e.g., $K^+ \rightarrow \pi^o + e^+ + \nu$. The spark chambers were triggered by a coincidence between a stopped K meson and a decay electron, with the additional requirement of no detected gamma ray. The time between the K^+ stop and the decay electron was recorded.

The electron from K^+_{e2} decay has a momentum in the kaon center of mass of 247 MeV/c, which is higher than that of any other direct decay product of K^+. The principal sources of background high momentum electrons in this experiment were: (1) $K^+ \rightarrow \pi^o + e^+ + \nu$, with a maximum

electron momentum of 228 MeV/c and a branching ratio of 5 percent and, (2) $K^+ \rightarrow \mu^+ + \nu$ followed by $\mu^+ \rightarrow e^+ + \nu + \bar{\nu}$, with a maximum electron momentum of 247 MeV/c and a branching ratio of about 1.2×10^{-4} per foot of muon path.

Due to the momentum resolution of 2 percent we expect the K^+_{e3} contribution to the background to be less than 5 percent of the predicted K^+_{e2} rate. In the experimental arrangement of Fig. 1, decays in flight of muons from $K^+_{\mu 2}$ decays occur over a total length of 5.5 feet. The decay electrons are usually emitted at large angles to the muon flight path and with a widely different momentum. From the 4" region between the stopping region and the end of the first module of the momentum chamber a background contribution of less than 4 percent is expected. In the momentum chamber, the spatial and momentum resolution make the contribution of muon decays in flight less than 10 percent. Most of the decays which occur between the momentum chamber and the exit of the Cerenkov counter can be excluded by comparing the measured position of the track entering the range chamber with the track extrapolated from the momentum chamber. The accuracy of this comparison is limited by multiple scattering. The fraction of muons which decay in this region and which satisfy our matching criteria is about 5×10^{-5}, or about twice the expected K^+_{e2} rate. It should be emphasized that these events will have a measured momentum appropriate to muons from $K^+_{\mu 2}$ decay since the decays occur after the momentum chamber.

In Fig. 2, the distribution in momentum of 4781 events is shown. These events satisfy the criteria that they emerged from the K^+ stopping region, traversed the Cerenkov counter, and were observed in the thick plate spark chamber. Here the K^+_{e3} spectrum falls off rapidly below $p \simeq 160$ MeV/c because electrons with lower momentum are deflected

by the 7 kilogauss magnetic field to miss the Cerenkov counter. The 700 events in the peak at 236 MeV/c and about 150 events at 205 MeV/c are largely the result of accidental coincidences between accelerator produced background in the Cerenkov counter and muons and pions from the $K^+_{\mu 2}$ and $K^+_{\pi 2}$ decays, respectively. The momentum scale was calibrated by using the known momentum of the $K^+_{\mu 2}$ peak. The $K^+_{\mu 2}$ peak is smaller by a factor of 300 than would be obtained without the Cerenkov counter. It is possible to eliminate by a range cut most of the events in the $K^+_{\mu 2}$ peak which have a measured mean range of 67 gm/cm^2 of aluminum with a straggle of about 4 gm/cm^2. High momentum electrons have an average apparent range of roughly one radiation length, or about 27 gm/cm^2 in aluminum, with a large straggle. The events with initial momentum above 210 MeV/c and range less than 45 gm/cm^2 were remeasured, and each event was inspected for possible equipment failures or mismeasurements. Figure 3 shows the effect of the range cut for events with momentum greater than 212 MeV/c, where it is seen that the peak at 236 MeV/c is reduced by a factor of about twenty.

The effect of the criteria imposed on the difference between the measured position of a track entering the range chamber and the extrapolated momentum chamber track is shown in Fig. 4. These criteria were based on distributions obtained for events with momentum between 200 and 220 MeV/c. The number of events above 240 MeV/c in the final sample did not change with small variations in these criteria. Fig. 5 shows the final events of Fig. 4 plotted in 1 MeV/c bins.

The time spectrum of the final events was compared with the time spectrum of a sample of K^+_{e3} events. Except for one event which

arrived very early and was eliminated, these events had a time spectrum consistent with decays at rest.

In the momentum interval from 242 to 252 MeV/c, which is $\pm$ 5 MeV/c about the mean K^+_{e2} momentum, a total of one background event is expected from muon decay in flight. The number of K^+_{e2} events computed on the basis of the (V-A) theory, using the observed number of K^+_{e3} events, and correcting for experimental bremsstrahlung and momentum resolution is approximately two. Note that the primary effect of bremsstrahlung is to remove events from the monoenergetic K^+_{e2} peak, rather than to shift the peak. The sum of one background and two real events expected is to be compared with the three events found. At present, therefore, with one-fourth of the data analyzed, our experimental result is consistent with the (V-A) theory.

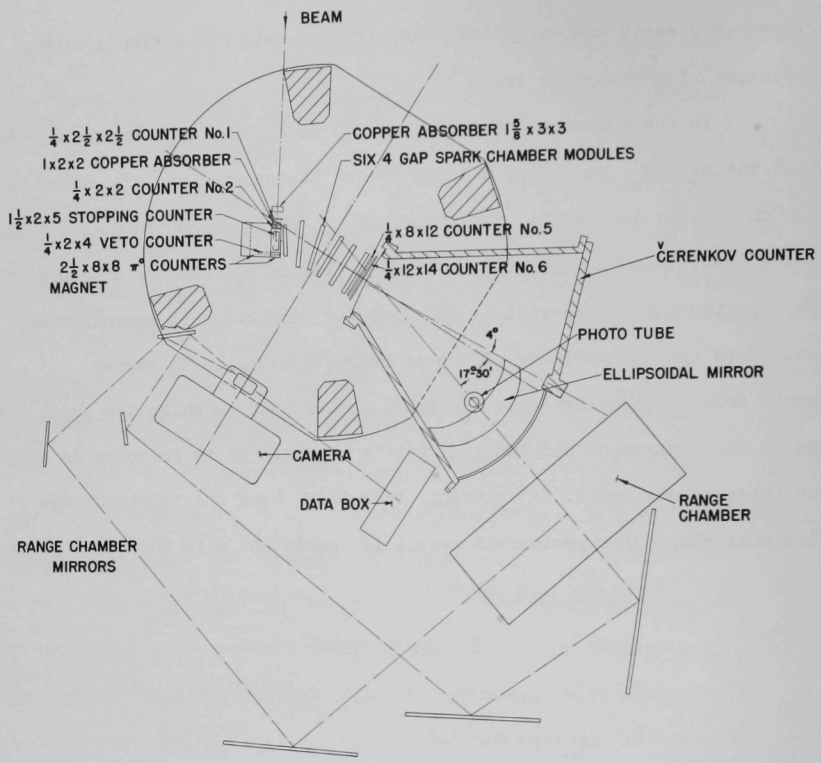


Fig. 1. Experimental Arrangement

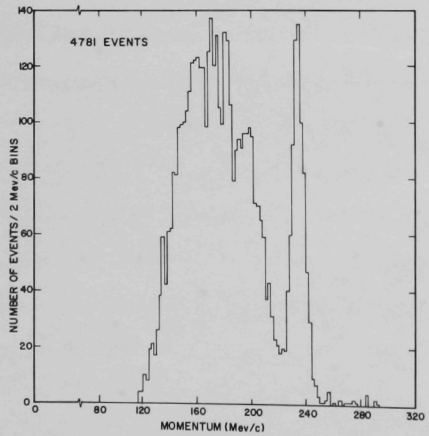


Fig. 2

Momentum Spectrum of all Events

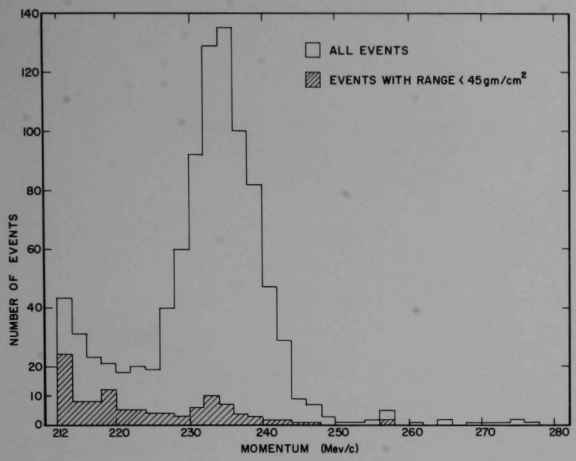


Fig. 3

Momentum Spectrum of Events with Range < 45 gm/cm^2 ($p > 212$ MeV/c)

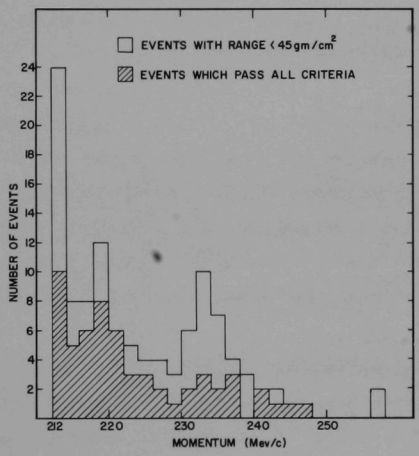


Fig. 4

Momentum Spectrum of Events with All Criteria Applied

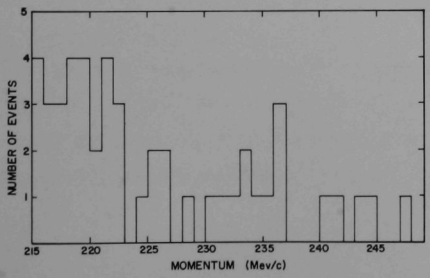


Fig. 5

Momentum Spectrum of Events with All Criteria Applied (1 MeV/c Bins)

K DECAY

George H. Trilling

Lawrence Radiation Laboratory
University of California
Berkeley, California

I. INTRODUCTION

Although the study of the decays of K mesons has been a subject of research for many years, it is only in the relatively recent past that enough quantitative results have become available to permit detailed comparisons with theoretical models. It is the purpose of the present paper to review the state of our knowledge on K-meson decay.

In attempting to collect into coherent form the results of the various experimental groups, one rapidly finds that there are such wide variations in the practices adopted by experimenters in making their error assignments that the usual method of weighting results inversely as the squares of their quoted errors is often more closely related to the optimism or pessimism of the various investigators than to the informational content of their data. For this reason I have adopted certain procedures with respect to the treatment of the data which can be summarized in the following terms:

A. In combining the results of experiments involving substantially equivalent experimental technique and analysis, I have assigned weights proportional to the statistics rather than related to the stated errors. In arriving at an estimate of the uncertainty for the averaged result I have generally adopted the relation between error and number of events given by the most conservative of the groups. In cases where different experimental methods have been used to arrive at independent values of particular quantities, I have relied more heavily on the estimated errors to obtain appropriate weights.

B. I have in certain cases revised the quoted errors, usually upwards, if in the light of the statistical and systematic uncertainties they appeared underestimated. Hence the errors quoted in this paper may differ from those given in the original references, and any mistakes arising from these revisions should be blamed on the present author and not on the experimenters whose results are quoted.

C. I have tended to disregard old measurements with large uncertainties in my present compilations. Systematic errors in early experiments are often grossly underestimated, and I believe that there is much virtue in giving more weight to a single recent measurement than to the average of a large collection of old observations even though the estimated errors of these two contributions may on the surface appear the same.

In the discussion which follows I have omitted any detailed consideration of the $\Delta S = \Delta Q$ selection rule, $K_1 - K_2$ mass difference, and CP violation as these are the subjects of other review papers at this Conference.

II. K^+ RATES

A. Lifetime

A recent precision measurement by Fitch et al,[1] has been combined with another fairly recent determination[2] to give the current best estimate,

$$\tau = (1.243 \pm 0.004) \times 10^{-8} \text{Sec.}$$

It is interesting to note that this value is significantly larger than the previous accepted value.

B. Branching Ratios

Table I shows a compilation of the available data on the K^+ branching ratios and corresponding rates. A few detailed comments concerning some of these numbers may be appropriate.

1. $K^+_{\pi 2}$ Mode

There has been a wide variation in the results of $K^+_{\pi 2}$ branching ratio measurements, which has at various times led to suggestions that some of the differences arise from real physical effects.[3] To add to the confusion two successive xenon-bubble-chamber measurements of this branching ratio give 18.6% and 22.4%[4,5] respectively each with a quoted error under 1%. The major problem of the xenon experiments

lies in the separation between $K^+_{\pi 2}$ and the $K^+_{\mu 3}$ modes. Consequently for the purposes of the present review, I have taken from the xenon data the sum of the $K^+_{\pi 2}$ and $K^+_{\mu 3}$ branching ratios whose average value is 24.6 ± 0.7% (the two xenon experiments agree fairly well on this sum), and subtracted the $K^+_{\mu 3}$ branching ratio from Table I, 3.2 ± 0.3% to obtain a $K^+_{\pi 2}$ branching ratio of 21.4 ± 0.8%. This figure agrees very well with the independent determination in a freon bubble chamber by Callahan and Cline,[6] namely 21.8 ± 0.9%. Since the xenon-chamber experiment relied on observing the π^0 decay photons whereas that of Callahan and Cline did not, the satisfactory agreement between these should set to rest any further doubts that pions from the $K^+_{\pi 2}$ mode are indeed always accompanied by the decay photons from simultaneously produced π^0.

2. K^+_{e2} Mode

In an experiment reported to the Conference, Bowen et al.[7] have looked for the $K^+ \rightarrow e^+ + \nu$ (K^+_{e2}) mode under conditions in which the background is no larger than the rate expected from the V-A coupling

$$\frac{\Gamma(K^+_{e2})}{\Gamma(K^+_{\mu 2})} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{M_K^2 - m_e^2}{M_K^2 - m_\mu^2}\right)^2 = 2.6 \times 10^{-5}$$

Their result is completely compatible with the V-A prediction and rules out with better than 90% confidence a rate larger than three times the V-A prediction.

3. K^+_{e4} and $K^+_{\mu 4}$ Modes

Although both the $\Delta S = \Delta Q$ $K^+_{e4}(\rightarrow \pi^+ + \pi^- + e^+ + \nu)$[8] and $K^+_{\mu 4}(\rightarrow \pi^+ + \pi^- + \mu^+ + \nu)$[9] modes have been observed, there has been no evidence for the corresponding $\Delta S = -\Delta Q$ modes $K^+_{e4}(\rightarrow \pi^+ + \pi^+ + e^- + \bar{\nu})$ and $K^+_{\mu 4}(\rightarrow \pi^+ + \pi^+ + \mu^- + \nu)$. However, since the final-state $\pi\pi$ interaction may tend to favor the $\Delta S = \Delta Q$ modes it is difficult to obtain any strong limit on the degree of forbiddeness of $\Delta S = -\Delta Q$ amplitudes with respect to $\Delta S = \Delta Q$ amplitudes.

4. Neutral Lepton Currents

The rates of the decay modes $K^+ \rightarrow \pi^+ + e^+ + e^-$[10] and

$K^+ \rightarrow \pi^+ + \mu^+ + \mu^-$[11] are less than 5×10^{-5} of the corresponding $K^+ \rightarrow \pi^0 + e^+ + \nu$ and $K^+ \rightarrow \pi^0 + \mu^+ + \nu$ rates.

5. Radiative Decay Modes

The rates for the modes $K^+ \rightarrow \pi^+ + \pi^0 + \gamma$[12] and $K^+ \rightarrow \pi^+ + \pi^+ + \pi^- + \gamma$[13] are compatible with those expected from inner bremstrahlung, without requiring large direct emission amplitudes.

III. K^0 RATES

A. Lifetime of $K_1^0 \rightarrow 2\pi$ Mode

A new precise determination of the K_1^0 mean life[21] has been combined with some of the more recent measurements to give a new best estimate,

$$\tau = (0.866 \pm 0.014) \times 10^{-10} \text{ Sec.}$$

B. K_2^0 Rates

Existing data on the rates for various K_2^0 modes have been obtained in two ways:

(i) In experiments in which K^0 are made in or close to the detector by incoming beams of pions, charged kaons or antiprotons, the numbers of $K^0 \rightarrow$ leptons and $K^0 \rightarrow 3\pi$ decays are determined, and the total number of K^0 produced obtained directly by observation of the usual $K_1^0 \rightarrow \pi^+ + \pi^-$ events. From the measured momenta and available path lengths the rates for the observed K_2^0 modes are then readily computed. For decays close to the K^0 production point, the problem of K_1^0 leptonic modes and the related question of the validity of the $\Delta S = \Delta Q$ selection rule comes into the analysis, but since the detectors are usually large compared to a K_1^0 mean life the results for the K_2^0 rates are not very sensitive to the $\Delta S/\Delta Q$ problem.

The major difficulty connected with this technique lies in the prodigious K_1^0 background which must be effectively prevented from, in some small fraction of the events, simulating the decay modes of interest. Thus in the experiment of Franzini et al.[21] about 100 leptonic and 3π decays had to be separated from a background of some 10,000 K_1^0 decays. The problem is probably greatest if the detector is a hydrogen bubble chamber, being somewhat reduced in a heavy liquid chamber by the distinctive signature of some of the decay modes of interest. It is worth noting that the one spark-chamber experiment which has contributed to this method of obtaining rates solved this problem very satisfactorily by triggering only on decays separated by some two K_1^0 mean

lives from the production point and using a rather large spark chamber to provide considerable decay path length.

(ii) Detectors have also been set up directly in K_2^o beams, thus completely avoiding the K_1^o background. Since the absolute K_2^o flux in such experiments is generally not obtainable with any useful precision, only branching ratios into modes to which the detector is sensitive can be determined. These branching ratios can be combined with independent determinations of the K_2^o mean life, as obtained from attenuation measurements, to calculate the absolute rates for the decay modes. These considerations are of course only valid if there is no "completely undetected mode" which would contribute to the mean life but not to the observed branching ratios.

Most of these branching-ratio determinations have been made either with cloud chambers or more usually with hydrogen bubble chambers as the detectors. It must be emphasized that these determinations are far more difficult than the corresponding ones for K^+ decay modes and in a certain sense less satisfying. Whereas in the case of the K^+ modes the individual events are identified as belonging to one mode or another, this is usually not possible for the K_2^o events. In the latter case, one must carry out a statistical analysis somewhat sensitive to the energy and angular distributions of the secondaries of the decay, and, more seriously, quite sensitive to the measurement errors.

In the present analysis, the various results from both direct rate observations and branching-ratio determinations have been subjected to a least-squares fitting program. The input data and its sources are given in Table II, and the results of the fit are listed in Table III. It is an assumption of the analysis that the $K_2^o \rightarrow \pi^+ \pi^- \gamma$ mode on which there exists only fragmentary information can be neglected insofar as its contribution to the total rate is concerned. The χ^2 for the overall fit is 6.76 for five degrees of freedom, corresponding to a probability level of 25%. Thus the various experimental data are reasonably self-consistent.

IV. THE $K \rightarrow 3\pi$ DECAYS

A. Rate Comparisons

The well-known $|\Delta \vec{I}| = 1/2$ rule for non-leptonic decays leads to several predictions for relations between the rates for the various $K \rightarrow 3\pi$ modes. Because the pion and kaon mass differences are not negligible in comparison to the energy release in the decay, it is essential to compare not the rates Γ but the ratios of rates to available phase space,

$$\gamma = \frac{\Gamma}{\Phi} \quad ,$$

where Φ is the appropriate Lorentz-invariant phase space. Several sets of these phase space factors Φ have appeared in the literature, but insofar as I have been able to tell, none of them are quite correct. A new set of values, believed to be accurate to about 1%, are shown in the second column of Table IV with the corresponding values of γ shown in the third column.

The $|\Delta \vec{I}| = 1/2$ rule requires that the final 3π states in both K^+ and K_2^o decay have $I = 1$ (for K_2^o decay the $I = 0$ is forbidden by CP conservation). The consequences of this prediction are:

$$\gamma\,(\pi^+ \pi^+ \pi^-) = 4\,\gamma\,(\pi^+ \pi^o \pi^o) \qquad (1a)$$
$$\gamma\,(\pi^o \pi^o \pi^o) = 3/2\,\gamma\,(\pi^+ \pi^- \pi^o) \qquad (1b)$$

Inspection of Table IV shows that both of these predictions are very well fulfilled by the experimental data. However these really test mainly whether the $I = 3$ symmetric final state is present to any significant degree and hence rule out sizable $|\Delta \vec{I}| = 5/2,\ 7/2$ contributions, but not $|\Delta \vec{I}| = 3/2$ contributions. However for a pure $|\Delta \vec{I}| = 1/2$ transition one also has the relations:

$$\gamma\,(\pi^+ \pi^- \pi^o) = 2\,\gamma\,(\pi^+ \pi^o \pi^o) \qquad (1c)$$
$$\gamma\,(\pi^o \pi^o \pi^o) = \gamma\,(\pi^+ \pi^- \pi^-) - \gamma\,(\pi^+ \pi^o \pi^o) \qquad (1d)$$

which are significantly affected by the presence of $|\Delta \vec{I}| = 3/2$ components. According to Table IV, relation (1d) is satisfied within the errors of measurement. Although relation (1c) fails by about 1.7 times the rather small standard deviation, the discrepancy is not sufficiently large to be considered a significant piece of evidence against the validity of the $|\Delta \vec{I}| = 1/2$ rule in describing the $K \rightarrow 3\pi$ decays. It is of interest in this connection to point out that the direct rate measurements of the $K_2^o \rightarrow \pi^+ + \pi^- + \pi^o$ mode agree very well with equation (1c),[27] and that the discrepancy arises completely from the experimental data on the branching ratio $\Gamma_\pi(+-0)/\Gamma_{charged}$. If one examines the various measurements from which the average branching ratio given in Table II is obtained, it can be seen that the overall consistency is not very good, and, in fact, that the two measurements presented to this Conference, namely 0.178 ± 0.017[33] and 0.144 ± 0.004,[32] differ by 2 standard deviations. In view of these considerations, one

must conclude that the $|\Delta \vec{I}| = 1/2$ rate predictions are all satisfactorily fulfilled by the present experimental data.

B. Pion Energy Spectra

1. Linear Representation

It is well known that the pion energy spectra in $K \rightarrow 3\pi$ decay do not precisely follow phase space. Weinberg[41] has suggested that the matrix element be expanded in the form:

$$M = 1 - \frac{a}{m_\pi^2} (S_3 - S_0)$$

where a is a constant

$S_i = (P_K - P_{\pi i})^2 = (M_K - m_\pi)^2 - 2M_K T_i$

i denumerates the three pions with i = 3 representing the odd pion in K^+ decay or the π^0 in $K_2^0 \rightarrow \pi^+ \pi^- \pi^0$ decay,

$S_0 = 1/3\ (S_1 + S_3 + S_3) = (M_K - m_\pi)^2 - 2/3\ QM_K$

T_i = kinetic energy of ith pion in the K rest frame.

The spectrum is then given by the product of the phase space and the squared matrix element,

$$|M|^2 \approx 1 - \frac{2a}{m_\pi^2} (S_3 - S_0)$$

or

$$|M|^2 \approx 1 + \frac{2a}{m_\pi^2} M_K T_{max} \left[\frac{2T_3}{T_{max}} - 1\right]$$

where the quadratic term in $|M|^2$ has been neglected. If the 3π final state has I = 1, the "a" values for the $\pi^+ \pi^+ \pi^-$ and $\pi^+ \pi^0 \pi^0$ modes obey the relation[42]

$$a\ (+00) = -\ 2a\ (++-) \qquad (2a)$$

Furthermore, if the decay obeys the $|\Delta \vec{I}| = 1/2$ rule the slopes of the energy distributions in $K^+ \rightarrow \pi^+ \pi^0 \pi^0$ and $K_2^0 \rightarrow \pi^+ \pi^- \pi^0$ must obey the relation[42]

$$a\ (+-0) = a\ (+00) \qquad (2b)$$

The experimental results of various groups for the three decay modes of interest are listed in Table V. It is evident that the data show very good agreement with (2b). On the other hand, the slope for the τ decay mode shows a tendency to be somewhat smaller than that expected from relation (2a). This disagreement of about 1.7 standard deviations is again not sufficiently large to be considered as a significant disagreement with the prediction (2a).

In conclusion, it can be said that the increased precision made possible by recent experiments with improved statistics has shown up no significant violation of the $|\Delta \vec{I}| = 1/2$ rule in $K \rightarrow 3\pi$ decay either in relation to the total rates or in relation to the pion energy spectra. It will, of course, be desirable to check by additional studies that with still further increases in data those deviations which are now on the edge of being significant do decrease.

2. The σ Resonance.

An $I = 0$, $J = 0$ pion–pion resonance with mass about 400 MeV has been suggested by Brown and Singer [49] to account for the large three–pion branching ratio of the η. These authors have further suggested that one could account for the departures of $K \rightarrow 3\pi$ spectra from pure phase space by supposing that these decays proceed through the intermediate state $K \rightarrow \pi + \sigma \rightarrow 3\pi$. The application of the Brown–Singer theory to experimental data on η decays gives as best fit values:[50]

$$m_\sigma = 395^{+17}_{-9} \quad \Gamma_\sigma = 100^{+21}_{-17} \quad \text{MeV}$$

Unfortunately the $K \rightarrow 3\pi$ data provide relatively little information on the possible existence of the σ meson, principally because the highest possible π–π invariant mass in the K decay is 40 MeV lower than the above value of m_σ. Indeed, as pointed out by Taylor et al.,[51] as long as the 3π data require no quadratic terms in the matrix element, one can only use this K decay information to derive a relation between m_σ and Γ_σ such that the predicted mean slope of the spectrum agrees with the experimental data. The above pair of values for m_σ and Γ_σ is not in very good agreement with the data from either the τ or the τ' mode.[46, 47]

A stronger item of evidence against the σ hypothesis is provided by the $\pi^+\pi^-$ spectrum in the K^+_{e4} decay ($K^+ \rightarrow e^+ + \pi^+ + \pi^- + \nu$).[8] Fig. 1 shows the experimental dipion mass distribution for the 69 events obtained in the Wisconsin Berkeley collaboration. Curve No. 4 which corresponds to

the above σ parameters is in total disagreement with the data.

V. THE $K \rightarrow \pi + (e,\mu) + \nu$ DECAY

A. Rate Comparisons

It has been proposed that the strangeness-changing current, in the current-current interaction scheme, has the properties of an isotopic spinor in charge space.[52] The $|\Delta \vec{I}| = 1/2$ rule for leptonic decays implies the following relations between K^+ and K_2^0 rates of decay into the three-body leptonic modes,

$$\Gamma_{2e} = 2\Gamma_{+e} \qquad (3a)$$

$$\Gamma_{2\mu} = 2\Gamma_{+\mu}. \qquad (3b)$$

Furthermore, the angular and energy spectra for the K_2^0 and K^+ decays are predicted to be precisely the same. Rather than checking directly whether the data satisfy equations (3), it has been found more convenient to consider the equivalent relations

$$\Gamma_{2e} + \Gamma_{2\mu} = 2\,(\Gamma_{+e} + \Gamma_{+\mu}) \qquad (4a)$$

$$\Gamma_{2\mu}/\Gamma_{2e} = \Gamma_{+\mu}/\Gamma_{+e} \qquad (4b)$$

The advantage of using (4) is that almost independent sets of experimental data are used to check (4a) and (4b); hence the experimental errors in the two tests are almost uncorrelated. From Tables I and III we find

$$\frac{\Gamma_{2e} + \Gamma_{2\mu}}{2\,(\Gamma_{+e} + \Gamma_{+\mu})} = 1.05 \pm 0.08$$

$$\frac{\Gamma_{2\mu}}{\Gamma_{+\mu}} \; \frac{\Gamma_{+e}}{\Gamma_{2e}} = 1.04 \pm 0.15$$

The agreement with the $|\Delta \vec{I}| = 1/2$ predictions is excellent.

B. Angular and Energy Spectra

1. Theoretical Preliminaries

The matrix element if one assumes vector coupling and locality of the lepton current can be written in the form[53]

$$M \propto \langle \pi | J_\lambda | K \rangle \; u(P_\nu)\, \gamma_\lambda\, (1 + \gamma_5)\; v(P_\ell)$$

where

$$< \pi | J_\lambda | K > = 1/2\ f_+ (P_K + P_\pi)_\lambda + 1/2\ f_- (P_K - P_\pi)_\lambda$$

The form factors f_+, f_- are functions of only $q^2 = (M_K - m_\pi)^2 - 2 M_K T_\pi$, the square of the invariant four-momentum transfer, and are relatively real if time reversal invariance holds in the decay. Furthermore, if the muon differs only through its mass from the electron, the functions f_+ and f_- will be the same for either lepton. However, since the f_- term leads to factors proportional to m_ℓ, the lepton mass, which are negligible for electron decay, only the form factor f_+ comes into play in the K_{e3} mode. Finally if the leptonic $|\Delta \vec{I}| = 1/2$ rule is valid, the functions f_+ and f_- must be the same for K^+ and K_2^o decays except for a multiplicative factor of $\sqrt{2}$.

If one considers the possibility of other than vector couplings, one can write down two other matrix elements corresponding to scalar and tensor coupling respectively each multiplied by a single form factor.

2. K^+_{e3} Decay

Data on K^+_{e3} decay have come principally from a xenon-bubble-chamber experiment[54, 55] and more recently from the Wisconsin-Berkeley freon-bubble-chamber run.[56] Both experiments have established that the scalar and tensor matrix elements fail completely to account for the experimental information, whereas the vector matrix element gives a satisfactory representation of the data. This point is most convincingly demonstrated in Fig. 2 taken from the freon experiment which shows the distribution of the angle $\alpha_{\pi\ell}$ between pion and dilepton lines of flight in the dilepton rest frame. The predictions for this distribution are $\mathrm{Sin}^2\alpha_{\pi\ell}$, constant, and $\mathrm{Cos}^2\alpha_{\pi\ell}$ for the vector, scalar and tensor matrix elements respectively independently of the q^2 dependence of the form factors. The fit to the vector prediction is excellent whereas the others are completely ruled out.

The energy dependence of the form factor f_+ has been studied in two independent analyses of xenon chamber film, in the freon chamber run, and in a study of the positron energy spectrum observed in a hydrogen bubble chamber[14]. The results expressed as expansions of the form

$$f_+ = 1 + \frac{\lambda\, q^2}{m_\pi^2}$$

are summarized in the left hand column of Table VI, and a histogram of the experimental pion energy distribution, compared with that expected for a constant form factor, is shown for the freon chamber data in Fig. 2. It is clear that there is no evidence whatsoever for any energy dependence of the form factor f_+, the average value of λ being 0.00 ± 0.02.

3. K^o_{e3} Decay

Energy and angular distributions in K^o_{e3} decay were first investigated in a hydrogen chamber by Luers et al,[28] and, more recently, have been the subject of both another bubble chamber experiment by Eisler et al,[37] and a spark chamber experiment, reported by Fisher et al.[57] All the data strongly favor the vector matrix element as expected.

Surprisingly enough the energy dependence of the form factor f_+ in K^o_{e3} decay appears to be substantial and, in fact, to disagree with the previously quoted K^+ result. The behavior of the form factor as determined in the spark chamber experiment [57] is shown in Fig. 3. Although this energy dependence is primarily suggested by the data of Fisher et al, it is not inconsistent with the Luers data. The average value of λ for the combined Luers and Fisher experiments is $\lambda = 0.12 \pm 0.04$, which if the stated errors are taken seriously, is incompatible with the K^+ value. These results can also be expressed in a different form for f_+,

$$f_+ = \frac{1}{M^2 - q^2},$$

where M is the mass of an appropriate J = 1 intermediate $K\pi$ state. The values of λ and M for the K^o_2 experiments are summarized in the right hand column of Table VI.

In the course of a hydrogen bubble chamber K^o_2 experiment, Hopkins[58] et al, have identified by bubble density some 737 K^o_{e3} decays. Because of the quadratic ambiguity in calculating the primary momentum for each event, they obtain two possible values for the center-of-mass energies of both pion and electron (the neutrino energy is obviously unambiguous). Fig. 4 gives their pion energy spectrum with each event

plotted as one half for one value and one half for the other possible value of the pion energy. The histogram is the result of a Monte Carlo calculation using an energy-independent form factor. It is seen that the agreement is in fact very good, and particularly that there is no systematic tendency for the data to fall significantly below the predictions at high values of the pion energy, as would be expected from the form-factor variations obtained in the experiment of Fisher et al. On the other hand, the agreement between theory and experiment for the neutrino energy distribution obtained by Hopkins et al, is not good; consequently their results cannot at this time be considered an unqualified endorsement of the present theory with constant form factors.

It is important to emphasize that the errors and confidence levels quoted in Table VI are purely statistical, and what conclusion one draws from the apparent disagreements between the K^+_{e3} and K^o_{e3} results concerning the energy variation of the form factors depends upon one's optimism concerning systematic errors. Because of the greater technical problems associated with K^o_2 experiments it seems probable that they are more subject to large systematic errors. It is clear that further study, with great attention paid to experimental biases, is needed to verify whether or not the K^+_{e3} and K^o_{e3} form factors behave differently and the $|\Delta \vec{I}| = 1/2$ leptonic rule is thereby significantly violated.

4. $K^+_{\mu 3}$ Decay

Although several experiments to investigate various aspects of $K^+_{\mu 3}$ decay have been carried out, I will mostly confine myself here to a discussion of the results obtained by the Wisconsin-Berkeley-Riverside-Bari (WBRB) collaboration from a stopping K^+ run in the Berkeley heavy liquid chamber filled with freon.[15] Apart from some early disagreements, the conclusions of the other experiments agree satisfactorily with those of the WBRB experiment whose statistics however are far more numerous.

The analysis of the $K^+_{\mu 3}$ decay is more complicated than that of the K^+_{e3} by virtue of the fact that the theory presents us with two rather than a single form factor. Furthermore the possible violation of time reversal invariance implies that the form factor ratio $\xi = f_- / f_+$

is not necessarily real and hence there is yet another possible parameter. In order to limit the number of variables it is reasonable to attempt the analysis on the assumption that f_+ and ξ can be treated as constants, a supposition which is in fact in good agreement, insofar as f_+ is concerned, with the K^+_{e3} data and $e - \mu$ universality. If we then accept this assumption, all experimental information concerning energy spectra, angular correlations, and polarization will depend only on ξ, the value of f_+ entering only in the magnitude of the absolute rate.

Information concerning Re ξ and Im ξ have been obtained from four sources within the same WBRB experiment. These are independent from each other in the sense that either different subsets of events are used or the quantities measured are kinematically independent. The four sources and the results obtained from them are listed in Table VII. A few additional clarifying comments may be helpful here:

(i) The μ^+ energy spectrum (based on 2650 events) was studied between 42 and 94 MeV to remove background from τ' and $K^+_{\pi 2}$ decays. All muon energies were determined by range with suitable chamber-geometry corrections applied to the distributions.

(ii) The longitudinal polarization was determined for 2950 events with muons in the energy range between 40 and 100 MeV. It is worth noting that Borreani et al, have recently measured the muon longitudinal polarization in the 6 – 27 MeV energy range[59]. Their result is completely consistent with the other polarization data, but eliminates on the basis of polarization measurements alone alternative values of ξ which for the earlier data can also provide an adequate fit.[60] A summary of all longitudinal polarization data taken from the Borreani paper is shown in Fig. 5.

(iii) The π^0 energy spectrum at known muon energies between 40 and 90 MeV was studied for some 444 events in which both gamma rays materialized. The dependence of population on muon energy was not used here because of possible biases arising from the requirement of double photon conversion. As indicated in Table VII this analysis gives rather little information on $|\text{Im}\ \xi|$, but a rather good value for Re ξ.

(iv) The μ^+ total polarization was studied in the muon energy range $40 < T_\mu < 90$ MeV for 397 events where again both photons convert permitting a determination of decay plane.

The results of the analysis can be summarized as follows:

(1) The vector nature of the interaction is well established. This is clearly seen in Fig. 6 which compares the experimental π^o spectrum at fixed muon energies for the 444 events discussed in (iii) above with the expected spectra for the scalar, tensor and vector couplings. Furthermore, the consistency of the values of ξ obtained from the various measurements gives further confidence in this conclusion.

(2) At the level of precision of the experiment there is no evidence for violation of time reversal invariance.

(3) Comparison of the measured ratio of $K^+_{\mu 3}$ and K^+_{e3} rates with that expected from the value of ξ determined from the $K^+_{\mu 3}$ data permits verification that $|f_+(\mu)| = |f_+(e)|$ within the uncertainty of a few per cent.

(4) The data permit some study of the energy dependence of f_+, but give almost no information on this point for f_-. Indeed for f_+, the value of λ obtained is $\lambda = 0.00 \pm 0.05$. Again this result is in excellent agreement with that for K^+_{e3} decay, but not with the spark-chamber data on K^o_{e3} decay.

5. $K^o_{\mu 3}$ Decay

Carpenter et al.[40] have made the first detailed study of $K^o_{\mu 3}$ decay in a spark-chamber experiment. As always, problems arising from the quadratic ambiguities in reconstruction of the kinematics make the analysis much more difficult than for K^+ decays. From an analysis of the Dalitz plot from some 1371 events with suitable corrections for this ambiguity problem they arrive at the following conclusions.

(i) Their data agree with the vector interaction and strongly disagree with tensor or scalar couplings regardless of form-factor variations. This result is evident from the neutrino energy distributions at fixed pion energies shown in Fig. 7.

(ii) The data are compatible with constant form factors and yield for ξ, on the assumption that Im $\xi = 0$,

$$\xi = 1.2 \pm 0.8$$

where the quoted error is largely systematic. This result is of course fully consistent with the K^+ data.

(iii) The data are also compatible with substantial energy variations in the form factors. Thus if one assumes a dominant K–π intermediate state of spin 1, mass M

$$f_+(q^2) = \frac{f_+(0)}{M^2 - q^2}$$

$$f_-(q^2) = f_+(q^2)\,\frac{M_K^2 - M_\pi^2}{M^2}$$

a good fit is obtained with a value of M

$$M = 540\,{}^{+140}_{-70}\ \text{MeV}.$$

This result is consistent with that obtained for f_+ in the K^o_{e3} experiment and, with the measured ratio of the K_{e3} and $K_{\mu 3}$ rates. The quality of the fits for both assumptions (ii) and (iii) are shown in Fig. 8.

(iv) There is no evidence for violation of time reversal invariance in that none of the theoretical fits to the data are improved by considering a complex ξ.

VI. FINAL REMARKS

The conclusions from the foregoing exposition are basically that the theoretical models, namely the $|\Delta \vec{I}| = 1/2$ rule for leptonic and non-leptonic decays, and the vector interaction with μ – e universality agree very well with the totality of the experimental data, the sole exception being that the form factor f_+ for K_{e3} decay appears to have a much stronger energy dependence in K_2^o than in K^+ decay. The performance of further K_2^o experiments with, if possible, a good understanding of systematic errors, will clearly be of great interest, in clarifying this point.

TABLE I – K^+ Rates

Mode	Branching Ratio	Rate (Sec^{-1})	Remarks
All Modes[a]		$(8.045 \pm .027) \times 10^7$	
$K^+ \rightarrow \mu^+ + \nu$[b]	$63.5 \pm 0.7\%$	$(5.11 \pm 0.06) \times 10^7$	
$K^+ \rightarrow \pi^+ + \pi^o$ [a]	$21.6 \pm 0.6\%$	$(1.74 \pm 0.05) \times 10^7$	
$K^+ \rightarrow e^+ + \pi^o + \nu$[c]	$4.49 \pm 0.25\%$	$(3.61 \pm 0.20) \times 10^6$	
$K^+ \rightarrow \mu^+ + \pi^o + \nu$[d]	$3.17 \pm 0.35\%$	$(2.55 \pm 0.28) \times 10^6$	
$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$ [e]	$5.59 \pm 0.11\%$	$(4.50 \pm 0.09) \times 10^6$	
$K^+ \rightarrow \pi^+ + \pi^o + \pi^o$[f]	$1.68 \pm 0.06\%$	$(1.35 \pm 0.05) \times 10^6$	
$K^+ \rightarrow e^+ + \nu$[a]	$\sim 1.6 \times 10^{-5}$	$\sim 1.3 \times 10^3$	
$K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu$[a]	$(3.6 \pm 0.8) \times 10^{-5}$	$(2.9 \pm 0.6) \times 10^3$	
$K^+ \rightarrow \pi^+ + \pi^- + \mu^+ + \nu$[a]	$(7.7 \pm 5.2) \times 10^{-6}$	$(6.2 \pm 4.2) \times 10^2$	
$K^+ \rightarrow \pi^+ + \pi^o + \gamma$[a]	$(2.2 \pm 0.7) \times 10^{-4}$	$(1.8 \pm 0.6) \times 10^4$	$55\ MeV < T_\pi + < 80 MeV$
$K^+ \rightarrow \pi^+ + \pi^+ + \pi^- + \gamma$[a]	$(1.0 \pm 0.4) \times 10^{-4}$	$(8.0 \pm 3.2) \times 10^3$	$E_\gamma > 10$ MeV
$K^+ \rightarrow \pi^+ + \pi^+ + e^- + \bar{\nu}$[a]	$< 2 \times 10^{-6}$	$< 1.6 \times 10^2$	$\Delta S/\Delta Q = -1$ Transition
$K^+ \rightarrow \pi^+ + \pi^+ + \mu^- + \nu$[a]	$< 3 \times 10^{-6}$	$< 2.4 \times 10^2$	
$K^+ \rightarrow \pi^+ + e^+ + e^-$ [a]	$< 1.1 \times 10^{-6}$	$< 0.8 \times 10^2$	Involves neutral lepton currents
$K^+ \rightarrow \pi^+ + \mu^+ + \mu^-$ [a]	$< 3 \times 10^{-6}$	$< 2.4 \times 10^2$	

(a) See text for discussion

(b) Calculated from 1 – Sum (other branching ratios)

(c) Input Data on branching ratio $4.7 \pm 0.3\%$ (Ref. 5) $5.12 \pm 0.36\%$ (Ref. 14)
$5.0 \pm 0.5\%$ (Ref. 4) $4.04 \pm 0.24\%$ (Ref. 15)

Values measured relative to the τ mode have been renormalized to the τ rate quoted in the Table.

(d)	Input data	3.0 ± 0.5%	(Rev. 5)
		3.52 ± 0.20%	(Ref. 62)
		2.82 ± 0.19%	(Ref. 15)
(e)	Input data	5.54 ± 0.12%	(Ref. 17)
		5.71 ± 0.15%	(Ref. 18)
		5.10 ± 0.2%	(Ref. 5)
		5.7 ± 0.3%	(Ref. 4)
		5.2 ± 0.3%	(Ref. 19)
(f)	Input data	1.8 ± 0.2%	(Ref. 5)
		1.5 ± 0.2%	(Ref. 19)
		1.7 ± 0.2%	(Ref. 4)
		1.71 ± 0.07%	(Ref. 20)

TABLE II

Input Data for K_2^o Rate Determinations

$$\Gamma_{total} = (1.85 \pm 0.17) \times 10^7 \text{ Sec}^{-1} \quad \text{(a)}$$

$$\Gamma_{charged} = (1.47 \pm 0.18) \times 10^7 \text{ Sec}^{-1} \quad \text{(b)}$$

$$\Gamma_e = (0.81 \pm 0.10) \times 10^7 \text{ Sec}^{-1} \quad \text{(c)}$$

$$\Gamma_e + \Gamma_\mu = (0.94 \pm 0.13) \times 10^7 \text{ Sec}^{-1} \quad \text{(d)}$$

$$\Gamma_\pi(+-0) = (0.254 \pm 0.025) \times 10^7 \text{ Sec}^{-1} \quad \text{(e)}$$

$$\Gamma_\pi(000) = (0.53 \pm 0.09) \times 10^7 \text{ Sec}^{-1} \quad \text{(f)}$$

$$\Gamma_\mu/\Gamma_e = 0.78 \pm 0.10 \quad \text{(g)}$$

$$\frac{\Gamma_\pi(+-0)}{\Gamma_{charged}} = 0.152 \pm 0.005 \quad \text{(h)}$$

$$\frac{\Gamma_\pi(000)}{\Gamma_{charged}} = 0.25 \pm 0.06 \quad \text{(i)}$$

(a) Input data $(5.3 \pm 0.6) \times 10^{-8}$ Sec (Ref. 23)
$(6.1 {}^{+1.5}_{-1.2}) \times 10^{-8}$ Sec (Ref. 24)

(b) (Ref. 22) with correction due to the new value of the K_1^o mean life.

(c) Reference 25.

(d) Reference 21.

(e) Input data $(1.4 \pm 0.4) \times 10^6 \text{ Sec}^{-1}$ (Ref. 21)
$(3.26 \pm 0.77) \times 10^6 \text{ Sec}^{-1}$ (Ref. 26)
$(2.57 \pm 0.30) \cdot 10^6 \text{ Sec}^{-1}$ (Ref. 27)

(f) Reference 27.

(g)	Input data	0.73 ± 0.15	(Ref. 28)
		0.81 ± 0.19	(Ref. 29)
		0.85 ± 0.18	(Ref. 30)
(h)	Input data	0.157 ± 0.03	(Ref. 28)
		0.151 ± 0.02	(Ref. 29)
		$0.15 \pm^{0.03}_{-0.04}$	(Ref. 30)
		0.159 ± 0.015	(Ref. 31)
		0.144 ± 0.006	(Ref. 32)
		0.178 ± 0.017	(Ref. 33)
(i)	Input data	0.24 ± 0.08	(Ref. 34)
		0.25 ± 0.08	(Ref. 35)

TABLE III – K^o Rates

Mode	Branching Ratio	Rate (Sec^{-1})	Comments
All K_1^o Modes[a]		$(1.155 \pm 0.019) \times 10^{10}$	
All K_2^o Modes [b]		$(19.9 \pm 1.0) \times 10^6$	
$K_2^o \rightarrow \pi^{\pm} + e^{\mp} + \nu$ [b]	$37.4 \pm 2.1\%$	$(7.45 \pm 0.50) \times 10^6$	Normalized so that total branching ratio for these modes = 100%
$K_2^o \rightarrow \pi^{\pm} + \mu^{\mp} + \nu$ [b]	$27.6 \pm 2.1\%$	$(5.49 \pm 0.50) \times 10^6$	
$K_2^o \rightarrow \pi^+ + \pi^- + \pi^o$ [b]	$11.9 \pm 0.6\%$	$(2.36 \pm 0.13) \times 10^6$	
$K_2^o \rightarrow \pi^o + \pi^o + \pi^o$ [b]	$23.1 \pm 2.0\%$	$(4.61 \pm 0.55) \times 10^6$	
$K_2^o \rightarrow \pi^+ + \pi^- + \gamma$ [c]	$< 0.3\%$	$< 5 \times 10^4$	
$K_2^o \rightarrow \pi^+ + \pi^-$ [d]	$(2.05 \pm 0.15) \times 10^{-3}$	$(3.15 \pm 0.17) \times 10^4$	CP violating
$K_2^o \rightarrow \mu^+ + \mu^-$ [e] $K_2^o \rightarrow e^+ + e^-$ $K_2^o \rightarrow e^{\pm} + \mu^{\mp}$	$< 10^{-4}$	$< 2 \times 10^3$	Involves neutral lepton currents
$K_2^o \rightarrow 2\gamma$ [f]	$< 10^{-3}$	$< 2 \times 10^4$	

(a) Input data on lifetimes

$(0.90 \pm 0.05) \times 10^{-10}$	Sec	(Ref. 36)
(0.94 ± 0.05)	"	"
(0.885 ± 0.025)	"	"
(0.85 ± 0.04)	"	"
(0.87 ± 0.05)	"	"
(0.86 ± 0.04)	"	"
(0.848 ± 0.014)	"	(Ref. 21)

(b) From fit of data in Table II

(c) Reference 63

(d) Compilation by J. Cronin, Argonne Weak Interactions Conference

(e) References 40 and 61.

(f) Reference 64.

TABLE IV – $K \rightarrow 3\pi$ Modes

Rate Comparisons

Mode	Phase Space Factor Φ	γ = Rate/ Φ (Sec^{-1})
$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$	1.00	$(4.50 \pm 0.09) \times 10^6$
$K^+ \rightarrow \pi^+ + \pi^0 + \pi^0$	1.24	$(1.09 \pm 0.04) \times 10^6$
$K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0$	1.22	$(1.93 \pm 0.11) \times 10^6$
$K_2^0 \rightarrow \pi^0 + \pi^0 + \pi^0$	1.49	$(3.10 \pm 0.37) \times 10^6$

Tests of $|\Delta \vec{I}| = 1/2$

	Experimental	Predicted
$\dfrac{\gamma\,(\pi^+ \pi^- \pi^0)}{2\gamma\,(\pi^+ \pi^0 \pi^0)}$	0.89 ± 0.07	1.00
$\dfrac{\gamma\,(\pi^0 \pi^0 \pi^0)}{\gamma\,(\pi^+ \pi^+ \pi^-) - \gamma\,(\pi^+ \pi^0 \pi^0)}$	0.91 ± 0.13	1.00
$\dfrac{\gamma\,(\pi^+ \pi^+ \pi^-)}{4\gamma\,(\pi^+ \pi^0 \pi^0)}$	1.03 ± 0.04	1.00
$\dfrac{\gamma\,(\pi^0 \pi^0 \pi^0)}{\frac{3}{2}\gamma\,(\pi^+ \pi^- \pi^0)}$	1.07 ± 0.13	1.00

TABLE V

Measurements of Odd-Pion Spectra in $K \rightarrow 3\pi$ Decay

$$|M|^2 \propto 1 - 2a\left(\frac{S_3 - S_0}{m_\pi^2}\right) = 1 + 2a\,\frac{M_K\,T_{Max}}{m_\pi^2}\left(\frac{2T_3}{T_{Max}} - 1\right)$$

$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$	$K^+ \rightarrow \pi^+ + \pi^0 + \pi^0$	$K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0$
0.102 ± 0.028 (a)	− 0.24 ± 0.02 (e)	− 0.24 ± 0.09 (g)
0.114 ± 0.02 (b)	− 0.30 ± 0.05 (f)	− 0.24 ± 0.09 (h)
0.083 ± 0.028 (c)		− 0.24 ± 0.04 (i)
0.083 ± 0.015 (d)		− 0.27 ± 0.05 (j)
		− 0.24 ± 0.05 (k)
		− 0.17 ± 0.06 (l)
		− 0.26 ± 0.06 (m)
Averages 0.093 ± 0.011	− 0.25 ± 0.02	− 0.24 ± 0.02

Comparisons with $|\Delta \vec{I}| = 1/2$

	Experiment	Predicted
$\dfrac{a(\pi^+\pi^0\pi^0)}{a(\pi^+\pi^+\pi^-)}$	− 2.7 ± 0.4	− 2
$\dfrac{a(\pi^+\pi^0\pi^0)}{a(\pi^+\pi^-\pi^0)}$	1.0 ± 0.11	1

(a) Reference 43
(b) Reference 44
(c) Reference 45
(d) Reference 46
(e) Reference 47
(f) Reference 20
(g) Reference 28
(h) Reference 29
(i) Reference 31
(j) Reference 32
(k) Reference 48
(l) Reference 33
(m) Reference 27

TABLE VI– Ke_3 Decay

Ke_3^+ Decay	Ke_3^o Decay

$$f_+ = 1 + \frac{\lambda q^2}{m_\pi^2}$$

Measured Values of λ (± 1 Standard Deviation)

0.038 ± 0.045 (a)	0.07 ± 0.06 (e)
-0.01 ± 0.029 (b)	0.15 ± 0.04 (f)
-0.04 ± 0.05 (c)	
$0.02 \begin{smallmatrix} +0.04 \\ -0.03 \end{smallmatrix}$ (d)	
Average 0.00 ± 0.02	Average $0.12 \pm .04$

$$f_+ = \frac{1}{M^2 - q^2}$$

95% Confidence Levels for M

$M > 700$ MeV	$M = 600 \begin{smallmatrix} +\infty \\ -150 \end{smallmatrix}$ MeV (e)
	$M = 480 \begin{smallmatrix} +110 \\ -50 \end{smallmatrix}$ MeV (f)

(a) Reference 54
(b) Reference 55
(c) Reference 14
(d) Reference 56
(e) Reference 28
(f) Reference 57

TABLE VII- $K^+_{\mu 3}$ Decay
(Data from Ref. 15)

Quantity Measured	Result
μ^+ Energy Spectrum	$\mathrm{Re}\ \xi = 0.0 \begin{smallmatrix} +1.1 \\ -0.9 \end{smallmatrix}$
	$\lvert \mathrm{Im}\ \xi \rvert = 0.0 \pm 1.0$
μ^+ Longitudinal Polarization	$\mathrm{Re}\ \xi = -0.7 \begin{smallmatrix} +0.9 \\ -3.3 \end{smallmatrix}$
	$\lvert \mathrm{Im}\ \xi \rvert = 0.5 \begin{smallmatrix} +1.4 \\ -0.5 \end{smallmatrix}$
π^0 Energy Spectrum at Fixed μ^+ Energies	$\mathrm{Re}\ \xi = 0.72 \pm 0.37$
	for $\lvert \mathrm{Im}\ \xi \rvert \lesssim 1$
Total μ^+ Polarization	$\mathrm{Re}\ \xi = -1.4 \pm 1.8$
	$\lvert \mathrm{Im}\ \xi \rvert = 1.6 \pm 1.3$
Overall Result	$\mathrm{Re}\ \xi = 0.34 \pm 0.35$
	$\mathrm{Im}\ \xi = 0.69 \begin{smallmatrix} +0.8 \\ -1.0 \end{smallmatrix}$

If one assumes $\mathrm{Im}\ \xi = 0$ and $\mu - e$ Universality

Combination of above Measurements	$\xi = 0.47 \pm 0.30$
Branching Ratio $\dfrac{\Gamma\ (K^+_{\mu 3})}{\Gamma\ (K^+_{e3})}$	$\xi = 0.42 \pm 0.63$
Average of these values	$\xi = 0.46 \pm 0.27$

If one assumes $\mathrm{Im}\ \xi = 0$ but not $\mu - e$ Universality

Combination of Branching Ratio and above Measurements	$\left\lvert \dfrac{f_+\ (\mu)}{f_+\ (e)} \right\rvert = 1.00 \pm 0.06$

REFERENCES

1. V. L. Fitch, C. A. Quarles and M. C. Wilkins, Phys. Rev. (To be Published).
2. A. M. Boyarski, E. C. Loh, L. Q. Niemela, D. M. Ritson, R. Weinstein, and S. Ozaki, Phys. Rev. 128, 2398 (1962).
3. K. Nishijima and M. M. Saffouri, Phys. Rev. Letters, 14, 205 (1965).
4. B. P. Roe, D. Sinclair, J. L. Brown, D. A. Glaser, J. A. Kadyk, and G. H. Trilling, Phys. Rev. Letters 7, 346 (1961).
5. F. S. Shaklee, G. L. Jensen, B. P. Roe, and D. Sinclair, Phys. Rev. 136, B1423 (1964).
6. A. Callahan and D. Cline, Phys. Rev. Letters 15, 129 (1965).
7. D. R. Bowen, A. K. Mann, W. K. McFarlane, A. D. Franklin, E. B. Hughes, R. L. Imlay, G. K. O'Neill, and D. H. Reading, Paper submitted to the Argonne Weak Interactions Conference
8. R. W. Birge, R. P. Ely, G. Gidal, G. E. Kalmus, A. Kernan, W. M. Powell, U. Camerini, D. Cline, W. F. Fry, J. G. Gaidos, D. Murphree, and C. T. Murphy, Phys. Rev. 139, B1600 (1965).
9. D. Cline and W. F. Fry, Phys. Letters 15, 293 (1965)
   D. E. Greiner, W. Z. Osborne and W. H. Barkas, Phys. Rev. Letters, 13, 294 (1964).
10. U. Camerini, D. Cline, W. F. Fry and W. M. Powell, Phys. Rev. Letters, 13, 318 (1964).
11. U. Camerini, D. Cline, G. Gidal, G. Kalmus, and A. Kernan, Nuovo Cimento 37, 1795 (1965).
12. D. Cline and W. F. Fry, Phys. Rev. Letters 13, 101 (1964).
13. P. Stamer, T. Huetter, E. L. Koller, S. Taylor, and J. Grauman, Phys. Rev. 138, B440 (1965).
14. G. Borreani, G. Rinaudo, and A. E. Werbrouck, Physics Letters 12, 123 (1964).
15. A. C. Callahan, U. Camerini, R. D. Hantmann, R. H. March, D. L. Murphree, G. Gidel, G. E. Kalmus, W. M Powell, C. L. Sandler, R. T. Pu, S. Natali, and M. Villani, Phys. Rev. (to be published).
16. V. Bisi, G. Borreani, R. Cester, A. Debenedetti, M. I. Ferrero, C. M. Garelli, A. Marzari-Chiesa, B. Quassiati, G. Rinaudo, M. Vigone, and A. E. Werbrouck, Phys. Rev. Letters 12, 490 (1964).

17. A. Callahan, R. March, and R. Stark, Phys. Rev. 136, B1463 (1964).

18. A. De Marco-Trabucco, C. Grosso, and G. Rinaudo, Phys. Rev. 136, B1423 (1964).

19. S. Taylor, G. Harris, J. Orear, J. Lee, and P. Baumel, Phys. Rev. 114, 359 (1959).

20. V. Bisi, G. Borreani, R. Cester, A. De Marco-Trabucco, M. I. Ferrero, C. M. Garelli, A. Marzari-Chiesa, B. Quassiati, G. Rinaudo, M. Vigone, and A.Werbrouck, Nuovo Cimento 35, 768 (1965).

21. P. Franzini, L. Kirsch, P. Schmidt, J. Steinberger, and R.J. Plano, Phys. Rev. 140, B127 (1965).

22. L. Auerbach, K. Lande, A. K. Mann, F. T. Sciulli, H. Uto, D. H. White, and K. K. Young, Phys. Rev. Letters 14, 192 (1965).

23. T. Fujii, J. Jovanovic, F. Turkot, G. T. Zorn and M. Deutsch, Submitted to the 1964 Dubna Conference on High Energy Physics.

24. P. Astbury, A. Michelini, C. Verkerk, F. Verkerk, W. Beusch, M. Pepin, and M. A. Pouchon, Physics Letters, 18, 178 (1965).

25. B. Aubert, L. Behr, L. M. Chounet, J. P. Lowys, C. Pascaud, Paper submitted to the Argonne Weak Interactions Conference.

26. J. A. Anderson, F. S. Crawford, R. L. Golden, D. Stern, T. O. Binford, and V. G. Lind, Phys. Rev. Letters, 14, 475 (1965),

27. Padova, Milano, Paris Collaboration, Paper submitted to the Argonne Weak Interactions Conference.

28. D. Luers, I. S. Mittra, W. J. Willis, and S. S. Yamamoto, Phys. Rev. 133, B1276 (1964).

29. R. Adair and L. Leipuner, Phys. Letters 12, 67 (1964).

30. P. Astbury, G. Finocchiaro, R. D. Fortune, A. Michelini, C. Verkerk, C. H. West, W. Beusch, M. Pepin and M. A. Pouchon, Physics Letters 16, 80 (1965).

31. P. Astbury, A. Michelini, C. Verkerk, F. Verkerk, W. Beusch,M. Pepin, and M. A. Pouchon, Phys. Letters 18, 178 (1965).

32. H. W. K. Hopkins, T. C. Bacon, and F. R. Eisler, Paper submitted to the Argonne Weak Interactions Conference.

33. P. Guidoni, V. Barnes, H. W. J. Foelsche, G. R. Kalbfleisch, G. W. London, K. Lai, T. Morris, Y. Oren, M. Webster, W. Willis, T. Ferbel, A. Firestone, J. K. Kim, S. Lach, J. Sandweiss, and H. D. Taft, Paper submitted to the Argonne Weak Interactions Conference.

34. M, K. Anikina, M. S. Zhuravleva, D. M. Kotlyarevskii, Z. S. Mandzhavidze, A. N. Mestvirishvili, D. V. Neagu, E. O. Okonov, N. I. Petrov, V. A. Rusakov, G. G. Takhtamyshev, L. V. Chkhaidze, Wu Tsun-Fan, JETP, 19, 42 (1964).

35. A. S. Aleksanyan, A. I. Alikhanyan, A. M. Gal'Per, R. L. Kavalov, Y. G. Kirillovugryumov, L. P. Kotenko, L. A. Kuzin, E. P. Kuznetsov, G. I. Merzon, JETP 19, 1019 (1964).

36. A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, and M. Roos, UCRL 8030 (March 1965).

37. F. R. Eisler, T. C. Bacon, and H. W. K. Hopkins, Paper submitted to 1964 International Conference on High Energy Physics, Dubna.

38. J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

39. W. Galbraith, G. Manning, A. E. Taylor, B. D. Jones, J. Malos, A. Astbury, N. H. Lipman, and T. G. Walker, Phys. Rev. Letters 14, 383 (1965)

40. D. W. Carpenter, A. Abashian, R. J. Abrams, G. P. Fisher, B. M. K. Nefkens, and J. H. Smith, Physical Review (to be published).

41. S. Weinberg, Phys. Rev. Letters 4, 87 (1960).

42. G. Barton, C. Kacser, and S. P. Rosen, Phys. Rev. 130, 783 (1963).

43. S. McKenna, S. Natali, M. O'Connell, J. Tietge, and N. C. Vashenya, Nuovo Cimento, 10, 763 (1958).

44. M. Ferro-Luzzi, D. H. Miller, J. J. Murray, A. H. Rosenfeld, and R. D. Tripp, Nuovo Cimento 22, 1087 (1961).

45. L. T. Smith, D. J. Prowse, and D. H. Stork, Phys. Letters 2, 204 (1962).

46. T. Huetter, S. Taylor, E. L. Koller, P. Stamer, J. Grauman, Phys. Rev. (to be published).

47. G. E. Kalmus, A. Kernan, R. T. Pu, W. M. Powell, and R. Dowd, Phys. Rev. Letters 13, 99 (1965).

48. A. Abashian, R. J. Abrams, D. W. Carpenter, G. P. Fisher, B. M. K. Nefkens, and J. H. Smith, Paper submitted to the 1964 International Conference on High Energy Physics, Dubna.

49. L. M. Brown and P. Singer, Phys. Rev. 133, B812 (1964).

50. L. M. Brown and H. Faier, Second Coral Gables Conference, p.219 (1965).

51. S. Taylor, T. Huetter, E. L. Koller, and P. Stamer, Circulated Preprint SIT-P160 (1965).

52. S. Okubo, R. E. Marshak, and E. C. G. Sudarshan, Phys. Rev. Letters, 2, 12 (1959).

53. N. Brene, L. Egardt, and B. Quist, Nuclear Physics, 22, 553 (1961).

54. J. L. Brown, J. A. Kadyk, G. H. Trilling. R. T. Van de Walle, B. P. Roe, and D. Sinclair, University of California, Radiation Laboratory Report UCRL 10205 (1962).

55. G. L. Jensen, F. S. Shaklee, B. P. Roe, and D. Sinclair, Phys. Rev. 136, B1431 (1964).

56 G. E. Kalmus, A. Kernan, U. Camerini, and C. Henderson, University of California, Radiation Laboratory Report UCRL 11553 (1964)

57. G. P. Fisher, A. Abashian, R. J. Abrams, D. W. Carpenter, B. M. K. Nefkens, J. H. Smith, and A. Wattenberg, Paper submitted to the Argonne Weak Interactions Conference.

58. H. W. K. Hopkins, Private Communication; See also Reference 37.

59. G. Borreani, G. Gidal, G. Rinaudo, A. E. Werbrouck, A. Caforio, C. M. Garelli, S. Natali, and M. Villani, Preprint (1965).

60. G. Gidal, R. March, W. M. Powell, and S. Natali, Phys. Rev. Letters 13, 95 (1964).

61. X. De Bouard, D. Dekkers, B. Jordan, R. Mermod, T. R. Willits, K. Winter, P. Scharff, L. Valentin, M. Vivargent, M. Bott-Bodenhausen, Phys. Letters 15, 58 (1965).

62. V. Bisi, G. Borreani, A. Marzari-Chiesa, G. Rinaudo, M. Vigone, and A. E. Werbrouck, Phys. Rev. 139, B1068 (1965).

63. B. M. K. Nefkens, (Private Communication).

64. L. Criegee, J. D. Fox, H. Fraunfelder, A. O. Hanson, G. Moscati, C. F. Perdrisat, and J. Todoroff, Circulated Preprint (1965).

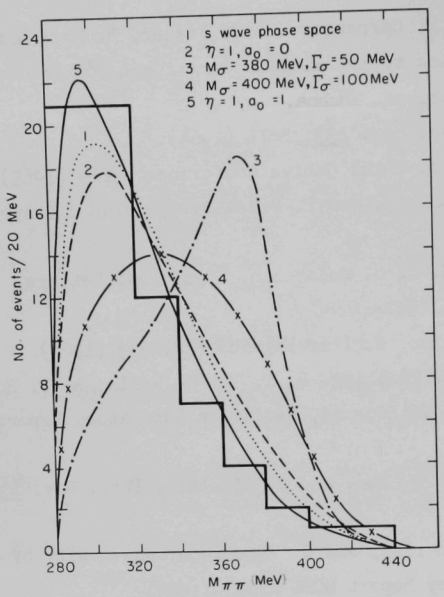
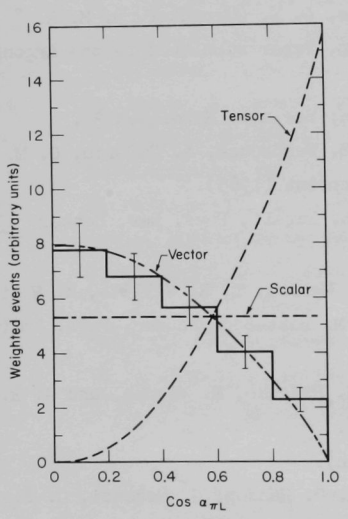


Fig. 1

$\pi^+ \pi^-$ Invariant Mass Plot for 69 Events of the Type $K^+_{e4} \rightarrow \pi^+ + \pi^- + e^+ + \nu$. The histogram shows the experimental data. The plotted curves indicate predictions for various models described in Ref. 8 Curve No. 4 corresponds to the parameters which fit the η data.



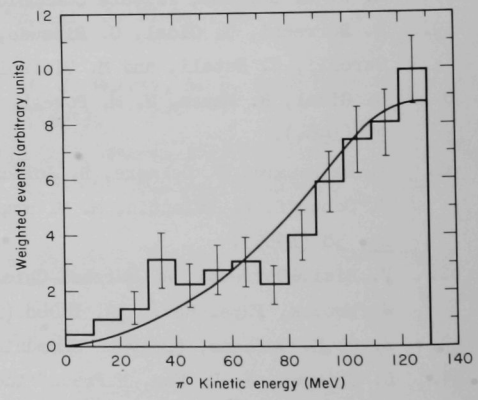


Fig. 2. Left: Distribution of cos $\alpha_{\pi\ell}$, Where $\alpha_{\pi\ell}$ Is the Angle between the Dilepton Line of Flight and the Pion in the Dilepton Rest System, in K^+_{e3} Decay (Ref. 56). Right: Pion kinetic energy spectrum for the same data. The curve refers to $\lambda = 0.02$ in the formula for f_+.

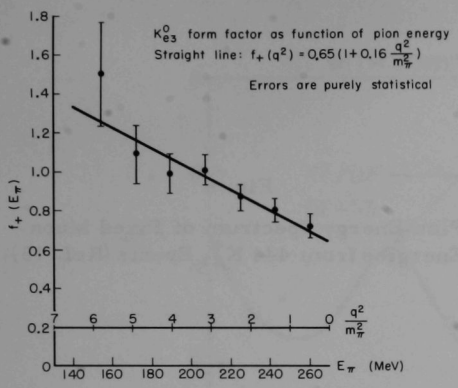


Fig. 3

Energy Dependence of the Form Factor f_+ in K^0_{e3} Decay from Ref. 57

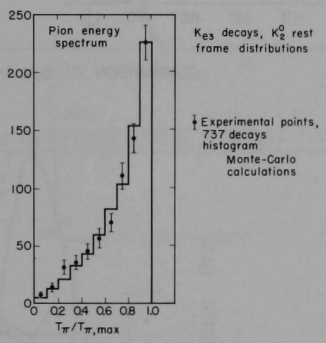


Fig. 4

Pion Energy Spectrum in K^0_{e3} Decay from Ref. 58

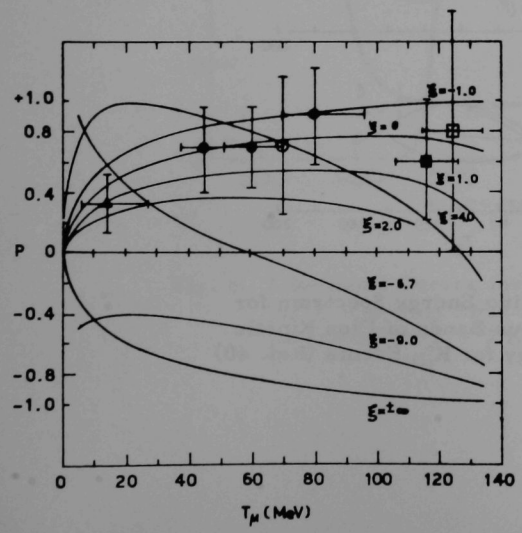


Fig. 5

Muon Polarization Data as a Function of Muon Energy for the $K^+_{\mu 3}$ Decay from Ref. 59

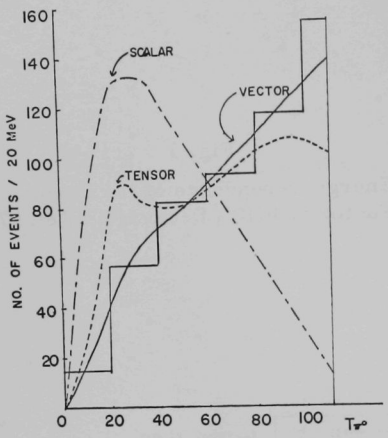


Fig. 6

Pion Energy Spectrum of Fixed Muon Energies from 444 $K^+_{\mu 3}$ Events (Ref. 15)

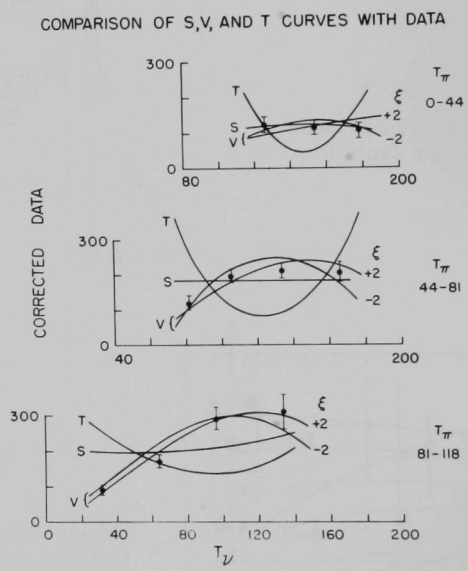


Fig. 7. Neutrino Energy Spectrum for Various Bands of Pion Kinetic Energy for $K^0_{\mu 3}$ Events (Ref. 40)

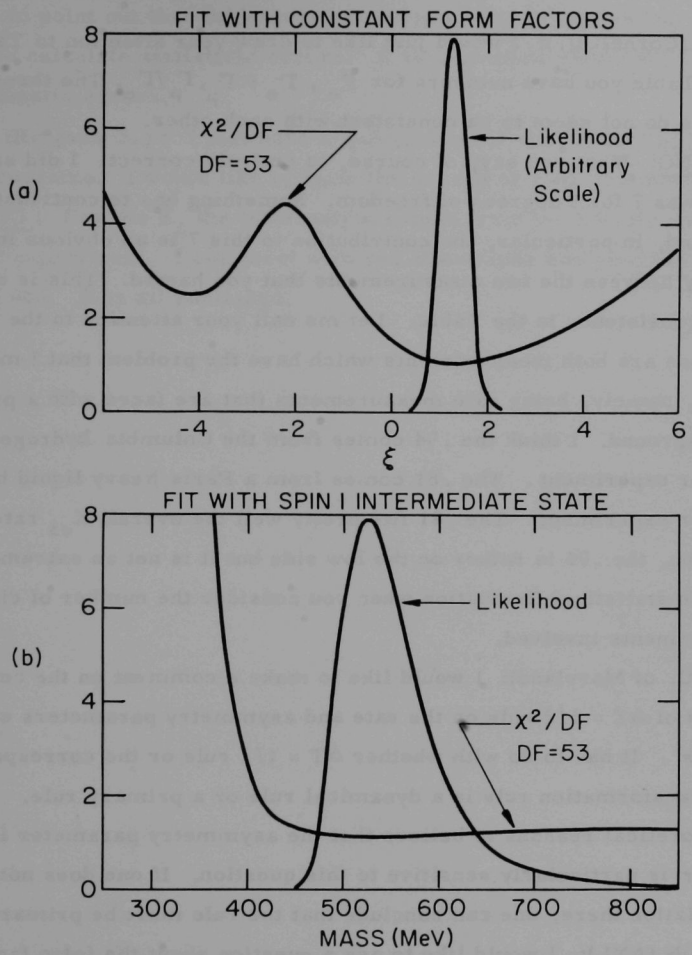


Fig. 8. Likelihood Curves for Fits to $K^{\circ}_{\mu 3}$ Data, for ξ (constant form factor), and M (intermediate J = 1 K-π state). (Ref. 40).

DISCUSSION

WHITE (Cornell U.): I would just like to draw your attention to Table 2. In that Table you have numbers for Γ_e, $\Gamma_e + \Gamma_\mu$, Γ_μ/Γ_e. The three numbers do not seem to be consistent with each other.

TRILLING: What you say, of course, is entirely correct. I did say that the χ^2 was 7 for 5 degrees of freedom. Something has to contribute to that 7 and, in particular, the contribution to this 7 is an obvious inconsistency between the two measurements that you named. This is not the only inconsistency in the Table. Let me call your attention to the fact that those are both measurements which have the problem that I mentioned earlier, namely, being rate measurements that are faced with a prodigious K_1 background. I think the .94 comes from the Columbia hydrogen bubble chamber experiment. The .81 comes from a Paris heavy liquid bubble chamber experiment. The .81 fits pretty well the overall K_{e3} rate. The other one, the .94 is rather on the low side but it is not an extremely improbable statistical fluctuation when you consider the number of different measurements involved.

PATI (U. of Maryland): I would like to make a comment on the consequences of $\Delta T = 1/2$ rule on the rate and asymmetry parameters of $K_2 \to 3\pi$. It has to do with whether $\Delta T = 1/2$ rule or the corresponding octet transformation rule is a dynamical rule or a primary rule. There are theoretical reasons to believe that the asymmetry parameter in $K_2 \to 3\pi$ is particularly sensitive to this question. If one does not find any violation there, one can conclude that the rule must be primary.

CHILTON (ANL): I would like to ask a question about the form factors. The disagreement between the form factors with K^+ and K^0 is very striking. I noticed large q^2 where you get the most significant effects. corresponds to low pion energy. It is not possible, is it, that there is some experimental problem connected with the difference between the low energy π^0 and the low energy charged π ?

TRILLING : Yes, it is possible. I think Professor Wattenberg would be the first to point out that the errors quoted are largely statistical, and, it is easy to calculate statistical errors. It is extremely difficult to know the systematic errors.

MEYER (Rutgers U.) : I just have a question about your limits on the neutral currents. I would like to know the source of your numbers.

TRILLING : For the K_2 the information comes from the Illinois spark chamber experiment. I can meet with you afterwards and give the references to you. It is all published.

SESSION III

SPECIAL FEATURES OF STRANGE PARTICLE DECAYS

Tuesday, October 26, 1965

CHAIRMAN: R. K. Adair
Yale University

Scientific Secretaries

G. R. Burleson, Northwestern University
L. G. Hyman, Argonne National Laboratory
D. W. McLeod, Argonne National Laboratory

TIME DISTRIBUTION OF K^o LEPTONIC DECAYS

B. Aubert, L. Behr, L. M. Chounet, J. P. Lowys, C. Pascaud

Ecole Polytechnique, Faculté des Sciences Accélérateur Linéaire
ORSAY S.O. FRANCE
(Paper presented by B. Aubert)

The time distribution of 315 $K^o \rightarrow \pi e \nu$ has been studied in the Ecole Polytechnique heavy liquid bubble chamber. Only electronic decays where the electron was directly recognized (stopping in the chamber) were used.

The K^o were produced by charge exchange of K^+ on neutrons from the nuclei of the liquid. Two kinds of mixture have been used:

1) C_3H_8 (55%) + CF_3Br (45%) d = 0.9 X_o = 21. Number of pictures: 94,600

2) CF_3Br (30%) + $C_2F_5C\ell$ (70%) d = 1.26 X_o = 17.5 Number of pictures: 108,600

In the second mixture we have also studies $K^o \rightarrow \pi^o \pi^o \pi^o$ as reported as this same conference.

The pictures were obtained at CERN in 1962 and 1963. The method used to process the data handling have been previously published (reference 1).

This experiment measures the number of events N^+ (t) $K^o \rightarrow \pi^- e^+ \nu$ and N^- (t) $K^o \rightarrow \pi^+ e^- \nu$, as a function of time. These distributions provide a test of $\Delta S = \Delta Q$ selection rule. If we observe a violation of this rule, then we are able to test PC conservation in electronic K^o decays (reference 2).

Let us define the following amplitudes

$$\left.\begin{array}{ll} f & K^o \rightarrow \pi^- e^+ \nu \\ f' & \overline{K}^o \rightarrow \pi^+ e^- \overline{\nu} \end{array}\right\} \Delta S = \Delta Q$$

$$\left.\begin{array}{ll} g' & K^o \rightarrow \pi^+ e^- \overline{\nu} \\ g & \overline{K}^o \rightarrow \pi^- e^+ \nu \end{array}\right\} \Delta S = -\Delta Q$$

CPT invariance implies $f' = f^*$

$g' = g^*$

If we consider the variables x and ϕ defined by

$$X = x\, e^{i\phi},$$

then the time distributions are

$$N^{\pm}(t) = C^{te}\Big[(1 + x^2 + 2x\cos\phi)e^{-\lambda_1 t} + (1 + x^2 - 2x\cos\phi)e^{-\lambda_2 t}$$

$$+ 2\,(2x\sin\phi\,\sin\Delta m t \pm (1 - x^2)\cos\Delta m t)\, e^{-\frac{\lambda_1+\lambda_2}{2} t}\Big]$$

CP Theorem implies $\phi = 0$ or π

$\Delta S = \Delta Q$ implies $x = 0$ and so we cannot test CP invariance in that case.

Figure 1 gives the experimental distributions (histograms), and the corresponding theoritical curves (smooth lines) obtained with the most probable values of X and Δm ($\mathrm{Re}\, X = 0.05$, $\mathrm{Im}\, X = 0.22$, $\Delta m = 0.47$)

Thus we can compute a likelihood function of 3 variables: $\mathrm{Re}\, X = x\cos\phi$, $\mathrm{Im}\, X = x\sin\phi$ and Δm. We represent the result in a space with 3 axis $\mathrm{Re}\, X$, $\mathrm{Im}\, X$ and Δm.

Figure 2 shows the most probable values with the confidence volume for 1 standard deviation (given by the solid line).

Our value for mass difference is

$$\Delta m = 0.47 \pm 0.21 \quad \hbar/c^2\tau_1$$

in good agreement with the present more accurate value (reference 3). Now if we assume that the mass value is $\Delta m = 0.5\ \hbar/c^2\tau_1$, we find

$$\mathrm{Re}\, X = 0.05 \pm 0.10 \qquad \mathrm{Im}\, X = 0.22 \begin{smallmatrix} +0.09 \\ -0.08 \end{smallmatrix}$$

We can make the following remarks:

1) To get the above results, we have used only events decaying between $t = 0.1\,\tau_1$ and $t = 15\,\tau_1$ (228 events).
We have checked that these results are not sensitive by changing our cut offs.

2) Our previous analysis (reference 1), assuming PC conserved, gave $x = 0.07 \begin{smallmatrix} +0.15 \\ -0.20 \end{smallmatrix}$; this is in agreement with our present result for $\mathrm{Re}\, X$.

3) This present result is really not in contradiction with the $\Delta S = \Delta Q$ rule. The ratio of probability for $X = 0$ to the probability for our most probable value is 6%.
However, we cannot exclude a small $\Delta S = -\Delta Q$ amplitude as shown by these values.

4) If we want to believe that we have really a non zero $\Delta S = -\Delta Q$ amplitude, this experiment shows that this amplitude is mainly imaginary, which implies PC violation.

Let us look more carefully to the likelihood function for Im X (figure 3). Im X = 0 cannot be excluded. On the other hand, if it is not zero, it must be small.

The absolute decay rates Γ_{1_β} and Γ_{2_β} have been computed. Taking the most probable values for Re X, Im X and Δm, we get

$$\Gamma_{2_\beta} = \frac{|f|^2 + |g|^2}{2(1+x^2)} (1 + x^2 - 2x \cos\phi) = (8.15 \pm 1.0)\, 10^6/\text{sec}$$

$$\Gamma_{1_\beta} = \frac{|f|^2 + |g|^2}{2(1+x^2)} (1 + x^2 + 2x \cos\phi) = (9.3 \pm 2.5)\, 10^6/\text{sec}$$

We can compare these values with those deduced from K^+_β decay rate assuming $\Delta I = 1/2$ and $\Delta S = \Delta Q$ leptonic rule.

One has the following relations:

$$\Gamma_{2_\beta} = \left| \sqrt{2/3}\ a(1/2,\ 1/2) + \sqrt{1/3}\ a(3/2,\ 1/2) - a(3/2,\ 3/2) \right|^2$$

$$\Gamma_{1_\beta} = \left| \sqrt{2/3}\ a(1/2,\ 1/2) + \sqrt{1/3}\ a(3/2,\ 1/2) + a(3/2,\ 3/2) \right|^2$$

$$\Gamma^+_\beta = \left| \sqrt{1/3}\ a(1/2,\ 1/2) - \sqrt{2/3}\ a(3/2,\ 1/2) \right|^2$$

$\Delta S = \Delta Q$ implies $a(3/2,\ 3/2) = 0$

$\Delta I = 1/2$ imples $a(3/2,\ 1/2)$ and $a(3/2,\ 3/2) = 0$

So

$$\Gamma_{1_\beta} = \Gamma_{2_\beta} = 2\,\Gamma^+_\beta = 7.68 \pm 0.49\ 10^6/\text{sec} \text{ (reference 4)}$$

Here again we see that our values are not in contradiction with the prediction of a selection rule, namely $\Delta I = 1/2$.

In conclusion we think that this experiment shows that there is no important deviation, if any, from the old theory: PC conserved, $\Delta S = \Delta Q$ and $\Delta I = 1/2$; but the accuracy is not sufficient to prove a small effect, of the order of ten per cent for example.

REFERENCES

1. B. Aubert, L. Behr, F. L. Canavan, J. P. Lowys, P. Mittner, L. M. Chounet, C. Pascaud, Physics Letters 10, p. 215; Physics Letters 11, p. 267; Physics Letters 17, p. 59.

2. R. G. Sachs, S. B. Treiman, Phys. Rev. Letters 8, p. 137; R. G. Sachs, Phys. Rev. Letters 13, p. 286.

3. Chuvilo talk - Dubna Conference (to be published).

4. G. Alexander, S. P. Almeida, F. S. Crawford Jr., Phys. Rev. Letters 9, p. 69; F. S. Shaklee, Technical Report, University of Michigan, Ann Arbor, March 1964.

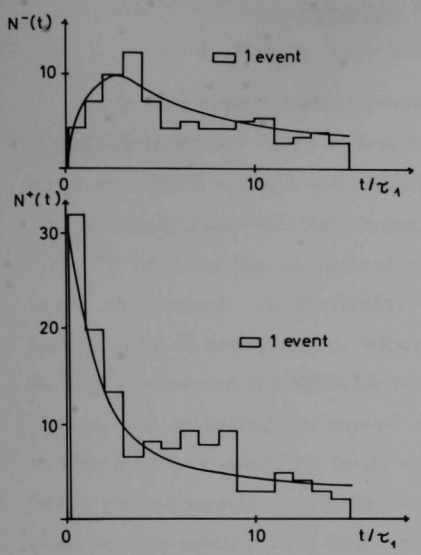


Fig. 1. Time Distributions of $K^\circ \to e^{\mp}\pi^{\pm}\nu$

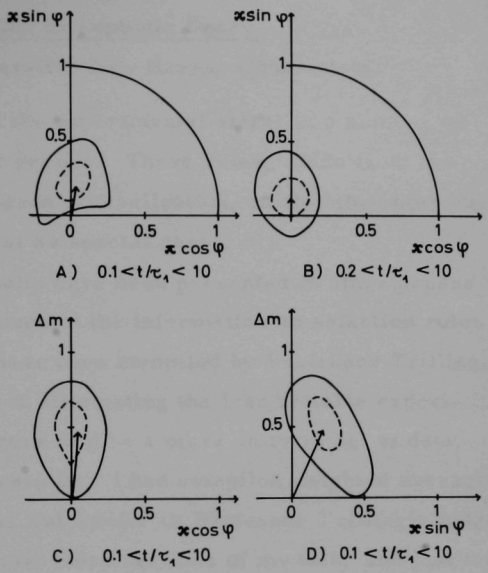


Fig. 2. Results of Maximum Likelihood with 3 Variables: ReX, ImX, Δm

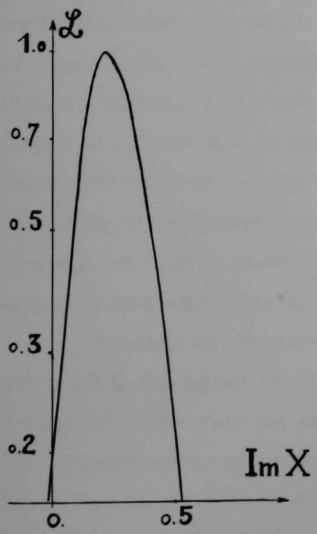


Fig. 3. Maximum Likelihood Function of ImX

Selection Rules in Leptonic Decay

W. J. Willis, Yale University, New Haven, Connecticut

In this report I shall review the experimental status of a number of proposed selection rules in leptonic decays. These rules, aside from the first one, form a sequence of increased generalization, in that the rules considered last imply rules earlier in the list as special cases.

Most of the numerical results have been presented in other papers in the conference. In particular, much of the information on selection rules comes from K decay rates, which have been compiled by Professor Trilling.[21] He has performed the difficult task of eliminating the less reliable experiments, and adjusting the quoted errors to give a more uniform set of data, to which he has applied a least squares fit. I had compiled weighted averages of the quoted values available to me, but I defer to Professor Trilling's judgment in this matter, and will cut short those sections of my talk, and just make use of his best estimates.

I have tried to summarize my conclusions in a table. I give here, for each selection rule, a simple statement concerning its validity. There are two kinds of information which the experiment may give about these rules. First, an experiment, or a comparison of results from different experiments may indicate that there is certainly some violation of a rule. If there is such evidence, it is indicated in the right hand column of the table, if the violation seems established beyond reasonable doubt. Evidence which is statistically valid only at confidence levels of the order of one per cent, or which is subject to doubt because of poorly understood systematic effects, or which is based on single events which are not highly constrained, is not considered conclusive.

Whether or not some violation of the rule has been established, one may ask what is the upper limit for the rate for transitions which violate the rule, compared to the rate for transitions which obey the rule. This seems to me the only objective way of stating the evidence for the validity of a hypothesis. I have tried to give the best upper limit, at the 90% confidence level, in the middle column. It is not always clear how to extract a limit for a given confidence level from the published results, and sometimes I have felt it necessary to

make some allowance for systematic errors. I make an apology to anyone who may disagree with my treatment of their results.

In a few cases, it is not clear what the correct rate is to compare with the possible rate which violates the rule in question. I have taken something which seemed reasonable to me but may be rather arbitrary, as in $\Delta S = 2$ decay.

I. Neutral Leptonic Currents

The low rate of the reaction

$$\mu \rightarrow e + \nu + \nu' \tag{1}$$

no longer seems to be a good argument for the absence of neutral leptonic currents since the demonstration that there are two neutrinos.[1] In this case, lepton conservation would suffice to forbid this reaction.

The decay

$$K^+ \rightarrow \pi^+ + e^+ + e^- \tag{2}$$

would not be suppressed by any other known selection rule if neutral lepton currents were allowed. A search for this decay has been carried out by Camerini et al.,[2] among an effective sample of 0.94×10^6 K^+ decays. Their result with a 90% confidence level is

$$\frac{r(K^+ \rightarrow \pi^+ e^+ e^-)}{r(K^+ \rightarrow \text{all modes})} < 2.45 \times 10^{-6} \tag{3}$$

or, by comparing with

$$K^+ \rightarrow \pi^0 e^+ \nu \tag{4}$$

$$\left(\frac{g_{ee^-}}{g_{e\bar{\nu}}}\right)^2 < 2.5 \times 10^{-5} \tag{5}$$

Apparent neutral currents generated by higher order electromagnetic terms are expected to give rates of the same order as this limit.[3]

A similar test is provided by the search carried out by Carpenter et al.,[4] as presented in Professor Abashian's contribution, for the reactions

$$K_2^o \to e^+ + e^-$$
$$\to \mu^+ + \mu^- \qquad (6)$$
$$\to \mu^\pm + e^\mp$$

They obtained a branching ratio limit of

$$\frac{r\,(K_2^o \to \mu^+\mu^-,\ e^+e^-,\ \mu^\pm\mu^\mp)}{r\,(K_2^o \to \text{ all charged modes})} \lesssim 10^{-4} \qquad (7)$$

By comparing the corresponding limit on the decay rate with the rate from $K^+ \to \mu^+ + \nu$, they find

$$\left(\frac{g_{\text{neutral currents}}}{g_{\text{charged currents}}}\right)^2 \lesssim 3 \times 10^{-5} \qquad (8)$$

The absence of neutral leptonic currents is, of course, to be expected if the weak interactions are mediated by charged bosons. However, neutral bosons coupled to baryon pairs have been suggested to allow for an exact $\Delta I = 1/2$ rule in non-leptonic decays;[5] the limits quoted above indicate that the neutral bosons must have a much weaker coupling to leptons than the charged ones do.

II. $\Delta S = \Delta Q$

This rule, where the change in strangeness is supposed to equal the change in charge of the strongly interacting particles in $\Delta S = 1$ transitions, is justly famous not only because of the striking effects predicted, but also because most of the selection rules we discuss later depend on the validity of this one. The $\Delta S = \Delta Q$ rule has been tested in three reactions. We discuss first the cases where a reaction is forbidden if the rule is valid.

A. Sigma leptonic decay

$$\Sigma^+ \to \ell^+ + n + \nu \qquad (9)$$

$$\Sigma^- \to \ell^- + n + \nu \qquad (10)$$

Here we mean by ℓ either an electron or a muon, although the two are distinguished in the experiments. This decay of Σ^+ is clearly forbidden by the $\Delta S = \Delta Q$ rule, while Σ^- decay is allowed. The ratio of the rates for these two reactions would seem, then, a fair test of $\Delta S = \Delta Q$. This comparison has been made in two experiments using samples of $\Sigma^\pm$ from K^- stopping in hydrogen bubble chambers. Large samples are required to give low upper limits on the Σ^+ decay since the Σ^- leptonic decay occurs only about 1/500 as often as the common pionic decay mode. The result of Courant et al.[6] is that no Σ^+ leptonic decay candidates meeting all the required criteria was found, while in a Σ^- sample effectively 3.8 times as large 73 Σ^- leptonic decays were found, leading to an upper limit at the 90% confidence level of

$$R = \frac{r(\Sigma^+ \to \ell^+ + n + \nu)}{r(\Sigma^- \to \ell^- + n + \nu)} < 0.12 \tag{11}$$

Nauenberg et al.[7] found one possible $\Sigma^+ \to e^+ + n + \nu$ event, leading to

$$R < 0.15 \tag{12}$$

at the 80% confidence level. These may be combined, giving an upper limit of

$$R < 0.08 \tag{13}$$

at 90% confidence level.

It may be recalled that Galtieri et al.[8] published several years ago a report of the observation in emulsion of an event for which the only probable interpretation was $\Sigma^+ \to \mu^+ + n + \nu$. It was found in a small sample of Σ^+ decays. In view of the results reported above, this event should probably not be taken as conclusive evidence for currents with $\Delta S = -\Delta Q$.

It is not known what the vector to axial vector ratio is for the $\Sigma^- \to n + e + \nu$ decay (or, indeed, to what extent other possible interactions are present). However, if one might argue that the vector part of the interaction should be roughly the same for the Λ and Σ^- leptonic decays. Then the Σ^- leptonic

rate can be compared with the vector part of leptonic rate, which has been measured after correction for the different phase spaces, and the excess attributed to the axial vector interaction. The conclusion is that the vector and axial vector parts of the decay rate are comparable in Σ^- decay. (This is in fact the result in the Cabibbo theory, but it would not be fair to use that argument in testing for $\Delta S = -\Delta Q$ currents, which are absent in that theory.) According to this argument, the upper limit on the vector current with $\Delta S = -\Delta Q$ is about twice that given by (13).

B. K_{e4} DECAY

The reactions studied are

$$K^+ \rightarrow \pi^+ + \pi^+ + e^- + \nu \tag{14}$$

$$K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu \tag{15}$$

The first one has $\Delta S = -\Delta Q$, the second $\Delta S = \Delta Q$. The Berkeley-Wisconsin group has searched for these reactions among the decays of K^+ stopping in a heavy liquid bubble chamber.[9] They found 69 examples of Reaction (15) and no examples of Reaction (14). In terms of 90% confidence upper limits, as in (11), this implies

$$R' = \frac{r\,(K^+ \rightarrow \pi^+ + \pi^+ + e^- + \nu)}{r\,(K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu)} < 0.06 \tag{16}$$

The effective mass distribution of the two pions indicates, as expected, that the two pion are dominantly in a relative s-state. Then, with the usual parity conventions, this is an axial vector transition. It is believed, from calculations of the S-wave $\pi^- N$ phase shifts for example, that the s-wave $I = 0$. $\pi\pi$ state is strongly attractive, but that the $I = 2$ state is not. This may be expected to cause a predominance of reaction (15) even if the $\Delta S = \Delta Q$ rule is not strictly valid, by a factor of $\lesssim 4$, as an upper limit.[9] The equivalent upper limit is $R \lesssim 0.25$.

C. $K^o_{\ell 3}$ Decay

Considering the reactions

$$K^o \rightarrow \pi^+ + \ell^- + \nu \tag{17}$$

$$K^o \rightarrow \pi^- + \ell^+ + \nu \tag{18}$$

We note that the first is forbidden, the second allowed by the $\Delta S = \Delta Q$ rule. However, in analyzing the decays which occur at times greater than a small fraction of a lifetime, we must analyze the decays in terms of K^o_1 and K^o_2. Let x be the ratio of the amplitudes for reactions (17) and (18). Then if we assume CP invariance, x is real and the time distribution for all decays has the form, for a beam initially K^o

$$N(t) = \frac{No}{2\tau_2} \left(a\, e^{-\frac{t}{\tau_1}} + e^{-\frac{t}{\tau_2}}\right) \tag{19}$$

where τ_1 and τ_2 are the K^o_1 and K^o_2 lifetimes, and

$$a = \left| \frac{1 + x}{1 - x} \right|^2 \tag{20}$$

If CP invariance is violated in this decay, another term must be added to (19) proportional to Im(x) sin (Δmt) $e^{-1/2(\frac{t}{\tau_1} + \frac{t}{\tau_2})}$, and a becomes less sensitive to small X values. The effect of this term is reduced if Δm, the $K^o_1 - K^o_2$ mass difference is small, in terms of its natural units, as it now seems to be. The time distribution for the number of <u>negative</u> leptons from $K^o_{\ell 3}$, N^-, is more sensitive to Im x, as it vanishes at t = 0 if $|x| = 0$, and it is finite at t = 0 if $|x| \neq 0$, whatever its phase. Even if $|x| = 0$, the distribution N^- is already quite appreciable by $\frac{t}{\tau_1} \sim 1/3$, because of the $\overline{K}^o$ amptitude developing in the beam due to K^o decay and the mass difference.

There are three recent experiments which bear upon this question, and these may be considered to supplant the older experiments of the same kind as the statistics are now much improved. One experiment studies a mixture of

K^o and $\bar{K}^o$ produced in $\bar{p}p$ absorption in a hydrogen bubble chamber. The other two experiments study the charge exchange of K^+ in a heavy liquid bubble chamber; thus their beam is initially K^o. The first experiment primarily measures α, the other two measure also the distribution of N^+ and N^-.

The leptonic decays in the first few K_1^o lifetimes represent only about one per cent of the number of $K_1^o \to \pi^+ \pi^-$ decays. Consequently, an important part of these experiments is the means of identifying the leptonic decays. In the heavy liquid chamber experiments, this was done by means of "spiralization" of the electrons in K_{e3}^o decay. The $K_{\mu 3}$ decays were not identified. In the hydrogen experiment, all decays which fitted a $K^o \to \pi^+ + \pi^- + \gamma$ with γ energy less than 50 MeV, or $K^o \to \pi^+ + \pi^- + \pi^o$ were eliminated, and the remainder retained as K_{L3}^o, including the $K_{\mu 3}^o$ as well as K_{e3}^o.

The results of at least two of the three experiments are in agreement that $\alpha \simeq 1$, when just N(t) is considered. Then, from the discussion given above, it can be seen qualitatively that if the experiments are to give a significant violation of $\Delta S = \Delta Q$, or $|x| \neq 0$, it must also be CP violating. The best fits to the data do give, in each case, values of x which are small and almost purely imaginary. Note that if x were really <u>zero</u>, we would expect the phase of the value of x actually found in an experiment of finite precision to be substantially <u>imaginary</u>, since the error on Im (x) is much larger than on Re(x). This kind of $\Delta S = -\Delta Q$ amptitude shows up in the hydrogen experiment only for the smaller sample of events for which the K^o produced can be identified as K^o or $\bar{K}^o$.

The best fits for the heavy liquid chamber experiments give $|x| \neq 0$ apparently primarily because of a few events with negative electrons at small times. This might be expected, since it was pointed out above that this is the most prominent effect of an imaginary x.

The Paris group[10] reports a best fit, based on 196 events, of[11]

$$x = \begin{pmatrix} +0.11 & & +0.15 \\ 0.035 - 0.30 & + & 0.21 - 0.11 \end{pmatrix} i \qquad (21)$$

with likelihood function 8% as large if $x = 0$. The slightly poor fit assuming $\Delta S = \Delta Q$ is largely due to one event with a negative electron and $t = 0.13\tau_1$. The mass difference is allowed to vary together with x in the likelihood fit, giving $\Delta m = 0.47 \pm 0.21$. In a similar analysis of similar data, based on 63 events the Padua group[12] finds a best fit with

$$|x| = 0.44 \begin{smallmatrix} +.19 \\ -.24 \end{smallmatrix}, \text{ with phase } \theta = -82 \begin{smallmatrix} +26^\circ \\ -68^\circ \end{smallmatrix} \tag{22}$$

with $\Delta m = 0.15 \begin{smallmatrix} +.35 \\ -.50 \end{smallmatrix}$. The probability of finding this bad a fit with $x = 0$, they report to be less than 5%.

Based on 109 events, the hydrogen chamber experiment of Franzini et al.,[11] yields

$$a = 1.64 \begin{smallmatrix} +1.26 \\ -0.88 \end{smallmatrix} \tag{23}$$

in a fit which does not depend on the mass difference. Allowing for CP violation, they study the difference in rate for the decays from initial K^o's and there from initial $\bar{K}^o$'s for the 45 events where this can be determined. They assume $\Delta m = 0.5$ and find

$$|x| = 0.25 \begin{smallmatrix} +.38 \\ -.25 \end{smallmatrix}, \quad \phi = 107 \begin{smallmatrix} +69^\circ \\ -42^\circ \end{smallmatrix}$$

The experiments, presented in this way at least, do not seem to be in violent disagreement. They indicate that if there is any $\Delta S = -\Delta Q$ amptitude, it is likely that it is also CP violating. (It may be noted in passing that the experiments on K^o_{L3} decay were thought at one time to be intrinsically more sensitive than the experiments where a forbidden reaction is looked for, because the K^o_{L3} experiments look at interference terms with the dominant $\Delta S = \Delta Q$ amptitude. However, this is no longer true if the $\Delta S = \Delta Q$ amptitude is out of phase with the dominant amptitude, i.e., if it is dominantly CP violating.) It remains to decide to what degree the existence of the $\Delta S = -\Delta Q$ currents is supported. This involves some nice statistical and experimental questions, but in practice it is sufficient to observe that none of the results supports a violation of $\Delta S = \Delta Q$ in a way which meets the criteria laid down in

the introduction to this paper. It can be said, however, that the suppression of $\Delta S = -\Delta Q$ currents by any large factor has not been established for K^o_{L3} decay. To compare with the other reaction which measure rates, we must ask for the upper limit on $|x|^2$. The upper limit on $|x|^2$ if CP is not violated is 0.1, from the likelihood function from the Paris experiment, with a similar limit from the hydrogen chamber experiment. If CP is violated, the limit becomes 0.25, set by the Paris experiment. This applies to the vector interaction, which is negligible in $K^+_{\ell 4}$ and probably accounts for about half of the Σ^- leptonic decay as mentioned above.

III. $|\Delta S| < 2$

Another reason for the importance of the $\Delta S = \Delta Q$ tests lies in the fact that if $\Delta S = -\Delta Q$ transitions do occur, and the weak interaction is supposed to have the form current of Fermious times current of Fermious, or intermediate bosons are supposed to exist, then in general $\Delta S = 2$ decays may be expected to take place, both leptonically and non-leptonically. These transitions would occur to the same order in the weak interactions as the $\Delta S = 0$ and 1 transition, and presumably with grossly similar rates.

There is a powerful argument against the occurance of non-leptonic $\Delta S = 2$ transitions:[13] the K^o and $\overline{K}^o$ would then be coupled to first order in the weak interaction and the $K^o_1 - K^o_2$ mass difference would be 10^6 times larger than it in fact is. Also, the decays

$$\Xi^- \rightarrow n + \pi^- \tag{24}$$

$$\Xi^o \rightarrow p + \pi^- \tag{25}$$

have not been observed. The upper limit for (24) from the results of Ferro-Luzzi et al.[14] is, at the 90 % confidence level,

$$\frac{\Xi^- \rightarrow n + \pi^-}{\Xi^- \rightarrow \Lambda + \pi^-} < 0.01 \tag{26}$$

and the upper limit for (25) is given by Lai[15] as

$$\frac{\Xi^{o} \rightarrow p + \pi^{-}}{\Xi^{o} \rightarrow \Lambda + \pi^{o}} < 0.03 \tag{27}$$

Useful limits for the leptonic decays

$$\Xi^{-} \rightarrow n + e^{-} + \nu \tag{28}$$

$$\Xi^{o} \rightarrow p + e^{-} + \nu \tag{29}$$

are not yet available.[14,15]

The value which might be expected for (28) and (29) can perhaps be obtained by multiplying the universal Fermi interaction rate by the square of the factor by which $\Lambda \rightarrow$ pev decay is smaller than the UFI prediction. This gives a branching ratio for (28) of $\sim 10^{-3}$.

The limit on the leptonic decays are interesting even though they can never approach the limit set by the $K_1^o - K_2^o$ mass difference. For example, Behrends and Sirlin[15] and Lee[16] have proposed a scheme involving six intermediate bosons which allows $\Delta S = \Delta Q$ transitions but no $\Delta S = 2$ transitions, but Wolfenstein[17] has proposed an alternative scheme, a modification of d'Espagnat's "veton" theory, in which the non-leptonic $\Delta S = 2$ transitions are suppressed much more than the leptonic ones.

In any case, the apparent lack of $\Delta S = 2$ transitions is consistent with the $\Delta S = \Delta Q$ rule, which we shall consider to be exact during the remainder of this paper.

IV. No Second Class Currents

Weinberg[18] pointed out some time ago that the possible forms of the semi-leptonic interactions may be divided into two classes, according to the G parity of the current of strongly interacting particles. The ordinary vector and axial vector interactions are of the first class, as are the interactions presumably induced by the strong interactions: psuedo-scalar and "weak magnetism." There exists other possible interactions which are of the second class. The conserved vector current assumption tells us that the second class currents originating with the strangeness non-changing vector

interaction, at least, are absent. It has been suggested that all the second class currents are absent or suppressed,[18] (See Section VI for a theory in which this is approximately true.)

If we assume the vector interaction in $K_{\ell 3}$ decay, there are two independent form factors, one of which is of the "induced scalar" form.[19] The prediction of the rule of no second class currents is that the ratio of the induced scalar form factors, f- to the ordinary vector-type form factor, f+, should be zero. Since f- is multiplied by a small factor in the electron decay, but not in the muon decay, a measure of this ratio can be obtained from the $K_{\ell 3}/K_{\mu 3}$ branching ratio. If this rule is correct, and the variation of the form factors with momentum transfer can be neglected, the branching ratio is predicted[20] to be $\frac{K_{\mu 3}}{K_{\ell 3}} = 0.65$. The best values for this ratio are, from Trilling's compilation

$$\frac{K^{+}_{\mu 3}}{K^{o}_{\mu 3}} = 0.69 \pm 0.06 \tag{30}$$

$$\frac{K^{o}_{2(\mu e)}}{K^{o}_{2(\ell 3)}} = 0.78 \pm 0.10 \tag{31}$$

There is certainly approximate agreement with the prediction; on the other hand, the upper limit on ξ, the ratio of f- to f+, is, from the K^{+} data compiled by Trilling,

$$\xi_{+} < 0.7 \tag{32}$$

This ratio would be predicted to be small, but if this rule were badly violated, one might expect $\xi \sim 1$. The upper limit on ξ_{+} is large enough so that the test is not very conclusive at present.

Another prediction is that

$$\frac{\gamma(\Sigma^{-} \rightarrow \Lambda + e^{-} + \nu)}{\gamma(\Sigma^{+} \rightarrow \Lambda + e^{+} + \nu)} = 1 \tag{33}$$

where the γ's are the rates for these reactions divided by the volume of

phase space. This correction is quite important due to the small energy release in this reaction, and the relatively large $\Sigma^- - \Sigma^+$ man difference.

It has been noted that if time reversal invariance and the particular charge symmetry of the currents proposed by Lee and Yang [5] hold, the absence of the second class currents in this reaction follows.[22] However, the charge symmetry condition alone is sufficient to obtain the relation (33). If an explicitly T-violating quantity is observed, the predictions of the two rules for this reaction are distinct.[22]

There is one experimental measurement of this quantity:[6]

$$\frac{\gamma(\Sigma^- \to \Lambda + e^- + \nu)}{\gamma(\Sigma^+ \to \Lambda + e^+ + \nu)_{exp}} = 0.7 \begin{smallmatrix} +.6 \\ -0.25 \end{smallmatrix} \tag{34}$$

which agrees, within the large errors, with the prediction.

V. $\Delta I = \frac{1}{2}$ Currents

This rule[23] limits the change in isotopic spin of the strongly interacting particles to $\frac{1}{2}$ unit. In a reaction like

$$K^+ \to \mu^+ + \nu \tag{35}$$

only $\Delta I = \frac{1}{2}$ is possible. Transitions with $\Delta S = -\Delta Q$ imply a change in I_z of $\frac{3}{2}$, violating this rule. If $\Delta S = -\Delta Q$ currents are supposed to be absent, there is still the possibility of currents with $\Delta I_z = \frac{1}{2}$, but $\Delta I = \frac{3}{2}$: this rule states that they do not exist.

Aside from neutrino induced reactions, the only convenient experimental test of this rule is a comparison of $K^+_{\ell 3}$ and $K^o_{\ell 3}$ decay. The prediction is that

$$\Gamma_{K^o_2 \to \pi^\pm + \ell^\mp + \nu} = 2\Gamma_{K^+ \to \pi^o + \ell^+ + \nu} \tag{36}$$

Trilling[21] has compared the results of his compilation of the K decay rates with the prediction. For completeness, his comparison of

the rates is given below, in the form of the ratios of the total rates, and the μ/e ratio:

$$\frac{\Gamma_{K_2^o \to \pi^\pm + e^\mp + \nu} + \Gamma_{K_2^o \to \pi^\pm + \mu^\mp + \nu}}{2\left(\Gamma_{K^+ \to \pi^o + e^+ + \nu} + \Gamma_{K^+ \to \pi^o + \mu^+ + \nu}\right)} = 1.06 \pm 0.06 \qquad (37)$$

$$\left(\frac{\Gamma_{K_2^o \to \pi^\pm + \mu^\mp + \nu}}{\Gamma_{K_2^o \to \pi^\pm + e^\mp + \nu}}\right) \Big/ \left(\frac{\Gamma_{K^+ \to \pi^o + \mu^+ + \nu}}{\Gamma_{K^+ \to \pi^o + e^+ + \nu}}\right) = 1.07 \pm 0.14 \qquad (38)$$

If we assume CP invariance, so that X, the ratio of $\Delta I = \frac{3}{2}$, to $\Delta I = \frac{1}{2}$ amptitudes, is real, then the ratio (37) is $\sim 1 + 4.2\,x$ for small x,[24] and the 90 % confidence level for x^2 is

$$x^2 < 0.001 \; . \qquad (39)$$

However, if we allow x to be complex, as we must since CP may well be violated here, we lose the sensitivity of the interference effect, and the upper limit becomes

$$X^2 < 0.14 \qquad (40)$$

taking simply the limit on the deviation of (32) from one.

It also follows from the rule that matrix elements for $K^+_{\ell 3} + K^o_{\ell 3}$ decay should be the same, aside from the relation between the magnitudes implied by (36). Thus, the ratio of form factors, ξ, should be the same in $K^+_{\ell 3}$ and $K^o_{\ell 3}$ decay. From Trilling's compliation,[21] the upper limit on the difference is

$$\xi_{K^o_{\ell 3}} - \xi_{K^+_{\ell 3}} < 2 \qquad (41)$$

using only the branching ratio determinations of ξ, to avoid questions of the

energy dependence of the form factors. The errors on ξ from the two kinds of decays overlap, so there is no evidence of violation of the rule.

The form factors may be expected to be functions of the pion energy, and according to this rule they should be identical functions in the different decays. In particular, if the form factor f_+ is considered to be a linear function of pion energy, the slope should be the same for $K^+_{\ell 3}$ and $K^o_{\ell 3}$ decay. As emphasized in Trilling's paper,[21] the K^+ experiments agree in giving a slope consistent with zero. Among the $K^o_{\ell 3}$ experiments, Bacon et al.[31] have reported a slope consistent with zero, while Prof. Wattenberg reported at this conference the observation of a slope which seemed significantly different from zero. Clearly, it cannot be decided whether the rule is violated until the inconsistency between the experiments is resolved. Meanwhile, the possible amount of violation as indicated by the difference in $f^2_{+K^+}$ and $f^2_{+K^o}$ is given in the Table.

VI. Octet Currents

In view of the apparent success of the eight-fold way in the strong interactions, it is natural to investigate the possibility that the weak interactions leading to leptonic decays of the strongly interacting particles are composed of an octet of hadronic currents times the leptonic currents.[25] An octet of currents has the properties $\Delta I = \frac{1}{2}$ for $\Delta S = 1$, $\Delta S < 2$, and $\Delta S = \Delta Q$. This possibility therefore seemed excluded when $\Delta S = -\Delta Q$ transitions seemed to exist. It now furnishes a possible basis for these rules, and makes a number of further predictions.

The matrix elements for a member of an octet decaying to a different member of the same octet are obtained as the coefficients of the octet members of the Clebsch-Gordon series expansion of the direct product of two octets. There are two octets in that series, giving rise to two parameters, D and F, for the vector interaction and two for the axial vector. However, if an extension of the conserved vector current is adopted, by assuming that the weak vector currents belong to the same octet as the electromagnetic currents, then $D_{vector} = 0$, from the known properties of the electromagnetic interaction.

At this point there occurs a violent contradiction with experiment if the usual form of the universal Fermi interaction is assumed, since the $\Delta S = 1$ decay rates are much smaller than those with $\Delta S = 0$, by a factor of ~ 20 after phase space corrections. If we wish to maintain the octet assumption, we must drop the universal interaction. The weakest alternative assumption is to suppose universality among $\Delta S = 0$ and $\Delta S = 1$ transitions separately. (This is called "Weak UFI" in the table.) Too few $\Delta S = 0$ leptonic decays are practically available to lead to an experimental test of the octet current rule without further assumptions, but for $\Delta S = 1$ decays there are a number of predictions. The matrix elements for some baryon transitions are[26, 24]

$$M(n \to pe\nu) = F + D \tag{42}$$

$$M(\Sigma^- \to \Lambda e\nu) = \sqrt{\frac{2}{3}}\, D \tag{43}$$

$$M(\Lambda \to pe\nu) = \sqrt{\frac{3}{2}}\,(F + \frac{1}{3} D) \tag{44}$$

$$M(\Sigma^- \to ne\nu) = F - D \tag{45}$$

$$M(\Xi^- \to \Lambda e^- \nu) = \sqrt{\frac{3}{2}}\,(-F + \frac{1}{3} D) \tag{46}$$

Since only the F terms is present for the vector part of the interaction, the best tests of the rule come from a measurement of the vector parts of the decays, which should be in the ratios $\frac{3}{2} : 1 : \frac{3}{2}$ for the decays (44), (45), (46); after correction for the different phase space in each reaction.

These predictions have been very much strengthened by a theorem due to Ademollo and Gatto,[27] which states that under the above assumptions, and with the usually assumed form of symmetry breaking, none of the vector parts of the interaction are affected by the breaking of the symmetry, to first order, when the physical masses are used on calculating phase space. This implies that the above predictions should be quite accurate.

Unfortunately, the only test which can be made at the moment is to use the V/A ratio measurements[28] for the decay (44), combine these with the best value of the rate,[29] and predict a lower limit for the decay (45). This inequality is certainly satisfied, but a satisfactory test depends on the measurement of V/A ratio in (45).

Cabibbo has suggested stronger assumptions which restore a kind of

universality, and led to a number of comparisons with experiment. The "Weak UFI" hypothesis is supplemented by the condition that the constant which multiplies the strangeness conserving currents is to be cos θ and that which multiplies the strangeness conserving currents is to be sin θ, where θ is to be determined by experiment.

Furthermore, the same value of θ is to be used for all decays, meson or baryon, vector or axial vector. Four constants, G (as determined from muon decay), θ, and F and D for the axial vector currents then suffice to predict all leptonic decays.

The experimental data have been found to be in fairly satisfactory agreement with this picture.[6,30,31] The new branching ratios given by Professor Trilling allow some more accurate comparisons. The $K^+_{\mu 2}$ branching ratio is given in terms of the $\pi^+ \to \mu^+ + \nu$ rate by[25]

$$F_{K_{\mu 2}} = \frac{\tau_K}{\tau_{\pi\mu}} \frac{MK}{M\pi} \left[\frac{1 - \left(\frac{M_\mu}{MK}\right)^2}{1 - \left(\frac{M_\mu}{M\pi}\right)^2} \right]^2 \tan^2 \theta \qquad (47)$$

whence

$$\theta_{K_{\mu 2}} = 0.266 \pm 0.0015 . \qquad (48)$$

Similarly, from the ratio of the K^+_{e3} rate to the $\pi^+ \to \pi^0 + e + \nu$ <u>predicted</u> rate,

$$\theta_{K_{e3}} = 0.246 \pm 0.006 . \qquad (49)$$

The difference between these angles (one for a vector, the other for an axial vector, decay) is possibly significant experimentally

$$\theta_{K_{\mu 2}} - \theta_{K_{e3}} = 0.020 \pm 0.006 \qquad (50)$$

but, within the spirit of the theory, corrections for form factor variations should be made, which might improve the equality.

Another value of θ is obtained from the analysis of the decays

of the baryon octet.[6] The value of θ_B and the D/F ratio are not distributed in a Gaussian fashion, and the variables are highly correlated, so the errors are only approximate:

$$\theta_B = 0.27 \pm 0.02 \tag{51}$$

$$D/F = 1.7 \pm 0.3 \ . \tag{52}$$

Brene et al.[30] have considered the effect of terms such as the weak magnetism, and induced psuedo-scalar. They obtain

$$\theta_B = 0.236 \pm 0.016 \tag{53}$$

The value of θ from baryon decays seems to agree with that from the meson decays. However, there may be some difficulty when the prediction for the vector coupling constant in nuclear β decay is compared with the observed value. The predicted value is G cos θ. To take advantage of the theorem of Ademollo and Gatto, we use for θ that for the vector decay, θ_{Ke3}. Then

$$\cos\theta_{Ke3} = 0.970 \pm .001 \tag{54}$$

which may be compared with the value from experiments on the decay of O^{14} and similar species[32]

$$\cos\theta_{V\beta} = 0.978 \pm .001 \ . \tag{55}$$

The two values do not agree, within the errors. Perhaps the trouble lies in the theoretical corrections to the nuclear decay rates.[33]

The quality of agreement between the theory and the data can be judged from Figure 1,[6] which is a plot showing the lines in the plane defined by the F and D parameters, which are implied by the measured decay rates in baryon decay. The angle θ is fixed at the value which gave the best fit to all the data, including cos θ from β-decay, but with a 1% error to allow for uncertainties in the corrections. All the lines should meet in a point, a condition best satisfied at point A. The fit predicts that the V/A ratio in Λ decay Reaction (44) should be -0.68, in good agreement with the experimental value

of $-0.9^{+0.25}_{-0.3}$.[28] A striking untested prediction is that the V/A ratio in Σ^- decay, Reaction (45), should be + 0.3.

A measure of the possible failure in the theory is the disagreement among the different determinations of θ^2. Whether we take the limit on the values given by (48), (49) and (50), or we take the disagreement between the values implied by (51) and (52), we obtain a possible spread in θ^2 of about 40%, as indicated in the Table.

Finally, it may be noted, as pointed out by Ademollo and Gatto,[27] that the second class currents are expected to be zero for octet currents, so that the rule stated in Section IV is also a special case of the present one. However, the second class currents are forbidden only to zeroth-order in the symmetry breaking, and the value of ξ is not expected to be actually zero, as shown in explicit dispersion theory treatments.[34] It is, however, predicted to be small (~ 0.1).

REFERENCES

1 G. Feinberg and L. Lederman, Annual Review of Nuclear Science, 13, 465 (1963).

2 U. Camerini, D. Cline, W. Fry, W. Powell, Phys. Rev. Letters, 13, 319, (1964).

3 M. Baker and S. Glashow, Nuovo Cimento 25, 857, (1962).

4 Carpenter et al. - Abashian's talk this conference.

5 T. D. Lee and C. N. Yang, Physical Review, 119, 1410 (1960).

6 H. Courant, H. Filthulth, P. Franzini, A. Minguzzi-Ranzi, A. Segar, R. Engelmarr, V. Hepp, E. Kluze, R. Burnstein, T. Day, R. Glasser, A. Herz, B. Kehoe, B. Sechi-Zorn, N. Seeman, G. Snow, W. Willis, Phys. Rev. (1964).

7 U. Nauenberg, P. Schmidt, J. Steinberger, S. Marateck, R. Plano, H. Blumenfeld, and L. Seidlitz, Phys. Rev. Letters 12, 679, (1964).

8 A. Barbaro-Galtierri, W. Barkas, H. Heckman, J. Patrick, and F. Smith, Phys. Rev. Letters, 9, 26, (1962).

9 R. Birge, R. Ely, G. Gidal, P. Kalmus, A. Kerman, W. Powell, U. Camerini, D. Cline, W. Fry, J. Gaidos, D. Murphree, and C. T. Murphy Phys. Rev. 139, B1600, (1965).

10 Paper presented to this conference by B. Aubert; and B. Aubert, L. Behr, F. Canavan, L. Chounet, J. Louys, P. Mittner, and C. Pascaud, Physics Letters, 17, 59 (1965); note that there are, in all the experiments, sign ambiguities affecting Im x and m.

11 P. Franzini, L. Kirsch, P. Schmidt, J. Steinberger, R. Plano, Phys. Rev. 140, B127 (1965).

12 M. Baldo-Ceolin, E. Caliani, S. Ciampolillo, C. Filippi-Filosofo, H. Huzita, F. Mattioli, and G. Miari, Nuovo Cimento, 38, 684, (1965).

13 L. Okun and B. Pontecorvo, JETP 5, 1297 (1957), but see also S. Glashow, Phys. Rev. Letters 6, 196 (1961).

[14] M. Ferro-Luzzi, M. Alston, A. Rosenfeld, and S. Wojcicki, Phys. Rev. 130, 1568 (1963).

[15] K. W. Lai, private communication.

[16] Behrends and Sirlin, in Weak Interactions, C. Fronsdal (editor), and T. D. Lee, Phys. Rev. Letters 9, 319 (1962).

[17] L. Wolfenstein, Nuovo Cimento, 29, 859 (1963).

[18] S. Weinberg, Phys. Rev. 112, 1375 (1958).

[19] S. McDowell, Nuovo Cimento 6, 1445 (1957); A. Pais and S. Treiman, Phys. Rev. 105, 1616 (1957); and L. B. Okun, Soviet Physics JETP 6, 409, (1958).

[20] N. Brene, L. Egardt and B. Quist, Nucl. Phys. 22. 553 (1961).

[21] G. Trilling, Report on K-Decay to this conference.

[22] T. D. Lee and C. S. Wu, Annual Reviews of Nuclear Science (to be published). I wish to thank Professor Lee for discussions on the relations among these hypotheses.

[23] M. Gell-Mann and A. H. Rosenfeld, Annual Reviews of Nuclear Science Vol. 7 ; S. Okubo, R. Marshak, E. Sudarshan, W. Teutsch, and S. Weinberg, Phys. Rev. 112 665 (1958); and L. Okun, Proceedings of the Conference on Mesons and Recently Discovered Particles, Padua-Venice, (1958).

[24] R. H. Dalitz, "Properties of the Weak Interactions," Oxford Preprint, 1964, (Lectures delivered at Varenna, 1964).

[25] N. Cabibbo, Phys. Rev. Letters 10 531 (1963).

[26] J. de Swart, Rev. Modern Phys. 35, 916 (1963).

[27] M. Ademollo and R. Gatto, Phys. Rev. Letters 13, 265 (1964).

[28] V. Lind, T. Binford, M. Good, and D. Stern, Phys. Rev. 135, B1483 (1964); C. Baglin, V. Brisson, A. Rousset, J. Six, H. Bingham, M. Mikolic, K. Schultze, C. Henderson, D. J. Miller, F. Stannard, R. Elliott, L. Rangan,

A. Haatuft, and Myklebost, Nuovo Cimento 35, 977 (1965); and J. Barlow, I. Blair, G. Conforto, M. Ferraro, C. Rubbia, J. Sens, P. Duke, and A. Mann, Physics Letters 18, 64 (1965).

29 The presently available data on hyperons decay rates is compiled in A. Rosenfeld, A. Barbaro-Galtieri, W. Barkas, P. Bastien, J. Kirz, and M. Roos, UCRL 8030, March (1965).

30 N. Brene, B. Hellesen, and M. Roos, Physics Letters 11, 344 (1964); see also: W. Dresckler, Nuovo Cimento 38, 345 (1965).

31 T. Bacon, F. Eisler, and H. Hopkins, International Conference on Weak Interactions at Brookhaven, 1963, p. 39.

32 J. Freeman, J. Jenkin, G. Murray and W. Burcham, paper contributed to this conference.

33 R. P. Feynman, Proceedings of the 1960 Annual Conference on High Energy Physics at Rochester (1960) p. 501; and T. D. Lee, "Weak Interactions and Questions of C, P, T Non-Invariances, Oxford Conference (1965), (to be published).

34 S. MacDowell, Phys. Rev. 116, 1047 (1959).

TABLE I

SELECTION RULE FOR LEPTONIC DECAY			90% Conf. Limit for Rate* of Violation	Is some violation established?
NO NEUTRAL LEPTONIC CURRENTS			2.5×10^{-5}	NO
$\Delta S = \Delta Q$	$\Sigma^{\pm} \to n + \ell + \nu$ (V, A)		0.08	NO
	$K^{+} \to \pi + \pi + \ell + \nu$ (A)		0.25	NO
	$K^{o} \to \pi + \ell + \nu$ (V)	CP Good	0.1	NO
		CP Bad	0.25	NO
$\Delta S = 2$			NO TEST	
NO SECOND CLASS CURRENTS	$\Sigma^{\pm} \to \Lambda + e + \nu$		~ 50% accuracy	NO
	$K^{\pm o}_{\ell 3}$ ($\xi \sim 0$?)		<.7	NO
$\Delta I = \frac{1}{2}$ Currents	$K^{\pm o}_{\ell 3}$ Rates	CP Good	0.001	NO
		CP Bad	0.14	NO
	μ/e: $\xi^{+} = \xi^{o}$ (from rates only)		2.	NO
	Form Factor: $(f^{+})^2 = (f^{o})^2$		~ 0.5	NO
OCTET CURRENTS	+ CVC + UFI		Bad by ~ 20	YES
	+ CVC + "WEAK UFI"		Inequality OK	NO
	+ "CABIBBO"		0.4 (in θ^2)	NO

* Tests which involve amptitudes have been "squared", e.g., use the $|x|^2$ defined in $\Delta S = \Delta Q$.

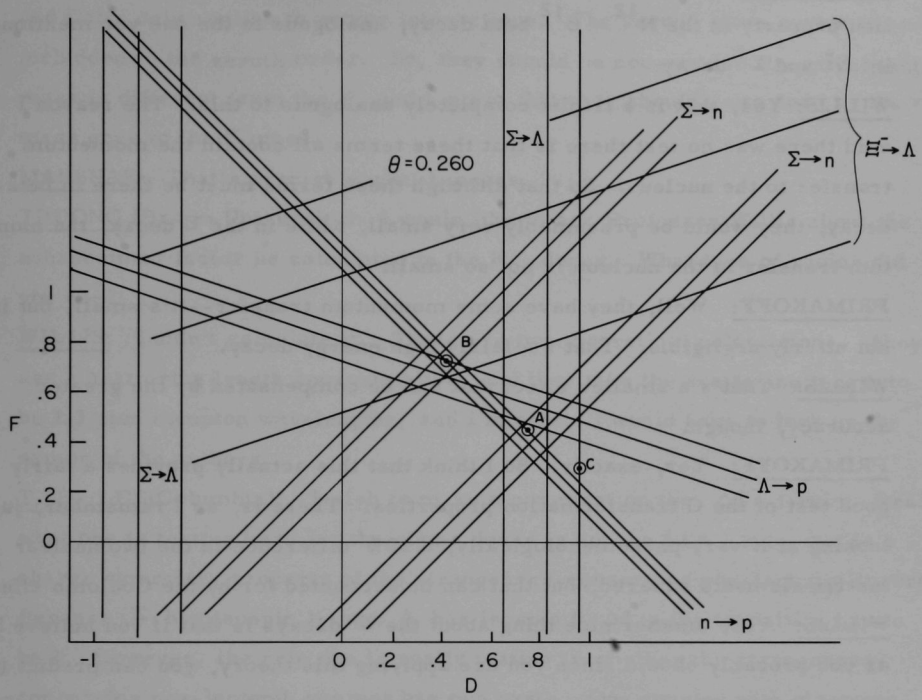


Fig. 1. This Shows the Results of Experiments on the Leptonic Decays of Hyperons in Terms of the Parameters F and D for the Axial Vector Currents, from Reference (6)

DISCUSSION

PRIMAKOFF (U. of Pennsylvania): I think there is a test of the G-transformation property in the N^{12} - B^{12} beta decay, analogous to the one you mentioned in Σ^- and Σ^+ decay.

WILLIS: Yes, that is a triplet completely analogous to this. The reason I said there was no test there is that these terms all contain the momentum transfer to the nucleus. So that although these terms must be there in beta-decay, they would be presumably very small, while in the Σ decay, the momentum transfer to the nucleon is not so small.

PRIMAKOFF: Well, they have some momentum transfer--it's small, but it's not utterly negligible. That's a fairly high energy decay.

WILLIS: That's a smaller effect that can be compensated by the greater accuracy, though.

PRIMAKOFF: Yes, exactly. So I think that this actually provides a fairly good test of the G transformation properties. There is, as I remember, just looking at it very phenomenologically, a 10% difference in the two nuclear matrix elements squared, but that can be accounted for by the Coulomb effects.

WILLIS: Yes, another nice thing about the Σ^- decays is that if you believe SU(3), as you probably should since you are applying this theory, you can predict (if you're looking for consistency) an awful lot of things about these decays. For instance, you know the transition moment here for evaluating weak magnetism, because it's related to that of the neutron. If you think you're going to be troubled by lack of charge independence, you know from the Coleman-Glashow relations exactly how charge independence is violated and you can correct for that. So, if you work with the miserable fact that it's a very rare decay, it's a very nice thing because you can predict everything to an arbitrary accuracy.

MARSHAK (U. of Rochester): You mentioned this one percent accuracy on the vector current, for example, in particular in connection with the $\xi = 0$ effect.

WILLIS: Well, the idea was that these predictions are good to the same order in symmetry breaking as the mass rules, which are good to about one percent.

MARSHAK: This is just the point. For example, in the ξ factor, if you do a simple dispersion estimate of the poles, then you get $M_K^2 - M_\pi^2$ in that ratio.

WILLIS: No, that's not good to one percent. I said that the theorem of Ademollo and Gatto only applies to vector interactions. The second class currents are forbidden to the zeroth order. So, they should be non-zero to the extent that the π mass is different from the K, and I guess that they should go to zero as the π mass goes to the K mass.

MARSHAK: That's precisely what happens.

TRUONG (Brown University): I would like to ask Professor Willis about the enhancement factor he calculated in the K_{e4} decay. What type of radius did you use?

WILLIS: I didn't calculate it. There are two theoretical calculations. They use a scattering length approximation, and they take the scattering length to be 1.3 pion compton wavelengths, and I'm afraid I would have to look up the names of the authors.

T. D. LEE(Columbia): I wish to make a comment on the $\Delta I = 1$ rule. Really, what one is testing here for the sigma decay is not the $\Delta I = 1$ rule, but is a charge symmetry property of the strangeness-conserving non-leptonic current. Because Σ has isospin 1, and Λ has isospin 0, ΔI in the transition has to be 1. However, the rule one is really testing is whether the strangeness-conserving non-leptonic current has two parts. One couples with electrons, the other couples with positrons. Now these two parts are related by hermitean conjugation. In the case of the beta decay, the hermitean conjugation requires that they be also related by charge symmetry which is the operation of 180° rotation around the Y-axis of the isospin space. For the Σ-decay, this will be a new proposition and is tested here. Whether the consequences of the charge symmetry requirement and Weinberg's classification of currents are identical or not depends on whether time reversal invariance holds or not. Therefore, there are two separate propositions. But it seems that time reversal has not been tested; so therefore, at the moment one can regard this measurement as a combined evidence of both. But I wish also to ask one question: In the experimental value you quoted, is the phase space included?

WILLIS: The use of the small gamma there implies that I have divided the experimental rates by the phase space factors, so that the appropriate number there is 1, not 1.7. I'm sorry--Professor Lee gave the answer that I should have given to the question of Professor Primakoff.

MARCH (U. of Wisconsin): I'd like to point out, in connection with the statement on this enhancement factor in the K_{e4}, that as long as you're talking about 90% confidence levels, since there is some lack of confidence in the enhancement factor, you might perhaps double the number--90% confidence of that is less than 8, or something like that.

WILLIS: Yes, I thought the 4 was already a little generous.

MARCH: Right. The other question is that you didn't say anything on one very important principle, namely μ universality. Would you care to make any remarks on that?

WILLIS: Professor Trilling gave the best test of μ universality I know of in his comparison of the spectra and branching ratios in K-decays. However, since there do seem to be some troubles in the spectrum and branching ratio, it might not be useless to have another number written down. What I propose to write down is the ratio of $\Sigma^- \rightarrow N + \mu^- + \nu_\mu$ to $\Sigma^- \rightarrow N + e^- + \nu_e$. The CERN group finds that $R_\mu = (\Sigma \rightarrow \mu^-)/(\Sigma \rightarrow e^-) = (0.66 \pm 0.15) \times 10^{-3}/(1.4 \pm .3) \times 10^{-3}$. This is the experimental number; the phase space ratio I'll have to search for, but I can tell you that if we take into account the rather large errors, the number is consistent with μ-universality. It needn't be, of course, because there are the induced pseudoscalar form factors for the muons and not for the electrons.

BLOCK (Northwestern University): I'd appreciate it if you'd give me a number--for $\sin^2 \theta$, or $\cos^2 \theta$ or θ^2 with its error, and tell me just how it was obtained.

WILLIS: Many people compute different errors on θ. For example, there's the question of whether or not one should include the K decays, since one has the feeling that the symmetry breaking will affect seriously these decays.

BLOCK: No, excuse me, my question wasn't clear. I meant in terms of just the hyperonic decays. In other words, the fit to θ you showed without using

the K or the π information.

WILLIS: The 45% I quoted utilizes the K information as well. If you like, we can strike out the K information--that's the ratio of $K_{\mu 2}$ to $\pi_{\mu 2}$ and the ratio of K_{e3} to π_{e3}. That leaves me with six measured numbers, and I still have three parameters. The probability is then 32% of getting a worse fit, which is quite satisfactory, and I get $\theta = 0.27$. I don't have the error written down here. It's approximately 0.01. There's another question there. The six pieces of input data are the decays $\Lambda \to P$, $\Sigma^- \to n$, $\Sigma^+ \to \Lambda$, $\Xi^- \to \Lambda$, (which doesn't add much), and the ratio of $G_v(O^{14})$ to $G_v(\mu)$. Now there is a small question, whether one should ignore the effects of symmetry breaking. You can ignore them, attempt to correct them, or forget about that measurement. In this particular fit, they were ignored and that gave the value 0.27.

SUDARSHAN (Syracuse University): I would like to make two remarks about the sigma to lambda decay. First of all, the $\Sigma^- \to \Lambda e^- \nu$ and $\Sigma^+ \to \Lambda e^+ \nu$ decays both have to have isotopic spin one currents. One of them is the plus component of an I = 1 current, the other one is the minus component of an I = 1 current. This experiment taken all by itself tests the question of whether the two components are components of the same current or whether they are components of two different currents. If you do not have any other experimental information, all that this particular experiment would test would be this one. The second point is that to the extent that we can neglect the momentum transfer dependence of the form factor, the $\Sigma^- - \Lambda$ and $\Sigma^+ - \Lambda$ transitions would get no contribution from the vector current. Therefore, this test is a test of the $\Delta I = 1$ rule or I = 1 current rule for the axial vector current.

WILLIS: Yes, your statement can be somewhat strengthened by the use of SU(3), because the variation in form factors which you mentioned should be the same as the electric form factor of the neutron, which is legendarily small.

LEITNER (Syracuse University): I want to ask if you have considered a relaxed universality model as you have it on the left board without the octet currents. Would you cross that off your list or not?

WILLIS: Such a model has no predictions. You have to put in something about the strong interactions.

LEITNER: No, just ignore the Clebsch-Gordon coefficients.

WILLIS: Well, yes, that's a good question. Suppose you set all the numbers here equal to one. You get almost the same χ^2. The lambda moves into the intersection region a little better, and the sigma to the lambda moves over a little bit.

CHILTON (Argonne): As a corollary to that, would you like to make any guesses as to when the experimental situation will be clarified to a point where one can say that the Cabibbo model is good, say to one percent.

WILLIS: Well, I wouldn't hold my breath until it is tested up to one percent. I think $\Sigma \rightarrow Ne\nu$ provides a reasonable test. Here since D is bigger than F, one predicts V + A interaction. There are many experiments going on--at least two that I know of--trying to measure the sign of V/A, and others for the magnitude.

BYERS (UCLA): I would like to remark on the $\Delta S = 2$ reaction that you discussed. Even if the interaction is considerably weaker than the $\Delta S = 1$, I believe for the $\Xi \rightarrow Ne\nu$, the branching ratio could be comparable to the Λ beta decay branching ratio, because with a large energy release the phase space for this decay goes like q^5, and there's considerably more energy. There's a factor of 58 or so.

WILLIS: That's taken into account. The 10^{-4} I get is by taking the Cabbibo model and the phase space.

MC FARLANE (U. of Pennsylvania): I would like to go back to a question that was asked a little while ago about μ-e universality. Surely the best test must be the π_{e2} to $\pi_{\mu 2}$ ratio, which is measured to be the predicted value within a few percent.

WILLIS: Yes, I guess it's our prejudice in favor of strange particles.

WOLFENSTEIN (Carnegie Tech.): One of the tests of the Cabibbo model and even of the somewhat weaker postulate, namely that the strangeness changing currents among themselves satisfy universality independent of the Cabibbo angle has to do with the Ξ decays. Now originally it looked from a small amount of data that the Ξ leptonic decay might not work so well. I wonder if there is going to be any more data on the $\Xi \rightarrow \Lambda e\nu$ decays, which seems like one of

the most crucial tests.

WILLIS: Yes, that's based on three events. One of them has another possible interpretation. Well, maybe someone knows of some new data. Professor Ticho perhaps?

TICHO (UCLA): To my knowledge there are only three events and one of them doubtful.

LEITNER: There are three events. Two of them are ours. One of the two which has gone into the collection of Rosenfeld and collaborators should not be counted because the two events that we searched for, we searched for by non-exclusive means, and they should not be used with the same denominator. So all you can say is that's an extremely crude number.

MARSHAK: I think perhaps it's worth just remarking on the refinement about the universal V-A theory. The Cabibbo formulation really brings in three parameters, the Cabibbo angle, and the admixture of axial vector F and D coefficients. Your remark about the renormalization effects really only applies to the Cabibbo angle. Since the recent work of Adler and Weisberger, several people have calculated renormalization effects on the F and D coefficients. In other words, it does seem as if the renormalization effects can account for two of the three Cabibbo coefficients, but not for the angle which seems to be an intrinsic effect. I think one should make that quite explicit. So fundamentally you're right that one needs the Cabibbo angle to reduce the strangeness-violating currents; but the other two parts do seem to be in agreement with renormalization effects.

WILLIS: Do I understand that you were saying that if you use generalized Goldberger-Treiman relations, you also get the right numbers as in several papers from your group?

MARSHAK: I'm saying that the Adler-Weisberger program, of course, was to calculate the axial vector coupling constant as a renormalization effect. In that sense, it has been successful. Recent papers by quite a few authors now have done the same job with the strangeness violating axial vector current, and that work is successful to the point of determining another of the three Cabibbo parameters. But that's not successful to the extent of being able to account for

the Cabibbo angle. So I think one should spell it out in that way perhaps.

SACHS(Argonne): I would just like to ask whether you could enter in that second row of your table for the Σ^+ decay, separate numbers for the decay into electrons and decays into muons instead of just combining the two together.

WILLIS: The Columbia-Rutgers-Princeton experiment looks at only the electrons. Let me give it to you in terms of everything together and then muons alone. And I have already given you everything together. So in terms of muons alone, the number is 0 where you expect 5.8. So if you want a 90% confidence level, it's 2.3 over 5.8.

SUDARSHAN: What is the value of θ if you consider only baryon decays?

WILLIS: Professor Block asked essentially the same question and I said the angle for the baryon decays alone is .27. The angle from the $K_{\mu 2}$ branching ratio, as I recall was .26. I haven't worked it out again with Professor Trilling's number, but they're clearly pretty close.

Hyperon Non-Leptonic Decays*

N. P. Samios
Brookhaven National Laboratory, Upton, New York

During this talk I will attempt to review what is known concerning the non-leptonic hyperon decays. To date there are seven known hyperons with weak decays:

$$\Lambda^o,\ \Sigma^+,\ \Sigma^-,\ \Sigma^o,\ \Xi^-,\ \Xi^o,\ \text{and}\ \Omega^- \quad .$$

In most cases the decay mode is $Y \rightarrow B + \pi$ except for $\Sigma^o \rightarrow \Lambda^o + \gamma$ which I will not discuss and $\Omega^- \rightarrow \Lambda + K^-$ which is one of the alternate decay modes of the Ω^-.

All evidence concerning the spins of hyperons indicates $J = 1/2$ for those that have been measured. A measure of the Ξ^- spin has been performed by the U.C.L.A. group[1] arriving at a result consistent with $J = 1/2$ and two standard deviations away from $J = 3/2$. The Ω^- spin is as yet unmeasured but expected to be 3/2 from SU(3) considerations.

The two major regularities that have been observed in hyperon decays are:

(1) $\Delta I = 1/2$ Rule. That is in the decay of hyperons the I changes by 1/2. Rates can be calculated by assuming that a spurion of $I = 1/2$ is coupled to the hyperon.

---

* Work performed under the auspices of the U. S. Atomic Energy Commission.

(2) $|\Delta S| \leq 1$. This regularity is mainly derived from a study of Ξ decays. Further evidence comes from arguments concerning the K_1- K_2 mass difference.

In addition there recently have been many predictions concerning the parity conserving and parity non-conserving amplitudes in these hyperon decays derived from many different assumptions concerning transformation properties of the decay interaction. Before discussing the relevance of the experimental data concerning these three areas I would like to spend a short time stating the conventions adopted and notations used to describe these decays.

Tables I and II contain the expressions used in evaluating the decay amplitudes. A few comments are now in order. (a) If one writes the matrix element in terms of the Pauli spin matrices σ then the rate is proportional to $\{|S|^2 + |P|^2\}$ where S and P are the phenomenological S wave and P wave amplitudes. On the other hand if one uses the Dirac spinors $\overline{U}$ and U then the rate is a function of A and B, the parity non-conserving and parity conserving amplitudes respectively. In this latter instance the amplitudes are independent of barrier factors, etc. and these are the amplitudes, namely A and B that will be used for comparisons with theoretical predictions. (b) The expressions for $\vec{P}_\Lambda$, $\vec{P}_p$ in terms of α_Σ and α_Λ for Λ's and p's decaying from an unpolarized source are spin independent, the only modification for higher spins being that the decay amplitudes would be P and D or higher instead of S and P. This enables one to measure $(\alpha_\Lambda \alpha_\Xi)$ independent of a knowledge of the Ξ spin as indicated. (c) In the ratio of β/α, time reversal invariance was assumed. (d) The sign of α determines the relative sign of B/A. Since the rate is

quadratic in the A and B amplitudes, a measurement of the rate and the asymmetry parameter α yields (within a relative sign difference) two solutions for A and B corresponding to different signs of γ.

One final note--in most cases there are many measurements of a given parameter X_i with the error σ_i and for the purposes of this conference it is useful to present some sort of best value. Thus in spite of the fact that in many cases various measurements disagree from each other by many standard deviations, the usual procedure has been to take

$$\bar{X} = \frac{\sum_i X_i/\sigma_i^2}{\sum_i 1/\sigma_i^2} \quad ; \quad \Delta\bar{X}_i = \sqrt{\sum_i 1/\sigma_i^2} \quad .$$

In order to take account of large spread in X_i, I have also calculated an alternate error $\Delta\bar{X}_2$ where

$$\Delta\bar{X}_2 = \frac{\sqrt{\sum_i (\bar{X} - X_i)^2/\sigma_i^2}}{\sqrt{\sum_i 1/\sigma_i^2}}$$

and take $\Delta\bar{X}$ to be whichever is the larger. You will note that the latter expression is a measure of the width of the distribution of measurements and in the case of each $\sigma_i = \sigma$ then

$$\Delta\bar{X}_2 = \sqrt{\frac{\Sigma(\bar{X} - X_i)^2}{N}} \qquad \text{i.e. root means square deviation.}$$

The second estimate of $\Delta\bar{X}$ has the further property of rarely being smaller than an individual measurement while the first estimate is always as small if not smaller than any individual measurement, which is a dangerous procedure when systematic errors are not understood.

Table III reviews the predictions of the $\Delta I = 1/2$ rule for the various hyperon decays. The predictions for the Λ, Σ, and Ξ hyperons are well known and I won't elaborate further. You will note the close similarity between the two noted decay modes for the Ω^- and Λ^o in the ratio of the α and γ parameters, as well as the branching ratios.

I will now proceed to review the experimental situation starting with the Λ^o decay. Table IV contains a compilation of the Λ^o lifetime and branching ratio. The lifetime measurements are not in good agreement and in fact a few of the measurements differ by ~5 standard deviations. The best value for $B^1_\Lambda = .675 \pm .027$ is in excellent agreement with the value of 2/3 expected from the $\Delta I = 1/2$ rule. Cronin and Overseth[2] have measured the asymmetry parameters for the decay mode $\Lambda^o \rightarrow p\pi^-$ to be

$$\alpha^-_\Lambda = +.62 \pm .05$$

$$\beta^-_\Lambda = +.18 \pm .24$$

$$\gamma^-_\Lambda = +.78 \pm .06 \quad .$$

From these numbers one can determine the rate

$$\Gamma(\Lambda \rightarrow p\pi^-) = (.262 \pm .028)10^{10} \text{ sec}^{-1}$$

and amplitudes

$$A = (.132\pm.007)10^5 \ (1/\text{MeV-Sec})^{1/2}$$

$$B = (.858\pm.119)10^5 \ (1/\text{MeV-Sec})^{1/2}$$

The ratio of the asymmetry parameters for the two Λ^o decay modes have been measured[3]

$$\frac{\alpha^o_\Lambda \ (\Lambda \to \pi^o n)}{\alpha^-_\Lambda \ (\Lambda \to \pi^- p)} = 1.10\pm.27$$

again in good agreement with the ratio 1 expected from the $\Delta I = 1/2$ rule. A further consistency check with the $\Delta I=1/2$ rule is afforded by a study of decay rates of ${}_\Lambda He^4$ into π^o and π^- modes as performed by Block et al.[4] The ratio of the γ parameter has not been measured. The best test for time reversal for Λ decay comes from the Cronin-Overseth measurements[2] which give

$$\frac{\beta^-_\Lambda}{\alpha^-_\Lambda} = .29\pm.39 = \tan(\delta_p - \delta_s) = (16\pm20)^o$$

The difference in the phase shifts at an energy of 37 MeV can also be determined from an analysis of $(\pi^{\mp} + p)$ interactions as performed by Barnes et al.[5] and yields $(\delta_p - \delta_s) = (-6.5\pm.5)^o$ differing from the above value by $\approx$ 1 standard deviation.

The experimental situation for the charged Σ decays is shown in Table V. The only new information is the experiment by Chang[6] involving 9600 $\Sigma^\pm$ decays which gives a precise measurement of $\Sigma^\pm$ lifetimes and decay branching ratio and a re-evaluation of α^o_+ for $\Sigma^+ \to p\pi^o$ by Keefe et al.[7]

The new value -.80±.18 was obtained by a re-examination of the 358 original events in the light of better experimental curves on the analyzability of proton polarization in proton carbon scattering as supplied by Peterson et al.[8] This tended to reduce the number of useful events but increased the reliability of the data. From Table V it should be noted that α is negative for all Σ decays so that the relative sign of B/A will also be negative. Since neither the value for any γ nor the sign have been measured there will be two solutions for A and B for each decay. The experimental rates for the decays are

	Decay Rate (sec^{-1})
$\Sigma^- \rightarrow \pi^- n$	$(.606\pm.015)10^{10}$
$\Sigma^+ \rightarrow \pi^+ n$	$(.584\pm.030)10^{10}$
$\Sigma^+ \rightarrow p\pi^o$	$(.646\pm.030)10^{10}$

One can now test the $\Delta I=1/2$ rule for Σ's, namely

$$\sqrt{2}\, A'(\Sigma_o^+) + A'(\Sigma_+^+) = A'(\Sigma_-^-)$$

where A' is the A or B amplitude in each respective decay. Among the multiple solutions there are two which come close to satisfying the above relation. These are shown in Figures 1 and 2. The errors on the ends of the vector for Σ_o^+ contains the Σ_-^- or Σ_+^+ errors respectively. One notes that the triangle almost closes and that in both cases it would close for $\alpha_o^+ = -1.0$. It should also be noted that the motion of the $\sqrt{2}\,\Sigma_o^+$ vector in the A,B plane is highly-non-linear in α_o^+. As will be seen later the orientation in Figure 2 [A $(\Sigma_+^+) = 0$] is preferred by the theorists. It is clear that one needs a better measurement of α_o^+ as well as $\gamma(\Sigma_-^-)$ and $\gamma(\Sigma_+^+)$ which are both

expected to be ≈ 1.0 in order to more accurately check the validity of the $\Delta I = 1/2$ rule in Σ decays.

Another method of demonstrating the same result was first done by Franzini and Zanello,[9] namely to solve for the A and B isotopic spin 3/2 and 1/2 amplitudes involved in the three decays. This involves making the following substitutions in the rate formula of Table II.

Σ^-_-	$A \to A_{3/2}$	$B \to B_{3/2}$
Σ^+_+	$A \to \frac{1}{3}(A_{3/2} + 2A_{1/2})$	$B \to \frac{1}{3}(B_{3/2} + 2B_{1/2})$
Σ^+_o	$A \to \frac{\sqrt{2}}{3}(A_{3/2} - A_{1/2})$	$B \to \frac{\sqrt{2}}{3}(B_{3/2} - B_{1/2})$

There are now six relations (three each for rate and asymmetry parameter α) with four unknowns, so that one is overconstrained two times. One can then calculate the χ^2 given by

$$\chi^2 = \sum_{i=1}^{6} \left(\frac{0_{i\ exp} - 0_{i\ theor}}{\sigma_{i\ exp}} \right) \quad , \text{ where } 0_i \equiv \Gamma_i, \alpha_i$$

and minimize this function by varying the four parameters. This was done using the Minfun program of Humphrey and yields the two solutions shown in Table VI. These solutions correspond to an interchange of S and P waves (not A and B because of the mass factors) and therefore to different values for the sign of $\gamma(\Sigma^-_-)$. The χ^2 values of 1.9 and 1.2 correspond to probabilities of 40 and 50% which implies excellent agreement with the

$\Delta I=1/2$ rule. As expected the main contribution to the χ^2 comes from α_o^+.

Before finishing the discussion of Σ decays one should mention a recent meaningful measurement of $\Sigma^+ \to p + \gamma$ made in a hydrogen bubble chamber by Bazin et al.[10] From a sample of $\approx 6{,}000$ Σ^+ decays they have observed 24 electromagnetic events yielding a branching ratio

$$R = \frac{\Sigma^+ \to p + \gamma}{\Sigma^+ \to p\pi^o} = (.37\pm.08)10^{-2} \quad .$$

The experimental situation concerning Ξ decay is summarized in Table VI. The ratio of the Ξ^o and Ξ^- lifetimes gives $\tau_{\Xi^o}/\tau_{\Xi} = 1.66\pm.23$ to be compared with a ratio of 2.0 expected from $\Delta I=1/2$ rule. There is now more extensive data concerning the Ξ^- and Ξ^o asymmetry parameters with their ratio $\alpha^-/\alpha^o = 1.23\pm.58$ in good agreement with the value 1.0. There appears to be a slight difficulty with the time reversal parameter β, in that three measurements are consistent with zero and a fourth ≈ 4 standard deviations from zero. This discrepancy is not understood at the present time and the indicated average omits this last measurement. The sign of γ for the Ξ^- is positive, while α is negative yielding the following amplitudes for Ξ^- decay

$$A(\Xi^-) = (.169\pm.504)10^5 \ (1/\text{MeV-Sec})^{1/2}$$
$$B(\Xi^-) = (-.697\pm.125)10^5 (1/\text{MeV-Sec})^{1/2} \quad .$$

Paranthetically one can note that the Ξ^-, Ξ^o mass difference (6.6±1.0)MeV now is in excellent agreement with that expected from SU(3)

namely,

$$M_{\Xi^-} - M_{\Xi^o} = (M_{\Sigma^-} - M_{\Sigma^+}) - (M_n - M_p) = 6.7 \pm .4 \text{ MeV}.$$

We finally turn to the Ω's. There are now seven events observed and they are summarized in Table VIII. The best value for the mass is 1674±3 MeV and the lifetime is $\approx(1\text{-}2)10^{-10}$ sec. All three decay modes have been observed but the data is too meagre to make any comparisons with the $\Delta T=1/2$ rule, even though as noted earlier the predictions are numerous.

A study of Ξ and Ω decays affords an area of studying the $|\Delta S| \leq 1$ rule. The possible modes of violation of this rule are

$$\Xi^- \to n\pi^- \qquad \Omega^- \to \Lambda^o\pi^-$$

$$\Xi^o \to p\pi^o \qquad \Omega^- \to \Sigma^o\pi^- \quad .$$

No such decays have been observed. The only systematic study published has been that of Ferro-Luzzi et al.[11] where they observed 67 events of the type

$$K^- + p \to \Xi^- + K^+$$
$$\searrow (\Lambda)\ \pi^-$$

yielding a limit

$$R\left(\frac{\Xi^- \to n\pi^-}{\Xi^- \to \Lambda\pi^-}\right) \leq .5\%.$$

I believe the actual limit is probably much lower since many more groups

have unsuccessfully searched for this decay mode but as of yet not published their results--probably $\leq$ .1-.2‰ is a better number. Needless to say the search for such violations in Ω^- decay is just beginning.

In the past year there has been some fallout from the Strong Interactions field to the Weak Interaction domain in that theorists have applied the group theoretical approach to the description of non-leptonic and leptonic decays. As is well known, the Cabibbo suggestion that the currents of strongly interacting charged particles coupled to leptons transform under SU(3) transformation like members of an octet is in remarkably good agreement with the data. A similar approach to the non-leptonic decays has proved fruitful for the prediction of the S wave but not the P wave amplitudes.

There have been at least 17 publications in Physical Review Letters (12) and Physics Letters on this subject. It is, of course, not possible to compare the experimental results with all of these papers. However, there are certain trends and universal predictions which one can examine. The most common assumptions are:

CP Invariance.

Currents of strongly interacting particles responsible for non-leptonic decays have specific transformation properties, i.e.

like a member of a unitary octet (i.e. octet dominance)
like a regular representation of SU(6)
like a <u>143</u> dimensional adjoint representation of $\tilde{U}$ (12)

In fact the procession of papers goes from SU(3) → SU(6) → relativistic SU(6). In addition there are assumptions concerning R, RP invariance, some of which are known not to be valid.

The two univeral predictions are:

$$A(\Lambda \to p\pi^-) + \sqrt{3}A(\Sigma^+ \to p\pi^o) = 2A(\Xi^- \to \Lambda\pi^-)$$

$$A(\Sigma^+ \to n\pi^+) = 0 \ .$$

The first (known as the Lee inequality) was derived by B. Lee, H. Sugawara and M. Gell-Mann. The former two invoking RP and R invariance and the last the less limited assumption of CP invariance and octet dominance. Since then, many authors too numerous to mention have also derived the same relation under the assumptions listed above. All authors who go beyond single CP invariance and octet dominance also make predictions on the B amplitudes, and in fact arrive at a similar expression as above, namely:

$$B(\Lambda \to p\pi^-) + \sqrt{3}B(\Sigma^+ \to p\pi^o) = 2B(\Xi^- \to \Lambda\pi^-) \ .$$

The amplitudes used for comparison with the above relations are shown in Table IX. The two sets of numbers in the Σ columns correspond to the two orientations of the triangular inequality. The comparison of the Lee inequality with the experimental data is shown in Figure 3. Again the errors on the $\sqrt{3}\ \Sigma_o^+$ vector include the errors in the Λ^o vector. The two vectors for the Σ_o^+ decay correspond to the two values for γ_o^+. As can be seen the triangle closes quite nicely for $\gamma_o^+ < 0$, and in fact better agreement is reached for $\alpha_o^+ \approx -1$. So that one has a situation where the theoretical predictions are satisfied although some of the basic premises are in question.

The question of whether $A(\Sigma^+_+) = 0$ is satisfied is still unsettled, the present experimental situation requiring either $A(\Sigma^+_+) = 0$ or $B(\Sigma^+_+) = 0$. However there are several experiments in progress intending to settle this question.

It should be noted that the speculations which gave rise to the B relationship also predict other relationships of which at least one in each paper leads to contradictions with experiments. I will mention two just as illustrations.

a) $\alpha_\Lambda = \alpha_\Xi$. Experimentally it is known that these asymmetry parameters are of opposite sign and arge.

b) $B(\Lambda^o_-) - 2A(\Lambda^o_-) = \sqrt{3}A(\Sigma^+_o)$

$$.60\pm.10 \stackrel{?}{=} .14\pm.03 \quad \text{badly violated.}$$

There was one paper by Dashen-Frautschi and Sharp[12] in which they applied bootstrap techniques to the parity non-conserving weak interactions. In addition to the above universal predictions among the A amplitudes they derived various other relationships in terms of one parameter related to the D/F ratio of the strong Yukawa couplings of baryon. The expected value was $1.5 < \xi < 1.8$.

Experimentally $\xi = 1.25\pm.10$ in reasonable agreement with their prediction (independent of CP and transformation properties of weak interactions).

To conclude, the $\Delta I = 1/2$ rule is in very good shape, all tests among the hyperon non-leptonic decays satisfying the theoretical predictions quite well. Further experiments are needed to determine the γ parameter for $\Sigma^- \to \pi^- + n$ and $\Sigma^+ \to \pi^+ n$ as well as a more accurate value for α in $\Sigma^+ \to \pi^o p$. Finally the accumulation of many more Ω^- decays will allow many further checks of the $\Delta I = 1/2$ and $|\Delta S| \leq 1$ rules.

REFERENCES

(1) H. Ticho, International Conference on Fundamental Aspects of Weak Interactions, Brookhaven National Laboratory, September, 1963.

(2) J. W. Cronin and O. Overseth, Phys. Rev. 129, 1795 (1963).

(3) B. Cork, L. Kerth et al., Phys. Rev. 100, 1000 (1960).

(4) M. M. Block et al., Nuovo Cimento 28, 299 (1963).

(5) S. W. Barnes, et al., Phys. Rev. 117, 226 (1960).

(6) C. Chang, Thesis, Columbia University, 1965.

(7) D. Keefe, private communication.

(8) V. Peterson, UCRL report.

(9) P. Franzini and D. Zanello, Phys. Letters 5, 254 (1963).

(10) M. Bazin et al., Phys. Rev. Letters 14, 154 (1965).

(11) M. Ferro-Luzzi et al., Phys. Rev. 130, 1568 (1963).

(12) M. Gell-Mann, Phys. Rev. Letters 10, 155 (1964).

B. W. Lee, Phys. Rev. Letters 12, 83 (1964).

M. Suzuki, Phys. Letters 14, 64 (1965).

B. Sakita, Phys. Rev. Letters 12, 379 (1964).

R. Dashen, et. al., Phys. Rev. Letters 13, 777 (1964).

G. Altarelli et. al., Phys. Letters 14, 70 (1965).

M. Ademollo et. al., Phys. Rev. Letters 14, 420 (1965).

E. Borchi et. al., Phys. Rev. Letters 14, 507 (1965).

K. Kawarabayashi, Phys. Rev. Letters 14, 86 (1965).

K. Kawarabayashi and R. White, Phys. Rev. Letters 13, 528 (1965).

S. P. Rosen, Phys. Rev. Letters 12, 408 (1964).

S. Pakvasa and S. P. Rosen, Phys. Rev. Letters 13, 773 (1964).

(12) Continued

S. P. Rosen, Phys. Rev. Letters 14, 758 (1965).

P. Babu, Phys. Rev. Letters 14, 166 (1965).

M. P. Khanna, Phys. Rev. Letters 14, 711 (1965).

R. Oehme, Phys. Letters 15, 284 (1965).

H. Sugawara, Nuovo Cimento 31, 635 (1964).

$\Xi^- \to \Lambda^o + \pi^-$ $\qquad$ $\Lambda^o \to p + \pi^-$

$$\alpha = \frac{2\,\mathrm{Re}\,S^* P}{|S|^2 + |P|^2} \; ; \; \beta = \frac{2\,\mathrm{Im}\,S^* P}{|S|^2 + |P|^2} \; ; \; \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2} \qquad \alpha^2 + \beta^2 + \gamma^2 = 1$$

$$I_\Xi(q_\Lambda) = 1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{q}_\Lambda \; ; \; I_\Lambda(q_p) = 1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{q}_p$$

Depends on Spin 1/2 Ξ^- and Λ

$$\vec{P}_\Lambda = \frac{1}{I_\Xi(q_\Lambda)} \left\{ (\alpha_\Xi + \vec{P}_\Xi \cdot \hat{q}\ )\hat{q}_\Lambda + \beta_\Xi (\vec{P}_\Xi \times \hat{q}_\Lambda) + \gamma_\Xi \hat{q}_\Lambda \times (\vec{P}_\Xi \times \hat{q}_\Lambda) \right\} ; \text{ If } \vec{P}_\Xi = 0 \quad \vec{P}_\Lambda = \alpha_\Xi \hat{q}_\Lambda$$

$$\vec{P}_p = \frac{1}{I_\Lambda(q_p)} \left\{ (\alpha_\Lambda + \vec{P}_\Lambda \cdot \hat{q}_p)\hat{q}_p + \beta_\Lambda (\vec{P}_\Lambda \times \hat{q}_p) + \gamma_\Lambda \hat{q}_p \times (\vec{P}_\Lambda \times \hat{q}_p) \right\} ; \text{ If } \vec{P}_\Lambda = 0 \quad \vec{P}_p = \alpha_\Lambda \hat{q}_p$$

Unpolarized Ξ^-'s $\quad I_\Lambda(q_p) = 1 + \alpha_\Lambda \alpha_\Xi \hat{q}_\Lambda \cdot \hat{q}_p$ $\quad$ Spin indep.

Unpolarized Λ's $\quad$ Proton polarization is same direction as proton momentum.

$$\beta/\alpha = \frac{2\,\mathrm{Im}\,S^* P}{2\,\mathrm{Re}\,S^* P} = \tan(\delta_p - \delta_s)$$

TABLE I

If $\quad M' = S + P\,\sigma \cdot q$

$$\text{Rate} = \left\{ S^2 + P^2 \right\} \cdot \text{Phase Space}$$

If $\quad M' \approx \overline{U}\,(A - B\,\gamma_5)\,U\,\phi \qquad\qquad M \to m + \mu$

$$\text{Rate} = \frac{q}{8\pi M^2} \left\{ A^2 \left[(M+m)^2 - \mu^2 \right] + B^2 \left[(M-m)^2 - \mu^2 \right] \right\}$$

Then $\quad \dfrac{P}{S} = \dfrac{B}{A} \left\{ \dfrac{(M-m)^2 - \mu^2}{(M+m)^2 - \mu^2} \right\}^{1/2}$

and

$$\alpha = \frac{2\,B/A \left\{ \dfrac{(M-m)^2 - \mu^2}{(M+m)^2 - \mu^2} \right\}^{1/2}}{1 + (B/A)^2 \left\{ \dfrac{(M-m)^2 - \mu^2}{(M-m)^2 - \mu^2} \right\}}$$

ignoring small phase shifts.

TABLE II

$\Delta I = 1/2$ Rule Hyperons

Λ^0		Σ		Ξ		Ω	
$\Lambda \to p\pi^-$	$-\sqrt{\frac{2}{3}}\, M(1/2, -1/2)$	$\Sigma^- \to \pi^- n$	$1\ M(3/2)$	$\Xi^- \to \Lambda\pi^-$	$1\ M(1)$	$\Omega^- \to \Xi^-\pi^0$	$\sqrt{\frac{1}{3}}\, M(1/2)$
$\Lambda \to n\pi^0$	$+\sqrt{\frac{1}{3}}\, M(1/2, -1/2)$	$\Sigma^+ \to \pi^0 p$	$\frac{\sqrt{2}}{3} M(3/2) - \frac{\sqrt{2}}{3} M(1-2)$	$\Xi^0 \to \Lambda^0\pi^0$	$\frac{1}{\sqrt{2}} M(1)$	$\Omega^- \to \Xi^0\pi^-$	$-\sqrt{\frac{2}{3}}\, M(1/2)$
$\frac{S_-}{S_0} = -\sqrt{2}$; $\frac{P_-}{P_0} = -\sqrt{2}$		$\Sigma^+ \to \pi^+ n$	$\frac{1}{3} M(3/2) + \frac{2}{3} M(1/2)$	$\Gamma(\Xi^-) = 2\ \Gamma(\Xi^0)$		$\frac{S_-}{S_0} = -\sqrt{2}$; $\frac{P_-}{P_0} = -\sqrt{2}$	
$B'_\Lambda = \frac{\pi^- p}{\pi p + \pi^0 n} = 2/3$		$\sqrt{2}\, A^1(\Sigma_0^+) + A^1(\Sigma_+^+) = A^1(\Sigma_-^-)$		$\frac{a_{\Xi^-}}{a_{\Xi^0}} = 1$		$B'_\Xi = \frac{\Xi^0\pi^-}{\Xi^0\pi^- + \Xi^-\pi^0} = 2/3$	
$\frac{a^-}{a_0} = 1$; $\frac{\gamma_-}{\gamma_0} = 1$				$\frac{\gamma_{\Xi^-}}{\gamma_{\Xi^0}} = 1$		$\frac{a_{\Xi^-}}{a_{\Xi^0}} = 1$; $\frac{\gamma_{\Xi^-}}{\gamma_{\Xi^0}} = 1$	

TABLE III

Λ^0

Lifetime (in units 10^{-10} sec.)

2.72 ± .16	Crawford et. al.	
2.29 ± .18	Eisler et. al.	
2.69 ± .11	Humphrey et. al.	
2.58 ± .11	Bertanza and Moneti	
2.44 ± .11	Garfinkel	
2.31 ± .10	Block et. al.	
2.70 ± .07	Murray	
2.68 ± .03	Golden et. al.	
2.36 ± .06	Block et. al.	
2.75 ± .12	Berge	
2.59 ± .09	Hubbard	(2.62 ± .25) 10^{-10} sec.

$$B'_{\Lambda} = \frac{\pi^- p}{\pi^- p + \pi^0 n}$$

.685 ± .017	Crawford et. al.	
.65 ± .05	Columbia	
.627 ± .031	Anderson et. al.	
.65 ± .06	Eisler et. al.	
.65 ± .05	Brown et. al.	
.72 ± .08	Baglin et. al.	
.709 ± .034	Chretien et. al.	(.675 ± .027)

TABLE IV

Σ^+

Lifetime (in units 10^{-10} sec.)

.75 ± .11	Berthelot et. al.	
.82 ± .09	Barkas et. al.	
.749 ± .054	Grard et. al.	
.765 ± .04	Humphrey et. al.	
.830 ± .018	Chang	(.813 ± .025) 10^{-10} sec.

$$B'_{\Sigma} = \frac{\pi^{\circ}p}{\pi^{\circ}p + \pi^{+}n}$$

.51 ± .02	Humphrey et. al.	
.54 ± .02	Chang	(.525 ± .02)

Σ^+ Asymmetry Parameters

$\Sigma^+ \rightarrow \pi^+ n$ (α^+_+)

-.20 ± .24	Tripp et. al.	
-.03 ± .09	Cork et. al.	(-.05 ± .09)

$\Sigma^+ \rightarrow \pi^{\circ} p$ $(\alpha^+_{\circ})$

-.90 ± .25	Tripp et. al.	
-.80 ± .18	Keefe et. al.	(-.84 ± .15)

Σ^-

Lifetime (in units 10^{-10} sec.)

1.58 ± .06	Humphrey et. al.	
1.67 ± .03	Chang	(1.65 ± .04) 10^{-10} sec.

Asymmetry Parameter

$\Sigma^- \rightarrow \pi^- n$ (α^-_-)

- .16 ± .21	Tripp et. al.	(-. 16 ± 21)

TABLE V

Sol. I.	Sol. II.
$A_{1/2} = +.082 \pm .010$	$A_{1/2} = -.242 \pm .007$
$A_{3/2} = -.158 \pm .002$	$A_{3/2} = +.010 \pm .010$
$B_{1/2} = -2.491 \pm .068$	$B_{1/2} = +.834 \pm .011$
$B_{3/2} = +.044 \pm .098$	$B_{3/2} = -1.569 \pm .021$
$X^2 = 1.9$	$X^2 = 1.2$
$\gamma(\Sigma^-) < 0$	$\gamma(\Sigma^-) > 0$

Units 10^5 (1/Mev-sec.)$^{1/2}$

TABLE VI

Ξ^- and Ξ^0

Group	τ_{Ξ^-} (10^{-10} sec.)	τ_{Ξ^0} (10^{-10} sec.)	α_{Ξ^-}	β_{Ξ^-}	γ_{Ξ^-}	α_{Ξ^0}	$M_{\Xi^-} - M_{\Xi^0}$ (Mev)
BNL-SYR	1.80 ± .16	--	-.47 ± .12	0.0 ± .3	+.88 ± .14	-.2 ± .4	6.9 ± 2.2
LRL	1.69 ± .07	$2.5^{+.4}_{-.3}$	-.41 ± .08	-.08 ± .26	+.91 ± .03	-.36 ± .30	
E.P.	1.91 ± .16	$3.8^{+1.0}_{-0.7}$	-.53 ± .16	-.25 ± .50	+.85 ± .05	-.49 ± .65	6.8 ± 1.6
UCLA	1.77 ± .12	3.03 ± .50	-.66 ± .15	+.63 ± .16	+.46 ± .22	-.44 ± .27	6.1 ± 1.6
	1.74 ± .07	2.9 ± .4	-.48 ± .08	-.06 ± .08*	+.90 ± .03*	-.39 ± .17	6.6 ± 1.0

* Omitting U.C.L.A.

TABLE VII

Ω^-

Mass (Mev)	Lifetime (10^{-10} sec.)	Decay Mode	
1677 ± 9	0.7	$\Xi^0 \pi^-$	B. N. L.
1674 ± 3	1.4	ΛK^-	
1671 ± 5	1.5	ΛK^-	
--	3.7	$\Xi^0 \pi^-$	
1673 ± 8	1.6	$\Xi^- \pi^0$	U. of Md.
1666 ± 8	1.85	$\Xi^0 \pi^-$	British Collab.
1675 ± ?	2.6	ΛK^-	CERN

TABLE VIII

	Λ^0_-	Ξ^-_-	Σ^-_-	Σ^+_+	Σ^+_0
			- .013 ± .017	+ .158 ± .004	
A	+.132 ± .007	+.169 ± .004			+ .144 ± .011
					+ .079 ± .020
			+ .158 ± .002	- .004 ± .007	
			+1.568 ± .024	- .039 ± .071	
B	+.858 ± .119	-.697 ± .125			- .785 ± .200
					-1.443 ± .114
			- .127 ± .168	+1.632 ± .042	

Units 10^5 (1/Mev-sec.)$^{1/2}$

TABLE IX

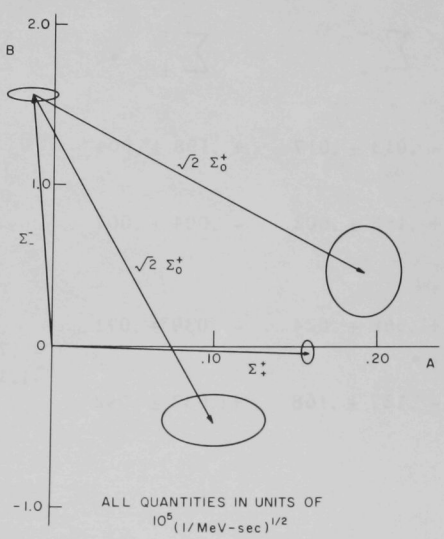


Fig. 1

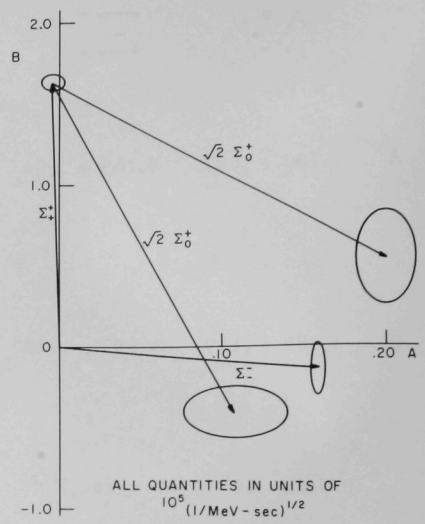


Fig. 2

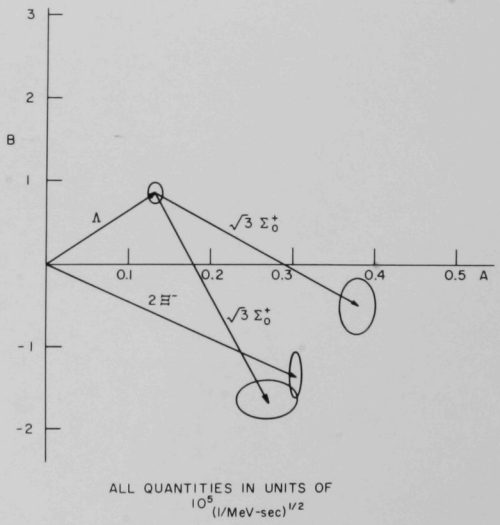


Fig. 3

DISCUSSION

BLOCK (Northwestern U.): I would like to point out that your compilation overlooked a piece of evidence for the $\Delta I = 1/2$ rule in Λ decay, which is more definitive than measuring the ratio α_o / α_-. The point, of course, is that when you measure α_o / α_-, you have a double solution. You can interchange the S and P waves. The measurement that we have done in ${}_\Lambda He^4 \rightarrow \pi^o + He^4$ establishes the relation $P_o^2 / (S_o^2 + P_o^2) = P^2 / (S^2 + P^2)$. I should, however, point out that we still have no idea of the relative phase between S and S_o, and this is still a completely open question.

SAMIOS: Do you know how to measure that?

BLOCK: No.

NAUENBERG (SLAC): In connection with the question which one is S wave and which one is P-wave in Σ decays, could you comment on this experiment at Princeton, in which there is a radiative decay?

SAMIOS : I don't know the result.

WILLIS (Yale U.): There is a little bit of information in the CERN experiment and somewhat more in the Princeton experiment on the ratio of $\Sigma^+ \rightarrow N\pi^+\gamma$ / $\Sigma^- \rightarrow N\pi^-\gamma$. It's safe to assume that these decays are only internal bremsstrahlung. They turn out to be somewhat sensitive to the P to S ratio. There are more decays of Σ^+ which, with the aid of $\Delta I = 1/2$ rule, can be used to infer that the Σ^+ decay is dominantly P wave and Σ^- decay is dominantly S wave, which is the way Samios indicated it ought to be. There is a slight question about that measurement, in that the Σ^+ does have this other decay mode $\Sigma^+ \rightarrow P + \pi^o + \gamma$, and the Σ^- doesn't have anything analogous. This may or may not be taken into account in the internal bremsstrahlung. It depends on the model.

FEINBERG (Columbia U.): In the analysis of the $\Delta I = 1/2$ rule for the Σ decays, were the phase shifts included at all?

SAMIOS : No, they were not.

FEINBERG: Do you have any idea whether that makes any effect?

SAMIOS: I think it's a very small effect. I think the main discrepancy just comes from α. If there's a much more accurate value of α, then one could include the effect of the phase shifts. But it's a small effect.

MARSHAK (Rochester U.) : In connection with these triangular relations, could you say what the agreement is for the P wave relation, namely the B amplitudes?

SAMIOS : The B is open . . . if we could have the last slide we could see it. If the triangle closed, the relations for both the S and P waves would be satisfied. In the S wave one just looks at whether they meet horizontally and in the P wave vertically.

MARSHAK : So both are really equally well satisfied. I wonder if I could ask Benjamin Lee to comment on the present situation explaining the P wave inequality. Just to summarize, there is an old discussion according to which the nonleptonic S part behaves like λ_6 and the P wave like λ_7. This is not a very satisfactory thing. If you assume that both behave like λ_6 with RP invariance, you get both of these triangular relations. But if you ask about the RP invariance, you then say the vector current is F-type and the axial vector is chiefly D-type. But the trouble is that the axial vector is not completely D-type. I'm very curious about the present thinking on this. Does Lee or anyone else want to comment?

ROSEN (Purdue U.): If you assume vector, axial vector coupling and the interaction transforms like λ_7, the triangular relations are automatically satisfied.

$K_1 - K_2$ MASS DIFFERENCE AND K_1^o REGENERATION .

Myron L. GOOD

Institut des Hautes Etudes Scientifiques *
91 BURES - sur - YVETTE (Essonne)
(France)

In this talk I will review the experimental situation regarding the magnitude and sign of the $K_1 - K_2$ mass difference, and will discuss $K_1 - K_2$ regeneration experiments from the viewpoint of attempting to learn from them as much as we can about the weak interactions. In particular, I will ask whether there any CPT tests to be found there.

A.) Magnitude of the mass difference.

Table I lists the measurements of the magnitude of the $K_1 - K_2$ mass difference known to me, and collected according to the method used. There is a tendency for the more recent values to cluster around $\Delta = 0.5$, and some lack of consistency in the sample, so perhaps a critical analysis is called for.

The "gap" method[6] is singularly free of ambiguity: Consider the time development of a K^o beam going through an absorber

$$\begin{pmatrix} a_S(t) \\ a_L(t) \end{pmatrix} = a'_S \chi'_S e^{i\gamma'_S t/2} + a'_L \chi'_L e^{i\gamma'_L t/2} = \underset{\sim}{\mathcal{M}}(t) \begin{pmatrix} a_S(0) \\ a_L(0) \end{pmatrix} \qquad (1)$$

---

* On leave from University of Wisconsin, Madison

Ref's. (1 - 9): See Table I .

Table I

EXPERIMENTAL DETERMINATIONS OF $|\Delta|$

$$\Delta = (M(K_S) - M(K_L))\tau_S$$

Strangeness oscillations		
1)	1.9 ± 0.3	Fitch, Perkins and Piroué Nuovo Cimento 22 1160 (1961)
2)	1.5 ± 0.2	Camerini, Fry, Gaidos, Huizita, Natale Willman , Birge, Ely, Powell and White P.R. 128, 352 (1962)
3)	$0.62 \begin{smallmatrix}+.33\\-.27\end{smallmatrix}$	Meissner, Crawford, Crawford, and Golden. (Private Communication)
Coherent regeneration, (compared to incoherent)		
4)	$0.84 \begin{smallmatrix}+.29\\-.22\end{smallmatrix}$	R. Good, Matsen, Muller, Piccioni, Powell White, Fowler, and Birge. P.R. 124, 1223 (1961)
Thickness dependence of coherent regeneration		
5)	$0.72 \pm .15$	Fuji, Jovanovitch, Turkot, and Zorn (Private Communication) (Earlier Report in PRL 13 253 (1964))
"Gap" Method		
6)	$0.55 \pm 0.13^*$	Christenson, Cronin, Fitch, and Turlay. Brookhaven Intl. Conf. on Weak Interactions, 1963, P.74; corrected for CP violation in ref. (12).
Leptonic decay charge ratio vs time		
7)	$0.47 \pm .20$	Ecole Polytechnique — J. Steinberger's Talk, Oxford Conf., 1965.
8)	$0.15 \begin{smallmatrix}+.35\\-.50\end{smallmatrix}$	Padua — J. Steinberger's Talk, Oxford Conf., 1965.
9)	0.5	Columbia — J. Steinberger's Talk, Oxford Conf., 1965.

* My error estimate; likelihood down $\sim 10^{-2}$ at $|\Delta| = .88$

where $\gamma'_{s,L}$ are the complex energy eigenvalues in the absorber and $\chi'_{s,L}$ the corresponding eigenvectors, and $a_{s,L}(t)$ are the amplitudes for the free space eigenstates $K_{s,L}$. $a'_{s,L}$ are the amplitudes for the in matter eigenstates $\chi'_{s,L}$ at $t = 0$, and are determined by the initial conditions. Now - all that has gone into these equations as physical assumptions is that the $K^o - \overline{K^o}$ system has two degrees of freedom, so that its time dependence is described by a 2 x 2 matrix.

Consider the application of eq'n.(1) to the situation of fig. 1 A and B . $t = 0$ is taken at the beginning of the <u>second</u> absorber in both cases.

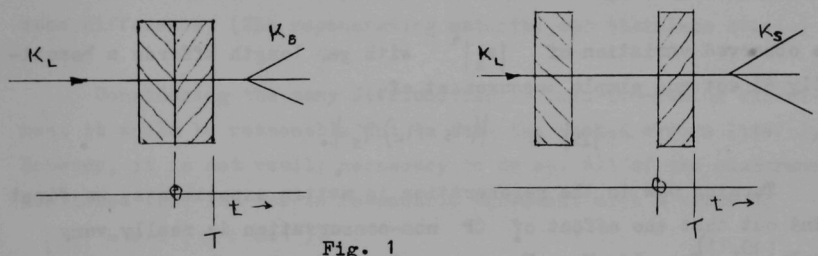


Fig. 1

In the situation 1A, the amplitude for K_s emerging from the second absorber is $a_s(T)$ and from eq'n.(1) may be written as

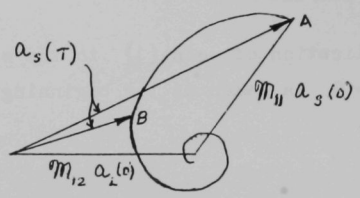
$$a_s(T) = \mathcal{M}_{11}\, a_s(0) + \mathcal{M}_{12}\, a_L(0)$$

where $\mathcal{M}_{11}$ and $\mathcal{M}_{12}$ depend on T and on the properties of the absorber.

Consider now the situation of fig. 1B (first absorber moved upstream). The amplitude emerging from the first absorber is the same as before; the amplitude $a_L(0)$ arriving at the second absorber

is the same as before (even including K_L decay); but the amplitude $a_s(0)$ arriving at the second absorber is modified by the weak interaction on its passing through the gap. Thus the contribution $\mathcal{M}_{11}\, a_s(0)$ rotates, and shortens, in the complex plane, in accordance with $e^{-t/2\tau_s + i(M_s - M_L)t}$

thus modifying $a_s(T)$



The observed variation of $|a_s|^2$ with gap length affords a beautifully direct and simple measurement of

$$|\Delta| \equiv |(M_s - M_L)\tau_s|$$

Turning now to the regeneration in matter experiments, we first point out that the effect of CP non-conservation is really very simple[10,11]. The old K_1, K_2 are replaced by K_s, K_L, the form of the equations remaining the same. Thus the equations for regeneration of K_s are the same as these for regeneration of K_1. The only effect that needs to be taken into account, therefore, is that the $\pi^+\pi^-$ decay mode has a small (coherent) contribution from the K_L amplitude. The correction is typically $\approx 10\%$ [11]

The coherent regeneration experiments, are those of Zorn et al[5] and of Piccioni et al[4]. Both of these are of necessarily somewhat less clear interpretation than the gap experiment.

In the experiment of Zorn et al[5] it is necessary to determine the energy spectrum from the same events that determine the mass

(10) M. Good P.R. 106, 591 (1957) (See Note added in proof)
(11) M. Whatley P.R.L. 9 317 (1962)

difference, and also considerable averaging of quantities over the spectrum is done. It is difficult to estimate the errors associated with these operations.

The experiment of Piccioni, et al[4] must be corrected for interference with the $K_L^o \longrightarrow \pi^+ \pi^-$ amplitude, this interference now being known to be constructive [12]. This would increase the quoted value of Δ by about 10 % [11]. However there is another effect, which is difficult to evaluate, namely the effect of more than one kind of scattering nucleus. In the incoherent regenerated group, one squares the amplitudes from the individual scatterers and then adds them up; in the coherent peak are adds first and then squares. This means that if there are two kinds of scatterer present, the forward peak is reduced somewhat, giving rise to too large a value of the mass difference. (The regenerating material was stainless steel.)

Considering the many difficulties in this pioneering experiment it would be reasonable not to take the quoted errors literaly. However, it is not really necessary to do so. All of the measurements mentioned thus far are in reasonable agreement with a value of $|\Delta| = 0.6$ ($\tau \simeq 0.1$).

The leptonic charge ratio experiments [7-9] also agree with such a value.

This leaves us with the strangeness oscillation experiments [1-3]. In the expt. of Fitch, Perkins, and Piroué [1] conditions were extremely difficult to control; the observed effect was small (~ 20 %) and subject to large corrections. This measurement will be disregarded, in favor of the later experiment of Fitch, Cronin, Christenson and Turlay.

---

(11) M. Whatley P.R.L. 9 317 (1962)

(12) Fitch, Roth, Russ, and Vernon P.R.L. 15, 73 (1965)

There remains the experiment of Fry, Camerini et al,[2] which is in clear disagreement with $|\Delta| = 0.6 \pm 0.1$.

It is natural to ask at this point if anything new and unsuspected is going on, for example whether the $K_S^0 - K_L^0$ mass difference is greatly increased by the presence of an absorber. The answer must be "no" , otherwise in the Piccioni experiment and others, in which the absorber was much denser, a large $K_S - K_L$ mass difference would have completely destroyed the very evident coherent forward peak. Nor is such an effect expected on theoretical grounds; the quantity $n - n'$ describing the effect of the absorber enters only quadratically, as:

$$\left|\left(\frac{1}{2\tau_S} - \frac{1}{2\tau_L}\right) + i\left(M_S - M_L\right)\right|^2 + c\left|m - m'\right|^2$$

Thus when regeneration effects are small, as they always are $\left(c^{1/2}(m-m') \ll \frac{1}{2\tau_S} \right)$ the mass difference remains unaffected for all practical purposes. Also, no $\sin \Delta t$ terms are introduced, even for a dense absorber; the time development should be the expected one.

Similarly, electromagnetic effects contribute nothing to either the regeneration or the mass difference, since the form factors for absorbing a photon of zero four - momentum transfer are the charge and magnetic moment, which should both be zero for the both K^0 and the $\overline{K^0}$. Thus there is no electromagnetic scattering in the forward direction.

The strangeness - oscillation method should give the same answer as the gap method. It seems worth repeating an experiment of this kind with good statistics and with tests for systematic errors.

I received yesterday the latest value of Meissner, Golden and (Crawford)[2] [3], based on the strangeness oscillation method in the 72" chamber, using the sequence

$$\pi^- + p \longrightarrow \Lambda + K^0$$
$$\hookrightarrow \overline{K^0} + p \rightarrow \Lambda \pi^+$$

Based on 70 events, they obtain

$$|\Delta| = 0.62 \begin{smallmatrix} +.33 \\ -.27 \end{smallmatrix}$$

in good agreement with the mean of the newer values, although with rather large errors.

Fry and Camerini have reexamined their data, and don't find anything wrong with it, but are inelined to disbelieve it, because of this other evidence.

B.) <u>Sign of the mass difference.</u>

This is not yet known with certainty, but probably will be known soon. Here one wants to provide, by a nuclear scattering, a general state $a K + b \bar{K}$, hopefully with known coefficients. The time dependence then contains terms in $\sin \Delta t$ as well as $\cos \Delta t$, and hence provides a determination of the sign of the mass difference. The method is basically due to Fry and Camerini.

Two interesting cases are:

I) K_2 beam, scatter, $s = -1$ interaction*:

$$K_2 + N \rightarrow f K - \bar{f} \bar{K} =$$

$$\left(\frac{f - \bar{f}}{\sqrt{2}}\right) K_1 + i \left(\frac{f + \bar{f}}{\sqrt{2}}\right) K_2 = \psi(t=0)$$

$$\psi(t) = \left(\frac{f - \bar{f}}{\sqrt{2}}\right) e^{i\gamma_1 t/2} K_1 + i \left(\frac{f + \bar{f}}{\sqrt{2}}\right) K_2$$

$$= \left[\left(1 + e^{i\gamma_1 t/2}\right) f + \left(1 - e^{i\gamma_1 t/2}\right) \bar{f}\right] K$$

$$+ \left[\quad\right] \bar{K}$$

$$= a(t) K + b(t) \bar{K}$$

$|a(t)|^2$ has a term in $(\mathrm{Im}\, f^* \bar{f})\ \mathrm{Im}\, e^{i\gamma_1 t/2}$

or $(\mathrm{Im}(f^* \bar{f}))\ \sin \Delta t$, which is sensitive to the sign of Δ.

---

* we ignore here CP violations, for simplicity. Also K_L decay is ignored, and Δ is absorbed into γ_1.

II) K^0 production, scatter at time t, observe K_1^0 decay:

$$K^0(t=0) \rightarrow \frac{1}{\sqrt{2}}\left(e^{i\gamma_1 t/2} + i K_2\right) \qquad \text{at time } t .$$

$$= \frac{1}{2}\left(e^{i\gamma_1 t/2} + 1\right)K + \frac{1}{2}\left(e^{i\gamma_1 t/2} - 1\right)\bar{K}$$

scatter, at t :

$$\psi_{sc} = \frac{f}{2}\left(e^{i\gamma_1 t/2} + 1\right)K + \frac{\bar{f}}{2}\left(e^{i\gamma_1 t/2} - 1\right)\bar{K}$$

$$= \frac{1}{2\sqrt{2}}\left[(f+\bar{f})e^{i\gamma_1 t/2} + (f-\bar{f})\right]K_1$$

$$+ \left[\text{———————}\right]K_2$$

$$= a_1 K_1 + a_2 K_2$$

Observe K_1 decay :

$$|a_1|^2 = \frac{1}{8}\left(|f+\bar{f}|^2 e^{-t/\tau_1} + |f-\bar{f}|^2 + (|f|^2 - |\bar{f}|^2)\cos\Delta t - 4(\mathrm{Im}\, f^* \bar{f})\sin\Delta t\right)e^{-t/2\tau_1}\Big)$$

The $\sin\Delta t$ terms can be quite large, specially if f, $\bar{f}$ have quite different phases, as is the case at energies of a few hundred Mev .

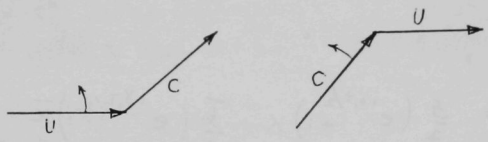
Kobzarev and Okun' [13] have proposed a transmission method for determining the sign (one measures the regeneration in two

---

(13) Kobzarev and Okun' , JETP 12, 426, (1961).

absorbers, as U - C vs. C - U). The feasibility has been studied by R. Good and E. Pauli [14] and the experiment has been tried by Zorn et al.

To see how the method works, imagine the absorbers to be thin. The K_s regenerated amplitude is then the vector sum of the contributions from the two absorbers. Moving the first absorber upstream rotates and shortens



the first vector, as a result of the mass difference and K_s decay. In the case with absorbers reversed the shortening is the same, but the effect of the rotation on the length is opposite. By comparing the two cases, the sense of the rotation can be determined. For the case drawn U - C would give a larger contribution then C - U , for example; but if the sense of the rotation were to be reversed, C - U would be the larger.

If $\phi = \phi_c - \phi_U$ is the difference in $K_L \rightarrow K_s$ scattering phase, the result clearly depends on the relative sign of Δ and ϕ .

Zorn et al, taking the sign of ϕ from optical model calculation ($\phi_c - \phi_U > 0$) quote [15] the preliminary result that $\Delta < 0$, i.e. the K_L is heavier than K_s .

---

(14) R. Good and E.Pauli, PRL 8 223 (1962)

(15) Fuji, Yovanovitch, Turkot, Zorn, and Deutsch, Proc.Int'l.Conf. High Energy Physics, Dubna, 1964, and private communication.

An interesting method has been developed by Piccioni et al,[18] in which the interference between regenerated K_s and the tail of the K_s amplitude from the original K^o production is observed. This has the great advantage that the phase of only one $K_L \rightarrow K_s$ scattering amplitude need be known, rather than the difference in phase between two. Since the sign of the imaginary part is known from total cross-sections, this in principle gives a result free of optical model uncertainties. This experiment has been performed but results are not yet avaible.

Dr. F. Crawford has asked to present their results on the sign of Δ after this talk.

I will not go into the determination of the mass matrix since this has been covered by the previous speakers.

C. CPT Tests:

The question of tests of CPT arises next. First Wolfenstein has observed[16] that the vector relation ship among η_{+-},[17] η_{oo}, $\mathrm{Im}\, A_2/A_0$ and ε as set forth in the paper of Wu and Yang, constitutes a test of CPT : Suppose one determines η_{+-} and η_{oo} experimentally, and then solves for ε and $\mathrm{Im}\, A_2/A_0$. The phase of ε thus obtained should agree with the one deduced from considerations of the smallness of various contributions to the decay matrix, namely that ε is dominated by the imaginary part of the off-diagonal element of the mass matrix:

$$\epsilon \approx \frac{-2\, \mathrm{Im}\, M_{12}}{\frac{1}{\tau_s}(1+2i\Delta)}$$

According to this, the phase of ε is $\tan^{-1} 2\Delta = \pm(50 \pm 10^o)$.

---

(16) L. Wolfenstein, CERN Preprint 1965

(17) T.T. Wu and C.N. Yang, PRL 13, 380, 1965

(18) Melhop, R. Good, Piccioni, and Swanson, Private communication.

If the phase of ε as determined from η_{+-}, η_{00} <u>disagrees</u> with this, one place to look for an explanation is CPT non-conservation, since litte but CPT has gone into the theory. (This test seems to be controversial, on the grounds that one does not know how to write down a CPT-non-invariant theory. None the less, the equality of the two phases is a prediction of the CPT conserving theory.)

Second, we may ask whether regeneration experiments provide any tests of CPT , of the type in which one observes a <u>large</u> fractional change in a <u>small</u> counting rate, (as opposed to tests in which small fractional changes (of order $\varepsilon \sim 10^{-3}$) in counting rates are observed).

The equation for time development of the K^0 beam in an absorber are useful for studying the CPT non-conserved case, because the effect of the absorber is to remove the one restriction placed by CPT on the mass matrix, namely that its diagonal elements should be equal.

If one expands the solutions of these equations to first order in the CP violating parameter ε and the phenomenological CPT violating parameter R , one obtains:

$$\begin{pmatrix} \alpha_1(t) \\ \alpha_2(t) \end{pmatrix} = a_S\, e^{i\gamma_S t/2} \begin{pmatrix} 1 \\ -(R - i\frac{\epsilon}{2}) \end{pmatrix} + a_L\, e^{i\gamma_L t/2} \begin{pmatrix} R + i(\epsilon/2) \\ -1 \end{pmatrix}$$

where $\alpha_{1,2}$ are the coefficients of the (old-fashioned) $K_{1,2}$. All observable effects that have a chance of giving a large percentage difference involve the K_1 amplitude associated with the long-lived component. The K_1 amplitude contains a term in $e^{i\gamma_S t/2}$ which is seen to be unaffected to order ε , and a term in $e^{i\gamma_L t/2}$ proportional to $R + i\frac{\varepsilon}{2}$. (Fitch-Cronin effect). The proportionality

to $R + i\frac{\varepsilon}{2}$ means that it is not possible to say whether CP violation (via ε), or CPT violation (via R) causes the effect.

For example, in an absorber we replace R by $R + R'$ where R describes the CPT violation in vacuum, (as above) and R' is the actual effect of the absorber. The regeneration of the short-lived component is then proportional to R', and one can observe interference of this with the Fitch-Cronin amplitude. The effect is proportional however to $R'\ (R + i\frac{\varepsilon}{2})$ and thus does not allow us to distinguish between R and ε.

Similarly, interference of the tail of the short-lived decay with the Fitch-Cronin amplitude measures again $R + i\frac{\varepsilon}{2}$. Thus there do not seem to be any CPT tests of the kind hoped for, in which a large percentage effect is observed.

There is, however, a way of ruling out the simplest CPT-violating hypothesis, namely a small $K^o - \overline{K^o}$ mass difference, as the sole cause of the Fitch-Cronin effect; this was remarked from the floor yesterday by Wolfenstein:

This case corresponds to

$$R = \frac{M_K - M_{\overline{K}}}{\frac{1}{\tau_s}(1 + 2\,i\Delta)} \qquad \text{and} \quad \varepsilon = 0 \ .$$

If one considers the experiment of Fitch, Roth, Russ, and Vernon[12], in which the regenerated K_s amplitude is made to interfere with the Fitch-Cronin amplitude, one observes the term $\mathrm{Re}\,(R'\,(R + i\frac{\varepsilon}{2}))$. If the effect of the absorber is principally absorptive one has

$$R' \simeq \frac{I}{\frac{1}{\tau_s}(1+2\,i\Delta)} \qquad \text{where } I \text{ is pure imaginary and}$$

$$\mathrm{Re}\,(R'\,(R + i\,\tfrac{\varepsilon}{2})) \sim \mathrm{Re}\left(\frac{I^{*}\,(M_K - M_{\bar{K}})}{\frac{1}{\tau_s}\left|(1+2\,i\,\Delta)\right|^2}\right) = 0\,,$$

in disagreement with the large constructive interference observed.

This represents the final end of all possible cosmological interpretations of the Fitch-Cronin effect (including spin zero particle exchange, which predicts no energy dependence).

It shows that K^o and $\overline{K^o}$ have the same mass to about

$$\frac{1}{3} \times \frac{\varepsilon}{2} \times \frac{h}{\tau_s}\,|1+2\,i\Delta| \approx \frac{1}{3}\,(2\cdot 10^{-3})\cdot 1.2\cdot 10^{-5}\ \mathrm{eV.} = 8\cdot 10^{-9}\ \mathrm{eV.}$$

thus
$$\frac{M_K - M_{\bar{K}}}{M_K + M_{\bar{K}}} \leqslant \frac{8.\ 10^{-9}}{10^{+9}} = 8.10^{-18}$$

and
$$\frac{M_K - M_{\bar{K}}}{M_{K_1} - M_{K_2}} \leqslant 2.10^{-3}\ ^{*}$$
which seems

to indicate (or at least to agree with) CPT conservation in the weak interactions to better than 2 parts in 10^3 .

Acknowledgements:

I wish to thank J.M. KAPLAN for interesting discussions and the Institut des Hautes Etudes Scientifiques for its hospitality.

* In the talk this was given as 10^{-4} , which was overoptimistic.

DISCUSSION

CRAWFORD (LRL): At the 1963 Weak Interactions Conference at BNL we presented preliminary evidence for the sign of $m = m_1 - m_2$, based on the method suggested by Camerini, Fry, and Gaidos. In our experiment we start with about 8000 lambda decays from lambdas produced via $\pi^- p \rightarrow \Lambda + K^o$. We rescan along the predicted K direction and look for an elastic K-p scatter followed by a decay $K_1 \rightarrow \pi^+ \pi^-$. Our likelihood ratio gave $\alpha(m < 0) \approx 2000\, \alpha(m > 0)$, based on our best guess for the $K^0 p$ and the $\overline{K}^o p$ elastic scattering phase shifts and, most important, based on the assumption $|m| \approx 1.5$. If we instead take $|m| \approx 0.5$, our likelihood ratio is decreased by roughly the cube root. Thus 2000/1 goes to about 13/1, if everything else is unchanged. We now have slightly more data. Using our present best guess for the phase shifts we obtain the likelihood ratio $\alpha(m = -0.5) / \alpha(m = +0.5) \approx 7/1$. We regard this result as completely inconclusive. As far as we are concerned, the sign of m is unknown.

We do not have any more data from this experiment. Nevertheless we do have hopes that we may be able to make a stronger statement than we can now. Our hopes are based on the fact that we are not satisfied as to the correctness of the elastic scattering phase shifts that we are using. Our best set consists of Solution I from Tripp, Ferro-Luzzi, and Watson for $\overline{K}p$, and the "Yang" choice for the Fermi-Yang ambiguity in the Kp phase shifts of Stenger et al. These phase shifts do not correctly predict our absolute yields. Another reason that we suspect the phase shifts is that our likelihood function $\alpha(m)$ peaks at $m \approx -3$. This disagrees with the value $|m| = 0.6 \pm 0.3$ that we obtain from the same sample of film using essentially the same experiment technique, except that instead of looking for a proton recoil followed by a decay $K_1 \rightarrow \pi^+ \pi^-$ as in the "sign of m experiment," we look for a π^+ recoil followed by a decay $\Lambda \rightarrow p\pi^-$. (Actually we do both experiments at once.) At present we are playing with the phase shifts, hoping to find a set which (A) agree with our absolute yields and

angular distributions, (B) give an $\alpha(m)$ which peaks reasonably near $|m| = 0.6$, and (C), does not disagree with the scattering data from which the phase shifts were obtained.

PICCIONI (LaJolla): I want to make a few remarks concerning whether there is a discrepancy among the different determinations of the K_1-K_2 mass difference. I do not think that the value we obtain will be substantially different even if our plate contained 100% nuclei of iron. The reason is that the $K_2^o \rightarrow K_1^o$ regeneration amplitude is substantially imaginary. So the effect mainly arises from the fact that the plate absorbs more $\bar{K}^o$ than K^o. I do not believe that it matters very much if there are a few nuclei of some other elements.

Another important point to note is that the recent better agreement between the different values is based on the leptonic decays of K mesons. This is certainly a good tool to study K^o, $\bar{K}^o$ oscillations. However, the mass determination in this case is made difficult by questions concerning the validity of $\Delta S = \Delta Q$ rule and the CP violation effects. I would also like to point out that recently some Russian authors who were somehow omitted from the list, use the regeneration principle with an intelligent trick which avoids the need to correct for the absorption of particles. They find the mass difference to be $.82 \pm .14$ and candidly state that the probability of their value agreeing with that of Fitch et al. is only 8%. It is possible, therefore, that we will reach an agreement but there is at least 50% probability that we will not.

The consequence of all this is that one might ask the question: how are we indeed sure that the regenerated K_1^o's are the same creatures as the originally produced K_1^o's? The experiment that we are doing now will enable us to answer this question, since we see the interference between the regenerated and the originally produced K_1^o's.

SESSION IV

ACCELERATOR NEUTRINOS AND INTERMEDIATE BOSONS

Tuesday, October 26, 1965

CHAIRMAN: M. Schwartz
Columbia University

Scientific Secretaries

C. H. Albright, Northwestern University
R. A. Lundy, Argonne National Laboratory

Search for Intermediate Bosons in Proton-Nucleon Collisions*

R. Burns, G. Danby, E. Hyman, L. M. Lederman,

W. Lee†, J. Rettberg, and J. Sunderland

Columbia University, New York, New York

and

Brookhaven National Laboratory, Upton, New York

(Paper presented by W. Lee)

We have carried out a measurement of the yield of high energy muons emitted at large angles to a beam of 20 BeV/c and 30 BeV/c protons at the AGS. Our objective was to set an upper limit to the production and decay probability of massive unstable states decaying into muons. The most interesting candidate for such a state is the intermediate boson W, supposed to mediate weak interactions. It has been recognized[1] that one important signature for a heavy W is the large transverse momentum given to the muon in the decay process

$$W \rightarrow \mu + \nu \quad . \tag{1}$$

Recently high energy neutrino experiments have established that $m_W > 2$ BeV.[2,3] Thus, for a W of mass 2 - 6 BeV, the transverse momentum of the emitted muon can vary from 1 - 3 BeV/c. This is much larger than is typically found in secondary particles emerging from high energy interactions. Furthermore, the conventional parents of muons, pions and kaons, can be largely "turned off" because of their relatively fast absorption by strong interactions in dense matter (~10 cm in tungsten) as compared to their mean free

*Work supported in part by the U. S. Atomic Energy Commission.

†Alfred P. Sloan Fellow.

path (550 m at 10 BeV) for decay. Thus, the rate of muon counts observed at large angles, relatively easily reached by W-decay, is an upper limit to $\sigma_W B$, where σ_W is the boson production cross section for AGS protons (per nucleon) and B is the unknown partial rate for reaction (1).

Figure 1 illustrates the experimental arrangement. The fast extracted proton beam of the AGS was transported in a vacuum pipe up to the 82-ft. steel shield of the BNL neutrino facility. An 18-in. block of hevimet (90% tungsten) absorbed the bulk of the beam and its secondary particles. Muons were counted by detectors inserted in 3 in. x 3 in. holes located in the steel shield at ranges corresponding to muon momenta greater than 9.6, 11 and 12.5 BeV/c. The very short "on-time" of the AGS extracted beam dictated the variety of counters employed. The flux from 0° out to about 5° was measured by integrating solid state detectors. The linearity of these detectors, and associated amplifiers and digitizers was verified over a counting rate range of from 10^3 counts/pulse down to 2 or 3 counts/pulse. The absolute calibration is only roughly known.

The region from $\sim 4^\circ$ to 9°, where the counting rates were below $\sim$ few counts/cm^2/pulse, was measured by a 1-cm^2 telescope of two scintillation counters separated by 0.5 in. of Pb. At larger angles a 30-cm^2 telescope was used to improve the data-taking rate. Detectors in all three holes were operated simultaneously. All counters were gated by the rf structure (the gates being a train of twelve 30-nsec pulses separated by 200 nsec and generated by a Cerenkov counter viewing the target). A guard counter effectively monitored the positioning of the external beam by counting secondaries generated by the halo around the proton beam. It was adjusted to veto counts if the beam drifted more than $\sim$ 1/2 in. off center in the 3-in. diameter part of the vacuum pipe by locating it within a shield of about 30 ft. of lead. This was stacked so as to screen the muon counters from any spray generated far upstream by beam halo (hitting flanges, etc.) and by interactions in an air space (20 mg of air plus Mylar) separating the machine vacuum from the beam transport system.

Muons were counted in each of the three holes and over an angular range from 0° to $\sim 12^\circ$. Two proton beam energies were used to cover the

W-mass range from ~ 2 to ~ 6 BeV. The results are presented in Fig. 2. The lower curves give the raw data except that the solid state points were normalized to join smoothly to the small telescope near 4°. A comparison of these points with the yields expected from an intermediate boson limits the product $\sigma_W B$ to the order of $3 - 4 \times 10^{-34}$ cm^2 for the mass range 3 - 6 BeV (see Fig. 3). However, it is obvious from a straightforward extrapolation of the curves that most of the counts are muons from pions and kaons. This is further borne out by a calculation of the expected yields, using beam survey results from BNL, CERN and earlier emulsion data from the neutrino runs.[3] Multiple scattering was included in the form of a gaussian with an rms parameter of 15 in. The agreements (broken curves shown in Fig. 2c, 2f) are well within thick target uncertainties.

Finally, experimental tests were carried out in order to perform a quantitative subtraction:

1) Moving target effect: 4" (about 1 mfp) of hevimet could be remotely moved through a distance of 1.5 ft. Since about half the muons observed come from pions and kaons emerging from ~ 1 mfp, these now have a flight path for decay which can be varied from ~ 10 cm (in hevimet) to 45 cm (in air). In Fig. 2 the upper curves represent the distribution of muons amplified by target motion. It is clear that most of the muons observed are from long-lived parents. W-muons would be affected only in higher order by the motion.

Let N_μ (d, L) represent the yield observed at a distance d from the axis of the beam with the movable 4" of the target at L feet from the remainder. Then the yield of muons at a depth D in the shield originating from a rapidly decaying source ($\tau \lesssim 10^{-9}$ sec) can be shown to be:

$$Y_W(d', 0) \leqq N(d', 0) - \left[\frac{N(0, 0)}{N(0, L) - N(0, 0)}\right] \{ N(d, L) - N(d', 0)\} \qquad (2)$$

where $d' \cong (1 - \frac{L}{D})\ d$.

This permits an experimental subtraction based upon the assumptions:

i) The muons observed near 0° are all from pions and kaons. This gives the experimental amplification of muons from long-lived parents due to target

motion. ii) This amplification is independent of production angle. A correction must be made for the change in angle at a given position due to the extra 1.5 ft. (out of 34 ft. for hole D). The subtraction is of course limited by statistics and the intervention of several small corrections (hence the inequality in Eq. 2) which are sensitive to details of the production mechanism.

2) Upstream source effect: Earlier runs indicated that above 10°, a "background" appears which was traced to ~ 0.1 gm/cm^2 of material in the beam (flag) at about 75 ft. from the shielding wall. Particles emitted at small angles from this point simulate muons emitted at $\gtrsim 10^{\circ}$ from the hevimet. To minimize this, the upstream material was reduced to a minimum of ~ 30 mg/cm^2 and lead shielding was added as shown in Fig. 1. Both steps resulted in a reduced background. Flags of 150 mb/cm^2 could be remotely inserted both here and further upstream where the air gap between AGS vacuum and transport vacuum was located. The shape of the flag-in data strongly suggests that counts above 10° (which at 30 BeV/c has a characteristic change in slope) are indeed upstream muons. A minimum subtraction may be made by assuming that the maximum upstream source effect comes from the 30 mg/cm^2. Since there are many additional possibilities, i.e. beam halo impacting on flanges, etc., this gives an upper limit to the residual muon count. This correction was negligible at 20 BeV/c.

The data used here came from 30 hours of AGS running and were duplicated in an earlier run differing in counter construction and shielding details. This gave similar results with somewhat reduced sensitivity. In Fig. 3 we present subtracted data for $E_{\mu} \geq 12.5$ BeV and for the 20- and 30-BeV/c proton runs, together with results of a calculation of muons from W decay. The statistical upper limits of the subtracted points are rarely more than a factor of two less than the original points.

The possibility of strong production of W's was suggested by Lee and Yang.[4] However, the very high momentum transfer and multitude of available channels makes a detailed calculation of massive W production uncertain by several orders of magnitude.[5] Similarly, the partial decay rate into

leptons cannot be reliably calculated for a heavy boson.[6] Consequently, we have treated the problem in the following ways: (1) assume all W's are produced at 0° with a total cross section per nucleon of σ_W. These decay promptly and isotropically in their c.m. to muons with a branching ratio B. The multiple scattering of the W-muons is treated with the same program as the π-K muons. (2) A somewhat more realistic calculation makes use of a model to calculate the angular distribution of W's. The σ_W is factored into a nucleon-nucleon total cross section, a semi-weak vertex and a nucleon propagator term. In the latter an exponential suggested by Yang and Wu was used.[7]

The results were arbitrarily normalized to $\sigma_W B = 2 \times 10^{-34}$ cm^2 and appear in Fig. 3. These are only slightly broadened relative to those of Method (1). It is important to note that, because we are comparing angular distributions of muons from W's with experiment, the results are quite model independent. This is because near threshold the W must go forward, and above threshold the W presumably wants to be produced with the smallest possible momentum transfer. The results based upon a statistical confidence level of $\geqslant$ 99% are presented in Table I. We conclude from this that for proton-nucleon collisions and in the mass range from $\sim$ 2.5 BeV to $\sim$ 6 BeV

$$\sigma_W B < 2 \times 10^{-34} \text{ cm}^2 \quad \text{(99\% confidence level)} .$$

Since each proton makes many pions, similar limits apply to pion-nucleon collisions averaged over pion spectra characteristic of the AGS. Anti-proton or K-nucleon cross sections are reduced roughly as the yields observed in secondary beams. It should be emphasized that this experiment integrates over all possible final states. In order to get some estimate for the sensitivity to mass, we have given in Table II the <u>relative</u> phase space for typical final states, using 20 and 30 BeV/c protons incident on nucleons having fermi motion.

It is seen that the 20 BeV/c run is reasonably sensitive to 4-BeV bosons and the 30 BeV/c run extends to a mass of 6 BeV. Clearly, the interpretation of these data insofar as the <u>existence</u> of bosons of $m_W < 6$ BeV must await a much better theoretical grasp of the problem of production of

Finally, we note that one can speculate on other reactions leading to large angle muons. For example, π^0 photons can produce wide angle muon pairs or perhaps heavier leptons. Further refinements of this type of measurement would have to contend with these sources.

We would like to thank M. L. Good for suggestions and T. Novey for information on a similar experiment being carried out at Argonne.[8]

TABLE I

Upper Limit of $\sigma_W B$ as a Function of Mass of W

Mass of W	Upper Limit of $\sigma_W B$	
2 BeV	3×10^{-34} cm^2	20 BeV/c protons
3 BeV	2×10^{-34} cm^2	
4 BeV	1×10^{-34} cm^2	
4 BeV	4×10^{-34} cm^2	30 BeV/c protons
5 BeV	2×10^{-34} cm^2	
6 BeV	2×10^{-34} cm^2	

TABLE II

Relative Phase Space for W-Production

M_W :	3	4	5	6	7 BeV	Final State
	1	0.8	0.6	0.4	0.15	N+N+W
30 BeV/c	1	0.75	0.48	0.25	0.04	N+N+W+π
	1	0.65	0.35	0.12	-	N+N+W+2π
M_W :	2.5	3	4 BeV			
	1	0.95	0.72			N+N+W
20 BeV/c	1	0.85	0.47			N+N+W+π
	1	0.74	0.31			N+N+W+2π

REFERENCES

[1] For example, P. Piccioni, Informal Conference on Neutrino Physics, CERN, 1965 (to be published); M. Schwartz, private communication; M. L. Good, private communication, circa 1964; A. Zichichi, quoted by G. Bernardini at DUBNA, 1964.

[2] G. Bernardini et al., Nuovo Cimento 38, 608 (1965).

[3] R. Burns, G. Danby, K. Goulianos, E. Hyman, L. Lederman, W. Lee, N. Mistry, J. Rettberg, M. Schwartz and J. Sunderland, Phys. Rev. Letters 15, 42 (1965).

[4] T. D. Lee and C. N. Yang, Phys. Rev. 119, 1410 (1960).

[5] Private communications from G. Feinberg, T. D. Lee, R. Pieirls, R. Serber and C. N. Yang. The following calculations of boson production by strongly interacting particles are known to us:

(a) T. D. Lee and C. N. Yang, Phys. Rev. 119, 1410 (1960)
W production in π-N or N-N collisions $\sim 10^{-32}$ cm^2.

(b) J. Bernstein and G. Feinberg, Phys. Rev. 125, 1741 (1962)
$\pi p \rightarrow Wp \sim 10^{-32}$ cm^2 for $m_W \approx 1$ BeV.

(c) J. Bernstein, Phys. Rev. 129, 2323 (1963)
$pp \rightarrow Wd \sim 10^{-34}$ cm^2 for $m_W \approx 1$ BeV.

(d) Mani, Ph. D. Thesis (Columbia University 1964) (unpublished)
$\bar{p} + p \rightarrow W\pi \sim 10^{-31}$ cm^2 for $m_W \approx 2$ BeV.

(e) J. Nearing, Phys. Rev. 132, 2323 (1963)
$pp \rightarrow Wd \sim 5 \times 10^{-34}$ cm^2 for $m_W \approx 1$ BeV.

(f) Chilton, Saperstein and Shrauner (preprint)
$pp \rightarrow ppW$ 10^{-31} cm^2, $m_W \approx 3$ BeV.

[6] V. Namias and L. Wolfenstein, Nuovo Cimento 36, 542 (1965). See also R. Carhart and J. Dooher (to be published). These authors have estimated the effects of form factor suppression in the W-mass range of 2.5 to 3 BeV and conclude that the leptonic mode will probably continue to be important with increasing W-mass in spite of the increasing number of channels.

[7] T. T. Wu and C. N. Yang, Phys. Rev. 137, B708 (1965).

[8] M. L. Good, Oxford International Conference on Elementary Particles, 1965 (to be published).

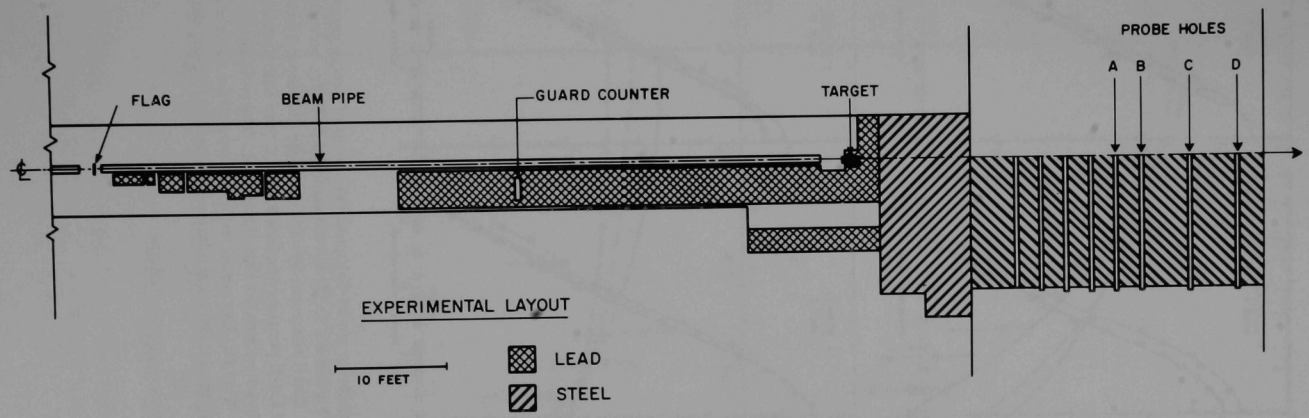


Fig. 1. Experimental Apparatus

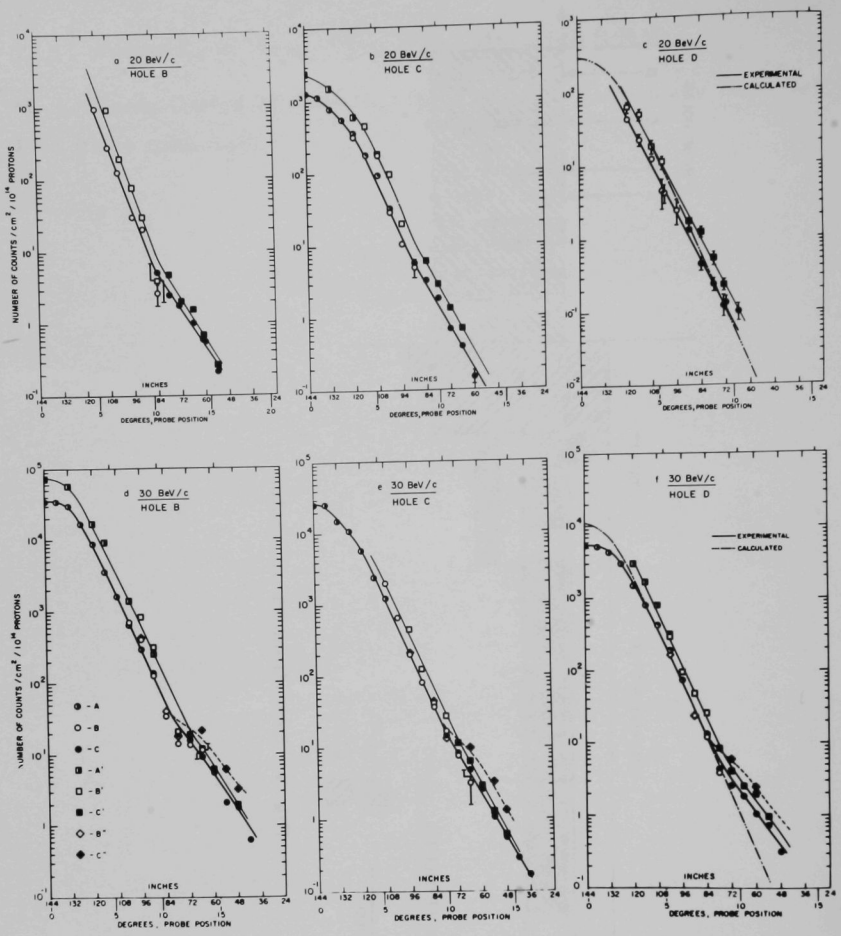


Fig. 2. Experimental Results. Figures 2a, 2b, 2c are 20-BeV produced muons of energy greater than 9.6, 11.0, 12.5 BeV/c, respectively. Figures 2d, 2e, 2f are the same for 30 BeV/c protons. Symbol A: Solid state detection; Symbol B: Small telescope; Symbol C: Large telescope; Symbols A', B' and C' correspond to target moved to 1.5-ft position; Symbols B" and C" are with upstream flag "in". The statistical errors when now shown are smaller than the symbol. The solid curves are drawn through the experimental points. The dot-dash curves in Figs. 2c and 2f are calculated from beam survey data. The dashed curves (Figs. 2d, 2e, 2f) are drawn through the "flag-in" data.

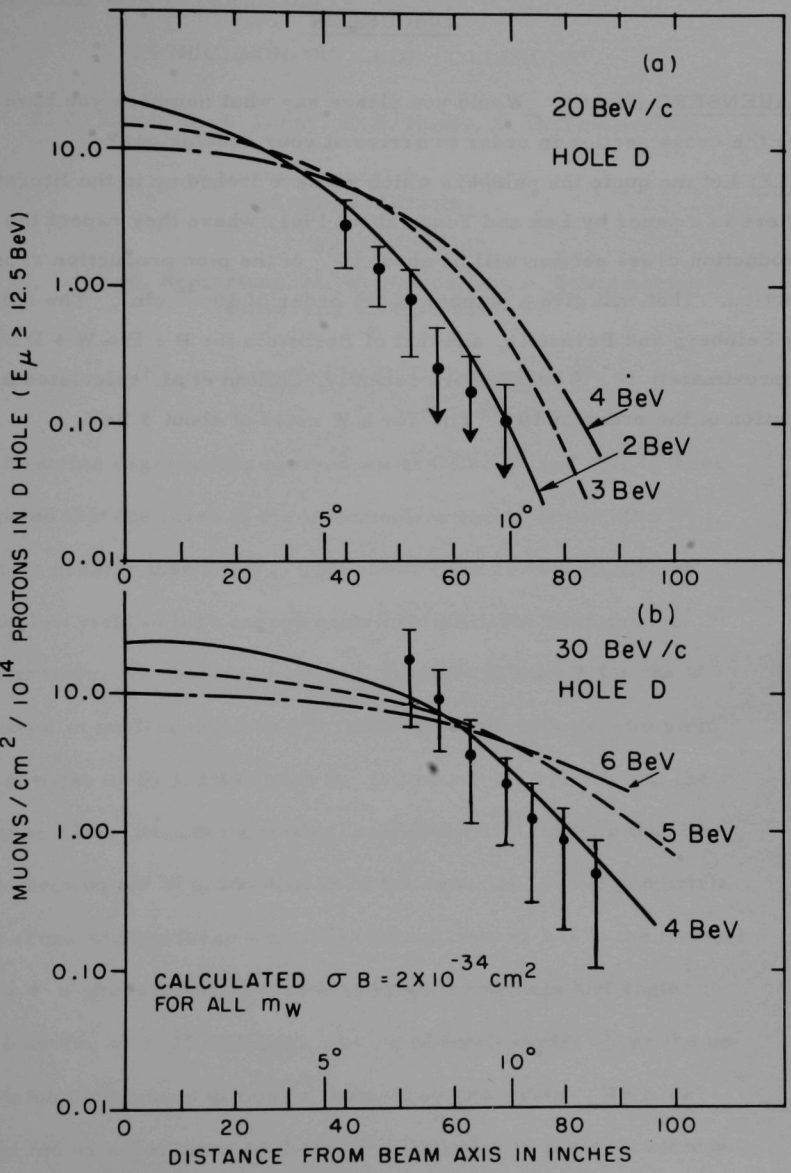


Fig. 3. Subtracted Results in Calculation of Muon Flux from W's. The W-yields are all normalized to $\sigma_W B = 2 \times 10^{-34}$ cm^2. In hole D, $E_\mu \geq 12.5$ BeV.

DISCUSSION

NAUENBERG (SLAC): Would you please say what numbers you have used for the cross section in order to arrive at your conclusions?

LEE: Let me quote the numbers which we have looked up in the literature. There is a paper by Lee and Yang, about 1961, where they expect the W production cross section will be about 10^{-6} of the pion production cross section. That will give a number of the order of 10^{-32} cm^2. The calculation by Feinberg and Bernstein, and that of Bernstein for $P + P \rightarrow W + D$ both give approximately 10^{-32} cm^2. More recently, Chilton et al. calculated a cross section of the order of 10^{-31} cm^2 for a W mass of about 3 BeV.

SEARCH FOR INTERMEDIATE VECTOR BOSON PRODUCTION IN NUCLEON-NUCLEON COLLISIONS*

R. C. Lamb, R. A. Lundy, T. B. Novey, D. D. Yovanovitch

Argonne National Laboratory
Argonne, Illinois

and

M. L. Good, R. Hartung, M. W. Peters, and A. Subramanian+
University of Wisconsin
Madison, Wisconsin

(Paper presented by D. D. Yovanovitch)

Neutrino experiments carried out at CERN[1] and BNL[2] have indicated that the mass of the intermediate vector boson, the W, must be greater than 2 BeV. This lower limit is essentially set by the low yield of high energy neutrinos available from present accelerators. It appears, however, feasible to search for the W produced in nucleon-nucleon interactions. This process can yield W's of mass up to 3.3 BeV with the proton energy available at the Argonne ZGS. Recent theoretical calculations[3] indicate that the cross section for W production is of the order of 10^{-6} of geometric. This cross section taken with a branching ratio of 1/3 to the channel $W \rightarrow \mu + \nu$ gives a flux of muons at large momentum and angle (4 - 6 BeV/c at $\sim 20^{\circ}$ lab angle) which is significantly above the unavoidable background of muons from other processes. We have conducted an experiment to detect W production in nucleon-nucleon

---

*This work performed under the auspices of the U. S. Atomic Energy Commission.

+On deputation from the Tata Institute of Fundamental Research,

interactions which is sensitive to W masses in the range of 2 to 3 BeV. We find no muon signal in excess of that due to π and K decay.

The experimental apparatus used is shown schematically in Fig. 1. A proton beam of 12.5 BeV/c momentum (2×10^9/pulse) was incident on a 3 in. long uranium target. In this parasite extracted proton beam, about 1/2% of the circulating beam of the ZGS is spilled during the 250 millisecond flat top. The beam spot, one cm in diameter, was continuously observed by a closed circuit TV - scintillator system. The incident proton intensity was calibrated by gold foil activation and monitored throughout the run by a triple telescope located at 150° production angle. A magnetic spectrometer viewed the target at a lab angle of 20°. This spectrometer, composed of entrance and exit 4 fold scintillator telescopes, has an acceptance solid angle of 2.8×10^{-4} sr and a momentum resolution of 22% (full width at half maximum). A massive shield was located adjacent to the target to suppress strongly interacting particles. Some additional discrimination against strongly interacting particles was obtained by the addition of a 430 gm/cm^2 absorber and a ninth counter to the exit arm of the spectrometer. Not shown on Fig. 1 is a large amount of additional lead shielding employed to reduce single rates and to stop high energy muons coming from the general direction of the accelerator.

Inasmuch as this method of detecting W's involves the observation of a very small muon signal, it is necessary to suppress all strongly

interacting particles by at least a factor of 10^5 and to minimize the decay of pions and kaons into muons. This would imply the use of a shielding material with the shortest possible interaction length; however such high Z material results in excessive scattering which tends to cause the particles produced more copiously at smaller angles to be scattered toward the spectrometer. We chose brass as the best compromise for shielding material. The maximum shield length must be less than the range of muons to be expected from the decay of W's.

In order to be sure that we were detecting only muons in the spectrometer we varied the thickness of the brass shield. Fig. 2a shows an absorption curve obtained for 4 BeV/c negative particles from the target. It is seen that after 1800 gm/cm^2 of brass there is no further exponential absorption. With a shield of this thickness the eight and nine fold coincidence rates became identical. The zero absorber point gave us an absolute calibration for 20° pion production. This combined with an interaction length obtained from the absorption curve enables one to calculate the residual muon level. The agreement of this level and the observed yield is strong evidence that we are detecting only muons from pions. Fig. 2b shows the comparison between the measured and calculated muon spectra for an absorber thickness of 1840 gm/cm^2. The momentum values refer to the initial momentum of particles emerging from the target. The departure of the observed points from the calculated curve at low momenta are due to the effects of the range cutoff and finite momentum resolution.

The agreement between the calculated and measured muon spectra is very good and indicates that there is no large contribution of muons from sources other than pion decay; however the scattering effects and secondary production in such a thick absorber are difficult to precisely account for. These difficulties are circumvented by another method, in which one varies the material near the target, changing the interaction length in such a way as to increase the yield of muons. The first 30 cm of brass was replaced by sixteen 6 mm lead plates spaced 12 mm apart. This leaves the number of radiation lengths in the shield unchanged. A measurement was then performed with the same substitution at the downstream end of the shield. The overall absorption of the shield is unchanged in these two measurements. The net difference of these two measurements is due only to a signal from π and K decay. Using this result it is possible to accurately subtract those muons due to π and K decay from the data shown in Fig. 2b. The result of this subtraction is shown in Fig. 3 expressed in units of $\frac{d^2\sigma}{d\Omega\, dp}$ per uranium nucleus. The errors shown are statistical.

The result is consistent with zero yield of muons from sources other than pion and kaon decay. The result can be expressed as an upper limit of the product of W-production cross section times the branching ratio for W decay into a muon. We find:

(W production cross section)(branching ratio) $\leq 4 \times 10^{-34}$ cm^2/sr BeV/c nucleon.

The number of effective nucleons in the uranium nucleus was estimated assuming an $A^{2/3}$ dependence.

A similar measurement was made for positive particles but the results are less sensitive due to the large inelastic proton yield (several times the positive pion yield.)

The expected rates and equivalent cross sections for muons from the reaction $p + n \rightarrow W^- + p + p$, $W^- \rightarrow \mu^- + \nu^-$ was calculated for different W masses using the production cross sections of Chilton et. al.[3] and are shown in Fig. 3. A one third branching ratio for this mode was assumed. Thus no boson production in the mass range of 2-3 BeV is seen if one assumes the cross sections as calculated by Chilton et. al. Confidence levels, calculated from χ^2 analysis of Fig. 3, for the non-existence of the W of mass 2.0, 2.5, and 3.0 BeV are 99%, 97%, and 60% respectively.

We would like to acknowledge the assistance of D. Drobnis of the Argonne Electronics Division and the technicians of the Neutrino group for their assistance in the experimental runs. We are also grateful to the ZGS operations staff for the reliable performance of the accelerator during the course of this work.

REFERENCES

[1] M. M. Block, H. Burmeister, D. C. Cundy, B. Eiben, C. Franzinetti, J. Keren, R. Møllerud, G. Myatt, M. Nikolic, A. Orkin-LeCourtois, M. Paty, D. H. Perkins, C. A. Ramm, K. Schultze, H. Sletten, K Soop, R. Stump, W. Venus, and H. Yoshiki, Phys. Letters 12, 281 (1964); G. Bernardini, J. K. Bienlein, G. Von Dardel, H. Faissner, F. Ferrero, J. M. Gaillard, H. J. Gerber, B. Hahn, V. Kaftanov, F. Krienen, C. Manfredotti, M. Reinharz, and R. A. Salmeron, Phys. Letters 13, 86 (1964).

[2] R. Burns, K. Goulianos, E. Hyman, L. Lederman, W. Lee, N. Mistry, J. Rettburg, M. Schwartz, J. Sunderland, and G. Danby, Phy. Rev. Letters 15, 42 (1965).

[3] F. Chilton, A. Saperstein, E. Shrauner, to be published.

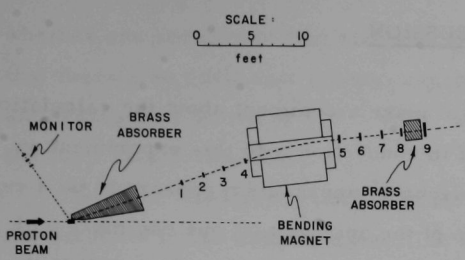


Fig. 1

Layout of Experimental Apparatus. Numbers 1 through 9 indicate plastic scintillator counters. Counters and the target are not to scale.

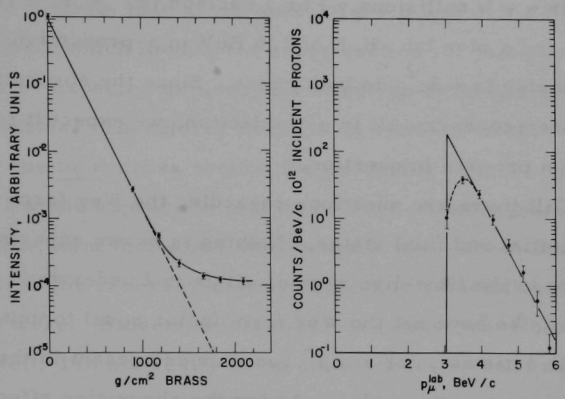
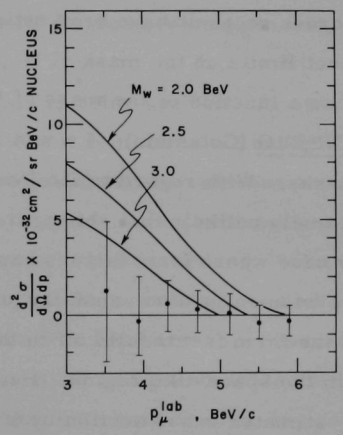


Fig. 2. a) Absorption Curve for 4 BeV/c Negative Particles from the Target. The points are experimental intensities measured by varying the thickness of the absorber. The solid curve is the fit to the data. b) Muon spectrum at 1840 g/cm^2 absorber thickness. The solid curve is the calculated muon spectrum from π decay. The cut-off near 3 BeV/c is the range cut-off of the absorber.

Fig. 3

The Points Are the Momentum Spectrum of the Muons when the π + K Decay Background Has Been Subtracted in the Manner Described in the Text. The solid curves are calculated from the production cross sections of Chilton et. al.



DISCUSSION

CHILTON (Argonne): I would like to make a comment about the calculation by Shrauner, Saperstein and myself in connection with this experiment on $N + N \rightarrow W + N + N$. The one-pion exchange mechanism appears to be a reasonable model for this process because of the analogy that one can make with ρ production in π - N collisions. For a nucleon lab K.E. of 12.5 BeV in the W-experiment and a pion lab K.E. of 1.6 BeV in ρ-production, the minimum momentum transfer is $\sim 3\mu_\pi^2$ in both cases. Since the absorptive one-pion exchange model is known to work well in ρ-production, we expect it to be reasonable for the W-production process in question.

Still there are questions regarding the $W\pi\pi$ form factor and absorption in the initial and final states. Nothing is known experimentally about the form factors in the time-like region, although I understand experiments are in progress. We have set the $W\pi\pi$ form factor equal to unity and consider this a reasonable estimate, for any 1^- resonances present in the 2-3 BeV region will tend to increase this value. As for the absorption effects, we have estimated them in a number of different ways and find that the cross section is reduced by a factor of one-third to one-fourth, which is quite comparable with that for ρ-production. This model gives a total cross section of the order of 10^{-32} cm^2.

Various other kinds of final state interactions, which could raise the cross sections have been estimated but not included in these numbers. One can set limits on the mass of W , by comparing the total cross section prediction as a function of the mass of W.

FEINBERG (Columbia): I would like to make two comments on Dr. Chilton's remarks. With regard to the form factor at the $W\pi\pi$ vertex, I think that it is extremely unlikely that setting it equal to unity is a good approximation. The only case where form factors have been measured in the time-like region is for proton-antiproton annihilation into an electron pair. There it was found that the form factor falls off in the time-like region at least as fast as it falls off in the space-like region. Hence, for a W mass of 3 BeV, it would reduce the estimated cross section by a factor of 1/600. Admittedly it is questionable

whether one should use this evidence of $p\bar{p}$ annihilation. I think, however, that there's no doubt that one can conclude that the calculation might be ambiguous by a factor of 100 to 1000, because we simply do not know what the form factor should be.

The other comment I would like to make is the following: I believe that the estimate of the total cross section for $p + p \rightarrow W$ + Anything, may be somewhat more reliable than an estimate of $p + p \rightarrow W + N + N$, because some of the effects which modify the cross section for just producing two nucleons might be expected to disappear after you have summed over all possible final states. Therefore, perhaps an estimate of this type might be reasonable for the total cross section for producing W's.

CHAIRMAN: I would appreciate it if there were no more discussion of this. I might note at this point that some months ago a very illustrious committee met at Brookhaven for several months and tried to establish what various W cross sections were. It decided that they were somewhere between 10^{-32} and 10^{-40} cm^2. Well, I'm not really being quite accurate, but I think there is a substantial amount of ambiguity in this, and I do not think this is the place to argue over the detailed nature of these questions.

CARHART (BNL): I just want to make a comment about the branching ratio into $\mu + \nu$. I agree with the comment that Chilton made that these experiments depend on an interpretation that is based on the theories as to how these things are produced and decay. And I do not have much to add, except to say that the same sorts of considerations apply to the decays into non-leptonic modes. And since a leptonic mode is being used to indicate the presence of the boson, you have to know that it dominates the decay scheme. We have made estimates of decay into two pseudo scalar mesons and also into baryon pairs with the Cabibbo hypothesis and, of course, this suffers from the same ambiguities in form factors that have been mentioned. But with a $1/q^2$ dependence typical of the ρ mass or a slightly higher mass, we find branching ratios into these final state channels typically a few parts in a hundred for the $B\bar{B}$ modes, and a few parts in a thousand for two pseudoscalar mesons. At 6 BeV there are so many modes open that it is hard to draw any conclusions.

BÉG (Rockefeller Institute): I just wanted to add a little bit to what Professor Feinberg said. The comparison with the ρ-production is misleading for the trivial reason that the $\rho\pi\pi$ form factor is not the same as the $W\pi\pi$ form factor.

CHILTON: I would like to make a brief comment on Dr. Feinberg's comment. The only point is that first, while it is true that the $W\pi\pi$ form factor is not known, it is essential that it is in the timelike region. And so if you are at all near to resonances, of course, you do get something which is greater than one. Since no W has been found, all calculations on W production, like that of Feinberg with Bernstein, suffer from the same defect. It seems other than that particular ambiguity, the calculation is a reasonable one, since it is quite successful in explaining ρ-production.

ν AND $\bar{\nu}$ INTERACTIONS IN A HEAVY LIQUID BUBBLE CHAMBER

CERN Heavy Liquid Bubble Chamber Group
Geneva, Switzerland

(Paper presented by D. C. Cundy)

Introduction

This report is based on analyses performed by :

J. Bartley, M.M. Block, H. Burmeister, D.C. Cundy, B. Eiben, C. Franzinetti, R. Møllerud, G. Myatt, M. Nikolic, A. Orkin-Lecourtois, M. Paty, D.H. Perkins, C.A. Ramm, K. Schultze, H. Sletten, K. Soop, R. Stump, W. Venus, H.W. Wachsmuth, H. Yoshiki.

The CERN ν and $\bar{\nu}$ experiments and preliminary results have been previously reported (1). In this paper we shall discuss only the results of the analysis of the ν and $\bar{\nu}$ events carried out since that report and limit ourselves to three topics :

1. Phenomenological account of $\bar{\nu}$ - run
2. A study of the elastic process :

$$\nu + n \longrightarrow \mu^- + p$$

$$\bar{\nu} + p \longrightarrow \mu^+ + n$$

3. A comparison of the single pion events with the $N^*_{33}(1238)$ production model.

The ν data were obtained by using $7{\cdot}3 \times 10^{17}$ protons of 24·5 GeV/c ($1{\cdot}28 \times 10^6$ pulses) incident on a copper target. The bubble chamber of 500 litres actual volume (220 litres fiducial volume) was filled with freon CF_3Br and was in a magnetic field of 27 kGauss.

The $\bar{\nu}$ data were obtained in two runs :

a) using 7.6×10^{16} protons of 24·5 GeV/c ($5{\cdot}7 \times 10^4$ pulses) incident on a tungsten target and the 500 litre chamber,

b) using $2{\cdot}97 \times 10^{17}$ protons of 22·1 GeV/c ($3{\cdot}23 \times 10^5$ pulses) incident on a copper target, and the enlarged CERN heavy liquid bubble chamber (1180 litres actual volume) with 638 litres fiducial volume.

For this work event types are recognized qualitatively and hence the [illegible] have been chosen to give high γ-ray and strange particle detection

The ν and $\bar{\nu}$ spectra used are shown in Fig. 1.

1. Phenomenological Account of the $\bar{\nu}$ - Run

i) Events Found in $\bar{\nu}$ - Run

The following event types, which could have a possible positive or negative lepton track, were in the fiducial volume :

Event class	No.
0, 1, many protons and a μ^+	32
identified single pions and a μ^+	13
ambiguous between $\mu^+ \pi^-$ and $\mu^- \pi^+$	15
single e^+	2
unambiguous ν events having a μ^- candidate	20

The two positron events are both $<0{\cdot}2$ GeV in energy, and are most probably asymmetric electron pairs.

To eliminate the background due to incoming pions events were selected by the following criteria :

the resultant momentum along the $\bar{\nu}$ direction is $>0{\cdot}3$ GeV/c,

the four-momentum transfer is not greater than the maximum possible for a collision of a $\bar{\nu}$ of energy equal to the visible energy of the event, with a stationary nucleon.

These requirements were satisfied by 34 $\bar{\nu}$ candidates which comprise :

17 non-pionic, 10 with a μ^+ and evaporation protons (i.e. <30 MeV kinetic energy) and 7 with a μ^+ and one or more protons with kinetic energy >30 MeV (called multi-proton events).

15 one pion events, of which there are 1 $\mu^+\pi^+$ (probably charge exchange of π^0), 3 $\mu^+\pi^-$, 5 $\mu^+\pi^0$, and 6 ambiguous between $\mu^+\pi^-$ or $\mu^-\pi^+$.

2 multi-pion events, one of which is ambiguous with a ν event.

This sample contains, however, background from neutron interactions. Very fast protons, and non-interacting π^+ can be mistaken for positive muons. From the identified neutron events the following background is estimated : 1 multi-proton event, 3 one pion events and 1 multi-pion event.

The number of unambiguous neutrino events is compatible with that expected from the neutrino contamination in the beam and it is also estimated that 4 of the ambiguous ($\mu^+ \pi^-$ or $\mu^- \pi^+$) events are also ν-events. This type of background is more important in an antineutrino run than in a neutrino run because the background ν-flux and the cross-sections for ν-interactions are both higher.

ii) Hyperon Production

The $\Delta S = \Delta Q$ rule allows the production of hyperons in the following reactions :

$$\bar{\nu} + p \longrightarrow \mu^+ + \Lambda^0$$

$$\bar{\nu} + n \longrightarrow \mu^+ + \Sigma^-$$

$$\bar{\nu} + p \longrightarrow \mu^+ + \Sigma^0$$

Excited hyperon states can also be produced.

During the scanning no event with a μ^+ and a hyperon was found. The detection efficiency for free hyperons is estimated to be > 90 % in the fiducial volume. Hence as no event was found we conclude that the cross-section for all processes leading to the production of a free hyperon, averaged over our $\bar{\nu}$-spectrum is less than $2{\cdot}5 \times 10^{-40}$ cm^2 per nucleon with 90 % confidence.

However it is possible that hyperons produced in $\bar{\nu}$-interactions would be captured in the parent nucleus to form hyper- or crypto-fragments. The probability for this to occur would depend on the momentum distribution of the hyperons. However, it should be less than the measured value of 30 % in K^- absorption at rest in freon [2]. Therefore with more than 90 % confidence we can say tha the cross-section for all hyperon production must be less than $3{\cdot}6 \times 10^{-40}$ cm^2 per nucleon, averaged over our neutrino spectrum.

Theoretical calculations have been performed by Cabibbo and Chilton [3], who have calculated the cross-section σ_Y (E_ν) for elastic hyperon production. They have used a form factor for the hyperon nucleon current (normalized to unity for $q^2 = 0$) equal to

$$f(q^2) = \frac{1}{1 + \frac{q^2}{M^2}}$$

where $M = M_{K^*} = 0{\cdot}891$ GeV/c^2 is the mass of the K^* vector meson.

They obtain a cross-section which, averaged over our $\bar{\nu}$-spectrum, is 5×10^{-40} cm^2 per nucleon (this would correspond, in our case, to 5 expected events). This seems too high, when compared with our experimental limit. We notice, however, that the magnitude of σ_Y is greatly influenced by the choice of $f(q^2)$. A value of $M \sim 0{\cdot}6$ GeV/c^2 would have been compatible with our experimental upper limit.

2. Elastic and Single Pion Production Cross-Sections and Form Factors

Almost all of our information on elastic and single pion production comes from the ν data. In studying such interactions in complex nuclei a major difficulty is the separation of the two processes.

The ν-event types from which the selection of the two reactions is made comprise :

a) μ^- with 0 or 1 proton $>$ 30 MeV kinetic energy

b) μ^- with 2 or more protons $>$ 30 MeV kinetic energy

c) μ^- with any number of protons and a single pion.

Reaction type b) will certainly contain both elastic and single pion events. To understand more fully these multi-proton events a Monte-Carlo programme was set up to calculate the probability that the protons expected in the elastic reaction would produce other protons with kinetic energies $>$ 30 MeV. This energy

limit is applied to take into account evaporation protons. The calculation predicted that 12 % of the elastic events should be multi-proton, which is to be compared with the experiment in which about equal numbers of single proton and multi-proton events were observed.

Another Monte-Carlo calculation to investigate pion absorption in complex nuclei indicated that if the N^*_{33} were produced, then in only about half the cases would the pion be observed. This is in agreement with experiment, where about equal numbers of single pion and multi-proton events were observed. These two Monte-Carlo calculations gave good agreement with other proton and pion experimental data. Thus it is concluded that the elastic sample is contained almost entirely in the event type a) and the single pion sample in event types b) and c). This conclusion has been verified experimentally for a sample of ν-events which have a small four-momentum transfer, q^2. We define q^2 by :

$$q^2 = (\vec{p}_\nu - \vec{p}_\mu)^2 - (E_\nu - E_\mu)^2$$

which can be reduced to :

$$q^2 = 2E_\nu\,(E_\mu - p_{\mu x}) - m_\mu^2$$

where E_ν is the neutrino energy, E_μ the muon energy, $p_{\mu x}$ the projection of the muon momentum on the neutrino direction and m_μ the muon mass.

In a ν-interaction the mass of the recoiling system M^* is given by the following equation when account is taken of Fermi-momentum p_f :

$$M^{*2} = -q^2 + 2(E_\nu - E_\mu)\,M_n + M_n^2 + 2\,\vec{p}_f\cdot(\vec{p}_\mu - \vec{p}_\nu)$$

where M_n is the nucleon mass.

It can be seen that, as $q^2 \longrightarrow 0$, the effect of the Fermi-momentum on the M^{*2} distributions becomes small.

A comparison of the M^* distributions for the single proton and multi-proton events indicates that the single proton events are distributed about the proton mass whereas the multi-proton events are distributed about a higher mass and much more widely spread, suggesting the absorption of a pion.

In addition, at low q^2, a meaningful and a more sensitive test is to compare the direction of expected recoil, for the elastic and N^*_{33} hypotheses, with that of the vector sum of the proton momenta in an event. It could be expected that the Fermi-momentum and scattering will smear the observed momentum distribution symmetrically about the original line of flight. The single proton events show the expected symmetry about the proton line of flight whereas the multi-proton are decidely asymmetric in a direction which favours pion production as can be seen in Fig. 2.

i) Elastic Event Analysis

The analysis of the elastic events was carried out to investigate the nucleon form factors. The vector form factors have been taken equal to the electro-magnetic isovector form factors as postulated by CVC theory. The induced pseudoscalar term was neglected. Thus the elastic cross-section was completely determined apart from the axial vector form factor.

For neutrino events the analysis was made for a visible energy above 1 GeV since below 1 GeV the q^2 distribution is not very sensitive to the form factors, and above 1 GeV the background due to neutrons and incoming pions is negligible. In the antineutrino case all events with a visible energy greater than 0·5 GeV were included. This lower limit avoided bias introduced by the longitudinal momentum criterion (§ 1.i)

Of the 120 non-pionic ν-events above 1 GeV, 72 events have only 0 or 1 proton with a kinetic energy > 30 MeV. For these events, using the visible energy as the ν-energy, we have calculated the mass of the recoiling system M^*. It is more convenient to work in M^{*2} because the smearing due to Fermi-momentum and experimental error is approximately symmetric.

Only events with $0{\cdot}48 < M^{*2} < 1{\cdot}28\ (\mathrm{GeV})^2$ are accepted as elastic. There are 54 such events and a Monte-Carlo calculation indicated that the selection should exclude only a few per cent of the true elastic sample. The M^{*2} distribution is slightly displaced from the proton mass, as would be expected from energy loss, and is almost symmetric as shown in Fig. 3.

To the 54 'elastic events' a calculated number of 6·5 multi-proton events of elastic origin must be added. These have been included in the energy distribution of the elastic events in proportion to the number of events which occur at any given energy. The probability of producing a multi-proton event is a function of q^2 and q^2 distributions for energies about 1 GeV are almost identical. The total elastic cross-section is shown in Fig. 4 as a function of energy and is compared with the theoretical cross-section, claculated by taking $F_A = F_V = F_{EM}$, where F_{EM} is the electro-magnetic isovector form factor.

In the case of the $\bar{\nu}$-run there are 10 events according to the criterion that events with a single μ^+ and protons below 30 MeV kinetic energy are elastic. The expected number for $F_A = F_V = F_{EM}$ is 9·5 events, which includes an estimated scanning efficiency of 75 % for this type of event.

Much more information on the form factor is contained in the four-momentum distribution. The q^2 distribution for the ν and $\bar{\nu}$ events is shown in Fig. 5 : the curves are calculated for $F_A = F_V = F_{EM}$, using the expected ν and $\bar{\nu}$ fluxes.

A maximum likelihood fit has been performed for the axial vector form factor using the parameterisation

$$F_A = \frac{1}{\left(1 + \frac{q^2}{M_A^2}\right)^2}$$

This type of form factor is preferred to the pole type as it gives asymptotic ν cross-sections. The best value obtained is $M_A = 0{\cdot}77 \pm 0{\cdot}12$ GeV; the error includes that due to an estimated $\pm$ 30 % uncertainty in the fluxes. The systematic error is impossible to estimate, however the maximum effect is obtained if one considers all the multi-proton events to be elastic. In this case the value of M_A rises to 1·5 GeV. The best value of M_A is to be compared with the vector form factor, which has the mass M_V in the mass parameterisation equal to 0·84 GeV. Thus it is concluded from our experiment that the vector and axial vector nucleon form factors are very similar.

ii) Single Pion Production

As the complex nucleus destroys much of the information concerning the production process it is only possible to compare single pion events with some production model. In this case the results are examined in terms of single pion production [4,5] via the N^*_{33} (1238), which is considered to be dominant.

If the N^*_{33} were produced, the mass of the recoiling system M^* would be 1238 MeV, with a half width of 125 MeV. However due to Fermi-momentum, nuclear scattering and energy loss, the M^* distribution is expected to be displaced to lower energies and to be much broader. Thus the following event types are classed as possible N^*_{33} production :

single proton events with $1{\cdot}28 < M^{*2} < 2{\cdot}2$ GeV^2

all multi-proton events with $M^{*2} < 2{\cdot}2$ GeV^2

all single pion events with $M^{*2} < 2{\cdot}2$ GeV^2

The lower value of M^{*2} of 1·28 GeV^2 for single proton events distinguishes against true elastic events and the upper value of M^{*2} of 2·2 GeV^2 for all three event types should include all but a few per cent of true N^*_{33} and exclude most of the 2 π events in which 1 π is absorbed.

A sample of 192 events passes these criteria. Taking the ν-energy to be the visible energy and using the expected ν-spectrum the production cross-section for events which are compatible with N^*_{33} production can be calculated and is shown in Fig. 6. The dashed curve is that calculated by Berman and Veltman [4] assuming that $F_A = F_V = F_{EM}$. The solid curves are those of Salin [5] who takes account of non-resonant production (estimated to be < 8 %), sets $F_V = F_{EM}$, and takes F_A to be of the pole form, $F_A = \dfrac{1}{1 + \dfrac{q^2}{M_A{}^2}}$. The assumption that $F_A = F_V = F_{EM}$ gives reasonable agreement with the data.

In Fig. 7 the cross-section for single pion events found in the $\bar{\nu}$-run is shown. For the $\bar{\nu}$-events no M^* cut can be applied owing to missing neutrons, however, by comparison with the ν analysis we class all μ^+ multi-proton events

as single pion events. The estimated ν background has been subtracted but not that due to neutrons which is estimated to be 4. The curve is that expected for $F_A = F_V = F_{EM}$ as calculated by Berman and Veltman. Agreement is reasonable.

In Fig. 8 the four-momentum distribution for the ν and $\bar{\nu}$ events compatible with N^*_{33} production is shown. The curves are those expected for $M_A = M_V = .900$ GeV using quadratic form factors and the theory of Berman and Veltman. A maximum likelihood estimate gives a value of $M_A = M_V = .85 \pm .05$ GeV. The error is statistical, the systematic error being impossible to estimate. However, if the ν-flux happened to be a factor of two higher than that calculated then a value of 0·6 GeV would be obtained.

Conclusion

From this analysis it is concluded that :

1. The elastic strange particle cross-section with 90 % confidence, is $< 3{\cdot}6 \times 10^{-40}$ cm^2 / nucleon, averaged over our $\bar{\nu}$-spectrum.

2. The axial vector form factor of the nucleon is close to the iso-vector form factor.

3. Assuming the dominance of the N^*_{33} resonance in single pion production for $M^{*2} < 2{\cdot}2$ (GeV/c^2)^2, the isobar form factors are similar to the nucleon form factors.

Form factor studies of elastic and N^* production in complex nuclei are presently limited by systematic errors. In the next phase of the neutrino programme single pion production will be investigated using events on free protons in propane. The ν-flux will be about 5 times greater than that used previously. Sufficient data can be expected to permit the study of the single pion process in much greater detail.

References

(1) M.M. Block et al. - Physics Letters 12 (1964) 281.

(2) Abraham et al. - Université Libre de Bruxelles, Bulletin 22 (1965) (to be published in Nuclear Physics).

(3) N. Cabibbo and F. Chilton - Physical Review 137 (1965) B 1628.

(4) S. Berman and M. Veltman - Nuovo Cimento 38 (1965) 993.

(5) Ph. Salin - private communication.

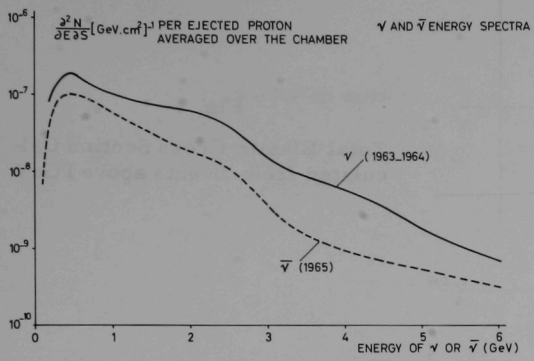


Fig. 1

Neutrino and Anti-neutrino Energy Spectra. The spectra have been calculated from secondary particle production data obtained by extrapolation of measurements at proton momenta of 18.8, 19 and 23.1 GeV/c.

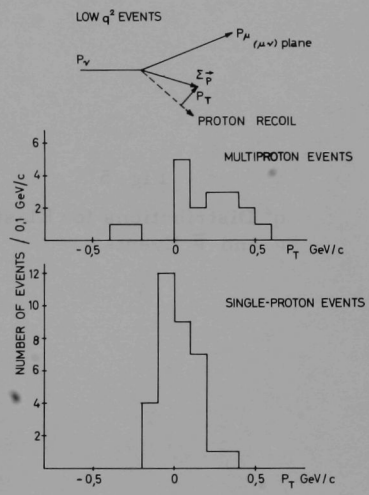


Fig. 2

Distribution of the Recoil Proton Transverse Momenta about the Direction of Expected Elastic Recoil Proton Direction

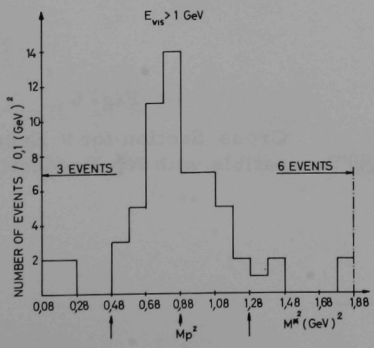


Fig. 3

M^{X2} Distribution for Single Proton ν Events

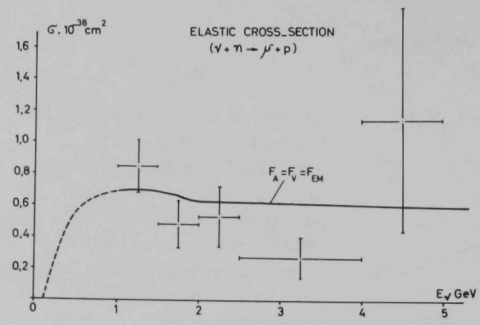


Fig. 4

Total Elastic Cross Section Calculated from Events above 1 GeV

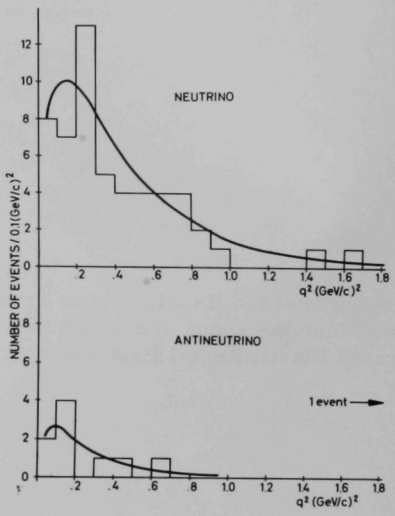


Fig. 5

q^2 Distributions for Elastic ν and $\bar{\nu}$ Events

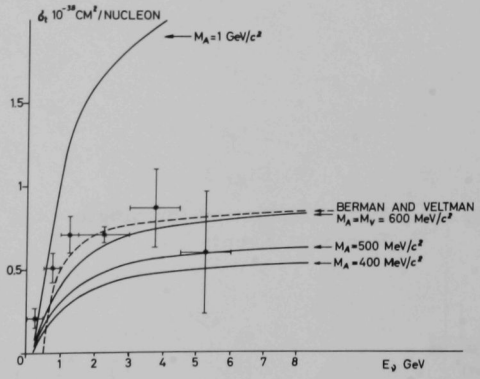


Fig. 6

Cross Section for ν Events Compatible with N^*_{33} Production

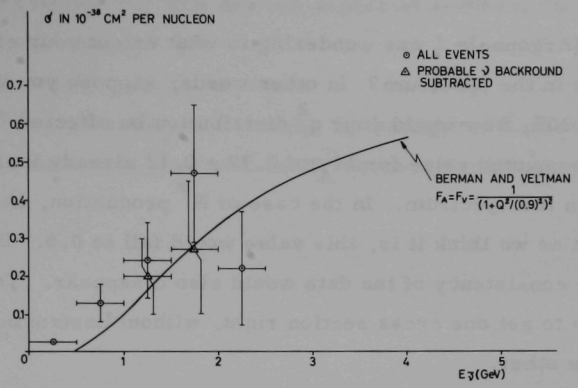


Fig. 7. Cross Section for $\overline{\nu}$ Events Compatible with N_{33}^{*} Production

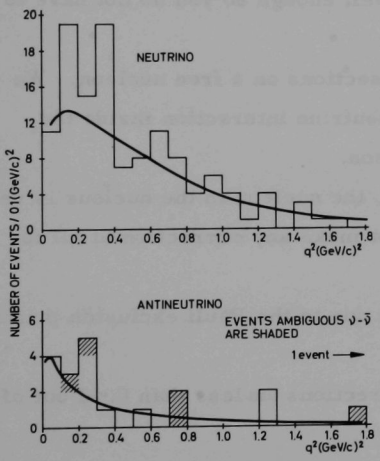


Fig. 8

q^2 Distributions for ν and $\overline{\nu}$ Events Compatible with N_{33}^{*} Production

DISCUSSION

YOVANOVITCH (Argonne): I was wondering to what extent your errors reflect uncertainties in the spectrum? In other words, suppose you varied the spectrum by 20%, how would your q^2 distribution be affected?

CUNDY: The quoted value for M_A of 0.77 ± 0.12 already includes a 30% uncertainty in the spectrum. In the case of N^* production, if the spectrum were twice as high as we think it is, this value would fall to 0.6. But then, you see, the complete consistency of the data would also disappear. You cannot adjust the spectrum to get one cross section right, without destroying the agreement with the other.

FEINBERG (Columbia U.): In your estimate of the axial form factor from the elastic scattering data, does part of the error there come from relating the cross section on a nucleus to the cross section on an individual nucleon, or do you feel you know that relationship well enough so you do not have to worry about that source of error?

CUNDY: We have calculated these cross sections on a free nucleon. We have assumed that the form factor of the neutrino interaction inside the nucleus is the same as that on a free nucleon.

FEINBERG: For low momentum transfer, the nucleon in the nucleus is very far from being free. You mean you did not make any correction at all for being in the nucleus?

CUNDY: Oh, yes, we included corrections due to the Pauli exclusion principle and the Fermi momentum.

FEINBERG: But, you think that those corrections are less than 0.12 out of 0.77. Is that correct?

CUNDY: Yes. We have taken the q^2 distribution from the theoretical work of Loveseth at CERN, who believes that these effects are small.

CHILTON (Argonne): I wonder if I might ask about the interpretation of the hyperon production. You say you expect no events if the mass in the form factor were about 0.6?

CUNDY: We would expect one event.

CHILTON: That is rather interesting, in the light of the results of yesterday, that the mass that goes with the K^o form factor does indeed seem to be rather low.

High Energy Neutrino Experiments at Accelerators

D. H. Perkins
Oxford University
Oxford, England

1. Introduction

Neutrino experiments at high energy accelerators offer the only present possibility of investigating the weak interactions over wide ranges of energy and momentum transfer, with the flexibility that collision processes permit. They suffer from the inherent difficulty that, whereas the mean free path of strongly-interacting particles in common materials and in particular reaction channels is of the order of metres, that of neutrinos is typically many astronomical units ($\sim 10^{12}$ metres). Nevertheless, within the next few years, the planned development of very intense neutrino beams, together with giant bubble chambers, will go at least halfway on a logarithmic scale, to overcome this penalty factor, and realize gross event rates actually approaching the maximum useful rate (i.e., one event per picture).

The spectacular progress in improving the event rate is illustrated in Fig. 1, taken from a recent CERN report.[1] This shows a roughly exponential increase in rate with time, amounting to a factor of 10^6 times between 1960, when accelerator neutrino experiments were first proposed,[2] and 1971, when the developments at BNL, ANL and CERN are likely to be fully realized. Beyond 1971, there are no reasons I know of to expect further large improvements - but one cannot exclude them. At the present moment, we are about halfway along the curve. Figure 1 will be discussed in more detail later, and I refer to it now only to strike the note of optimism necessary when discussing such long-term and difficult projects, about which misgivings have frequently been expressed.

I shall begin by attempting to list some of the problems of weak interaction physics which we might hope neutrino experiments to answer, and what improvements in experimental conditions are needed to answer them, using the situation at CERN/BNL 1963/64 as a basis. I shall indicate only very briefly the state of the existing experimental data, since they are mostly already published, and the most recent unpublished data (from CERN) is discussed in detail at this conference by D. C. Cundy.[3]

Finally, a brief description is given of the programmes of beam improvement, machine development and giant chambers which are needed to obtain the necessary increase in event rate.

2. Physics problems

It is usual to factor out the weak 4-fermion coupling into baryon and lepton brackets, and to consider the baryon and lepton currents

separately. This turns out to be convenient also when discussing the experimental limitations. By and large, the practical study of the properties of the baryonic currents depends on the quality of the detector; for example, the identification of secondaries from the interaction, effects of nuclear absorption and other sources of systematic error. For this class of problem one needs large hydrogen or deuterium chambers of high quality, to observe reactions on free or quasi-free nucleons. On the other hand, the investigation of leptonic currents depends much more on the shape of the neutrino spectrum and the purity of the beam (e.g., $\bar{\nu}$ and neutron background). For this type of problem, one needs the biggest available bubble chambers filled with the heaviest liquids, or large spark-chamber arrays, in order to look at rare processes, and to provide sufficient stopping power to measure muon polarization.

2.1.) Problems related to weak baryonic currents

Study of weak baryon currents with a neutrino beam is analogous to that of the e.m. current with a γ-ray or electron beam. The neutrinos probe both the V and A parts of the weak coupling, for $\Delta S = 0$ and $\Delta S = 1$ transitions. One can, in principle, get at the V and A parts separately, by comparing ν and $\bar{\nu}$ cross-sections, but since this involves subtractions one will have to be very much more confident about flux estimates than one is now. Another way is to measure the polarization of the emerging baryon, in subsequent scattering or decay processes. In practice, these difficulties have been avoided by assuming CVC, and taking the V part from electron scattering or photoproduction experiments.

Since we are limited to nucleon targets, and $\Delta S = 0$ and $\Delta S = 1$ transitions, the possible reactions allowed by the $\Delta Q/\Delta S$ rule are:

$$\Delta S = 0 \begin{cases} \nu + n \to \mu^- + p \ldots (1) & \nu + N \to \mu^- + N^* \ldots (3) \\ \bar{\nu} + p \to \mu^+ + n \ldots (2) & \bar{\nu} + N \to \mu^+ + N^* \ldots (4) \end{cases}$$

elastic inelastic

elastic inelastic

$$\Delta S = 1 \begin{cases} \bar{\nu} + p \to \mu^+ + \Lambda \ldots (5) \\ \bar{\nu} + p \to \mu^+ + \Sigma^0 \ldots (6) \\ \bar{\nu} + n \to \mu^+ + \Sigma^- \ldots (7) \end{cases} \qquad \bar{\nu} + N \to \mu^+ + Y^* \ldots (8)$$

Here, N^* and Y^* represent various nucleon and hyperon isobars (from the inelastic processes). The amplitudes of these reactions are related by selection rules ($\Delta I = \frac{1}{2}$), and, more loosely, by SU3 invariance. To evaluate all the coefficients (as well as form factors) associated with these reactions, and check on the predictions, will constitute a formidable programme of work. At a more refined level, using the Adler[4] theorems, it will be important to check the validity of the CVC and PCAC hypotheses.

The existing bubble chamber data from CERN, from reactions in freon (CF_3Br), has allowed a first study of some of the above reactions. The main conclusions are as follows:

a) N → N transition (1) and (2)

If the form-factors are parametrized in the one-pole form $F_{A,V} = \left(1 + \frac{q^2}{M^2_{A,V}}\right)^{-1}$, $M_V = 0.6$ GeV being taken from the electron-scattering data and CVC, one obtains

$$M_A/M_V = 0.9 \pm 0.25, \tag{9}$$

the error including a ±30% uncertainty in the ν-fluxes. The quantum numbers of the object or objects responsible for the vector structure must be $J^{PG} = 1^{-+}$, and it is usually assumed to be dominated by the $\rho(M = 0.75\,\text{GeV})$. For the axial structure, one needs one or more 1^{+-} objects, for which the A1(M = 1.1 GeV), if it exists, is the only known candidate. Of course, there will be nonresonant contributions as well as pole terms, and it is clear that it will take many years of experimentation to sort out the mess.

b) N → Y transition (5), (6) and (7)

The data obtained in the recent $\bar{\nu}$-run at CERN is very fragmentary.[3] No (μ^+-hyperon) events were observed, and, as expected from what we know of the inverse (decay) processes, the conclusion is that the cross-section is down by more than an order of magnitude on the $\Delta S = 0$ process. A calculation of the cross-section has been made by Cabibbo and Chilton,[5] assuming a pole-type form-factor with $M_{V,A} = M^*_K$ (0.89 GeV). This would predict 5 elastic hyperon events. Since one also expects a comparable number from the Y* (inelastic) process, there appears to be a definite disagreement with experiment.

c) N → N* transition (3), (4)

The CERN bubble chamber data(3) show strong evidence that the single-pion production is dominated by the process

$$\nu + N \rightarrow \mu^- + N^*_{33} \rightarrow \pi + N. \tag{10}$$

The M* distribution, π^+/π^0 ratio, q^2-distribution and cross-sections, for both ν and $\bar{\nu}$, are in quite good agreement with theory, assuming that the transition form-factors are the same as in the elastic process.[6,7]

It must be emphasized, however, that the experimental results to date are from collisions in complex nuclei, and involve large corrections for absorption effects. In view of this, it is vital that future experiments be done with free or quasi-free nucleons (H, D, C_3H_8 or C_3D_8).

Table 1 shows the approximate event rates, for a number of reactions, based on the CERN HLBC data. The rates are given per 1.7 x 10^{16} protons incident on the target - corresponding roughly to one day's full running at CERN during the 1963/64 experiments, with 3 sec repetition rate at 25 GeV proton energy. The table refers to total event rate. A reduction factor of up to 2 should be inserted to allow for the fact that not all events are useful. In the CERN analysis, for example, it was necessary to exclude events of $E_\nu < 1$ GeV, both to eliminate background and to reduce dependence of the q^2-distribution on the shape of the neutrino spectrum. The rates are given per ton of neutrons or protons; for orientation, the useful masses of protons or neutrons contained by existing or proposed chambers are given in Table 2. It is then clear that, with the large chambers, some useful experiments in propane or hydrogen could be done with the ν-beam intensities available today. But study of the rarer channels, for example hyperon production, will necessitate at least the 50-fold improvement in beam foreseen in the accelerator development programmes - see columns 3, 4, 5 of Table 1. Similar remarks apply to experiments requiring large statistics, for example the testing of the CVC and PCAC hypotheses.

2.2.) Problems relating to lepton currents

a) Conservation rules

The upper limit to possible violations of lepton and muon number, from the CERN neutrino experiments[8,9] is ~1%. This level is imposed chiefly by systematic uncertainties in the ν_e and neutron fluxes, rather than statistics, and substantial improvements are therefore unlikely.

b) Intermediate boson

The spark-chamber data from BNL and CERN set lower limits to the W-mass for the leptonic decay mode $W \rightarrow \mu, e + \nu$, and the CERN bubble-chamber data, for the nonleptonic modes $W \rightarrow \pi$'s etc.[10] If the nonleptonic decay mode dominates, $M_W > 1.7$ GeV. If the leptonic branching ratio exceeds 50%, $M_W > 2$ GeV.* The boson yield falls off exponentially with increasing mass, so that, even if the product of ν-beam intensity and detector mass were increased by 1000, it is unlikely that, with existing synchrotrons, the boson could be detected if $M_W > 3$ GeV. For the Russian 70 GeV machine, and an effort comparable to that in the CERN/BNL boson hunt, the corresponding upper limit would be in the region of $M_W \sim 5$ GeV.

*These are "99% confidence" limits.

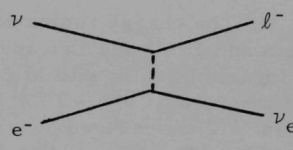
c) Lepton-lepton scattering

For neutrinos, the cross section for scattering by electrons for a point interaction well above threshold is

$$\sigma = \frac{q^2}{\pi}(m^2 + 2m\,E_\nu)\ \mathrm{cm}^2 \tag{11}$$

where m = electron mass, E_ν is the neutrino energy in the L.S. The threshold energy is

$$(E_\nu)_{\text{threshold}} = (m_\ell^2 - m^2)/2m$$
$$= 0 \text{ for } \nu_e$$
$$= 10 \text{ GeV for } \nu_\mu$$



where m_ℓ is the mass of the charged lepton. For $\bar{\nu}$, σ is reduced by a factor 3. Deviations from a point interaction do not occur until $E_\nu \approx M_W^2/2m$ (= 6250 GeV for M_W = 2.5 GeV!).

For existing ν_μ beams, the ν-e event rate will be ~10^4 times less than for the corresponding ν-nucleon scattering (a factor 100 for the very low flux above the 10 GeV threshold energy, and a factor ~100 for the cross section). The events would be very characteristic, consisting of a high energy muon at very small angle to the ν-beam. The event rate for the very weak ν_e component of the beam (giving fast electrons) would be of the same order. Even with enormously improved beams and larger detectors, the few events observed would be a curiosity, which might perhaps serve as a check on the high-energy ν-spectrum. For existing accelerators, the momentum transfers involved would not be appreciably different from that in μ-decay.

d) Neutral currents, and neutrino charge form-factor

No evidence for neutral leptonic currents has been found in decay processes. The process

$$\nu + p \rightarrow \nu + p \tag{12}$$

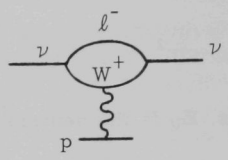
was looked for in the CERN experiments.[8] For $q^2 > 0.5\ \mathrm{GeV}^2$, the cross section was shown to be $< 10^{-40}\ \mathrm{cm}^2$(i.e., <3% of the charge-cross section).

Even in the absence of neutral currents (W^0) the above process must occur through a second-order e.m. interaction. For a massless neutrino, the interaction with the e.m. field is described by a single form-factor, related to the charge radius by

$$F(q^2) = \frac{e}{6} q^2 \langle r^2 \rangle \tag{13}$$

The CERN results then give

$$\langle r^2 \rangle < 5.10^{-31} \text{ cm}^2 \tag{14}$$



The charge radius and cross section have been computed by Bernstein and Lee[11] and Lee and Sirlin[12] for the above diagram; they increase logarithmically with M_W. For M_W = 5 GeV, and zero anomalous magnetic moment, $\langle r^2 \rangle \sim 10^{-33}$ cm^2 for both ν_e and ν_μ. Thus the cross section for (12) is reduced by a factor $\approx \alpha^2 = 10^{-4}$ compared with that for $\nu + n \rightarrow \mu + p$. The energy distribution of the recoil protons will be similar to that of the vector part of the $n \rightarrow p$ transition.

The detection of ν,p scattering is likely to be a formidable, though not quite hopeless, task. For a 10-ton detector and the beam intensity improvements envisaged in the next few years, one can expect about 1 event per day. With very good shielding, it will doubtless be possible to eliminate the low-energy neutrons which at present leak round the shield (and which would give protons recoils at $\sim 10^4$ times the above rate!). Unfortunately, the undetected ν-interactions in any solid material surrounding the detector generate high energy neutrons, which give proton recoils at 1000 times the ν,p rate. The solution is perhaps to place the detector in an isolated position downstream of the shielding, and to subtract background by making a careful analysis of the longitudinal and lateral distribution of the recoil protons. With spark chambers, timing may also be used. A giant bubble chamber, with a giant magnet yoke surrounding it, is probably not the ideal detector.

e) Space-time structure

Tests of the V-A theory and possible CP violation can be made by measurement of the longitudinal and transverse polarizations of stopping μ^+, using $\bar{\nu}_\mu$ beams. To measure the degree of polarization within $\pm 10\%$, at least 1000 useful events are required, and even with the big heavy-liquid chambers, this implies a total bank of 10^4-10^5 events, (since most of the muons do not come to rest). Reference to Table 1 shows that even with the improved beam intensities in the years ahead, long runs will be required and 1% accuracy will be very difficult to obtain. As suggested by Block[13], the transverse polarization of the proton in elastic reactions could be analyzed by its subsequent scattering on carbon in a propane chamber.

3. Improvements in neutrino event rate

3.1. Internal proton beam

As indicated in Table 1, the circulating beam intensities at CERN and BNL are to be increased; firstly by installation of new RF to increase the repetition rate by ~2.7 times; and secondly by use of higher energy injectors, which are expected to result in a further 5-fold improvement. To these factors may be added the gradual, year-by-year increases in machine intensity, probably representing a further factor of 2 by the end of this decade.

A small extra factor may be gained by optimizing the proton beam energy. In CERN and BNL, experiments have generally been carried out at or near the full energy (25 or 28 GeV), in order to have the maximum number of high-energy neutrinos for W-production. For baryonic transitions, however, the cross sections mostly level off below E_ν = 3 GeV, so that the range to be optimized is from 1 to 3 GeV. Then some advantage (up to ~1.5 times) can be gained by running at lower proton energy (say, 18 GeV) and higher repetition rate. In the new CERN neutrino area, provision is made to vary the shield thickness for such contingencies.

3.2. Neutrino beam efficiency

Intensive studies of methods to enhance the ν-flux, by improving the focussing of the pion and kaon secondaries emerging from the target, have been made recently in several laboratories.

Up to the present, the enhancement of the ν-beam has relied on single-stage devices - the magnetic horn[14] at CERN and ANL, and the plasma lens at BNL.[15] Horn systems have proved very reliable in operation, producing improvement factors of order 5÷10 times as compared with an unfocussed beam. The plasma lens has not so far proved so successful. The principal of the horn is that it renders parallel a beam of secondaries of a particular momentum, from a point source, over a wide range of emission angles;* but it over- or under-focusses particles of lower or higher momentum, or those emitted from target points away from the horn apex. This difficulty can be partly overcome (as it is in optical systems) by placing one or more magnetic lenses downstream of the horn - see Fig. 2. However, drift spaces between the different stages are necessary, so that successive corrections work on successively smaller fractions of the original beam (the rest of the particles having already decayed). The present CERN proposal[16] is for a 3-stage system, yielding fluxes 3-4 times greater than for the first stage (horn) alone. Attempts have also been made to improve the efficiency of the horn itself by reshaping it for long targets. Figure 2 shows one design, which uses a Ti target 0.8 m long in place of the 0.3 m Cu target of the Van der Meer horn. The advantages of such an arrangement

*The optimum momentum is $3i/25\pi\alpha^2$ GeV/c, where i is the current in megamps, α the horn angle in radians.

are shown in Fig. 3, which gives, for three different energies, the relative ν-flux produced when the beam protons interact at different points along the target length. Especially at high energy, the old horn design is efficient only for interactions near the front of the target, whereas the new horn has a much flatter response. This makes possible the use of long targets of light material, with higher escape probability for the secondaries, and the resulting gain factor is about 1.5.

A somewhat different multistage focussing device has been proposed by Palmer at BNL[18] - the so-called "magnetic fingers." These differ from the CERN device in the shapes of the conductors. For a target of finite length, the expected performance is somewhat inferior to that of the CERN design - see Fig. 4.

To summarize, the best systems based on the above principles are expected to give fluxes about 5 times those from the old one-stage device, and to approach within less than a factor 2 of the flux from an ideal system. The fine details of such devices depend on the neutrino energy band considered, as well as the lateral dimensions of the detectors. Even with an ideal system based on present principles, only about 20% of the pions and kaons decay before plunging into the shield. It is not impossible that in time this drawback may be partly overcome by use of continuous focussing or the discovery of radically new principles.

3.3. New detectors

Several giant propane and hydrogen bubble chambers are now building or in the design stage. Details are given in Table 2. It is important to realize that, in sealing up the rates in Table 1 using the sensitive masses of the different chambers, the rate does not necessarily go linearly with the volume. This is because the ν beam, especially at high energy, is rather narrowly collimated, with a spread of a few tens of cms. There is no question that, the bigger the chamber, the better the quality factor of each event; but the number of events goes typically as the product of length and transverse direction (rather than frontal area). So the rates in Table 1, based on the small CERN HLBC, need to be reduced by a factor of order 2 when applied to the five big chambers.

There are some rare reactions, for example ν-p scattering and lepton-lepton scattering, which will be difficult to tackle even with the big bubble chambers, and for which very large spark chamber arrays will be the most suitable instruments. Otherwise, the low event rates, and the necessity of extracting the maximum out of every event observed, makes neutrino physics largely a bubble chamber field.

References

1. CERN report MPS/Int. DL 65-11 (1965).
2. Schwartz, M., P.R.L. 4, 306 (1960); Pontecorvo, B., JETP 37, 1751 (1959).
3. Cundy, D. C., Proc. ANL Conf. on Weak Interactions, p. 257 (1965).
4. Adler, S. L., P.R. 135, B963 (1964); also Bartley and Franzinetti, CERN NPA/Int.-65-14 (1965).
5. Cabibbo, N. and Chilton, F., P.R. 137, B1628 (1965).
6. Berman, S. and Veltman, M., Nuov. Cim. 38, 993 (1965).
7. Salin, Ph. - in course of publication; Albright, C. H. and Liu, L. S., P.R.L. 13, 673 (1964); Papastamation, N. J. and Sutherland, D. G., P.L. 14, 246 (1965).
8. Block, M. M., et al., P.L. 12, 281 (1964).
9. Bienlein, J. K., et al., P.L. 13, 80 (1964).
10. Bernardini, G., et al., Nuov. Cim. 38, 605 (1965); Lederman, L., et al., CERN conf. Neutrino Phys. (1965).
11. Bernstein, J. and Lee, T. D., P.R.L. 11, 512 (1963).
12. Lee, T. D. and Sirlin, A., Preprint (1964).
13. Block, M. M., CERN conf. Neutrino Phys. (1965).
14. Van der Meer, S., Proc. Sienna Conf., Vol. 1, p. 536 (1963).
15. Lederman, L., CERN conf. Neutrino Phys. (1965).
16. Asner, A. and Iselin, Ch., CERN 65-17 MPS (1965).
17. Venus, W. and Perkins, D. H. (in course of publication).
18. Palmer, R., CERN conf. Neutrino Phys. (1965).

TABLE 1. Neutrino Reaction Rates, per day and per ton of Neutrons and Protons

(1 day = 1.7×10^{16} protons)

Reaction	Existing Beam (CERN '63-65)	New Focussing (X4) (CERN '66)	Increased Repn. Rate (X2.7) (CERN '68)	New Linac (X5) (CERN '71)
$\nu + n \rightarrow \mu^- + p$	15	60	160	800
$\bar{\nu} + p \rightarrow \mu^+ + n$	2	8	22	110
$\bar{\nu} + p \rightarrow \mu^+ + \Lambda,\ \Sigma^o$	0.05	0.2	0.5	2.5
$\nu + p \rightarrow \mu^- + p + \pi^+(3,3)$	27	108	290	1500
$\nu + n \rightarrow \left\{\begin{matrix}\mu^- + n + \pi^+ \\ \mu^- + p + \pi^o\end{matrix}\right\}$	9	36	97	500
$\nu + N \rightarrow \mu + N + n\pi (n>1)$	10	40	110	500
$\nu + N \rightarrow \mu + Y + K + n\pi$ (associated prodn.)	1	4	11	55

TABLE 2. Bubble Chambers for Neutrino Physics

Chamber	Filling	Date	Dimensions (metres)	Fid. Vol. (m^3)	Mass Free n or p (tons)	Total Mass (tons)
CERN	C_3H_8 or C_3D_8	1965	1.2 x 1	0.64	0.05	0.28
Wisc./ANL	C_3H_8 or C_3D_8	end 1967	3.6 x 1.5	4.5	0.35	1.9
Gargamelle	C_3H_8 or C_3D_8	early 1969	4.5 x 1.9	10.0	0.80	4.4
ANL, BNL, CERN	H_2 or D_2	~1970	~4 x 3	~15	~1.0	-

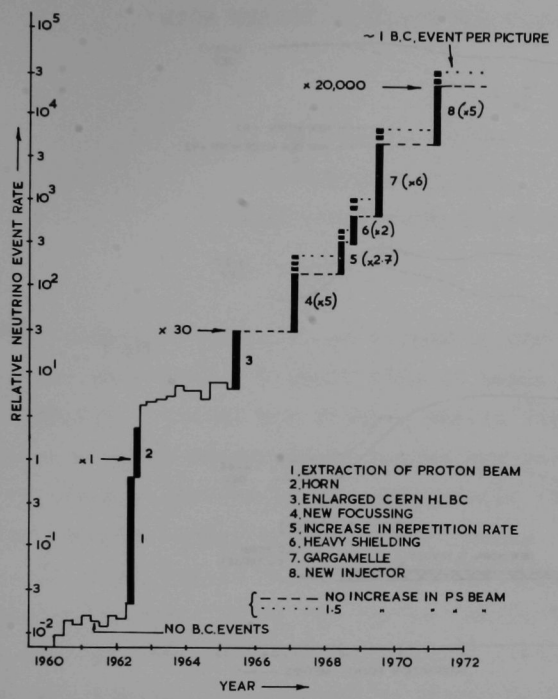


Fig. 1

Timescale of CERN Neutrino Facility

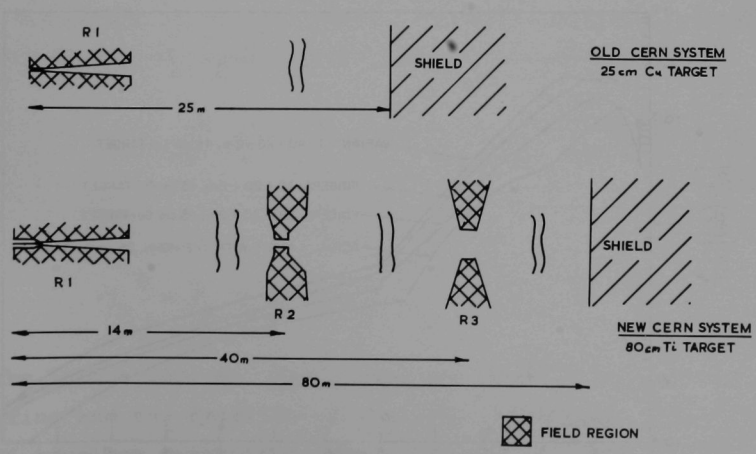


Fig. 2. Diagrammatic Representation of Old and New Focussing Systems

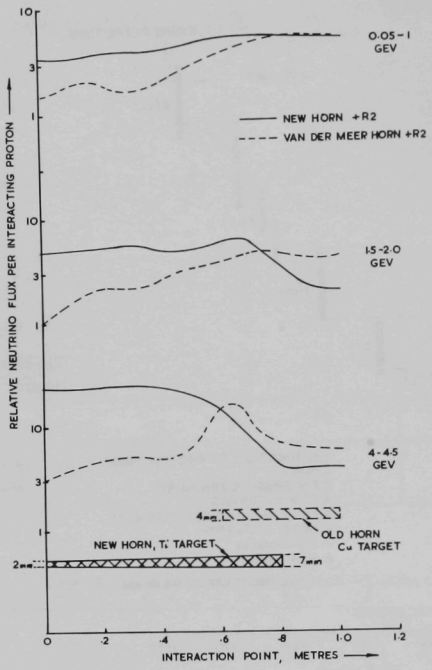


Fig. 3

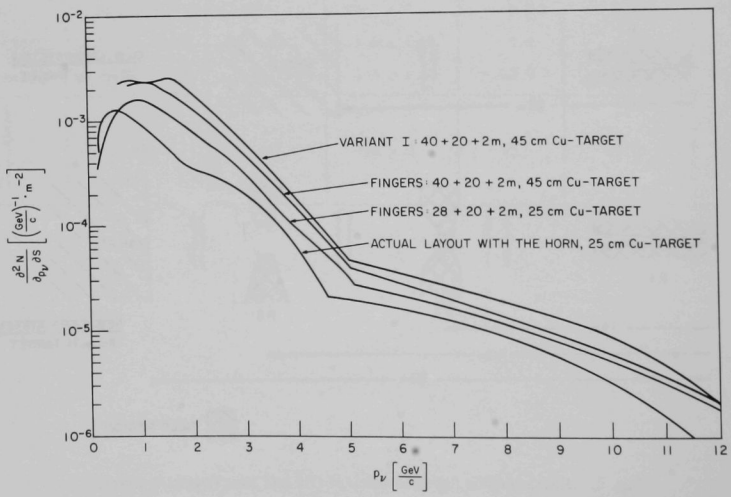


Fig. 4. Neutrino Flux Density of the "Magnetic Fingers" Arrangement Compared to the Magnetic Horn Layout and to the New Focussing System, Variant I. All fluxes averaged over 40 cm radius detector area.

HIGH ENERGY SEMILEPTONIC REACTIONS

Stephen L. Adler*
Harvard University
Cambridge, Massachusetts

The subject of my talk, as listed in the program, is the theory of neutrino reactions. I would like to begin by restricting the scope somewhat. I will not discuss purely leptonic phenomena, or reactions in which intermediate bosons are involved.[1] What I will do is to discuss the theory of semileptonic interactions, as it pertains to high energy neutrino experiments. Much of what I have to say, in fact, really deals with strong interaction physics -- with how information about the strong interaction vector and axial-vector current octets can be obtained in neutrino experiments.

I. Present Theory of Semileptonic Interactions

According to present ideas, the semileptonic interactions are described by a current-current effective Lagrangian[2]

$$\mathcal{L} = \frac{G}{\sqrt{2}} j_\lambda^{\ell} J_\lambda^{h} + \text{adjoint} + \left(? \begin{array}{c}\text{Possible CP}\\ \text{Violation}\end{array} \right) \tag{1}$$

Here

$$j_\lambda^{\ell} = \bar{\psi}_e \gamma_\lambda (1 + \gamma_5) \psi_{\nu_e} + \bar{\psi}_\mu \gamma_\lambda (1 + \gamma_5) \psi_{\nu_\mu} \tag{2}$$

is the lepton current, describing the annihilation of the incoming neutrino and the creation of the outgoing lepton, and G is the Fermi coupling constant (numerically $G \approx 10^{-5}/M_N^2$). The current J_λ^h describes the coupling of the hadrons to the leptons, and is given by

---

Society of Fellows

$$J_\lambda^{\ h} = \cos\theta\,(\mathcal{F}_{1\lambda} + i\,\mathcal{F}_{2\lambda} + \mathcal{F}_{1\lambda}^{\ 5} + i\,\mathcal{F}_{2\lambda}^{\ 5})$$

$$+ \sin\theta\,(\mathcal{F}_{4\lambda} + i\,\mathcal{F}_{5\lambda} + \mathcal{F}_{4\lambda}^{\ 5} + i\,\mathcal{F}_{5\lambda}^{\ 5}). \qquad (3)$$

The current

$$\mathcal{F}_{j\lambda} \qquad \begin{matrix} j = 1, \ldots, 8 \\ \lambda = 1, \ldots, 4 \end{matrix} \qquad (4)$$

is the unitary spin (or vector) current octet, and

$$\mathcal{F}_{j\lambda}^{\ 5} \qquad \begin{matrix} j = 1, \ldots, 8 \\ \lambda = 1, \ldots, 4 \end{matrix} \qquad (5)$$

is an octet of axial-vector currents. The Cabibbo angle θ is given numerically by

$$\theta \approx 0.26\,. \qquad (6)$$

The terms in $J_\lambda^{\ h}$ proportional to $\cos\theta$ and $\sin\theta$ describe respectively the $\Delta S = 0$ and the $|\Delta S| = 1$ weak interactions.

A. "Built-in" postulates

A number of separate postulates have been incorporated into the theory of semileptonic processes outlined in Equations (1) - (6). They are of two basic types: postulates referring to the leptonic and overall structure of the effective Lagrangian, and postulates referring specifically to properties of the hadronic current.

The main postulates of the first type are:

(1) We have assumed a two component neutrino, and a local lepton current coupled to the hadrons by vector and axial-vector couplings.

(2) We have assumed μ - e universality, in building $j_\lambda^{\ \ell}$ out of muonic and electronic parts with equal coefficients;

(3) In most of this talk I will assume that no CP violating term is present in the effective Lagrangian. Note that the CP violation

discovered in K-meson decays does not require that the semileptonic interactions violate CP. I will discuss below tests of CP (or equivalently, T) in high energy semileptonic weak interactions.

The main postulates incorporated in our assumption about the hadronic current are:

(4) Strangeness conserving reactions - We have built in the $\Delta I = 1$ rule, which states that J_λ^h $(\Delta S = 0)$ and J_λ^h $(\Delta S = 0)^\dagger$ are members of an isospin 1 triplet (like π^+ and π^-);

Strangeness changing reactions - The assumption incorporates the $\Delta S = \Delta Q$ rule. Also built in is the $|\Delta I| = 1/2$ rule, which states that J_λ^h $(|\Delta S| = 1)$ and J_λ^h $(|\Delta S| = 1)^\dagger$ are members of different isospin 1/2 multiplets (like K^+ and K^-).

(5) The <u>strong form</u> of the conserved vector current (CVC) hypothesis is also built in. The strangeness-conserving vector current is $J_\lambda^V = \cos\theta\,(\mathcal{F}_{1\lambda} + i\,\mathcal{F}_{2\lambda})$ and the electromagnetic isovector current is $e\,\mathcal{F}_{3\lambda}$, with $\mathcal{F}_{1\lambda} + i\,\mathcal{F}_{2\lambda}$, $\sqrt{2}\,\mathcal{F}_{3\lambda}$ and $\mathcal{F}_{1\lambda} - i\,\mathcal{F}_{2\lambda}$ the members of an isospin one triplet. Thus, matrix elements of the $\Delta S = 0$ vector current and of the isovector electromagnetic current are simply related. <u>A fortiori</u>, the <u>weak form</u> of the CVC hypothesis

$$\partial_\lambda J_\lambda^V = 0 \tag{7}$$

is satisfied.

Except for the assumption of CP conservation in semileptonic processes,[3] the "built-in" hypotheses have been well verified in low energy experiments. There are many ways of constructing a theory of weak interactions which satisfies these postulates; one is not <u>required</u> to use the octet form of the hadronic current stated in Eq. (3). The evidence on hyperon decays favors the assumption of an octet hadronic current, but this hypothesis is not yet on as firm a basis as the postulates of a local lepton current, V-A variants, μ-e universality, $\Delta I = 1$ and CVC.

B. Additional postulates

There are two important additional postulates connected with the hadronic current but not implicit in what we have written so

far. The first is the hypothesis[4] that the divergences of the strangeness-conserving and strangeness-changing axial-vector currents are very nearly equal to the pion and kaon fields, respectively, at least when the divergences are sandwiched between states $\langle\alpha|$ and $|\beta\rangle$ with small invariant momentum transfer $(k_\alpha - k_\beta)^2$ [say, with $(k_\alpha - k_\beta)^2$ of the order of $M_\pi^{\,2}$]. This is frequently called the partially-conserved axial-vector current (or PCAC) hypothesis, and may be stated mathematically as

$$\partial_\lambda \left(\mathcal{F}_{1\lambda}^{\;5} + i\ \mathcal{F}_{2\lambda}^{\;5}\right) \approx C_\pi\, \phi_\pi\ ,$$

$$\partial_\lambda \left(\mathcal{F}_{4\lambda}^{\;5} + i\ \mathcal{F}_{5\lambda}^{\;5}\right) \approx C_K\, \phi_K\ . \tag{8}$$

The constants C_π and C_K can be related to particle masses and coupling constants by taking the matrix elements of these equations between baryon states.

The second additional hypothesis is an algebra of the vector and axial-vector currents first suggested by Gell-Mann.[5] Gell-Mann proposes that even in the presence of the SU_3 symmetry breaking interaction, the following equal-time commutation relations hold exactly:

$$\left[\mathcal{F}_{i4}(x),\ \mathcal{F}_{j4}(y)\right]\Big|_{x_0=y_0} = -f_{ijk}\ \mathcal{F}_{k4}(x)\ \delta(\underset{\sim}{x}-\underset{\sim}{y})\ ,$$

$$\left[\mathcal{F}_{i4}(x),\ \mathcal{F}_{j4}^{\;5}(y)\right]\Big|_{x_0=y_0} = -f_{ijk}\ \mathcal{F}_{k4}^{\;5}(x)\ \delta(\underset{\sim}{x}-\underset{\sim}{y})\ ,$$

$$\left[\mathcal{F}_{i4}^{\;5}(x),\ \mathcal{F}_{j4}^{\;5}(y)\right]\Big|_{x_0=y_0} = -f_{ijk}\ \mathcal{F}_{k4}(x)\ \delta(\underset{\sim}{x}-\underset{\sim}{y})\ . \tag{9}$$

If we define octet vector and axial-vector charges according to

$$F_i(t) = -i\int d^3x\ \mathcal{F}_{i4}\ (\underset{\sim}{x},t)\ ,$$

$$F_i^{\;5}(t) = -i\int d^3x\ \mathcal{F}_{i4}^{\;5}\ (\underset{\sim}{x},t)\ , \tag{10}$$

they satisfy the equal time commutation relations

$$\left[F_i(t),\ F_j(t)\right] = i\ f_{ijk}\ F_k(t)\ ,$$

$$\left[F_i(t),\ F_j^{\ 5}(t)\right] = i\ f_{ijk}\ F_k^{\ 5}(t)\ ,$$

$$\left[F_i^{\ 5}(t),\ F_j^{\ 5}(t)\right] = i\ f_{ijk}\ F_k(t)\ . \qquad (11)$$

The charge commutation relations are a less restrictive postulate than the density commutation relations, since even if the density commutation relations of Eq. (9) contain total spatial derivative terms on the right hand side, the integrated versions are the same. The first two charge commutation relations are nothing more than the statement that the $F_i(t)$ are the unitary spin generators, and that the $F_i^{\ 5}(t)$ form a unitary octet. The commutation relation requiring the axial charge, commuted with itself, to close back into the vector charge is <u>not</u> required by the octet character of the vector and the axial-vector currents.

There are several pieces of evidence now for the validity of PCAC in the strangeness-conserving case. First of all, PCAC predicts (or more properly, was invented to explain) the successful Goldberger-Treiman relation[6] for the charged pion lifetime. Secondly, PCAC implies a consistency condition[7] on pion-nucleon scattering, which states that the low energy isospin-symmetric S-wave scattering amplitude is very small. This is what is found experimentally. Thirdly, using PCAC <u>and</u> the axial charge commutation relation in the strangeness-conserving case, one can derive[8] the following sum rule relating g_A, the axial-vector renormalization in β-decay, to the pion-nucleon coupling constant g_r and the $\pi^{\pm}$ p total cross section $\sigma^{\pm}$:

$$1 - \frac{1}{g_A^{\ 2}} = \frac{4M_N^{\ 2}}{g_{r0}^{\ 2}}\ \frac{1}{\pi}\int_{M_N+M_\pi}^{\infty} \frac{W dW}{W^2-M_N^{\ 2}}\left[\sigma_0^{\ +}(W) - \sigma_0^{\ -}(W)\right]. \qquad (12)$$

W is the center of mass energy, and the subscript 0 indicates quantities evaluated off the mass shell, at zero pion mass. This sum rule predicts $g_A \approx 1.2$, in agreement with experiment.

Similarly, PCAC and the axial-vector algebra in the strangeness-changing case predict correctly the hyperon decay axial-vector coupling constants.[9] Thus there is evidence for the validity of the axial charge algebra. Clearly, it would be desirable to test the algebra, independent of the assumption of PCAC.

I would now like to discuss consequences of the hypotheses for high energy neutrino reactions. As is frequently the case in physics, the relatively easy experiments do not provide an unambiguous test of any of the hypotheses, and the experiments which do provide a clearcut test are hard. I will talk about both types of experiment. First I will discuss the elastic and (3,3) resonance production experiments currently in progress at CERN. Then I will describe tests of the various hypotheses which may be possible in future neutrino experiments.

II. Analysis of CERN Experiments

Let us consider the reaction

$$\nu_\ell + N \rightarrow \ell + \Gamma \tag{13}$$

with N a nucleon and Γ a system of strongly interacting particles. Let k be the four-momentum transfer between the leptons,

$$k = k_\nu - k_\ell \ . \tag{14}$$

A. Elastic reactions

The simplest case is the elastic reaction,

$$\nu_\ell + n \rightarrow \ell^- + p \ . \tag{15}$$

The hadronic current matrix element is

$$\langle p(q_2) \mid \mathcal{F}_{1\lambda} + i\ \mathcal{F}_{2\lambda} + \mathcal{F}_{1\lambda}{}^{5} + i\ \mathcal{F}_{2\lambda}{}^{5} \mid n(q_1)\rangle$$

$$= \left(\frac{M_N{}^2}{q_{10}q_{20}} \right)^{1/2} \bar{u}(q_2) \left[\gamma_\lambda\ F_1{}^V(k^2) - \sigma_{\lambda\eta}\ k_\eta\ F_2{}^V(k^2) \right.$$

$$\left. + \gamma_\lambda\ \gamma_5\ g_A(k^2) - i\ \gamma_5\ k_\lambda\ h_A(k^2) \right] u(q_1)\ . \tag{16}$$

The elastic cross section can be computed in terms of the vector form factors $F_1{}^V(k^2)$ and $F_2{}^V(k^2)$, the axial-vector form factor $g_A(k^2)$ and the induced-pseudoscalar form factor $h_A(k^2)$. The induced-pseudoscalar form factor appears <u>only</u> in terms in the cross section which are proportional to the square of the lepton mass. According to PCAC, $h_A(k^2) \approx 2\ M_N\ g_A(0)\ /\ (k^2 + M_\pi{}^2)$. Even when the lepton is a muon, an h_A of this magnitude contributes no more than a few percent to the differential cross section, and thus is in effect unmeasurable. Eventually one will be able to determine independently the three form factors $F_1{}^V(k^2)$, $F_2{}^V(k^2)$ and $g_A(k^2)$, thereby testing the CVC prediction that $F_1{}^V$ and $F_2{}^V$ are the isovector Dirac and Pauli form factors measured in electron scattering experiments. For the time being, all that is possible is to use the CVC prediction for $F_1{}^V$ and $F_2{}^V$ in order to extract information about the k^2 dependence of g_A from the neutrino data.

PCAC makes an interesting prediction about the momentum transfer dependence of g_A. According to PCAC, the pion field is the divergence of the axial vector current, and thus the process of pion emission and the axial vector current are intimately related. In particular, PCAC implies[10] a connection between $g_A(k^2)$ and $V_6{}^{(-)}$, an isospin-antisymmetric longitudinal amplitude in pion electroproduction:

$$\frac{\dfrac{g_A(k^2)}{g_A(0)} - F_1{}^V(k^2)}{k^2} = \frac{M_N}{g_{r0}}\ V_6{}^{(-)}\ (\nu=0,\ \nu_B=0,\ q_\pi{}^2=0,\ k^2)\ . \tag{17}$$

Here ν is the energy variable, ν_B the momentum transfer variable and $-q_\pi^2$ the $(\text{mass})^2$ of the electroproduced pion. Let us assume that $V_6^{(-)}$ satisfies an unsubtracted fixed-momentum-transfer dispersion relation,

$$V_6^{(-)}(\nu=0,\ \nu_B=0,\ q_\pi^2=0,\ k^2) = \frac{2}{\pi}\int_{\nu_{MIN}}^{\infty} \frac{d\nu'}{\nu'}\ \mathrm{Im}\ V_6^{(-)}\ (\nu',\nu_B=0,q_\pi^2=0,k^2). \tag{18}$$

On the cut from ν_{MIN} to ∞, Im $V_6^{(-)}$ can be directly calculated from measured electroproduction multipoles (apart from the extrapolation in pion mass from M_π to 0). Thus we can measure $g_A(k^2)\ /\ g_A(0)$ by doing electroproduction experiments.[11] This is true in principle, even if the dispersion relation for $V_6^{(-)}$ requires a subtraction, since we can also measure the subtraction constant. Unfortunately, it may not be possible to test Eq. (17) for a long time to come, since this will require accurate knowledge of the hard-to-measure longitudinal electroproduction multipoles.

B. Single pion production

The simplest inelastic reaction, and the only one for which detailed data is available, is pion production around the (3,3) resonance region:

$$\nu_\ell + N \rightarrow \ell + \begin{cases} N_{3,3}^{\ *} \\ \pi N \text{ background}. \end{cases} \tag{19}$$

So far only the total cross section $\sigma\ (E_\nu)$ and the differential cross section $d\sigma\ /\ d(k^2)$ have been measured.

Two theoretical approaches have been used to study this reaction. The first[12] is to use an SU_6-type theory to relate

$$\langle N_{3,3}^{\ *} \mid J_\lambda^{\ h} \mid N\rangle$$

to (20)

$$\langle N \mid J_\lambda^{\ h} \mid N\rangle\ ;$$

this is possible since the N and $N_{3,3}^*$ are both in the same representation of the higher symmetry group. However, since this approach is wrong by about a factor of two in predicting (3,3) photoproduction, it is not clear what sort of accuracy should be expected in the weak production case.

The second approach is to work in analogy with the old Chew, Low, Goldberger and Nambu (CGLN) calculation[13] of photoproduction, which we know works quite well.[14] This analysis goes as follows: Only three of the even-parity, isospin and angular momentum 3/2 multipoles are important in the N to $N_{3,3}^*$ transition. These are the amplitude $M_1^{+(3/2)}$ for the vector current and $\mathcal{E}_1^{+(3/2)}$ and $\mathcal{L}_1^{+(3/2)}$ for the axial vector current. We make the following model for them:

$$M_1^{+(3/2)} = M_1^{+(3/2)\mathrm{BORN}} \left[\mu_p + 1 - \mu_n\right] \cdot \frac{f_{3,3}}{f_{3,3}^{\mathrm{BORN}}} \; ;$$

$$\mathcal{E}_1^{+(3/2)} = \mathcal{E}_1^{+(3/2)\mathrm{BORN}} \cdot \frac{f_{3,3}}{f_{3,3}^{\mathrm{BORN}}} \, ,$$

$$\mathcal{L}_1^{+(3/2)} = \mathcal{L}_1^{+(3/2)\mathrm{BORN}} \cdot \frac{f_{3,3}}{f_{3,3}^{\mathrm{BORN}}} \; . \tag{21}$$

Here $f_{3,3}$ is the I = J = 3/2 pion-nucleon scattering partial wave amplitude and $f_{3,3}^{\mathrm{BORN}}$ is the (3,3) projection of the pion-nucleon Born approximation. The quantity $M_1^{+(3/2)\mathrm{BORN}} \left[\mu_p + 1 - \mu_n\right]$ is the part of the Born approximation for $M_1^{+(3/2)}$ proportional to the difference between the proton and neutron total magnetic moments.

This model automatically satisfies the Fermi-Watson theorem, which requires that the weak production multipoles have the same phase as the (3,3) pion-nucleon scattering amplitude. The model also gives each multipole approximately the correct nearest left hand singularity, since this singularity, a short cut about 1 pion mass below the physical threshold, comes from the multipole projec- [illegible] approximation. The three multipoles in Eq. (21)

are the dominant part of the solution.

In addition, one adds the (3,3) multipoles coming from the one pion exchange Born diagram, according to a prescription worked out by CGLN. Finally, to account for the background one uses the S- and small P-wave multipoles computed from the Born approximation. (The Born approximation diagrams are shown in Fig. 1.) Thus, the whole solution is generated from the Born approximation, which in turn can be calculated from the elastic weak interaction form factors.

This model gives predictions for pion photoproduction and electroproduction (which involve only the vector current part of the solution) as well as for weak pion production. Fig. 2 compares the model with π^0 and π^+ photoproduction data,[15] and Fig. 3 with electroproduction data[16] up to a momentum transfer [at the (3,3) resonance peak] of $k^2 = 93\ f^{-2}$.* The agreement of the theoretical curves with the experimental points is good.

Fig. 4 shows the comparison of the model with the CERN data[17] on weak pion production. The axial-vector form factor has been parametrized according to $g_A(k^2) = 1.18 / (1 + k^2 / M_A^2)$. A mass of $M_A = 1200$ MeV is in best agreement with the experimental data. A model rather similar to the one which I have used[18] has been studied by Salin,[19] who finds best agreement with experiment for $M_A = 600$ MeV. The difference in numerical results is due, I suspect, to differences in the models employed for the dominant multipoles. This model dependence of the analysis limits the usefulness of weak pion production measurements in determining the k^2 dependence of the axial-vector form factor.

---

* In Fig. 3, E_i is the energy of the incident electron, E_f and Ω_f are the energy and solid angle of the scattered electron, and θ_{if} is the electron scattering angle, all in the laboratory frame. k_R^2 is the invariant momentum transfer at the peak of the (3,3) resonance.

III. Direct Tests of the Postulates

We have seen that the present theory of semileptonic interactions makes predictions for the reactions which are studied in the CERN experiment. However, the experiments described above do not test directly and individually the various postulates. Now I would like to discuss experiments which provide direct tests of the postulates:

A. Selection rules. To begin with, it is clear that once there are large numbers of events available, by measuring appropriate branching ratios one can test the $\Delta S = \Delta Q$, $\Delta I = 1$, and $|\Delta I| = 1/2$ rules, and also check the suppression of strangeness-changing events due to the smallness of the Cabibbo angle.[20] These tests are completely analagous to ones already well known in low energy weak interactions.

B. Locality. Let us consider the reaction

$$\nu_\ell + \alpha \rightarrow \ell + \Gamma \tag{22}$$

with α a nucleus and Γ a system of strongly interacting particles. Let E_ν, E_ℓ, Ω_ν, Ω_ℓ be respectively the energies and the angular variables of the neutrino and lepton. If local coupling of the leptons is correct, the differential cross section has the form[21]

$$d\sigma = \sum_j f^j_{\text{KNOWN}} (E_\nu, E_\ell, \Omega_\nu, \Omega_\ell)\, F^j_{\text{UNKNOWN}} \left(k^2, \begin{matrix}\text{internal}\\ \text{variables,}\\ \text{of } \Gamma\end{matrix} \begin{matrix}\text{polariza-}\\ \text{tion}\\ \text{of } \alpha\end{matrix}\right). \tag{23}$$

Only a small number of terms are present in the sum Σ_j. Eq. (23) is the analog for neutrino reactions of the Rosenbluth formula, with the "form factors" $F^j_{\text{UNKNOWN}}(k^2,\ldots)$ the analogs of the electromagnetic form factors. Eq. (23) can be tested by doing experiments at a large number of different values of the neutrino and lepton energy and angle variables.

C. T (or CP). In the absence of polarized targets, there are two basic ways of testing T invariance in high energy weak interactions.

The first[22] is to look at a reaction

$$\nu_\ell + N \rightarrow \ell + B \tag{24}$$

where the baryon B is the only strongly interacting particle present in the final state. A transverse polarization of B would imply that T is violated. The second way[23] is to look at $\nu_\ell + \alpha \rightarrow \ell + \Gamma$, with the nucleus α unpolarized and with all strongly interacting final states Γ summed over, for fixed lepton energy and fixed lepton-neutrino angle. A transverse lepton polarization implies that T is violated. Summing over strongly interacting final states is necessary in order to eliminate the effect of final state interactions on the lepton transverse polarization.

D. CVC and PCAC. There is a characteristic property of high energy neutrino reactions which makes possible tests of the CVC and PCAC hypotheses.[24] Consider the reaction $\nu_\ell + \alpha \rightarrow \ell + \Gamma$ in the configuration in which the lepton emerges parallel to the incident neutrino. When the lepton mass is neglected, it is easy to prove that the squared matrix element for this process depends only on the divergence of the hadronic current:

$$| M_{\nu_\ell + \alpha \rightarrow \ell + \Gamma} |^2 = \frac{2 E_\nu E_\ell}{(E_\nu - E_\ell)^2} | \langle \Gamma | \partial_\lambda J_\lambda^h | \alpha \rangle |^2 . \tag{25}$$

Thus, conservation of the vector current (in $\Delta S = 0$ reactions) implies that there is no vector-axial-vector interference, and hence no parity-violating effects, in the parallel configuration.

Furthermore, if CVC is valid, by looking at parallel configuration events we can unambiguously measure the divergence of the axial-vector current, and hence can test PCAC. According to PCAC, the forward lepton differential cross section is related to the cross section for the <u>strong process</u> $\pi^+ + \alpha \rightarrow \Gamma$:

$$\frac{d^2\sigma(\nu_\ell + \alpha \rightarrow \ell + \Gamma)}{dE_\ell \, d\Omega_\ell} = \left[\begin{array}{c} \text{KNOWN} \\ \text{FACTORS} \end{array} \right] \cdot \sigma(\pi^+ + \alpha \rightarrow \Gamma) . \tag{26}$$

The factors of proportionality depend only on the mass of the system Γ. Thus, PCAC predicts that for forward lepton and for a fixed mass M_Γ, the distribution of final states in $\nu_\ell + \alpha \to \ell + \Gamma$ is identical with that in $\pi^+ + \alpha \to \Gamma$. For example, PCAC implies that

$$\frac{dN(\nu_\ell + N \to \ell + \pi + N)}{dN(\nu_\ell + N \to \text{anything with } S = 0)} = \frac{\sigma(\pi^+ + N \to \pi + N)}{\sigma(\pi^+ + N \to \text{anything})} . \qquad (27)$$

E. Current algebra. In high energy neutrino reactions it is possible to test directly the algebra under commutation of the fourth components of the current octets.[25] According to a variety of the locality theorem mentioned above, the differential cross section, when only the neutrino and lepton are observed, takes the form

$$\frac{d^2\sigma\left[\left(\frac{\nu_\ell}{\nu_\ell}\right) + p \to \left(\frac{\ell}{\ell}\right) + I(S = 0)\right]}{d(k^2)\ d\,k_0} = \frac{G^2 \cos^2\theta}{4\pi\, E_\nu^2}$$

$$\times \left[k^2\alpha^{(\pm)}(k^2,k_0) + (2E_\nu^2 - 2E_\nu k_0 - 1/2\ k^2)\beta^{(\pm)}(k^2,k_0) \mp (2E_\nu - k_0)k^2\gamma^{(\pm)}(k^2,k_0)\right] \qquad (28)$$

for strangeness-conserving reactions. A similar equation holds for strangeness-changing reactions. The fourth component of the four-momentum transfer, denoted by k_0, depends only on k^2 and on the invariant mass M_Γ of the final state hadrons Γ. By making measurements at a variety of neutrino energies E_ν, for fixed k^2 and k_0, one can separately determine the "form factors" $\alpha^{(\pm)}$, $\beta^{(\pm)}$ and $\gamma^{(\pm)}$.

Starting from the local commutation relations for the fourth components of the strangeness-conserving vector and axial-vector currents, one can derive the sum rule

$$2 = \int_{(k^2/2M_N)-}^{\infty} d\,k_0 \left[\beta^{(-)}(k^2,k_0) - \beta^{(+)}(k^2,k_0)\right]$$

$$= g_A(k^2)^2 + F_1^V(k^2)^2 + k^2\, F_2^V(k^2)^2$$

$$+ \int_{M_N+M_\pi}^{\infty} \frac{M_\Gamma}{M_N}\, d\,M_\Gamma \left[\beta^{(-)} - \beta^{(+)}\right]. \tag{29}$$

In the second form of the sum rule, I have changed the integration variable from k_0 to M_Γ and have separated off the elastic contribution. This sum rule holds for <u>each</u> fixed k^2. In order to derive the sum rule, in addition to the local current commutation relations one must assume that a certain amplitude obeys an unsubtracted energy dispersion relation. [The assumption of an unsubtracted dispersion relation also is necessary to derive Eq. (12), the sum rule for the axial-vector coupling constant g_A.] When $k^2 = 0$, the sum rule tests only the commutation relations of the vector and axial-vector charges (the fourth components of the currents integrated over all space). When $k^2 > 0$, the sum rule tests the local commutation relations of the fourth components of the currents. If the commutators are changed by adding terms which vanish when integrated over all space, the sum rule for $\beta^{(+)}$ is modified.

The sum rule has an interesting consequence for the limit of neutrino cross sections as the neutrino energy goes to infinity. The differential cross section with respect to momentum transfer, $d\sigma / d(k^2)$, is related to $d^2\sigma / d(k^2)\, d\,k_0$ by

$$\frac{d\sigma}{d(k^2)} = \int_{(k^2/2M_N)-}^{E_\nu(1-k^2/4E_\nu^2)} d\,k_0 \; \frac{d^2\sigma}{d(k^2)\,d\,k_0}\,. \tag{30}$$

As $E_\nu \to \infty$, the upper limit of the integration over k_0 extends to ∞. Furthermore, as $E_\nu \to \infty$, $d^2\sigma/d(k^2)d\,k_0$ approaches $(G^2 \cos^2 \theta / 2\pi)\,\beta$. Thus, the sum rule on $\beta^{(\pm)}$ implies that

$$\lim_{E_\nu \to \infty} \left\{ \frac{d\sigma\left[\bar{\nu}_\ell + p \to \bar{\ell} + \Gamma(S=0)\right]}{d\,(k^2)} - \frac{d\sigma\left[\nu_\ell + p \to \ell + \Gamma(S=0)\right]}{d(k^2)} \right\}$$

$$= \frac{G^2 \cos^2 \theta}{\pi} . \tag{31}$$

Adding the similar result for the strangeness-changing case to get the total cross section gives the result

$$\lim_{E_\nu \to \infty} \left[\frac{d\sigma_T(\bar{\nu} + p)}{d(k^2)} - \frac{d\sigma_T(\nu + p)}{d(k^2)} \right] = \frac{G^2}{\pi} (\cos^2 \theta + 2 \sin^2 \theta) ,$$

$$\lim_{E_\nu \to \infty} \left[\frac{d\sigma_T(\bar{\nu} + n)}{d(k^2)} - \frac{d\sigma_T(\nu + n)}{d(k^2)} \right] = \frac{G^2}{\pi} (-\cos^2 \theta + \sin^2 \theta) . \tag{32}$$

In other words, local fourth component commutation relations imply the somewhat surprising statement that, in the limit of large neutrino energy, $d\sigma_T(\bar{\nu} + N) / d(k^2) - d\sigma_T(\nu + N) / d(k^2)$ becomes independent of k^2.

To conclude, we see that there are a number of experiments which directly test the hypotheses on which our present understanding of semileptonic weak interactions is based. Most of these experiments will be hard, and some may not be possible until an accelerator in the 300 BeV energy range is built. Such a machine would, of course, make possible the study of purely leptonic weak interactions, as well as the semileptonic. Clearly there is a great deal to be learned in future high energy weak interaction experiments!

REFERENCES

1. T. D. Lee, in the Proceedings of the 1965 CERN Neutrino Conference, reviews these aspects of high energy weak interactions.
2. M. Gell-Mann, Phys. Rev. 125, 1067 (1962); N. Cabibbo, Phys. Rev. Letters 10, 531 (1963).
3. N. Cabibbo, Phys. Letters 12, 137 (1964).
4. Y. Nambu, Phys. Rev. Letters 4, 380 (1960); M. Gell-Mann and M. Lévy, Nuovo Cimento 16, 705 (1960).
5. M. Gell-Mann, Physics 1, 63 (1964).
6. M. L. Goldberger and S. B. Treiman, Phys. Rev. 110, 1178 (1958).
7. S. L. Adler, Phys. Rev. 137, B1022 (1965) and Phys. Rev. 139, B1638 (1965).
8. W. I. Weisberger, Phys. Rev. Letters 14, 1047 (1965); S. L. Adler, Phys. Rev. Letters 14, 1051 (1965).
9. D. Amati, C. Bouchiat and J. Nuyts, to be published; L. K. Pandit and J. Schechter, to be published; C. A. Levinson and I. J. Muzinich, to be published; W. I. Weisberger, to be published.
10. Y. Nambu and E. Shrauner, Phys. Rev. 128, 862 (1962).
11. Y. Nambu, in F. Gürsey, ed., Group Theoretical Concepts and Methods in Elementary Particle Physics (Gordon and Breach, New York, 1964), p. 350.
12. C. H. Albright and L. S. Liu, Phys. Rev. Letters 14, 324 (1965) and to be published.
13. G. F. Chew, M. L. Goldberger, F. E. Low and Y. Nambu, Phys. Rev. 106, 1337 (1957).
14. G. Höhler and W. Schmidt, Ann. Phys. (N.Y.) 28, 34 (1964).
15. R. G. Vasil'kov et.al., Soviet Physics - JETP 10, 7 (1960); W. S. McDonald et.al., Phys. Rev. 107, 577 (1957); A.V. Tollestrup et. al., Phys. Rev. 99, 220 (1955); R. L. Walker et.al., Phys. Rev. 97, 1279 (1955).
16. A. A. Cone et.al., Phys. Rev. Letters 14, 326 (1965).
17. CERN NPA/Int. 65-11, 20 April 1965, unpublished.
18. S. L. Adler, to be published.

19. Ph. Salin, to be published.

20. M. M. Block, Phys. Rev. Letters 12, 262 (1964); V. M. Shekhter, Soviet Physics - JETP 14, 1388 (1962); A. Sirlin, Nuovo Cimento 37, 137 (1965); N. Cabibbo and F. Chilton, Phys. Rev. 137, B1628 (1965).

21. T. D. Lee and C. N. Yang, Phys. Rev. 126, 2239 (1962); A. Pais, Phys. Rev. Letters 9, 117 (1962).

22. S. L. Adler, Nuovo Cimento 30, 1020 (1963); A. Fuji and Y. Yamaguchi, Progr. Theoret. Phys. (Kyoto) 33, 552 (1965); I. J. Ketley, Nuovo Cimento 38, 302 (1965).

23. S. M. Berman and M. Veltman, Phys. Letters 12, 275 (1964).

24. S. L. Adler, Phys. Rev. 135, B963 (1964).

25. S. L. Adler, to be published.

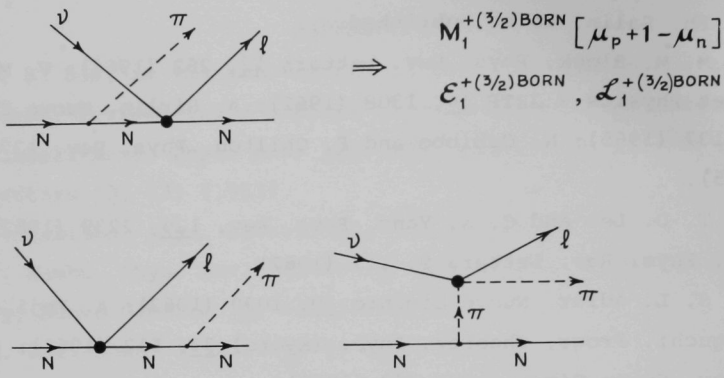


Fig. 1. Born Approximation

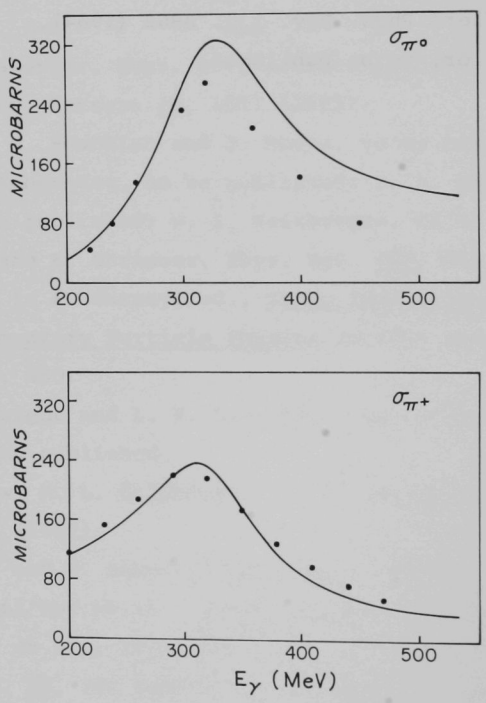


Fig. 2. Photoproduction

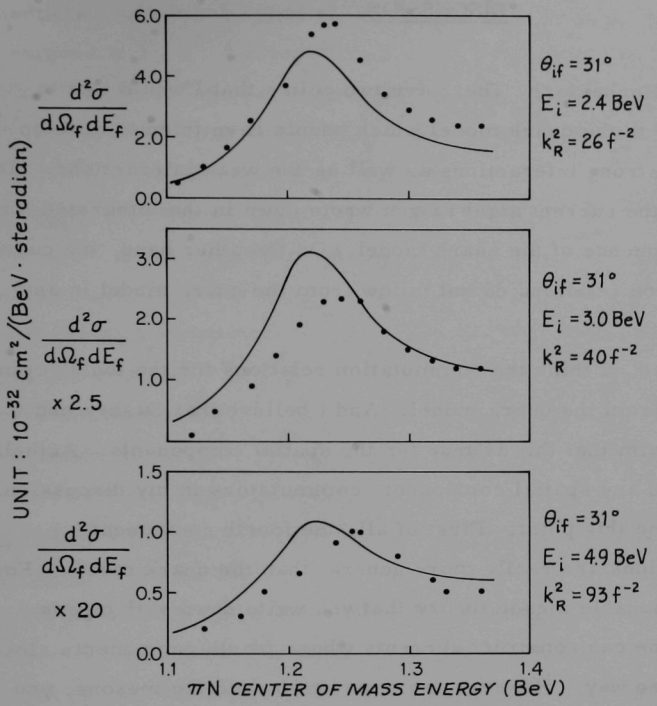


Fig. 3

Electroproduction

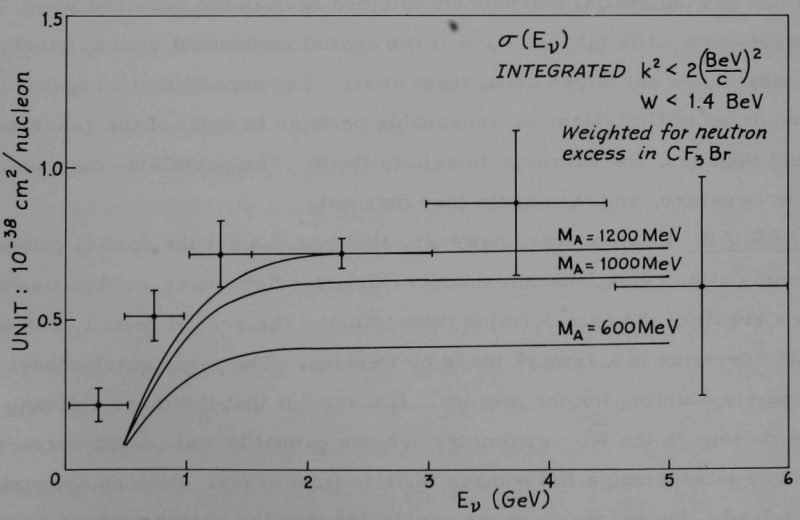


Fig. 4. Weak Pion Production

DISCUSSION

MARSHAK (U. of Rochester): There are two points that I would like to make. Both refer to the quark model which people have tried to develop to understand the strong interactions as well as the weak interactions. The first point is that the current algebra you wrote down in the integrated form is a natural consequence of the quark model. On the other hand, the current density commutation relations do not follow from the quark model in any obvious way.

ADLER: I disagree. I think the commutation relations for the fourth components do follow from the quark model. And I believe that Dashen and Gell-Mann also claim that this is true for the spatial components. Actually, I have not assumed any spatial component commutators in my discussion. Let me elaborate on this point. First of all, the fourth component commutation relations are really more general than the quark model. For in almost any reasonable meson theory that you write down with meson terms included, one can construct currents whose fourth components close back in the required way. However, as soon as you add the mesons, you cannot get the spatial components to close back in the required way. This makes me a little bit less sure of the spatial component commutators, and is why I have not talked about them at all. Let me add that I regard the postulates of Gell-Mann as reasonable because in most of the renormalizable field theories, the currents do satisfy them. The postulates may even be true in nature, and then again they may not.

MARSHAK: It is not true, however, that you can get the spatial component commutation rules from the quark model, for Schwinger ambiguities arise as a result of the four-fermion interaction. The second point I wish to make pertains to a remark made by Perkins. The same quark model leads to parity doubling for the mesons. It turns out that the mass splitting for the mesons in the $\overline{W}_3$ symmetry scheme cannot be calculated correctly by simply introducing a finite mass term to first order. Such an approximation leads, for example, to the conclusion that the vector mesons are in an octet which is not consistent with experiment. It then follows that the A_1

particle - which has opposite G parity to that of the ρ meson - cannot be assigned to $J = 1^+$ but rather to $J = 2^-$, contrary to Perkins' statement. This illustrates my major point that the quark model with the $\overline{W}_3$ group makes some definite predictions - which experiment can test - about the strong interactions as well as the weak.

FUBINI (Institute for Advanced Study): I would just like to emphasize that there are questions regarding the number of subtractions in the derivation of the sum rules. You were able to derive a sum rule for β by starting with the time component commutators and adopting an unsubtracted dispersion relation. Concerning the commutation rules for the space components, it is extremely likely that one needs to adopt subtracted dispersion relations. So that there you probably cannot play the same game as for the time components.

ADLER: I presume that you refer to the formulas I derived for α and γ.

FUBINI: Yes, exactly.

ADLER: I haven't shown on the slides the commutation relations for the space components in the Gell-Mann--Dashen algebra. You can derive sum rules for the other form factors α and γ, and there I agree that it is much more likely that subractions are required. One of the reasons I'm suspicious of this is that, if you use the sort of limiting derivation that I have used in deriving the axial-vector coupling constant, you can obtain the sum rule for β. Callen at Princeton derived it that way, and it is very simple. But you cannot obtain the sum rules for α and γ in the same fashion, which makes one think that the integral for β is convergent, while the other two relations really need subtractions.

FEINBERG (Columbia): You derived a relation which holds at infinite energy, which you said was a good test of the current commutators. I wonder if you could comment on what "infinite" energy means, that is, to how high an energy one has to go. The reason that this question is somewhat more relevant here than for the strong interactions is that we know that first order weak interactions are inadequate above some very high energy. So, the question arises whether "infinite" energy in your case means smaller or larger than that at which the higher order weak

interactions are important.

ADLER: First of all, even if you go to 300 BeV center of mass energy, I think the higher order weak interactions will not necessarily cause trouble because of the fact that all of the semi-leptonic interactions are saturated, or cut off, by the strong interaction form factors. On the other hand, for the purely leptonic reactions, one finds trouble because no cutoff occurs and the cross section rises as E^2. For the semi-leptonic reactions, there is a cutoff of some characteristic mass which is typically 1 or 2 BeV. For example, the reaction $\nu_\ell + n \rightarrow \ell^- + p$ does not violate unitarity because it gets cut off by the form factors. Since the higher order effects should be cut offin the same way there will be no trouble.

FEINBERG: I think that is not completely clear because you have to sum over a large number of higher order processes and even though each one of them individually may not become large, the sum includes many channels. But independently of that, do you have any feeling for what high energy means in the sense of your infinite energy theorem?

ADLER: It would be reasonable to start looking at this for a neutrino energy of 20 or 30 BeV; I make this claim on the very limited insight gained in the calculations for (3, 3) resonance production. If one looks at the neutrino and the antineutrino cross sections, one finds that they differ because of the γ term which has opposite signs in the two cases; however, they start becoming equal for (3, 3) production at an energy of about 5 BeV. Since the two cross sections start becoming equal at 5 BeV, the 30 BeV energy region may be a reasonable place to look, for perhaps the masses involved there are high enough to saturate the sum rule.

BERNSTEIN (NYU): I have two related comments. First, if it's really true that the axial-vector and vector form factors are the same, then this is a very remarkable fact for which there must be some relatively simple explanation. Second, you pointed out that two different values have been derived by you and Salin for M_A, which you say arise from the two different models taken for (3, 3) production. Does the model which gives the 600 MeV value, as opposed to your value of 1200 MeV, agree as well with the electroproduction data as yours does?

ADLER: Salin has not compared his model with electroproduction data. Actually, I think that the cross sections derived from his model would be too small. Salin has put in a more rapid fall-off in k^2 in his vector part, while using a slower fall-off in the axial part than I have, so that the axial part contributes the bulk of his cross section. Hence it is hard to compare the two results off hand. Concerning your first remark, although the results of Salin and those of Berman and Veltman indicated that $M_A = M_V$, I found a somewhat larger value for M_A. I think that one should be cautious about using the (3, 3) to determine the axial vector radius for these model questions are complicated. Since the interpretation in the elastic reactions is unambiguous, the value of M_A determined from them should be more reliable.

CHILTON (ANL): Concerning your proposed test of PCAC, I seem to recall that Bell has pointed out that if one performs the experiments in nuclei, the nuclear effects can confuse the interpretation considerably. Do you have any comment to make on that point?

ADLER: Yes. I didn't want to go into this point in detail, because those tests follow from zero mass pion cross sections. Now true pions do not have zero mass, so Bell considered the following: When a neutrino penetrates a large nucleus, we naively expect the total cross section to be the sum of the cross sections for the individual nucleons and hence proportional to A. But when a pion hits a large nucleus, absorption occurs and the cross section behaves as $A^{2/3}$. This clearly indicates a large difference in extrapolating off the mass shell.

Bell studied this in an optical model for nuclear matter and found that there are two terms in scattering of the pion which is off the mass shell. There is a surface term which goes as $A^{2/3}$ and also a volume term which is proportional to A. The volume term is multiplied by $k^2 - M_\pi^2$, so that on on the mass shell the volume term vanishes and you get only the absorption effect. For an off-the-mass-shell pion, Bell estimated the coefficient of the A term and found that it actually was rather small because of the properties of the nuclear matter. One would therefore expect that for heavy nuclei, when

the lepton emerges in the forward direction, the neutrino cross section would go as something between $A^{2/3}$ and A. So what he actually found was that simply by looking at total absorption experiments in light nuclei and heavy nuclei, for forward leptons, you get a test of PCAC.

Let me say that the physical idea is the following: When the lepton emerges forward, according to PCAC, the only interaction between the lepton pair and the nucleus is via an exchanged pion. Now the pion has a long range field, and the picture of Bell is essentially that when a neutrino penetrates a nucleus, it is surrounded by virtual leptons coming out forward in a cloud of virtual pions. This pion cloud is screened in essentially the same way as the Coulomb field. Hence if PCAC is valid, as a result of this screening, the cross sections for forward leptons should not grow as fast as the atomic number. On the other hand, for non-forward leptons the interaction is mediated by much heavier mass particles like the ρ-meson, whose fields do not extend out as far; therefore, their fields are not screened as much and thus you do not expect much of a reduction in the cross section in going from a light to a heavy nucleus.

FRANZINETTI (CERN): I would just like to make a remark concerning the comparison of the calculations of Salin's and of Adler's on (3, 3) resonance production by neutrinos. I understood from a private conversation with Dr. Adler that he also obtains consistency with the q^2 distribution, so that taking his model rather than Salin's does not lead to any inconsistency with the experimental data. This fact is important because should the theory require too large a variation of the experimental data, inconsistencies would most probably arise since the experimental analysis was carried out so as to make the elastic and the inelastic results internally consistent. For example, if you were to assume that the selection of events is not correct, in the sense that too high a number of events has been included among the inelastic ones when some of them are in fact elastic, then you would upset the whole elastic analysis and would probably get different results for the elastic cross section. The same thing would happen if you would assume that the quoted neutrino spectrum has been incorrectly calculated to more than 30 or 40%. In other words, while accepting Adler's model rather than

Salin's does not lead to any trouble at the present moment, any model which is put forward in connection with the analysis of the inelastic events must satisfy a number of requirements to be consistent with the experimental results.

SESSION V

STRANGENESS--CONSERVING BETA DECAY

Wednesday, October 27, 1965

CHAIRMAN: R. H. Hildebrand
The University of Chicago

Scientific Secretaries

R. A. Lundy, Argonne National Laboratory
R. Winston, The University of Chicago

The Momentum Dependence of the Helicity of Beta Particles *

J.S. GREENBERG and D.M. LAZARUS

Yale University

New Haven, Connecticut
(Paper presented by J. S. Greenberg)

A large body of empirical information on the weak decays of non-strange particles is compatible with the VA theory of weak interactions with "conserved vector current." In the particular case of the beta decay of nuclei, this theoretical description has received substantial confirmation from measurements of spectral shapes, β-ν correlations, the β-asymmetry from polarized nuclei, β - γ circular polarization correlations, the helicity of the neutrino, and the helicity of β-particles.[1] All but the first two depend on the presence of parity nonconservation in the beta decay interaction for the manifestation of a measurable effect. However, it is a characteristic of nearly all these experiments that the scalar and pseudoscalar quantities measured are not very sensitive to possible small admixtures of S and T couplings to the predominant V and A contributions. Also the functional dependence of the measured pseudoscalar quantities on the important ratio, $C'_{A,V}/C_{A,V}$ severely limits the accuracy with which this ratio can be determined. Because of this lack of sensitivity in the currently utilized methods for measuring these quantities, high precision experiments are required to set even modest limits on the possible contribution from the small couplings, and on the deviation of

* Supported in part by the National Science Foundation.

the ratio $C'_{V,A}/C_{V,A}$ from unity. Such higher precision probes of the theory are clearly desirable, as are more precise tests of other aspects of the theory, such as the violation of time reversal invariance, and the contribution from pseudoscalar coupling.

Precision measurements of the helicity of beta particles emitted from unpolarized nuclei provide one means of extending the existing experimental information on some of the above mentioned aspects of the beta decay interaction. Here we report on the results of a Mott scattering analysis of the momentum dependence of the helicity in the allowed Gamow-Teller transition in Co^{60}. A velocity range of 0.7c to 0.4c was covered in these measurements. This work was partly motivated by an intended precision measurement of the momentum dependence of the polarization of beta particles from the interesting first forbidden transition in RaE, where there exists the possibility of extracting information on time reversal invariance,[2-4] and observing the effects of the conserved vector current.[5] At present, however, it is not clear that these effects can be separated uniquely from the nuclear physics that is involved in the analysis.

For allowed transitions, the V-A theory with two component neutrinos ($C'_{V,A} = C_{V,A}$) predicts that the helicity of the beta particles is $\pm(v/c)$. (The effects of finite nuclear size and contributions from second forbidden transitions have been neglected.) This energy dependence has been confirmed for v/c greater than 0.6 by a number of experimental techniques and for

a variety of beta emitters[1] with typical accuracies of a few per cent at energies greater than 500 keV, and not better than 6% at the lower energies. With the accuracy quoted at the lower energies, the ratio of C'_A/C_A is determined with an error of 30-45% depending on the mean value for the polarization. For Fermi transitions the uncertainty is even larger due to the poorer precision with which the polarization has been measured. In the interesting region below $v/c \sim 0.6$, where the velocity varies rapidly with energy, the measurements have been subject to large uncertainties and the experimental behavior of the helicity with energy has remained ambiguous. Precise measurements become increasingly difficult as the energy decreases because of the multiplying difficulties in evaluating systematic errors at the lower beta energies. A number of deviations from the above predictions have been reported,[6-8] with the measured polarization generally found to be less than (v/c). These deviations have been attributed in part to a variety of depolarization processes usually evaluated with large uncertainties. Due particularly to some of these difficulties, the momentum dependence of the helicity has not been investigated in sufficient detail for a single transition at the lower momenta to permit a meaningful comparison with theory.

The choice of the Mott scattering method for polarization analysis at energies below 200 keV as well as a detailed account of data evaluation and treatment of systematic uncertainties associated with this method have been discussed in a previous paper from this laboratory.[9] The present measurements were performed with the apparatus shown in Fig. 1, which is an improved version

of the apparatus used in the previous investigation. The electrostatic analyzer was used for energy selection and to transform the polarization from longitudinal to transverse suitable for Mott scattering analysis. To increase the data accumulation rate and therefore reduce the effect of drifts, the transmission of the cylindrical analyzer was enhanced by a factor of approximately ten by preceding the electrostatic analyzer with a magnetic quadrupole doublet which introduced focussing in a plane perpendicular to the focussing plane of the electrostatic analyzer. The electrons were scattered from evaporated gold foils and detected at a mean angle of 70° to the beam direction by two surface barrier silicon detectors whose resolution was better than 9.5 keV. The counters were arranged 180° apart in azimuth and interchanged periodically by rotating the whole scattering chamber. In addition to possessing a low sensitivity to gamma radiation, the good resolution of these detectors provides excellent discrimination against background for energies below 50 keV, an energy region which was not previously readily accessible with scintillation counters. They also facilitated the investigation of inelastic scattering effects and secondary scattering from the walls and collimators of the apparatus. In addition to these two detectors, a third detector was used to monitor the stability of the beam. The Co^{60} sources were prepared by electroplating the active material onto a 0.9 mg/cm^2 Ni backing. An arrangement was provided to vary both the source and backing thickness independently in order

to investigate the depolarization effects due to the finite thickness of each as a function of energy.

The various systematic uncertainties in the experimental method deriving from spurious instrumental asymmetries not associated with spin dependent scattering, source and source backing depolarization, multiple and plural scattering in the gold scatterer, and depolarization effects due to scattering in the apparatus were all investigated experimentally. The data were also corrected for background effects, which were negligible except at the lowest energy studied, and for finite geometry effects which modified the asymmetry function $S(\theta)$[11] at 70° by less than 10%.

As expected, the largest errors occur for the lowest energies. At the present state of the investigations, it is estimated that the principal contributor to the systematic error at these lowest energies, is the spurious geometric asymmetry. Because of the behavior of the spin dependent scattering asymmetry with energy, this error increases in relative importance to the statistical error, as the energy decreases, since it remains relatively constant in magnitude with energy, while the spin dependent asymmetry is decreasing with energy. The geometric asymmetry was measured by making use of unpolarized electrons from internal conversion sources covering the energy range of interest. The results of such a measurement on the 163 keV K conversion line in In^{114m} are illustrated in Fig. 2, which shows the asymmetry obtained when

all the scattered electrons are detected as well as the asymmetry for the electrons contained in the full width at half maximum of the elastically scattered peak. The small difference at $\phi = 90^{\circ}$ in the two asymmetries is due to electrons that have undergone secondary collisions in the apparatus. An upper limit to the uncertainty in the geometric asymmetry at the lowest energy measured can be obtained by assuming that the full polarization is measured at $v/c = 0.7$ and that the deviations within the error at the latter energy is due entirely to a geometric misalignment. However, some supplementary measurements on the effect of misalignment on the geometric asymmetry showed that this was a gross overestimate, so that half this error is presently being used as a conservative estimate applied at all energies. The energy dependence of the geometric asymmetry was also studied and found to decrease slightly with energy.

The effects of multiple and plural scattering in the gold scattering foil on the measured asymmetry was investigated by varying the foil thickness from $\sim 30\ \mu g/cm^2$ to $\sim 300\ \mu g/cm^2$. The results are illustrated in Fig. 3 for the four momenta measured. A linear extrapolation of the inverse of the asymmetry to zero foil thickness was used to determine the single scattering asymmetry. The validity of employing such a linear extrapolation was investigated in a separate experiment, the results of which will be published elsewhere. These results together with theoretical calculations by Shin R. Lin and R. L. Gluckstern[10] indicate that this procedure should be valid over the range of scatterer thicknesses used. In the analysis, both linear and quadratic fits were employed. The quadratic form did not appreciably change

the extrapolated value for the inverse of the asymmetry.

The variation of the measured asymmetry with source backing thickness is shown in Fig. 4. Again a linear fit to the data was made to extrapolate to zero backing thickness. A quadratic function produced no significant improvement to the fit. In addition, two sources of thickness 170 $\mu g/cm^2$ and 345 $\mu g/cm^2$ were studied for source depolarization effects at each energy. No effects were detected within the errors quoted below.

The polarizations calculated from the extrapolated asymmetries are plotted against velocity in Fig. 5. All systematic corrections to the data have been applied, as discussed above, and the errors included in error limits shown. The results obtained using the unscreened asymmetry function calculated by Sherman,[11] and the screened asymmetry function calculated by Lin,[12] both suitably averaged over the finite size of the beam and detectors, are included in the figure. The errors in the screened calculation are presently not known and are not included in the error bars shown. There is a rather large discrepancy between Lin's calculations and calculations by Holzwarth and Meister.[13] The solid line indicates the expected v/c dependence of the polarization.

The data are compatible with this velocity dependence although the polarizations calculated using the screened asymmetry function lie consistently high. This may be accounted for by the present uncertainty in the geometric asymmetry, as well as by an error in the screened values for $S(\theta)$. The average

value of the four determinations of $-(P/\ v/c)$ from the screened value of $S(\theta)$[12] is 1.023 ± 0.024, which yields for $C'_A/C_A = 1.00 \pm 0.05$.

REFERENCES

1. "Beta and Gamma Ray Spectroscopy," Vol. 2, Editor, Kai Siegbahn, North-Holland Publishing Co., Amsterdam 1965, Chapters XXIII-XXIV.
2. A. Bincer, E. Church and J. Weneser, Phys. Rev. Letters 1, 95 (1958).
3. V. Geshkenbein, S.A. Nemirovskaya and A.P. Rudik, Soviet Phys. JETP 36, 360 (1959).
4. T. Kotani and M. Ross, Prog. Theor. Phys. (Japan) 20, 463 (1958).
5. J. Fujita, Phys. Rev. 126, 202 (1962); J.P. Deutsch and P. Lipnick, Nuclear Physics 61, 97 (1965).
6. H. Bienlein, K. Güthner, H. von Issendorff and H. Wegener, Nuc. Inst. and Meth. 4, 79 (1959); Z. Physik 154, 376 (1959).
7. A. van Klinken, Nuc. Phys. 53, 613 (1964).
8. V. Eckardt, A. Ladage and U.V. Moellendorff, Phys. Letters 13, 53 (1964).
9. J.S. Greenberg, D.P. Malone, R.L. Gluckstern and V.W. Hughes, Phys. Rev. 120, 1393 (1960).
10. Shin R. Lin and R.L. Gluckstern, private communication.
11. N. Sherman, Phys. Rev. 103, 1601 (1956).
12. S.R. Lin, Phys. Rev. 133, A965 (1964).
13. G. Holzwarth and H.J. Meister, Nuc. Phys. 59, 56 (1964); Tables of Asymmetry, Cross Section , and Related Functions for Mott Scattering of Electrons by Screened Gold and Mercury Nuclei, Institut Für Theoretische Physik Der Universität München, Germany.

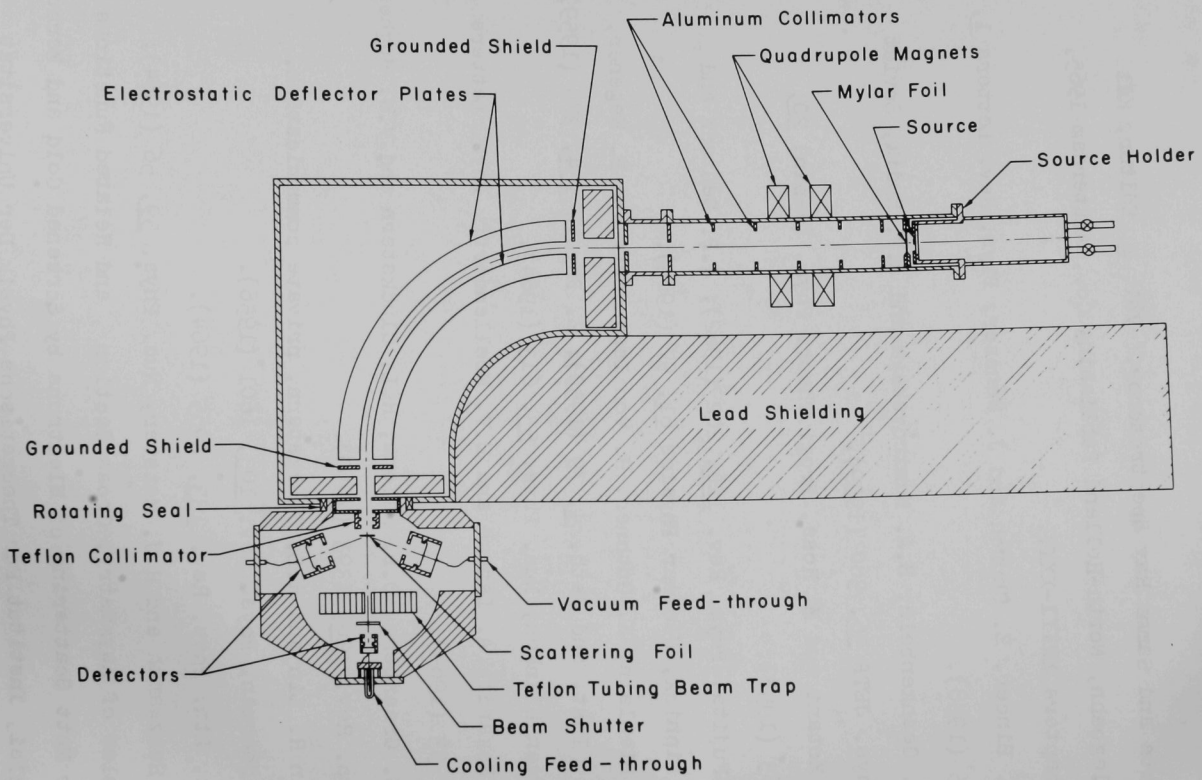


Fig. 1. Mott Scattering Apparatus: The Detectors Are Shown in the Position where the Asymmetry is a Minimum.

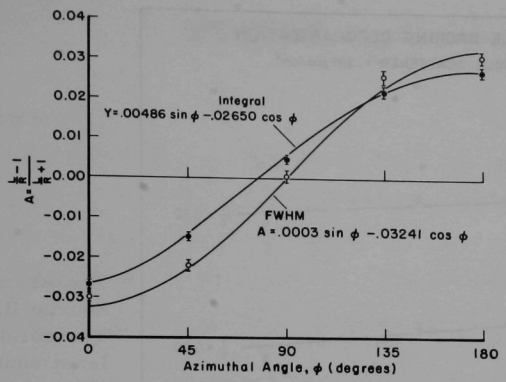


Fig. 2. Azimuthal Dependence of the Geometric Asymmetry that Was Obtained for the 163 keV Conversion Electrons from In^{114m}. The solid lines are best least squares fits to the data. The "Integral" curve refers to all scattered electrons detected, while "FWHM" refers to the electrons contained in the full width at half maximum of the elastically scattered peak. $\frac{L}{R} = \left[\frac{N_1(\theta,\phi)}{N_2(\theta,\phi)} \cdot \frac{N_2(\theta,\phi+\pi)}{N_1(\theta,\phi+\pi)}\right]^{1/2}$, where N_1 and N_2 refer to the counting rates in counter No. 1 and No. 2. θ is the polar scattering angle, and ϕ is the azimuthal position of counter No. 1.

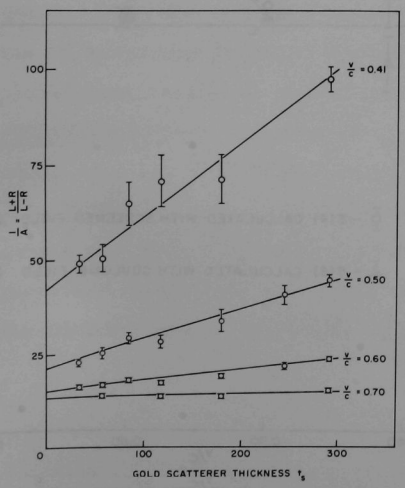


Fig. 3

The Inverse of the Scattering Asymmetry versus the Scatterer Foil Thickness. The solid lines are linear least squares fits to the data.

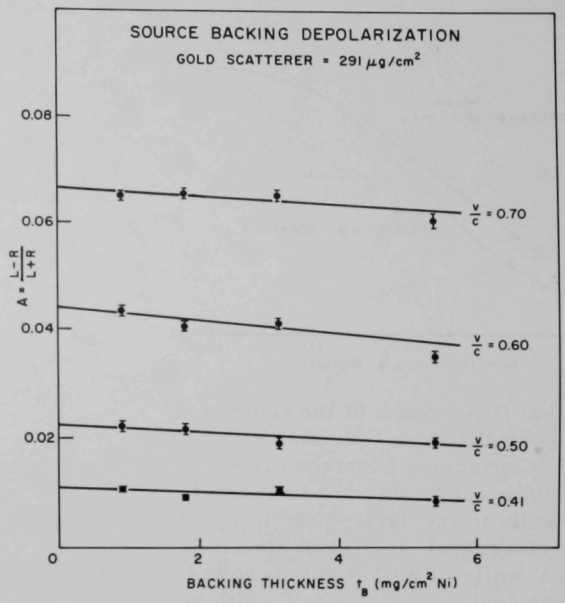


Fig. 4

The Asymmetry versus the Source Backing Thickness. The solid line is a linear least squares fit to the data.

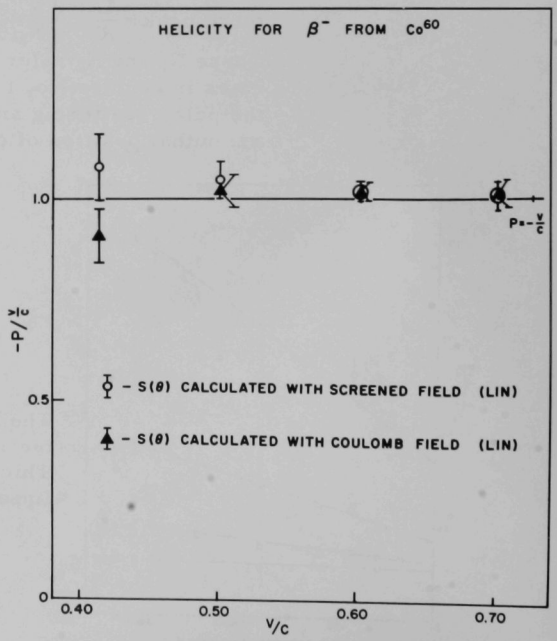


Fig. 5

The Measured Polarization $(P/v/c)$ As a Function of v/c for $S(\theta)$ Calculated with an Unscreened Coulomb Field[10] and $S(\theta)$ Calculated with a Screened Coulomb Field.[11] The solid line is for $P = -(v/c)$.

DISCUSSION

URETSKY (Argonne):

I wonder if the mystery is not that the ft value for aluminum is a little lower, but that the ft values of the heaver nucleii seem to remain so remarkably constant. I think the chances at this stage of the game are, in view of the fairly large errors for the heavier nucleii, that if these were remeasured with high precision one might see the fluctuations that were suggested by your graph.

FREEMAN: Yes, I tried to make that point. I think that the fluctuations we do see may very well be indicative of a general tendency but it still leads to some embarrassment unless we can find a simple explanation for these fluctuations.

A. SIRLIN (New York Univ.): I just have a comment about the question of universality in the Cabibbo theory. I reviewed the subject at the beginning of the summer and I computed the angle θ not from the baryonic decays but from the $K^+_{\ell 3}$ decays. The theoretical justification for this is that there is a beautiful renormalization theorem due to Ademollo, Gatto, Fubini and Furlan which says that the renormalization effects are expected to be of second order in symmetry breaking. So that it is natural to look at the angle θ in the K-decay. I did that and got $\theta = 0.23$. If we use this value of θ and if we consider the 1% error that Berman, Kinoshita and myself assigned to the radiative corrections, one finds no disagreement within this 1% error, with universality.

BERNSTEIN (New York Univ.): I just want to make an elementary comment which supports what Uretsky said, namely that the current is not conserved; it is conserved only if you neglect the mass differences between neutron and proton and all such electromagnetic or isotopic spin violating effects, and therefore, in general you really would not expect it to make itself $\sqrt{2}$ for all the nucleii and it is something of a miracle that it is close to $\sqrt{2}$ as you find it.

An Apparent Small Anomaly in the ft Value of a Superallowed Fermi Transition

JOAN M. FREEMAN, J. G. JENKIN, G. MURRAY
Atomic Energy Research Establishment, Harwell, England.

and

W. E. BURCHAM
University of Birmingham, England.
(Paper presented by J. M. Freeman)

The ft value for a pure Fermi beta transition between two members of a $J = 0^+$, $T = 1$ isobaric triplet is related to G_V, the polar vector coupling constant for the β decay, through the relation

$$G_V^2 \, |M|^2 \, (ft) = 2 \pi^3 \hbar^7 \ln 2 / m_o^5 c^4,$$

where $|M|$ is the Fermi nuclear matrix element for the transition. In the absence of charge-dependent effects, or mesonic exchange effects, $|M|$ has the constant value $\sqrt{2}$. ft value measurements are thus of considerable interest in testing the conserved vector current (CVC) hypothesis. The latter, firstly, makes a prediction about the ratio G_V/G_μ, where G_μ is the coupling constant for muon decay. In its original form the theory predicts this ratio to be unity; in the modification proposed by Cabibbo[1], taking account of strangeness non-conserving decays as well as strangeness conserving decays, the ratio G_V/G_μ is expected to be equal to a factor $\cos\theta$, where $\theta \approx 0.26$. Secondly, the CVC hypothesis implies that there should be no mesonic exchange effects contributing to the Fermi matrix elements for the β decays[2]. Provided charge-dependent effects are negligible (isobaric spin mixing leading to modification of the matrix elements), this implies equality of the ft values for all pure Fermi transitions.

Accutate ft values have now been obtained for seven cases of this type, having been calculated from precision measurements of the end-point energies and half-lives for the beta decays. The results are shown in Table 1. Radiative corrections have

Table 1

ft values for transitions between $J = 0^+$ $T = 1$ isobars

Decay	ft value (sec)	reference
O^{14} $(\beta^+)N^{14}$	3127 ± 10	3)
$Al^{26m}(\beta^+)Mg^{26}$	3086 ± 12	5)
Cl^{34} $(\beta^+)S^{34}$	3138 ± 19	6)
Sc^{42} $(\beta^+)Ca^{42}$	3122 ± 9	7)
V^{46} $(\beta^+)Ti^{46}$	3131 ± 8 3138 ± 25	7) 4)
Mn^{50} $(\beta^+)Cr^{50}$	3125 ± 9	7)
Co^{54} $(\beta^+)Fe^{54}$	3132 ± 17	6)

been included in these calculations. The O^{14} measurement was made by Bardin et al[3], and one of the V^{46} measurements by Jänecke[4]. The other results were obtained at Harwell; in the Al^{26m} case the beta end-point was deduced from a Q-value measurement of the appropriate (p,n) reaction, using a He^3 neutron detector, while in the remaining five cases a (p,n) threshold measurement was made by an activation technique.

At first sight the ft values given in Table 1 show a remarkable consistency, and encourage the inference that they are in fact all equal. This would then support the CVC theory and the assumption of negligible charge-dependent effects. The average of these ft values leads to a value for G_V of $(1.4034 \pm 0.0016) \times 10^{-49}$ erg cm^3 and a ratio G_V/G_μ of 0.978 ± 0.001. (The quoted error is statistical, and should have added to it the uncertainty of ± 0.5% in the radiative correction[8]). This result is consistent with the Cabibbo value when the latter is corrected as suggested by Sakurai[9], so that the CVC theory is then further supported.

However, a closer inspection of the results listed in Table 1 reveals that the ft value for Al^{26m} is appreciably and possibly significantly lower than the others. In view of the interest in such a difference we have made new measurements on the β end-point energy and half-life of the $Al^{26m}(\beta^+)Mg^{26}$ decay, adopting different techniques from those previously used for this case.

The β end-point was this time deduced from a measurement of the threshold for the reaction $Mg^{26}(p,n)Al^{26m}$, using the same method as in the Harwell measurements for the other nuclei. Protons from the Harwell tandem generator bombarded a Mg^{26} target for a time equal to the half-life of the Al^{26m} decay. The beam was then interrupted and the positron activity induced in the target was counted for a similar period. The positron yield was thus studied as a function of proton bombarding energy to give a threshold curve as shown in fig. 1. Because of resonance effects the range of the curve used for determining the threshold point, by the usual method of extrapolation of the 2/3 power of the yield minus background, was limited to 5 keV above threshold. We calculated that the maximum systematic error introduced in this way was ± 1 keV. The proton energy at threshold was measured by scattering the beam through a well-defined angle into a broad-range magnetic spectrograph which had previously been calibrated using the very accurately known α-particle groups from a ThC' source. The mean of eight independent threshold measurements, including estimates of all the errors involved in the measurements, was 5207.4 ± 2.0 keV. The corresponding reaction Q-value is -5012.5 ± 1.8 keV, which is in excellent agreement with the previous measurement (-5012.6 ± 2.2 keV) using a He^3 neutron detector. The β end point energy is deduced to be 3207.8 ± 1.9 keV.

A new measurement was also made of the half-life of Al^{26m}, since there are rather large discrepancies between some of the previous results from different laboratories. Two different reactions were used to produce the Al^{26m} activity ($Mg^{26}(p,n)Al^{26m}$ and $Na^{23}(\alpha,n)Al^{26m}$) so that a significant error introduced in either case by the production of a contaminant activity would be revealed. The decays were followed for about 32 half-lives, using a crystal-controlled multiscaler system. Two separate detection and amplification systems were used, and a wide range of beam intensities and counter bias settings, to check for and avoid rate-dependent effects. The final mean value obtained for the Al^{26m} half-life was 6.376 ± 0.006 sec, which is consistent with the previous Harwell measurement (6.374 ± 0.016 sec). An upper limit of 0.01% has been established for the branch decay of Al^{26m} to a higher level in Mg^{26} so that no correction to our measured half-life is required.

For the ft value calculation use was made of the National Bureau of Standards Fermi function tables, corrections for finite nuclear size and electronic screening being taken from Durand et al[10] and Rose[11] respectively. An electromagnetic radiative correction of 1.6% was calculated from the formula of Kinoshita and Sirlin[8]. The final ft value for Al^{26m} is 3086 ± 8, in exact agreement with the earlier value. The result is indicated in fig. 2 and confirms that the Al^{26m} ft value is significantly lower (by about 1½%) than the mean for the other six cases; in other words the ft

values for the Fermi transitions are apparently not all equal.

Looking for an explanation for this situation we consider the following:

Calculations of the integrated Fermi function f, including allowances for finite nuclear size and for the screening effect of atomic electrons, are now available from several sources and an error as large as 1% is unlikely here. The Al^{26m} nucleus is in an excited state and liable to be appreciably distorted. However one finds that the f value is very insensitive to variations in the nuclear radius parameter, and so is unlikely to be much affected by this.

In the absolute values of the radiative corrections (1.7 to 1.3%) there is the possibility of an error of up to 1% because the formula requires the application of an arbitrary cut-off. However relative errors of this magnitude, varying from one nucleus to another due to nuclear structure effects, would seem unlikely. Further investigations of radiative corrections are desirable.

Charge-dependent effects, as noted above, could cause variations in the nuclear matrix elements and hence in the ft values. However a number of calculations, notably those of Blin-Stoyle, Nair and Papageorgiou[2], both on a shell model basis and with a Fermi gas model, indicate that the magnitudes of these effects are too small to account for the present result. It is to be noted that we require a correction to the square of the Al^{26m} matrix element <u>smaller</u> by 1½% than in the other cases.

If mesonic exchange effects are responsible for the observed ft value fluctuations then the CVC theory is invalidated. However calculations by Blin-Stoyle et al[2] imply that in this event the exchange effects would introduce considerably larger differences between the ft values than we observe.

The explanation of our results thus remains an open question at the moment.

References

1) N. Cabibbo, Phys. Rev. Letters 10, 531 (1963).
2) R.J. Blin-Stoyle, S.C. Nair and S. Papageorgiou, Proc. Phys. Soc. 85 477 (1965)
3) R.K. Bardin, C.A. Barnes, W.A. Fowler and P.A. Seeger, Phys. Rev. 127, 583 (1962)
4) J. Jänecke, Physics Letters 6, 69 (1963)
5) J.M. Freeman, J.H. Montague, D. West and R.E. White, Physics Letters 3 136 (1962)
6) J.M. Freeman, J.H. Montague, G. Murray, R.E. White and W.E. Burcham, Physics Letters 8, 115 (1964)
7) J.M. Freeman, G. Murray and W.E. Burcham, Physics Letters 17, 317 (1965)
8) T. Kinoshita and A. Sirlin, Phys. Rev. 113 1652 (1959);
S.M. Berman and A. Sirlin, Ann. Phys. 20, 20 (1962).

9) J.J. Sakurai, Phys. Rev. Letters 12 79 (1964).

10) L. Durand, L.F. Landovitz and R.B. Marr, Phys. Rev. 130 1188 (1963)

11) M.E. Rose, Phys. Rev. 49 727 (1936).

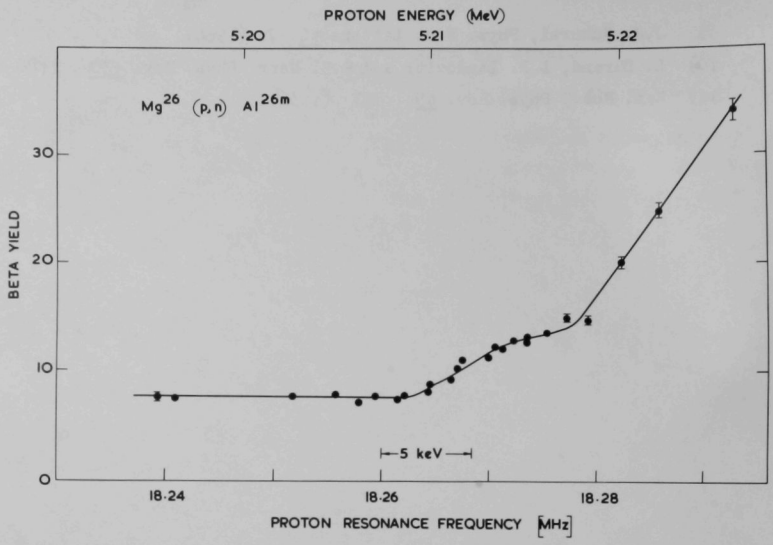


Fig. 1. Thick Target Yield of Positron Activity from Al^{26m} Produced in the Reaction $Mg^{26}(p, n)\ Al^{26m}$ Close to Threshold

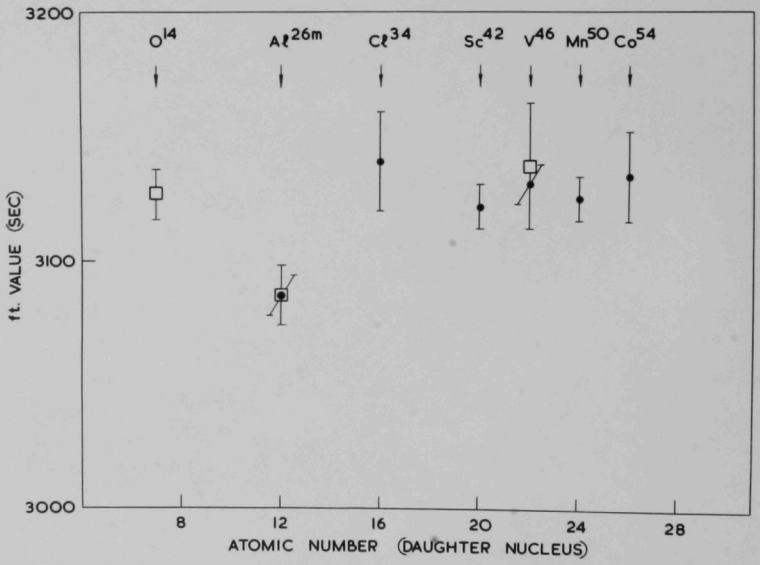


Fig. 2. ft Values for Pure Fermi Beta Decays; ● Results Obtained by the Present Method, □ Results Obtained by Other Methods or in Other Laboratories

INDICATION OF PARITY MIXING IN AN ELECTROMAGNETIC TRANSITION

G. Scharff-Goldhaber and M. McKeown
Brookhaven National Laboratory
Upton, L. I., New York
(Paper presented by G. Scharff-Goldhaber)

For a long time it was known that the metastable state of Hf^{180} decays mainly through an extremely K-forbidden E1 transition of 57 KeV, as shown in Fig. 1. We decided therefore that it was worth searching for a parity-forbidden M1 component of the 57 KeV transition. To be quite certain of such an admixture one would have to carry out some kind of polarization measurement as was done by Boehm and Kankeleit[1] and Bock and Schopper[2] for the 482 KeV γ-transition in Ta^{181}, and by Abov, Krupchitsky and Oratovsky[3] and Forte and Saavedra[4] for the γ-rays following neutron capture in Cd^{113}.

As a first guide to the determination of an M1 admixture to the 57 KeV transition, we measured the L-conversion coefficients in the three different subshells by means of the double focusing spectrometer of the BNL Chemistry Department, using an evaporated Hf_2O_3 source of ∿ 50 μg/cm^2 thickness. Table 1 shows the results: The absolute conversion coefficients given in the second column were obtained by comparing the L electron lines of the 57 KeV transition with the conversion electron lines of E2 transitions between levels of the rotational band in Hf^{180}, and using Rose's theoretical E2 conversion coefficients. Columns 3 and 4 list Rose's conversion coefficients for a 57 KeV E1 and M1 transition, respectively. It is seen that the measured conversion coefficient for the L_I line is much higher than the E1 conversion coefficient. We therefore computed the M1 admixture needed to account for the measured L_I conversion coefficient and arrived at 9.5%. It is seen that for this admixture an excellent agreement with the measured L_{II} and L_{III} conversion coefficients is obtained, whereas no fitting of the experimental values is possible by assuming and M2 or E3 admixture.

Of course, E1 penetration effects cannot be entirely excluded as an alternative explanation of the anomaly. However, if the interpretation of a parity mixed γ-transition is correct, the hindrance factor for the M1 part of the transition is ∿ 10^{15}, which does not seem unreasonable.

Assuming time reversal invariance, a 9.5% M1 admixture in the 57 KeV transition implies a 58% circular polarization of the γ-ray, and approximately 10% average polarization of the L_I, L_{II}, and L_{III} conversion electrons.[5] We are now preparing a measurement of polarization in this transition.

References

1. F. Boehm and E. Kankeleit, Phys. Rev. Lett. 14, 312 (1965).
2. P. Bock and H. Schopper, Phys. Lett. 16, 284 (1965).
3. Y. G. Abov, P. A. Krupchitsky and Y. A. Oratovsky, Physics Letters 12, 25 (1964). Compt. Rend. du Congres Int. de Phys. Nucl., Paris 1964 5/c 344.
4. M. Forte and O. Saavedra, Ispra preprint.
5. R. Carhart, private communication.

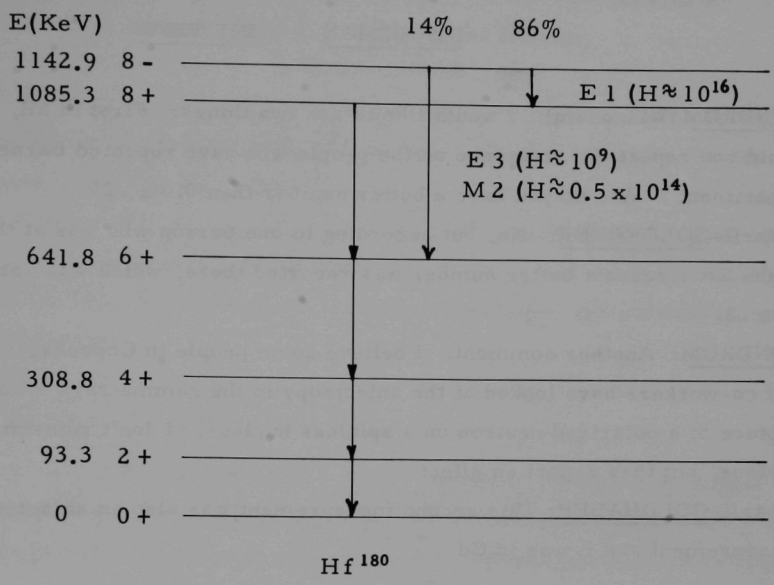


Fig. 1. Decay Scheme of Hf^{180m}(5.5h)

Table 1

L - Conversion Coefficients of

57 KeV Transition in Hf^{180m}

		Theory (Rose)				
	Measured	E 1	M 1	90.5% E 1 +9.5% M 1	M 2	E 3
L_I	0.308 ± 0.022	0.108	2.20	0.308	64	12
L_{II}	0.067 ± 0.009	0.047	0.235	0.065	5.8	640
L_{III}	0.056 ± 0.008	0.062	0.025	0.058	22	640

DISCUSSION

PONDROM (Wisconsin): I would like to ask two things. First of all, could you repeat the reference on the people who have repeated Barnes experiment ? And do you have a better number than 0.3 ± .2?

Scharff-GOLDHABER: No, but according to one person who was at the Karlsruhe Conference a better number was reported there, which was very close to .3 ± .2.

PONDROM: Another comment. I believe some people in Copenhagen, Abrahams and co-workers have looked at the anisotropy in the gamma rays following the capture of a polarized neutron on a spinless nucleus. I don't remember the nucleus, but they report an effect.

Scharff-GOLDHABER: This second measurement was also an anisotropy measurement and it was in Cd.

WEAK INTERACTIONS OF NON-STRANGE PARTICLES

V. L. Telegdi, University of Chicago
Chicago, Illinois

There is no need for a comprehensive survey of this field, as the latest review (Mukhin's report at the 1964 Dubna Conference) is quite recent, and generally available (from CERN).

Therefore, I shall attempt to cover only certain special topics. Further, for the reasons of time, I shall discuss even these topics more briefly here than in the manuscript prepared for the Proceedings, and not necessarily in the same order.

1) CVC

a) The value of G_V^β

According to CVC, all $0^+ \rightarrow 0^+$ transitions within a I-multiplet (superallowed Fermi transitions) should have the same ft-values after certain small corrections have been applied. These corrections fall into two classes:

(i) departures from the standard assumptions made in computing ft for an allowed decay,

(ii) radiative corrections.

No serious problems concerning (i) appear to arise, whereas the corrections (ii) are subject to some controversy. Calculations based on a perturbative approach[1] give a correction of $-(1.5 \pm 0.5)\%$, in the (intuitively attractive) sense that the "true" ft is to be obtained from the observed ft by increasing the latter by this amount. This correction factor is obtained from a divergent result by imposing a "natural" cut-off. An approach based on dispersion techniques[2] leads to a correction in the opposite sense, but the interpretation of its results in terms of a renormalized G_V^β within the spirit of CVC is unclear. Additional uncertainties in (ii) connected with the possible existence of a W boson can presumably be dismissed in view of the high mass limit ($m_w > 5$ BeV/c) set by recent experiments[3].

Table 1, kindly supplied by Dr. Joan Freeman, summarizes the relevant ft values. These include all "standard" corrections (i) and radiative corrections following Kinoshita and Sirlin. With the exception of Al^{26m}, (to which Dr. Freeman's contributed paper is primarily devoted), all ft's are seen to be

equal. We consider this agreement, in view of the varying structure of the nuclei involved, as a strong confirmation of CVC. Conversely, the observed agreement makes attempts to attribute the "discrepancy" between G_V^β and G (see below) to nuclear structure effects unappealing.

Using the value for G from μdecay (when the perturbative radiation corrections are unique and finite!) and G_V^β from, say, ft (0^{14}) one gets

$$G_V^\beta/G = (0.979 \pm 0.005), \tag{1}$$

where the error is a crude allowance for the theoretical uncertainties.

The CVC hypothesis, as originally formulated, demands of course $G_V^\beta/G = 1$. Theoreticians have spent much energy trying to explain away this "discrepancy". The most appealing explanation lies in Cabibbo's theory of all non-leptonic decays, where it appears, so to speak, as a side product. In this theory, universality means

$$G_V^\beta/G = \cos\theta, \tag{2}$$

where θ, the Cabibbo angle, is determined from the comparison of $\Delta Y = 0$ and $|\Delta Y| = 1$ decays. The value $\theta = 0.26 \pm 0.01$ is obtained by a fit to the most recent set of data by Willis et al.,[5] in agreement with the $tg^2\theta$ obtained from the ratio of the vector transitions $(K \to \pi)/(\pi^+ \to \pi^0)$ by Cabibbo. Numerically, Eq. (2) then predicts

$$G_V^\beta/G = 0.966 \pm 0.003), \tag{2a}$$

i.e. disagreement with theory is now somewhat reduced and changed in sign. Sakurai[6] has questioned, on the basis of renormalization arguments, the way in which [4, 5] θ is derived from the observed rates. He advocates a relation

$$(\sin\theta)_{true} = C \sin\theta \tag{3}$$

and gets C = 0.81 from a specific model. This leads to $(\cos\theta)_{true} = 0.979$; with this value, Eq. (2) would be in perfect agreement with experiment. On the other hand, Ademollo and Gatto[7] have shown that SU(3) breaking forces do not (to first order) produce any renormalization effect of the vector current coupling. Granting this result, it would appear correct to use the θ as obtained

from the purely vector K-π comparison in Eq. (2), without Sakurai's factor C. (This θ, incidentally, agrees with the best value[5] from all decays.)

(b) Weak magnetism

For the $1^+ \to 0^+\beta^\pm$ decays within the A = 12 multiplet, the experiment of Wu et al.[8] has shown remarkable agreement with the theoretically predicted departures from the allowed spectra shapes. This result has been compared with earlier work in detail[9].

In the A = 8 multiplet, one has the advantage that two kinds of measurements can be performed, viz. (i) ($\beta^\pm$-α) correlation, (ii) $\beta^\pm$ spectral shape comparison. Whereas the experiments[10] on (i) agree well with the CVC predictions, recent studies of the spectra give somewhat disconcerting results[11].

(c) Forbidden Fermi Transitions

In electromagnetism, the CV connects the current and charge density operators $\vec{j}, j_o$. For this reason one can express (in the limit of long photon wavelengths) certain $\vec{j}$ matrix elements in terms of those of j_o. This is the essential content of the famous Siegert theorem.

Fujita[12] and Eichler[13] have exploited the CVC idea to extend the Siegert theorem to the weak vector current. They thus obtain relations like $\langle \vec{j}^{\pm} \rangle = f(\Delta E, Z) \langle j_o^{\pm} \vec{r} \rangle$, or, in standard β-decay parlance, the ratio $\langle \alpha \rangle / \langle i\vec{r} \rangle$. The latter can be estimated from a model, whereas the former would require the knowledge of the nuclear interaction.

Some examples of application:

(i) RaE ($1^- \to 0^+$)

$$\langle \vec{\alpha} \rangle / \langle i\,\vec{r} \rangle = \begin{cases} -39 \text{ (Expt.}^{14}\text{)}, \\ -38.5 \text{ (Theory}^{13}\text{)}. \end{cases}$$

(ii) Ce^{141} ($7/2^- \to 5/2^+$)

$$\langle \vec{\alpha} \rangle / \langle i\,\vec{r} \rangle = \begin{cases} +29.4 \pm 1.5 \text{ (Expt.}^{15}\text{)} \\ +30 \text{ (Theory}^{13}\text{)} \end{cases}$$

It is clear that such comparisons constitute consistency checks, rather than a proof, of the CVC hypothesis.

2) The ratio $G_A^\beta / G_V^\beta \equiv x$

Adler[15] and, independently, Weisberger[16], have recently managed to predict theoretically $-x = 1.18 \pm 0.02$. Whereas the data from which the experimental value of this important ratio is derived have not changed for years, widely varying values have recently been quoted for it in the literature. For reference purposes, we consider it useful to reproduce the arithmetic here:

$$\frac{ft(0^{14} \to N^{14*})}{ft(n)} = \frac{3127 \pm 10}{1210 \pm 35} = \frac{1 + 3x^2}{2} \tag{4}$$

$$-x = 1.18 \pm 0.02 \tag{5}$$

where the (-) sign comes from the neutron decay asymmetry experiments[17,18]. The ft-values in Eq. (4) are as computed by Durand et al.[2], except that the radiative corrections of Kinoshita, Sirlin, and Berman[1] were adopted [$(1.9 \pm 0.5)\%$ for n, $(1.5 \pm 0.5)\%$ for 0^{14}]. The deviations in (4) include experimental errors but no allowance for theoretical uncertainties.

The electron asymmetry parameter in neutron decay, A, can be used to give a completely independent, but less accurate value of x,

$$A = -\frac{2x(x+1)}{1+3x^2} \tag{6}$$

The weighted mean of the ANL-Chicago[17] (-0.11 ± 0.02) and Chalk River[18] (0.09 ± 0.05) values is $A_{exp} = -(0.107 \pm 0.018)$, yielding

$$-x = (1.24 \pm 0.05), \tag{7}$$

in good agreement with (5).

(a) Weak (parity violating) forces between nucleons

There is at present a wide-spread belief that weak processes can be described by a current-current interaction, i.e. through a Lagrangian

$$\mathcal{L} = \frac{G}{2} J_\mu J_\mu^+ ,$$

where, in an obvious notation,

$$J_\mu = [(\bar{N} \gamma_\mu P) + (\bar{\nu} \gamma_\mu e) + (\bar{\nu} \gamma_\mu \mu) + \ldots]$$

While such an interaction would follow from the existence of an intermediate boson (which at present is no longer popular), the converse is not true. What experimental evidence is there for such an interaction?

The outstanding feature of the current-current picture is the prediction of (purely leptonic or purely hadronic) "self-terms", like $(\bar{\nu}\gamma_\mu e)$ $(\bar{e}\gamma_\mu \nu)$, $(\bar{N}\gamma_\mu P)$ $(\bar{P}\gamma_\mu N)$ etc. The remarkable scattering process

$$\nu(\bar{\nu}) + e \rightarrow \nu(\bar{\nu}) + e,$$

corresponding to the first of these terms, has to date not been observed, though there exists some indirect (astrophysical) evidence for its occurrence. On the other hand, there has been a considerable, and perhaps successful, experimental effort to detect weak, parity-violating interactions in nuclear matter. Before turning to a discussion of the relevant experiments, we wish to emphasize that even conclusive proof that such interactions actually do occur in nature will be only partial evidence for the (NP) (PN) term in question. A variety of ad-hoc, phenomenological Lagrangians could perhaps be formulated to account for the observed effects.

With a parity-violating potential in nuclear matter, nuclear states $|J>$ would no longer be of well-defined parity, but would consist of a mixture, e.g.

$$|J> = |J^{\pm}> + f\, |J^{\mp}>,$$

where the coefficient F is a measure of the admixture of the "wrong" parity. From the current-current picture, one predicts[19] F to be a few times 10^{-7}.

There are two classes of experiments in this field, namely (a) those sensitive to F, and (b) those sensitive to F^2. It is clear that experiments demonstrating parity violation <u>directly</u>, i.e. through the observation of a pseudo-scalar quantity (if you want to find a nut, use a screw!), belong to class (a).

It is clear that such comparisons constitute consistency checks, rather than a proof, of the CVC hypothesis.

2) The ratio $G_A^\beta / G_V^\beta \equiv x$

Adler[15] and, independently, Weisberger[16], have recently managed to predict theoretically $-x = 1.18 \pm 0.02$. Whereas the data from which the experimental value of this important ratio is derived have not changed for years, widely varying values have recently been quoted for it in the literature. For reference purposes, we consider it useful to reproduce the arithmetic here:

$$\frac{ft(0^{14} \rightarrow N^{14*})}{ft(n)} = \frac{3127 \pm 10}{1210 \pm 35} = \frac{1 + 3x^2}{2} \tag{4}$$

$$-x = 1.18 \pm 0.02 \tag{5}$$

where the (-) sign comes from the neutron decay asymmetry experiments[17,18]. The ft-values in Eq. (4) are as computed by Durand et al.[2], except that the radiative corrections of Kinoshita, Sirlin, and Berman[1] were adopted [$(1.9 \pm 0.5)\%$ for n, $(1.5 \pm 0.5)\%$ for 0^{14}]. The deviations in (4) include experimental errors but no allowance for theoretical uncertainties.

The electron asymmetry parameter in neutron decay, A, can be used to give a completely independent, but less accurate value of x,

$$A = -\frac{2x(x+1)}{1+3x^2} \tag{6}$$

The weighted mean of the ANL-Chicago[17] (-0.11 ± 0.02) and Chalk River[18] (0.09 ± 0.05) values is $A_{exp} = -(0.107 \pm 0.018)$, yielding

$$-x = (1.24 \pm 0.05), \tag{7}$$

in good agreement with (5).

(a) Weak (parity violating) forces between nucleons

There is at present a wide-spread belief that weak processes can be described by a current-current interaction, i.e. through a Lagrangian

$$\mathcal{L} = \frac{G}{2} J_\mu J_\mu^+ ,$$

where, in an obvious notation,

$$J_\mu = [(\bar{N} \gamma_\mu P) + (\bar{\nu} \gamma_\mu e) + (\bar{\nu} \gamma_\mu \mu) + \ldots]$$

While such an interaction would follow from the existence of an intermediate boson (which at present is no longer popular), the converse is not true. What experimental evidence is there for such an interaction?

The outstanding feature of the current-current picture is the prediction of (purely leptonic or purely hadronic) "self-terms", like $(\bar{\nu}\gamma_\mu e)$ $(\bar{e}\gamma_\mu \nu)$, $(\bar{N}\gamma_\mu P)$ $(\bar{P}\gamma_\mu N)$ etc. The remarkable scattering process

$$\nu(\bar{\nu}) + e \rightarrow \nu(\bar{\nu}) + e,$$

corresponding to the first of these terms, has to date not been observed, though there exists some indirect (astrophysical) evidence for its occurrence. On the other hand, there has been a considerable, and perhaps successful, experimental effort to detect weak, parity-violating interactions in nuclear matter. Before turning to a discussion of the relevant experiments, we wish to emphasize that even conclusive proof that such interactions actually do occur in nature will be only partial evidence for the (NP) (PN) term in question. A variety of ad-hoc, phenomenological Lagrangians could perhaps be formulated to account for the observed effects.

With a parity-violating potential in nuclear matter, nuclear states $|J>$ would no longer be of well-defined parity, but would consist of a mixture, e.g.

$$|J> = |J^{\pm}> + f\, |J^{\mp}>,$$

where the coefficient F is a measure of the admixture of the "wrong" parity. From the current-current picture, one predicts[19] F to be a few times 10^{-7}.

There are two classes of experiments in this field, namely (a) those sensitive to F, and (b) those sensitive to F^2. It is clear that experiments demonstrating parity violation <u>directly</u>, i.e. through the observation of a pseudo-scalar quantity (if you want to find a nut, use a screw!), belong to class (a).

In both cases, it is actually not F, but rather FR that matters, where R is an "encouragement" factor. While F is, loosely speaking, a property of nuclear matter, R depends crucially on type of transition $i \to f$ connecting two specific states. Assume the transition would take place, if $|f\rangle$ and $|i\rangle$ were parity eigenstates, by some "regular" mechanism, say E1 photon emission. The "wrong" parity components of either $|i\rangle$ and $|f\rangle$ contribute then matrix elements of an "irregular" operator, say M1 emission in this case. Calling the regular operator "dominant", we then define

$$FR \equiv \frac{\langle f \,||\, \text{irregular} \,||\, i \rangle}{\langle f \,||\, \text{dominant} \,||\, i \rangle} .$$

R will be large, when the dominant mechanism while allowed by spin and parity, is slowed down by some other approximate selection rules.

(b) Experiments sensitive to F

(i) Circular polarization

If the dominant electromagnetic transition $i \to f$ is ML (magnetic 2^L-pole), then the leading irregular electromagnetic amplitude brought in by parity violation will be EL (electric rad. of same multipolarity). The coherent superposition of these two electromagnetic amplitudes (differing in the interchange $\vec{E} \leftrightarrow \vec{B}$) yields circularly polarized radiation, with a degree of polarization

$$\mathcal{P} = 2FR;$$

this formula holds only when the dominant transition is not of mixed [say ML + E (L + 1)] character.

An interesting, and perhaps not entirely academic, case is the capture of thermal neutrons by deuterons. As the neutrons are s-wave, the dominant process is clearly M1 emission. It is obviously a "discouraged" one, as indicated by the low capture cross section which makes heavy-water piles possible. This discouragement is caused by a selection rule which would be rigorous for certain assumptions about nuclear forces. There is no restriction for the "irregular" E1 transition. Thus R is large; unfortunately, H. Feshbach has to date not done his homework, and we lack a reliable estimate of R. The thought that all the heavy-water piles

should have been emitting spontaneously polarized, monochromatic photons for years without us noticing it is, however, an intriguing one!

(ii) The Ta^{181} experiments

F. Boehm and E. Kankeleit[20] have investigated the γ-ray connecting the 482-keV, $5/2^+$ excited state of Ta^{181} to the $7/2^+$ ground state. The regular transition is M1, the irregular one E1. The M1 transition is strongly hindered (by $\sim 3.\ 10^6$), a fact that can be well explained through selection rules operating on the asymptotic quantum numbers (402 and 404) which the two states of the strongly deformed Ta^{181} have in the Nilsson scheme. In view of this hindrance, the transition proceeds actually to 97% by E2 - a multipolarity that cannot, by interference with the irregular E1, yield circular polarization. Thus one has,

$$\mathcal{P} = \frac{2}{1 + q^2} RF, \tag{8}$$

where q is the M1/E2 mixing ratio. The nature of the admixed $5/2^-$ and $7/2^-$ states is also well understood in terms of the Nilsson model. The E1 transitions involving these states are not hindered. Using a detailed model, S. Wahlborn[21] predicts

$$\mathcal{P}_{th} \simeq -1.3 \times 10^{-4}.$$

To detect such a small circular polarization would not be a trivial matter even in the optical region! The situation is, of course, even more difficult with γ-rays, where the iron transmission polarimeters have efficiencies of the order of 1% only; the experiment we are discussing aims to detect an effect of 10^{-6}.

Using the apparatus indicated in Fig. 1 (which should be self-explanatory), Boehm and Kankeleit report

$$\mathcal{P}_{exp} = -(2.0 \pm 0.4) \times 10^{-4}, \tag{9}$$

in essential agreement, in sign and magnitude, with the predicted value. Their preliminary experimental value[22], $-(5 \pm 2) \times 10^{-4}$, was based on an overestimate (by a factor 2) of their detection efficiency and hence is consistent with result (9).

Following the Cal Tech work, the same transition was investigated by Bock and Schopper[23] in Germany. Their result,

$$\mathcal{P}_{exp} = + (0.3 \pm 2.1) \times 10^{-4}$$

is unfortunately consistent both with a null effect and with (9). Further work by both groups is in progress.

(iii) Polarization of internal conversion electrons.

The internal conversion electrons ejected by a (virtual) photon of mixed parity will, in general, be longitudinally polarized. It is interesting to point out, following F. C. Michel[19], that their degree of polarization, $\mathcal{P}_{e\ell}$, can be considerably larger than the $\mathcal{P}$ of the corresponding unconverted photons.

Consider a dominant M1 transition with an E1 "irregular" admixture, i.e. E1(M1), such that K shell conversion can occur. The M1 conversion (coefficient β_1) corresponds to 1s → ks, and the E1 conversion (coefficient α_1), to 1s → kp. From obvious overlap arguments, one has $\beta_1 > \alpha_1$, and one will expect $\mathcal{P}_{e\ell} \approx (\beta_1/\alpha_1)$RF.* For an M1(E1) transition, consider e.g., conversion in the $L_{II}(2p_{1/2})$ shell. The process 2p + E1 → ks yields α_2, and its competitor, 2p + M1 - kp, β_2. Thus $\alpha_2 > \beta_2$, and one gains a factor of order (α_2/β_2). The necessary separation of the conversion electrons from the various L subshells prior to scattering experiment is, however, a delicate experimental problem. No results are available to date.

(iv) β-γ angular correlation.

If both members in a sequence of nuclear radiations involve opposite parity waves, then a backward-forward asymmetry can arise in their angular correlation. Thus one would expect a term A cos θ in a β-γ correlation involving a "parity violating" γ-transition, provided of course that the intermediate state be sufficiently shortlived so as not to be perturbed by external fields. As opposed to circular polarization, the investigation of such an effect would have two advantages: (a) no reduction by a factor $\sim 10^2$ through efficiency, (b) no dilution of the effect by the admixed regular multipole (say E2 to M1), i.e. absence of the factor q in Eq. (8).

---

*Notation: k stands for continuum; the conversion coefficient for electric (magnetic) radiation is customarily indicated by $\alpha_n(\beta_n)$, where n specifies the shell.

Theoretical predicitions for such effects were given as early as 1959 by Krüger,[24] but to date no experimental results have been reported.

(v) γ-$\langle\vec{\sigma}\rangle$ correlation.

If a γ-transition following (thermal) neutron capture is "parity violating", then a circularly polarized photon will be emitted. If the captured neutron has a polarization $\langle\vec{\sigma}\rangle$, then one can further expect a correlation of the type $1+A\langle\vec{\sigma}\rangle\cdot\hat{k}$ with the direction of emission $\hat{k}$. Qualitatively, one anticipates $A \approx \mathcal{P} \approx$ RF. An experiment to detect A was first devised and performed in 1959 by Adair and collaborators,[25] with the result

$$A = (1.2 \pm 7.8) \times 10^{-4}, \tag{10}$$

obtained by investigating the ground state transition nominally ($1^+ \rightarrow 0^+$, 9.05 MeV) in $Cd^{113}(n,\gamma)Cd^{114}$. Cd^{114} is, because of the spins involved as well as for a number of other reasons[25], particularly favorable. The transitions to the excited states, e.g. $1^+ \rightarrow 2^+$ etc., should obviously show only smaller effects.

The experiment was repeated in 1964 by Abov and collaborators[26], using the apparatus of Fig. 2 (where, in the main set of measurements, $\langle\vec{\sigma}\rangle$ points along the line connecting the NaI detectors). A rotating depolarizer (Fe shim) is the main novel feature as compared to Ref. 25. Abov et al. report

$$A = -(3.7 \pm 0.9) \times 10^{-4}, \tag{11}$$

i.e. a non-zero result to 4 std. deviations. It is worth noting that a control experiment involving a lower energy (E1) transition in Cd^{114} yielded an effect smaller than the error allowed for above.

Presented only with these results, one might perhaps conclude that parity non-conservation in nuclear matter is now an established fact. Unfortunately, this conclusion would be premature. A more recent repetition of the Adair experiment, this time at Ispra, by Forte and Saavedra[27], yields*

$$A = +(0.22 \pm 1.1) \times 10^{-4}, \tag{12}$$

---

*The Ispra group also investigated the $d(n,\gamma)H^3$ reaction finding $A = (0.3 \pm 1.6) \times 10^{-4}$. This numerical result was not available at the time of the talk. We are indebted to Dr. G. Scharff-Goldhaber in making the Ispra preprint available

i.e., a result compatible with (11) and with zero! However, this is not the last word either. A group at Risø (Denmark) is also redoing this crucial experiment. They are finding statistically significant results which appear to confirm those of Abov et al.**

(b) Experiments sensitive to F^2

The experiment on the $8^- \rightarrow 8^+$ transition in Hf^{180m} discussed in the interesting paper presented here by Dr. G. Scharff-Goldhaber falls in this category. This nominally E1 transition is enormously retarded (5.5 hours halflife!); thus the contribution of the "irregular" M1 could be exceptionally enhanced (i.e., large R). The presence of this M1 component is inferred from anomalies in the measured L-conversion coefficients.

Two remarks are perhaps of interest: First, the selection rule which explains the slowness of the dominant (E1) mode (the initial and the final state belong to two different rotational bands!) operates also against the irregular M1 component. Second, the assumption usually made about internal conversion coefficients, namely that they depend (for a given γ-energy and atom) only on the multipolarity and not on the e.m. nuclear matrix elements, may not apply to extremely retarded transitions. In other words, the selection rules that affect the real photons may not apply identically to the virtual ones responsible for the conversion process. There is indeed some evidence[28] that many retarded E1 transitions in heavy nuclei exhibit anomalous L_I and L_{II} conversion coefficients. A theoretical attempt to interpret this evidence (in terms other than parity mixing!) has been given by Nilsson and Rasmussen.[29]

4) Application of elementary particle concepts to the β-decay of complex nuclei.

Weak processes involving complex nuclei are, almost exclusively, treated by assuming a given weak Hamiltonian for the nucleon (say, V-xA) and describing the nuclear states in terms of model wavefunctions involving the nucleon coordinates only, i.e., in the impulse approximation. This approach is historically motivated through the analogous treatment of the electromagnetic

---

** This statement is based on a personal communication and was not included in the talk.

properties of atoms. It fails, however, already for the electromagnetic properties of nuclei where we all believe in the existence of exchange currents.

In very simple terms, the problem could be paraphrased as follows: If a free nucleon interacts by (v-xA), is x the same for a bound nucleon? To see that this problem is a physical one, consider the decays $n \to p$ and $H^3 \to He^3$. Comparing their ft-values, and allowing for the fact that, in the impulse model, $\langle He^3 | \vec{\sigma} | H^3 \rangle \leq \langle p | \vec{\sigma} | n \rangle^2 = 3$, one sees that the neutron "inside" He^3 decays faster than the free neutron! (It is clear from CVC that a change in $x \equiv G_A/G_V$ is to be attributed to a change in G_A).

Kim and Primakoff[30] have recently treated this problem by applying the PCAC (i.e., the Goldberger-Treiman relations) notions directly to the "trion" (the T = 1/2 doublet with A = 3), and to complex nuclei in general. In the usual π-pole dominance approximation, the first G-T relation* for nucleons may be conveniently written as

$$x_{np} = G_A(n \to p)/G_V \approx a_\pi f_{\pi np}, \tag{13}$$

where

a_π = the pion decay amplitude = $F_A^{\pi 0}(p_\pi^2 = -m_\pi^2)$ = π-vacuum form factor

= 0.95 ± 0.01 (from π - μ decay rate),

$f_{\pi np}$ = π^+ - nucleon coupling constant,

= 1.43 ± 0.03 (from $\pi^\pm p$ elastic and np exchange scattering).

Note that (13), is well satisfied, as with x = 1.18 ± 0.02, it yields $f_{\pi np}$ = 1.24 ± 0.03.

For any transition between the members, (i, f) of a J = 1/2 isodoublet, one may write down mutatis mutandis (say, $n \to i$, $p \to f$), relations like (13). Thus

$$(x_{if}/x_{np})^2 = [G_A(i \to f)/G_A(n \to p)]^2 = (f_{\pi if}/f_{\pi np})^2 \tag{14}$$

---

*We omit the relation with the induced P coupling.

Unfortunately, the scattering data required to get $f_{\pi if}$ are not yet available for any nucleus. Kim and Primakoff get around this difficulty by extending a known relation between the anomalous moments of nucleons, viz.

$$|(\mu_p - 1) - (\mu_n - 0)| = kf^2_{\pi np} = 3.70 \tag{15}$$

to other isodoublets of mass number A, requiring

$$|(\mu_f - \frac{Z}{A}) - (\mu_i - \frac{Z}{A})| = kf^2_{\pi if} g(A) \tag{16}$$

where $Z = Z_f$, and g(A) an a-priori unknown function, taken as $g(A) = A^{1/3}$.

The comparison of the Kim-Primakoff theory with experiment is shown in Fig. 3 as a function of A. The solid curve shows the square of the ratio (14) as extracted from experimental ft-values, the dashed curve the prediction of the standard (impulse approximation) theory, and the dot-dashed curve corresponds to Eq. (15). In view of the assumptions underlying the latter, the agreement is remarkable.

In closing this section, we remark that attempts to connect axial-vector matrix elements with magnetic moments are not new. The Kim-Primakoff curve is, so to speak, the modern version of the Kofoed-Hansen-Winther plot,[31] well known to the older generation.

5) Muon Decay

The decay of the muon is, except for radiative corrections, a purely leptonic process. Precision measurements of the various parameters characterizing the decay of both polarized and unpolarized muons are, in a rough sense, as important and as desirable as accurate determinations, say, of the magnetic moment of the electron. Given any experimental precision, the theory should be able to provide an adequately accurate prediction for comparison. This is particularly true for the generally accepted V-A interaction (which yields finite radiative corrections) and in the case that the intermediate boson either does not exist or has a very large mass.

The most frequently determined decay parameter is Michel's ρ. Table II is a summary of the currently available experimental values (omitting early or incompletely evaluated work). At the 1964 Dubna Conference the somewhat disturbing entries (f) and (g) became known. Mukhin, in this rapporteur's talk,

took a grand mean in which these two entries propitiously average towards the desired $\rho = 3/4$. Since then (in fact, at the January 1965 New York Meeting) digitized spark-chamber spectrometer measurements by groups at Columbia and at Chicago have been presented; the Columbia work has been published. Figs. 4 and 5 are taken from Ref. (32), while Figs. 6 and 7 relate to our work at Chicago. The sources of systematic errors in these two experiments are, to the extent that they are known, certainly rather different. The Columbia experiment has a 4 times smaller statistical error than the present Chicago determination; on the other hand, Columbia has a poorer χ^2-fit. The agreement of these two ρ-values with each other and with the theoretical value $\rho = 3/4$ constitutes, in view of these facts, a welcome corroboration of our preconceived notions.

Assume, however, that we had experimental proof that $\rho = 3/4$ to arbitrary accuracy. Does this prove that the popular V-A interaction actually holds in nature? Certainly not. (In fact, we shall show that the V-A theory was, with one notable exception, assumed, in obtaining ρ from experiment!) The general derivative-free $(\mu\, e)(\nu\, \nu)$ interaction has, assuming lepton conservation but not time reversal invariance (which is not in good repute these days), 19 independent coupling constants. Thus we would need to know the values of, at least, an equal number of observable parameters to fix the nature of the interaction purely empirically. There are however, in practice, only four accessible parameters (aside from the electron helicity, h), namely those characterizing the decay spectrum N(x):

$$N(x)dxd\Omega = [\, M(x;\rho\,,\, \eta\, m_e/m) - \xi \langle \vec{\sigma}_\mu \rangle \hat{x} B(x;\, \delta\,)]\; x^2 dx d\Omega \qquad (17)$$

where M and B are known functions* of $x \equiv p/p_{max}$. Hence, we must be more modest. Let us postulate that neutrinos are two-component (with $\nu = \nu_L$), and compare the predictions of this "V + ϵ A" interaction with experiment (see Table III, where the V-A predictions are included for convenience).

From Table III, we see that ρ and δ do not contribute anything to our knowledge of ϵ. The low-energy spectral parameter η is a good measure of ϵ,

---

*Symbols chosen to commemorate our friends Michel and Bochiat. As a compensation, we have adopted the notation of Kinoshita and Sirlin for the parameters.

assuming the characteristic value $\eta = 0$ for V-A (but, also for V+A). Now all experimenters, except Plano (Ref. d in Table II), assumed $\eta = 0$ in fitting their spectra for ρ and in computing the error in ρ. The motivation for this lies in the fact that, statisitically, ρ appears to be most efficiently determined from the upper part (say $x > 0.5$) of the spectrum (in fact, the recent Columbia and Chicago experiments were confined to this region), whereas η, appearing as the coefficient of $(m_e/m)(1-x)/x$, would seem to influence only the low-energy spectrum. The inclusion of η has however, even for high energies, a drastic effect. For N events in the region $0.75 \leq x \leq 1$, the standard deviation in ρ is $\delta\rho = 2.6\ N^{-1/2}$, if the constraint $\eta = 0$ is imposed. If, on the other hand, the same data are fit for ρ and η simultaneously, $\delta\rho$ increases to $30\ N^{-1/2}$ (and $\eta = 3000\ N^{-1/2}$). This is due to the fact that η affects the spectrum in a way comparable to what a small change in ρ would do. Using the constraint $|\eta| < 1$, which holds for the general interaction, $\delta\rho \approx 2.6\ N^{-1/2} + 0.01$ becomes a good approximate rule.

Within the spirit of the "V+ϵ A" approach, η is the interesting parameter of the isotropic spectrum. Hence one should really fit the experiments, by imposing $\rho = 3/4$, for η! Similarly, ξ is the relevant parameter of the anisotropic spectrum (h, a more difficult quantity to measure, is equal to ξ). For ξ we have a very accurate Russian determination (see Table III), whereas no experiment specifically designed to measure η has yet been completed. Thus we are lacking even the two parameters required to determine the complex constant ϵ. Further modesty imposes itself. We may either postulate T-invariance, in which case the known ξ yields $\epsilon = -(0.79^{+0.21}_{-0.11})$, or else assume $\epsilon = -e^{i\phi}$, in which case ξ yields $\phi = (0.21^{+0.11}_{-0.21})$.

It is of course of interest to ask the more ambitious question as to what S, T, P admixtures (i.e., departures from the 2-component neutrino theory with fixed chirality) are compatible with the experimental parameters as they are now known. This question has been explored by a student of Kallen, Mrs. C. Jarskog[33]. Realizing that only μ and e variables are practical observables, she inserts $(g_i + g_i\gamma_5)$ in the $(\bar{\mu}e)$ covariant (rather than, as is customary, in the $(\bar{\nu}\nu)$ part), i.e. she emphasizes the chiralities of the charged leptons.

She shows that $\rho = \delta = 3/4$, $h = \xi = 1$ are <u>sufficient</u> conditions to restrict the interaction to the form $g_V [\bar{e}\underline{\gamma}(1 + \gamma_5)\mu][\bar{\nu}\underline{\gamma}(1 - g_A/g_V \cdot \gamma_5)\nu]$ (in the customary notation, not hers). This interaction also yields $\eta = 0$. Thus one is forced to go to experiments involving ν-observables to prove that $g_A/g_V = -1$. The price for not assuming 2-component neutrinos is a high one indeed!

Mrs. Jarskog concludes that the experimental errors (on the data available to her about a year ago) allow large admixtures of S, T and P. She finds, with certain simplifying assumptions, $|g_T| \leq 0.3|g_V|$, and $|g_S| \leq 0.4|g_V|$. The more accurate values of ρ and ξ now available (Table III) do not appreciably improve these bounds, at least as long as more accurate values of δ and h are not determined.

Table I

Radiatively corrected ft values for transitions between $J = 0^+$ $T = 1$ isobars.

Decay	ft value (sec)
O^{14} $(\beta^+)N^{14*}$	3127 ± 10
Al^{26m} $(\beta^+)Mg^{26}$	3086 ± 12
Cl^{34} $(\beta^+)S^{34}$	3138 ± 19
Sc^{42} $(\beta^+)Ca^{42}$	3122 ± 9
V^{46} $(\beta^+)Ti^{46}$	3131 ± 8 3138 ± 25
Mn^{50} $(\beta^+)Cr^{50}$	3125 ± 9
Co^{54} $(\beta^+)Fe^{54}$	3132 ± 17

Table II

EXPERIMENTAL VALUES OF ρ

Method	ρ	Institution	
Diffusion Chamber	0.67 ± 0.05	Chicago[a]	(1958)
Magnetic Spectrometer	0.62 ± 0.02	LRL[b]	(1956)
Spiral Orbit Spectrometer	0.741 ± 0.027	LRL[c]	(1959)
H_2 Bubble Chamber	0.780 ± 0.025	Columbia[d]	(1960)
He Bubble Chamber (μ^-)	0.751 ± 0.034	Duke[e]	(1962)
Magnetic Spectrometer	0.661 ± 0.016	Liverpool[f]	(1964)
Diffusion Chamber (μ^-)	0.867 ± 0.035	Dubna[g]	(1964)
Sonic Spark Chamber Spm.	0.747 ± 0.005	Columbia[h]	(1965)
Wire Spark Chamber Spm.	0.760 ± 0.009	Chicago[i]	(1965)

(a) L. Rosenson, Phys. Rev. 109, 958 (1958).

(b) K. Crowe, et al., Proc. 6th Rochester Conf. on High Energy Physics, p. IX-47 (New York Interscience, 1956).

(c) W. F. Duziak, et al., Phys. Rev. 114, 336 (1959).

(d) R. J. Plano, Phys. Rev. 119, 1400 (1960).

(e) M. Block, et al., Nuovo Cimento 23, 1114 (1962).

(f) J. Barlow, et al., Proc Phys. Soc. (London) 84, 239 (1964).

(g) D. B. Pontecorvo, et al., XII International Conference on High Energy Physics, Dubna 1964.

(h) M. Bardon, et al., Phys. Rev. Letters 14, 449 (1965).

(i) R. Ehrlich et al., to be published.

Table III

	ρ	δ	η	$\xi^{(e)}$	$h^{(e)}$
$V+\epsilon A$	3/4		$\frac{\lvert\epsilon\rvert^2-1}{2(1+\lvert\epsilon\rvert^2)}$	$\frac{-2\mathrm{Re}(\epsilon)}{1+\lvert\epsilon\rvert^2}$	$=\xi$
$V-A$			0	1	1
Expt.	$3/4^{(a)}$	$0.78 \pm^{(b)}$ 0.5	$\pm\left(0.11\,{}^{+0.06}_{-0.11}\right)^{(c)}$ 0.01	$0.978\pm^{(d)}$ 0.030	$1.03\pm^{(f)}$ 0.14

(a) Assumed value; compare Table II.

(b) Ref. (d) in Table II (Plano).

(c) Computed from (d), assuming ϵ real.

(d) I. I. Gurevich et al., Phys. Letters 11, 185 (1964).

(e) For μ^+; for μ^-, multiply by (-1).

(f) Optimistic average of recent values.

REFERENCES

1) T. Kinoshita and A. Sirlin, 113, 1652 (1959); S. M. Berman and A. Sirlin, Ann. Phys. 20(1962).

2) L. Durand, L. F. Landowitz, and R. B. Marr, P. R. 130, 1188 (1963).

3) Lamb et al., PRL 15, 800 (1965); Burns et al., PRL 15, 830 (1965).

4) N. Cabibbo, PRL 10, 531 (1963).

5) W. Willis et al., PRL 13, 291 (1964).

6) J. J. Sakurai, PRL 12, 79 (1964).

7) Preprint

8) Lee, Mo, and C. S. Wu, PRL 10, 253 (1963).

9) C. S. Wu, Rev. Mod. Phys. 36, 618 (1964).

10) Nordberg, Morinigo and Barnes, Phys. Rev. 125, 321 (1962); K. Krebs, H. Reisenberg and V. Soergel, Zs. f. Phys. 159, 232 (1960).

11) V. Soergel et al. (Talk at the Heidelberg Weak Interaction Meeting (March 1965

12) J. I. Fujita, P. R. 126, 202 (1962).

13) J. Eichler, Zs. f. Phys. 171, 463 (1963).

14) H. Daniel, Nuclear Phys. 31, 293 (1962).

15) D. D. Hoppes, E. Ambler, R. W. Hayward, and R. S. Kaeser, P. R. L. 6, 115 (1961).

16) See their contributions to this conference.

17) Burgy, Krohn, Novev, Ringo and Telegdi, Phys. Rev. 120, 1829 (1960).

18) M. A. Clark and J. Robson, Can. J. Phys. 38, 693 (1960).

19) F. C. Michel, Phys. Rev. 113B, 329 (1964); also R. J. Blyn-Stoyle, Phys. Rev. 118, 1605 (1960), and ibid. 120, 181 (1961).

20) F. Boehm and E. Kankeleit, Phys. Rev. Letters, 14, 312 (1965).

21) Quoted in Ref. 20.

22) F. Boehm and E. Kankeleit, Compt. Rend. du Congres Int. de Physique Nucl., Paris 1964, 5/c 344.

23) P. Bock and F. Schopper, Physics Letters, 16, 284 (1965).

24) L. Krüger, Zs. f. Phys. 157, 369 (1959).

25) Haas, Leipuner, and Adair, Phys. Rev. 116, 1221 (1959).

26) Abov, Krupchitsky and Oratovsky, Phys. Letters, 12, 25 (1964).

27) M. Forte and O. Saavedra, Euratom (Ispra) preprint.

28) Asaro, Stephens, Hollander, and Perlman, Phys. Rev. 117, 492 (1960).

29) S. G. Nilsson and J. O. Rasmussen, Nucl. Phys. 5, 601 (1958).

30) C. W. Kim and H. Primakoff, U. of Penna. preprint.

31) O. Kofoed-Hansen and A. Winther, Dan. Mat. Fys. Medd. 27 No. 14 (1953).

32) Bardon et al., PRL 14, 449 (1965).

33) C. Jarskog, Lund preprint.

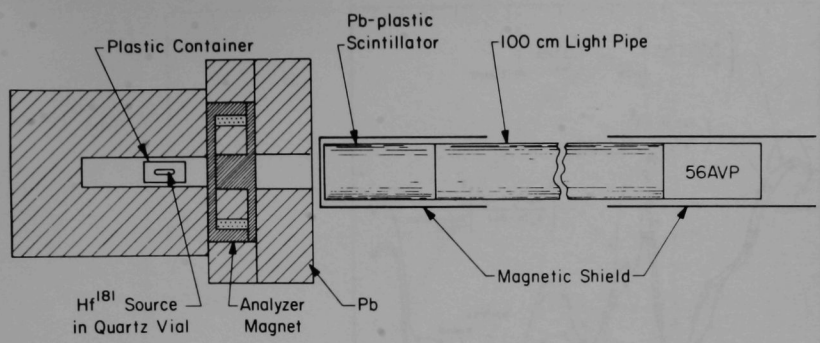


Fig. 1. Experimental Arrangement for the Detection of Circular Polarization

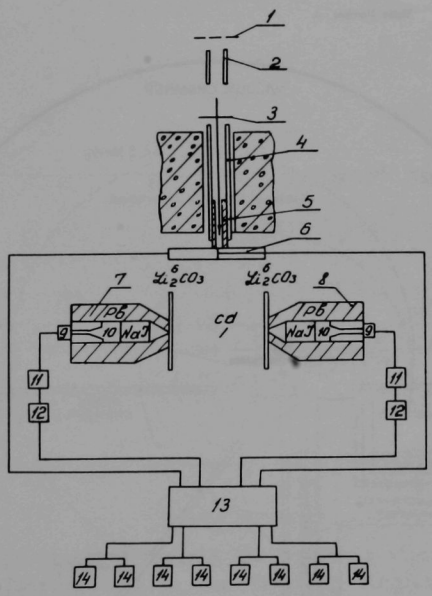


Fig. 2. 1. Constant Shim. 2. Magnet for Spin Flip. 3. Foil for Spin Flip. 4. Magnetic Guide. 5. Collimator. 6. Rotating Shim. 7. Channel No. 1. 8. Channel No. 2. 9. Cathode Follower. 10. Photomultiplier. 11. Amplifier. 12. Analyzer. 13. Commutator. 14. Scaler.

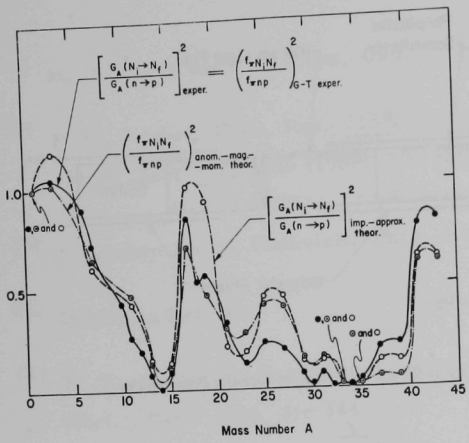


Fig. 3

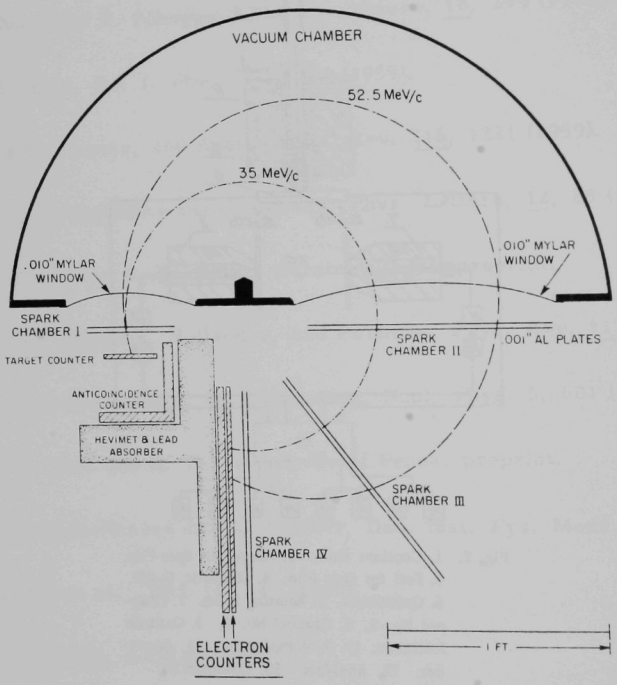


Fig. 4. Experimental Arrangement. The entire setup is in a homogeneous magnetic field. The two circular trajectories have been drawn for the minimum and maximum positron momenta accepted at a field of 6.62 kG. The two 0.003-in. Mylar windows for each chamber, which are not shown, are the only other material in the path of the positrons.

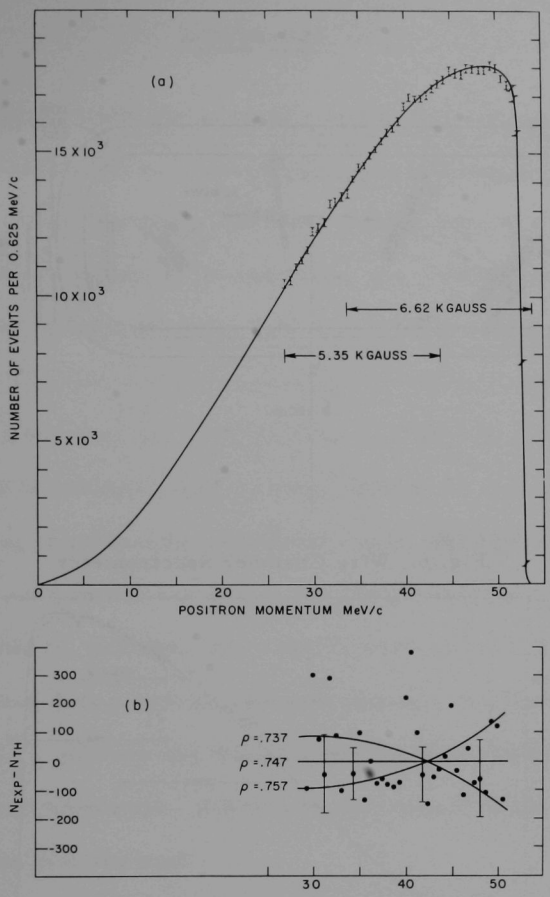


Fig. 5

(a) Experimental Points for Magnetic-field Settings, Normalized to the Overlap Region. The solid line is the theoretical spectrum for $\rho = 0.75$. The Michel spectrum

$$\rho(x)\,dx = \tfrac{1}{2}\{12x^2 - 12x^3 + \rho[(32/3)\,x^3 - 8x^2]\}\,dx,$$

where x is the positron momentum divided by its maximum value, has been corrected for internal radiation, bremsstrahlung, and ionization loss. (b) The deviation of experimental points from the best-fit theoretical curve for $\rho = 0.747$, showing typical experimental errors for four points. Curves for $\rho = 0.737$ and 0.757 are shown for comparison.

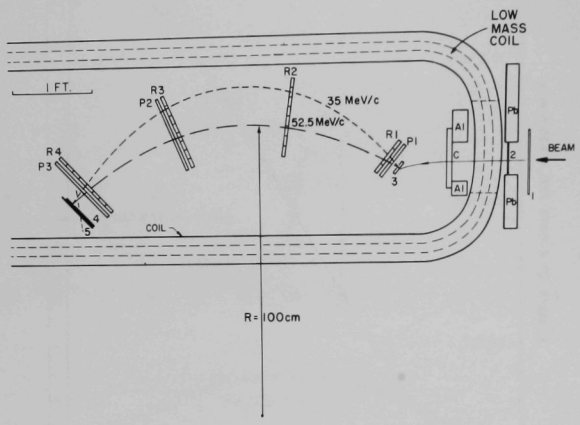


Fig. 6. Wire Chamber Spectrometer

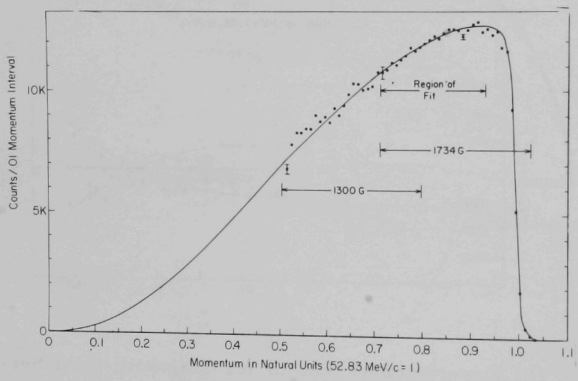


Fig. 7. Muon Decay Spectrum from Chicago Wire Chamber Spectrometer

DISCUSSION

HILDEBRAND: I would like to make a couple of comments myself. Since you advertised that Derenzo and I were trying to measure the low energy end of the μ decay spectrum, and that we didn't make it, I'd like to point out that if we had measured the spectrum, you wouldn't know what to do with it, because the theorists haven't done their part of the job. There are large corrections for internal conversion and all the corrections that have been made so far make the approximation that (M_e/M_μ) is neglected, which is equivalent to setting η equal to zero, so this is a very bad situation when you are trying to correct an experiment that is supposed to measure η.

TELEGDI: All I want to say is that one meager content of these grandiose ρ experiments is, perhaps, that if the V-A theory holds, the radiative corrections have been done properly. Because you have to correct so heavily to get the right ρ, you may say that at least Kinoshita, Sirlin, and these people have done their homework. But they haven't done it at the lower end to the approximation that you need.

HILDEBRAND: We are counting on Mr. Kinoshita to bail us out of this. My other remark is that you pointed out, quite correctly, that this relationship between η and ξ, which is often quoted, holds only for a two component theory. But assuming a two component theory does not mean that you can just as well set $\eta = 0$.

TELEGDI: No, I said, even this thing bears an important assumption in it and restricts ρ already. The assumption that makes this relationship valid already restricts ρ.

WILLIS (Yale): I suppose that the ρ value measurements are the best test of locality in the leptonic interactions. If you parametrize the non-locality in some way, can you say what mass that corresponds to?

TELEGDI: I can parametrize it if the non-locality can be expressed, which I presume it always can, in terms of some kind of a length or mass. Then I can take as a model the intermediate boson theory, which has a mass and hence length in it. Then we can say that $1/3\ (M_\mu / M_w)^2 \leq 0.005$, where $1/M_w$ is now the length of this theory rather than a boson mass and 0.005 is the Columbia uncertainty. That would be the best way I could put it. It is a little bit like some of these extremely penetrating questions such as, "what do you do when CPT doesn't hold?" I remember that there is an old paper by Klein and Bludman that discusses non-local effects. It is essentially the same situation as with g-2. If things don't work, how do you describe the departures parametrically? I don't have the answer to that. Now in the meantime, of course, you heard from yesterday's contribution that the honest boson mass, if the boson exists, has a much higher value than we expected it to be. To hypothesize bosons looking indirectly at the consequences has become pointless. You can't answer such questions with the kind of errors that we have.

ADLER (Harvard): I would like to go back to the question of whether the coupling constant in β-decay is really the same as the coupling constant in μ-decay. The CVC hypothesis is really somewhat of a misnomer. The strong form of CVC really states that the weak hadronic current is proportional to the $I_1 + iI_2$ component of the isospin current and that the isovector electromagnetic current is the third component, I_3. Now, in the absence of electromagnetic interactions, the $(I_1 + iI_2)$ component of isotopic spin is conserved, so that the coupling constant for the $I_1 + iI_2$ component is $\sqrt{2}$ times the coupling constant for I_3. But as soon as you turn on electromagnetic interactions, it is well known that isotopic spin is no longer conserved and, consequently, the coupling constant for $I_1 + iI_2$ component is changed by terms of order α from the coupling constant for the I_3 component. Fubini and Furlan have written a paper in which they have given formal expression for this renormalization of the weak coupling constants. It is not possible to evaluate this numerically yet, but I think it is very important to say that the radiative corrections do not give the complete picture, and until there is an evaluation of the Fubini-Furlan formula, worrying excessively about the radiative corrections really doesn't make a great deal of sense.

TELEGDI: I am grateful for this clarification of whatever misleading statements I have been making. I would just like to say that, from a very lowbrow point of view, there has been a great deal of effort spent by a large number of people to compute, in the impulse approximation, the isotopic spin impurities in nuclear states. Also some of these impurities are accessible by nuclear physics experiments and don't seem to be present.

ANDERSON (Chicago): In the old days the purpose of measuring the Michel parameter ρ was essentially to make a decision between 4-component and 2-component nuetrinos in β decay.

TELEGDI: In the old days it was not 4-or 2-component neutrinos, but it was to decide between two identical or two different neutrinos.

ANDERSON: Well, getting back to the point, there used to be five interaction constants, including the vector and axial vector. What can you say, in view of these more precise experiments that you reported, regarding the possible existence of the other three interactions?

TELEGDI: I said in my talk that of course one had a vast multitude of constants, such as five, if one didn't stick to the 2-component way of writing things. I also said that the experiments just do not determine those constants. In this paper by the Swedish lady physicist, there is an analysis of the type that you request, but not with the most modern numbers. I hope to revise her estimates which, of course, may lead to very pessimistic conclusions. I just wanted to emphasize here that if you are very, very modest and say neutrinos are 2-component, you can't even prove V-A, let alone the vast forest of five possible interactions. The restriction seems to be rather poor.

ANDERSON: But I am sure that if you found ρ very different from 0.75 you would make a different remark.

TELEGDI: I think perhaps that the question and the answer don't commute. Maybe I can answer in a different way. There was a time when ρ was 3/4 and δ was 3/4 and everything was wonderful; but at this point people found that the electron was 20% polarized. Instantly the theorists found a set of coupling constants that fixed up everything, including the wrong polarization. So the hopes aren't too good.

SCHARFF-GOLDHABER (BNL): I completely agree with Professor Telegdi's nut-and-screw argument concerning the meaning of our measurement and I should like to point out that the title of our contribtution was supposed to be "Indication of Parity Mixing in an Electromagnetic Transition", but the "indication" has been dropped in the program.

S. P. ROSEN (Purdue): Do you know how well the polarization of the muon from π - decay is known? There is an ambiguity in the interpretation of the whole scheme if you don't know the sign of that polarization.

TELEGDI: It is well known from three experiments.

ROSEN: In both μ^+ and μ^-?

TELEGDI: I think that the Columbia experiment, which is a Mott scattering experiment, in on μ^-. This has to be, otherwise the muon doesn't get near the nucleus. The Russian cosmic-ray experiment and the CERN experiment on this problem study the Møeller scattering of positively charged μ's. These last two experiments are statistically weaker than the Columbia experiment, but the sign is certainly well established.

MARSHAK (Rochester): In connection with the CVC question, I'd like to point out that one reason we think that it has been explained is because the Cabibbo angle comes out quite nicely. The strong evidence for the Cabibbo theory comes from strangeness violating decays and the extra assumption that $\cos^2 \theta + \sin^2 \theta = 1$. One really should have a bit of an open mind about the other possible sources of the discrepancy. Adler has mentioned one, and indeed Riazuddin, about a year ago, tried to use a model to estimate the effect of the electromagnetic interaction on the CVC using a partially conserved vector current model, and found you can get corrections of the right order of magnitude. Another possible explanation which is quite speculative, but could also come into the picture in connection with the intermediate vector boson theory of Ryan, Okubo, and myself. If you want to understand why you have such a heavy vector boson, if it exists at all, and understand the SU_3 symmetry, etc., you could have, in principle, a quadratic strong interaction of this intermediate vector boson, and still have the weak interactions come out correct. In such a theory also, one has corrections to CVC hypothesis. If the mass is several BeV, the estimates are of the same order as those given by Cabibbo theory. I just want to make clear that we are jumping the gun a bit to say we now understand completely. This is a comment, not a question.

TELEGDI: I would like to ask whether your considerations of intermediate bosons, whatever their nature may be, are tenable in view of the measured non-production of W's both here and at the AGS.

MARSHAK: If one takes the mass that is given by the experiments up to the recent one, the W would have to have a mass somewhere in the region between 2.5 and 3 BeV. Now in principle then, you could try to do the experiment with about 15 BeV anti-protons and try to find pair production of intermediate bosons in $\bar{p}p$ collisions, and that should have a large cross section. The recent experiment, of course, is greatly dependent on what the theoretical estimate of the production cross section is. If you believe a 6 BeV mass value, then of course our experiment might not even be capable of being done until we get the 200 BeV machine. But if it is still within the range of 3 BeV, then the Serpukov machine should be able to do it.

BERMAN (SLAC): I would like to make a cautionary remark to experimentalists who think they might want to study the muon decay in more detail to learn the possible 5 or 10 interaction constants. Although we normally think that a system of muons and electrons is a system where you can calculate the radiative corrections to at least the first order in α, it is not true if you write an arbitrary weak interaction between electrons and muons in the μ decay. In fact, it is only for a very specialized form that the radiative corrections are finite, and if you intend to measure the five interaction constants to a level of accuracy where you think the radiative corrections might be significant, then you have to deal with the fact that the radiative corrections are not finite for S, T and P interactions. Also, there are two classes of experiments which would be very helpful in studying

these interaction constants to the level of accuracy of their radiative corrections, and they are all involved with low energy electrons. They are at the spectrum at the very low energy end, the possible polarization of the electron at very low energies, and the correlation between electron polarization and muon polarization at low energies. None of these experiments, to my knowledge, have ever been done.

TELEGDI: As I understand, your main message is the following: If you are worried about S and T at the 30% level, you don't care about radiative corrections. At the level where you care it matters because only for V and A is there a generalized Ward theorem.

BERMAN: I don't know what the level is. Certainly, for a factor of two on the effect, you don't have to worry about radiative correction. At 30%, if you are studying a spectrum effect, you have to be careful about energy resolution where you might get very large radiative corrections.

PATI (Maryland): Could I make a small remark in connection with Dr. Adler and Dr. Marshak's comment on the Cabibbo current and the question of universality between the muon and β-decay coupling constant? As far as I can see, it is true that the Cabibbo form prescribes a relationship via SU_3 in the hadronic part. The total current is the sum of the leptonic current plus a hadronic current and, for example, (Λp), (Σn) and (pn) currents are related to each other by SU_3 plus an additional angle θ. But the relationship between the lepton current and the hadron current is not guided by any motivation and it is ad hoc. So in that sense, we shouldn't always

count upon taking the G cos θ as the term to be associated with the β-decay coupling constant and G for the μ decay coupling constant. For example, it could be G cos θ for both of them. In other words, if the total current is the sum of all terms, and if there is a guiding principle for relationship of the relative coefficients between certain terms, then presumably there should be some relationship for all the terms, including the leptonic terms.

SIRLIN (NYU): I have three quick comments. One is about the Cabibbo form of the weak hadronic current. I think there is a very profound theoretical argument by Gell-Mann that leads to this form although it doesn't specify θ . The argument has to do with the algebra of the currents, namely you observe that if one looks at the lepton current and its hermitian conjugate, these two currents with two different neutrinos define two operators which close the algebra of SU_2. And from there he postulates that the hadronic current is constructed, as mentioned by Dr. Adler, to define the same algebra. And if you look at that, that fixes the form. I think this is a very profound statement of the universality.

TELEGDI: It is a profound statement, I agree with that. I think that a simpleminded way of putting it is that if you have, say, three quarks with their symmetries, you would like to arrange μ , e and ν in the same symmetry. You want to extend this triplet of objects that transforms in a given way. You want to attribute this property to the μ , e and ν retaining the μ , e universality. But I consider it to be an esthetic principle.

SIRLIN: Then, there is the question of locality. This fixes non-locality of a certain type, for example that implied by intermediate vector bosons; but one could think of, say, the electron and neutrino coming at different space-points, etc. This is the type of non-locality that Bludman and I studied some time ago, and perhaps the $\pi \rightarrow e + \nu$ is a good test for that.

TELEGDI: In other words, my answer to the question was incorrect.

SIRLIN: Well, there are some types of non-locality involving derivatives that might be a different type; say, the electron and neutrino coming at different space-time points.

TELEGDI: I should be grateful for any theoretical formulations that enable us to use our errors to put some limit on something. I may have overlooked an important paper, for which I apologize.

SIRLIN: The last statement is about muon decay. I remember from the old work of Kinoshita and myself that we were able to write complete classes of interactions that have the same ρ and δ values. But we also remarked that if you looked at the spectrum of polarized electrons, you have much more information.

TELEGDI: Maybe I should, for the benefit of the experimentalists, explain what Dr. Sirlin just said from a practical point of view. I said that, the number of kinematically accessible quantities in μ decay is pitifully small, because the neutrinos are hard to detect. Now how does one get around this? In his paper with Kinoshita, Sirlin includes a discussion of the following variety: Assume that you had a machine that lets through only right-handed electrons,

and you put this machine in coincidence with the rest of your apparatus. You do all the μ decay experiments over again with this magnificant filter on one side that lets through right-handed or left-handed electrons only. If you impose this extra coincidence requirements, you have a wealth of new constants. But in view of the fact that even in β-decay one is trying hard to prove that the polarization is v/c to 5%, I would like to say that such filters are not available in the immediate future. The first talk in this session illustrates this fact very well.

The Case-Witwatersrand Underground Neutrino Program*

by

M. F. Crouch, H. S. Gurr, T. L. Jenkins, W. R. Kropp, F. Reines, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio, U. S. A.
and
B. Meyer and J. P. F. Sellschop
University of the Witwatersrand, Johannesburg,
Republic of South Africa
(Paper presented by F. Reines)

The following is a status report on the Case-Wits deep underground experimental program which is aimed primarily at the study of neutrinos arising from the interaction of cosmic rays with our atmosphere and secondarily at neutrinos from the sun. We already have some results to report regarding atmospheric neutrinos but we regard our work as still in the early stages: the most significant result to date is the detection of a ν_μ signal and the determination, albeit crude, of a rate.

As described in the literature, and as will be discussed by Keuffel in the following paper, the muons produced along with neutrinos as a consequence of Π, μ decay in the earth's atmosphere, are the main source of background for a ν_μ experiment which is based on the production of μ's as a consequence of ν_μ interactions with matter. Accordingly, we sought the deepest underground location possible for our laboratory - 10,492 ft. below the surface at the East

---

*Work sponsored in part by U. S. Atomic Energy Commission.

Rand Proprietary Mines, Johannesburg, South Africa. Another well-known feature of the ν_μ signal is its angular distribution which favors the horizontal for the greater neutrino energies and is more or less isotropic at lower (∿10 BeV) energies. This is to be contrasted with the muons from Π, μ(and K, 2μ) decay which are sharply peaked toward the local zenith.

Our equipment was designed with these features in mind: it consisted in the first phase of the experiment, of two parallel vertical walls of scintillation detectors 1.9 meters high and 37 meters long with a separation of 1.8 meters, Fig. 1. Each wall was made up of 18 detecting elements - lucite boxes 5.5 meters long, 5.8 cm. high, and 12.5 cm. thick, filled with liquid scintillator and viewed on the ends by four 5" photomultiplier tubes, Fig. 2. A particle penetrating an element could be located along its long axis by the ratio of photomultiplier responses, energy deposition in the element could be determined by the ratio and sum of the photomultiplier signals.

This array constitutes a hodoscope of area 110 m^2 which has a maximum sensitivity in the horizontal direction and can discriminate strongly against vertically directed particles. Fig. 3 shows the tunnel prior to installation of the detector. Figs. 4 shows a view of the equipment underground.

OPERATION OF EQUIPMENT

The outputs of each of the 144 photomultiplier tube was displayed on two oscilloscopes, one scope for each side of the tunnel, whenever a fourfold coincidence of the type A,B,C,D occurred on at least one side of the tunnel. A light pulser was routinely used at the center of each tank to check its operation and the overall electronic logic and display. Energy calibrations (± 15%) were made using cosmic rays above ground and relating them to a radioactive source as well as to the light pulser.

Data

The results to-date (October 2, 1965) are summarized in the tables. Table 1 shows all single tank events with energy deposition > 16 MeV. The period of operation covered is October 27, 1964 to October 2, 1965, and allowing for the "on time" of the equipment corresponded to a live time of

147 days of all tanks.

For our system, then, assuming all these events are due to penetrating muons from the earth's atomsphere ("ordinary" muons) we have the observed rate:

$$59 \times \frac{365}{147} = 147/\text{yr}.$$

Table 2 shows multitank events which are interpreted as single vertically travelling particles - ordinary muons. The event of 25 July appears not to fall in this category and may result from the passage of two particles.

Rate:

$$15 \times \frac{365}{147} = 37/\text{yr}.$$

Table 3 shows multitank events in which tanks on both sides of the tunnel recorded pulses. These events may be interpreted in a variety of ways:

a) multiple muons from above ground

b) inelastic event

c) bosons??

d) other?

In particular, the event of 22 August could be interpreted in at least three ways: e.g. either as

1) 3 vertically travelling μ's

2) 1 horizontal μ, 1 horizontal Π

3) 2 horizontally travelling μ's (a W?)

Rate:

$$4 \times \frac{365}{147} = 10/\text{yr}$$

Table 4 shows two-tank events involving one tank on each side of tunnel which occurred in the 147 days of full operation of the system.

Rate:

$7 \times \frac{365}{147} = 17.4/\text{yr}$ and $\pm$ 7/yr is a crude measure of the statistical uncertainty in the rate.

The sensitivity times run time of our system for such events is described by the number > 61 m^2 yrs steradians.

An analysis of the contribution to Table 4 of causes other than ν_μ interactions in the rock surrounding the detector rules against all but ν_μ in

this category. We have, in this connection considered direct cosmic ray μ's which fall into the acceptance angle of the equipment, electron showers, photonuclear processes, muon showers. Our rate of ν_μ induced events is, in these units, 0.29 m^{-2} yr^{-2} $ster^{-1}$. If we estimate from these 17.4/yr the total number of single tank events due to ν_μ and assume iostropy to obtain an upper limit we find 32/year ν_μ, 1 tank events.

Analysis of Results in Terms of ν_μ Interaction

We have analysed these results with a view to placing lower limits on the mass of the intermediate vector boson proposed by theorists as mediating the weak interaction. Our main conclusions, subject primarily to the large statistical errors indicated by ± , are these:

1) $\frac{m_w}{m_p} > 2.4 \begin{smallmatrix} +? \\ -0.4 \end{smallmatrix}$ if we make no assumptions regarding modes of W decay

2) $\frac{m_w}{m_p} > 3.0 \begin{smallmatrix} +? \\ -0.5 \end{smallmatrix}$ if we assume the W decays 1/4 of the time to $\mu + \nu_\mu$.

In arriving at these conclusions we used the machine code of Wu, et al, to calculate the cross section for W production up to 100 BeV and then used the coherent asymptotic formula of Lee, Markstein, and Yang above 100 BeV. Table 5 summarizes the values of these cross sections up to 100 BeV. In addition we assumed a zero anomalous magnetic moment for the W(K=0) and a product muon energy of $E_\nu/7$, on the average. According to calculations of Von-Gehlen, the prompt muon actually receives much more of the energy than this so that we are making a conservative assumption, i.e. one which will give a lower W mass limit.

With these factors in mind and allowing for the difference between rock (mainly SiO_2) and aluminum, we used a ν_μ spectrum folded into our detection efficiency, allowing for angular aperture and muon range to obtain a predicted rate of 4 or 8/year, depending on whether we make assumption (1) or (2).

In order to arrive at the m_w limit we must estimate how many of the observed 17.4/year (± 7) are not accounted for by known neutrino interactions. Table 6 summarizes these expectations. Inelastic events due to E_ν < 10 BeV

were predicted using measurements of the CERN neutrino group. An estimate was made of the total number of inelastic events due to higher energy ν_μ, assuming a constant cross section above 10 BeV with the resulting rate of 2.7/year. It should be emphasized that although we don't know this cross section it is reasonable to expect it to continue increasing with energy as more reaction channels appear. The situation is complicated by the dependence of detection efficiency on the range of the product muon which may not increase linearly with ν_μ energy because of the energy taken off by the other particles produced.

The total expected elastic and inelastic on this basis is 9.4/year leaving 17.4±7 - 9.4 = 8±7 /year to be accounted for.

Though the spirit of the above estimate has been to take a conservative view, in which we attributed all possible counts to the W in the attempt to obtain a firm lower limit on the mass, we are saddled with large statistical uncertainties as indicated by the ± on the mass limits quoted at the beginning of this section. More machine calculations will be done as well to establish even more closely accuracy of asymptotic limit for the coherent cross section since it dominates the interaction at the higher energies. It is interesting that the limits arising from these early data already begin to compare favorable with those produced at high energy machines.

FUTURE PLANS

ν_μ

It is clear from the foregoing that we require more events and more information per event. With this in mind we have already enlarged our array to include 50% more detectors of the kind described and have added two direction sensing sections using Cerenkov detectors to "put a head on the arrow". The entire 67 meter long system now exists and should be completely operative in the next few months.

Fig. 5 shows the Cerenkov tanks with the light tight covers removed. Fig. 6 shows Cerenkov sections plus an end view of the regular scintillation bays.

A further, and somewhat more extensive, modification of the equipment is also underway. We are now preparing a new laboratory at a slightly deeper level in the East Rand Proprietary Mine, near Johannesburg. It will be at the depth of $\sim$ 10,650 ft. (8500 m.w.e.) and is designed solely for the task of neutrino studies. The new detecting array is planned to use the present scintillation counters as triggers for an extensive spark chamber system now being designed. We look forward to an increase in sensitivity over our present array by a factor of five together with the detailed information on track orientation from the spark chambers. The planned detector will have a scintillation-spark chamber array 2 meters high and 120 meters long.

ν_e

In addition to the work described, we have been studying the problem of the detection of solar ν_e using the elastic scattering process

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

It will be recalled that according to ideas of Fowler and others the sun produces B^8 which decays to give at earth $\sim 10^7$ cm^{-2} sec^{-1} of end point energy 14 MeV. We have studied the background seen in our large area (and large volume - 16 tons) detector in the energy range 6 - 14 MeV and find a predicted signal/background $\sim$ 1/70. Since the surface to volume ratio of the array was made large because of the requirements of ν_μ detection and the energy resolution is based on the higher energies associated with ν_μ, it is clear a specially designed detector would be much better suited to solar ν_e detection. Such a detector has been designed and is now being built. It is essentially nothing more than a pot filled with 1000 gallons of scintillator viewed by $\sim$50 photomultiplier tubes. The signal expected is $\sim$ 10/year with a background somewhat below this value. It would be nice to see the sun via its neutrinos and detect the elastic scattering reaction at the same time!

ACKNOWLEDGMENT

We wish to thank Mr. A. A. Hruschka for his help in the design and construction of the detector and laboratory. Mr. B. Shoffner designed and supervised construction of much of the electronics. The hospitality of the East Rand Proprietary Mines is gratefully acknowledged.

REFERENCES

A. C. T. Wu, Chen-Ping Yang, Kurt Fuchal, and Sidney Heller, Phys. Rev. Letters 5, 94 (1964).

We are indebted to Kurt Fuchel for the loan of their machine code.

Burns, Goulianos, Hyman, Lederman, Lee, Mistry, Rettberg, Schwarts, Sunderland and Danby, Phys. Rev. Letters 15, 42 (1965).

Lee, Markstein, and Yang, Phys. Rev. Letters 7, 429 (1961).

Reines, Crouch, Gurr, Jenkins, Kropp, Smith, Meyer and Sellschop, Phys. Rev. Letters 15, 429 (1965).

TABLE 1

Single Tank Events
[October 27, 1964 to October 2, 1965]

Date	Time Greenwich (h)	Tank	Energy Deposited (MeV)	Location Distance from North End (ft)
9 Nov. '64	00:48	E1L	45	-
23 "	16:05	E1L	48	-
25 "	15:09	E1L	63	-
14 Feb. '65	02:52	W5M	26	-
24 "	15:04	W2M	39	-
11 Mar.	11:03	E4L	54	-
11 "	21:40	W5M	51	-
12 "	15:38	E2L	26	-
22 Apr.	05:40	E1L	115	4.0
30 "	04:35	W5L	29	8.0
7 May	01.11	E2U	43	8.5
7 "	08:56	E3L	76	0.5
10 "	14:08	E3U	48	4.0
13 "	20:57	E4L	27.5	10.2
14 "	10:15	W4L	19.5	6.6
14 "	04:06	W5U	24.2	11.9
20 "	21:50	E1L	26.5	1.5
22 "	23:20	W1M	370	7.0
26 "	19:35	W2L	30	0.5
29 "	04:51	E3M	80	17.5
10 June	11:06	W4M	90	6.5
10 "	18:27	E4U	88	17.5
10 "	20:36	W2U	27	5.2
12 "	22:01	E5L	18	8.5
14 "	01:49	E1L	30	8.0
14 "	22:34	E1U	71	13.0
15 "	09:07	W1L	24	9.0
16 "	06:37	W5M	100	2.0
22 "	23:43	E2U	16.5	10.0

TABLE 1 (cont.)

Date	Time Greenwich (h)	Tank	Energy Deposited (MeV)	Location Distance from North End (ft)
1 July '65	20:44	W3M	16.5	4.0
6 "	01:17	W1L	18.5	11.0
6 "	07:35	W4M	89.5	8.5
6 "	08:13	W6L	37.5	7.0
8 "	05:12	E2U	16.0	8.0
8 "	06:56	W4M	82.0	16.0
9 "	05:52	W1L	39.0	6.0
10 "	03:18	E6U	25.0	7.5
10 "	20:42	W1M	22.5	9.5
13 "	02:07	W2M	21.6	12.5
14 "	02:24	W5M	27.0	11.0
23 "	20:32	W6U	46.0	17.0
25 "	12:50	W4L	41.0	17.5
4 Aug.	21:04	W3L	25.0	10.0
5 "	14:01	E3M	29.0	7.0
8 "	08:02	W5U	122.0	16.0
12 "	17:42	W4M	78.0	17.0
16 "	06:48	E4U	34.0	13.0
26 "	23:52	E3U	78.0	15.5
27 "	02:24	E2L	37.5	11.0
1 Sept.	11:35	W3M	87.0	11.5
5 "	01:24	W4L	47.0	16.0
9 "	23:35	W1L	57.0	2.0
11 "	05:42	E4M	41.0	16.4
11 "	23:48	E5M	19.5	8.0
12 "	14:33	W2L	32.0	3.0
13 "	00:32	E4M	88.0	1.0
16 "	05:70	E2L	38.0	1.5
30 "	01:45	E1L	No calibration as yet.	
1 Oct.	04:31	W3M	No calibration as yet.	

During this period the full 36 element system operated for 147 days and recorded 59 events.

TABLE 2

Multitank Events (on one side of tunnel).

Date	Time Greenwich	Tank	Location of Event (meters from north end)	Energy Deposited in Detector (MeV)
13 Dec., '64	10:31	E2M	3.4	75
		E2L	2.1	59
22 "	11:03	E1U	3.7	37
		E1M	4.3	51
		E1L	4.6	16
11 Feb., '65	02:20	E1U	1.7	84
		E1M	1.6	78
		E1L	1.8	21
7 May	02:10	W5M	1.8	65
		W5L	1.4	97
12 June	13:40	E3U	3.9	60
		E3M	3.4	122
		E3L	1.7	19
*25 July	19:40	E4U	0.9	79
		E4M	0.6	11
		E4L	3.4	19
12 Aug.	05:44	W3U		4.5
		W3M	0.3	120
		W3L		13
21 Aug.	04:23	W2U		31
		W2M	1.4	51
		W2L		6.5

There are, in addition to those listed, 7 2-tank events observed for which the calibration is not yet available. [13, 15, 24, 28 July; 24, 26 Aug; 1 Sept. All are in adjacent tanks.]

15 Events, 147 Days Operation

Notes: Event of *25 July may be 2 or more particles since event in E4L is not near events in other two detectors and a small pulse appeared on the W side, W4M-B tube.

Events of 12, 21 Aug. are abritrarily assumed to be same tank location because information incomplete.

TABLE 3

Multitank Events (on both sides of tunnel)

Date	Time Greenwich (h)	Tank	Location of Event (meters from north end)	Energy Deposited in Detector (MeV)
27 Oct., '64	19:39	E1M	3.6	58
		E1L	?	~ 10
		W1U	1.1	158
		W1M	2.3	116
		W1L	2.4	37
14 Feb. '65	22:35	E4M	3.9	65
		E4L	?	?
		E5M	0.09	51
		W4M	2.9	49
		W4L	4.2	34
*28 June	22:39	E2U	3.0	55
		W2U	2.7	10
		W2M	2.7	6.5
22 Aug.	03:37	E3L	1.5	94
		W3L	1.4	59
		W4L	0.46	69

*We have our doubts about this one because of similar pulse behaviour on immediately subsequent run.

4 events, 147 days operation

TABLE 4
Neutrino Events

Eightfold events (coincidences involving one element of each side).
Run time for events was 879 bay days (147 days).

Date	Time Greenwich (h)	Tank	Location of Events (meters from north end)	Energy Deposited in Detector (MeV)
23 Feb., '65	21:48	E4L	2.1	29
		W4L	2.8	18
1 Mar.	00:20	E5M	0.03	55
		W5U	4.9	118
17 Mar.	18:52	E4L	3.6	19.4
		W4L	1.7	16.0
20 Apr.	14:16	E2M	4.6	23.5
		W2M	3.4	24.5
1 June	22:37	E1L	5.5	18.5
		W2L	0.55	18.0
3 June	01:42	E4U	2.4	5.0
		W4M	3.7	18.0
1 July	15:21	E3M	1.3	21.0
		W3U	3.0	30.0

TABLE 5

Results of W Production Cross Section Calculations Based on Machine Codes of Wu, et al for Al $\frac{m_W}{m_p} = 3.0$

E_ν (BeV)	σ coh. (cm^2/Al)	(p) σ incoh. (cm^2/Al)	(n) σ incoh. (cm^2/Al)	σ total (cm^2/Al)
15	0	1.8×10^{-37}	0.75×10^{-33}	2.6×10^{-37}
38	0	2.4×10^{-36}	0.53×10^{-36}	3.0×10^{-36}
100	5.3×10^{-36} (8.1×10^{-36} L.M.Y. asymptotic limit)	7.9×10^{-36}	1.04×10^{-36}	1.38×10^{-35}

TABLE 6

Summary of Predicted ν_μ Rates

Elastic	2
Inelastic (<10 BeV)	4.7
(>10 BeV)	2.7
Boson $\frac{m_W}{m_p} = 2.4$ assumption 1	8
$\frac{m_W}{m_p} = 3.0$ assumption 1	

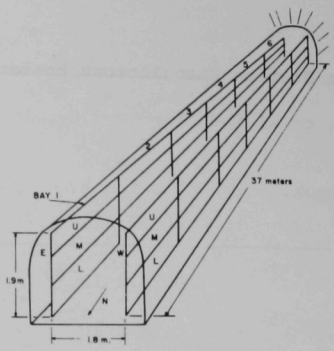


Fig. 1. Schematic of Detector Array

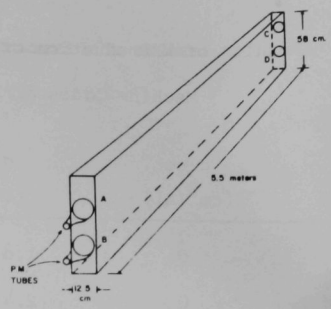


Fig. 2. Sketch of Detector Element

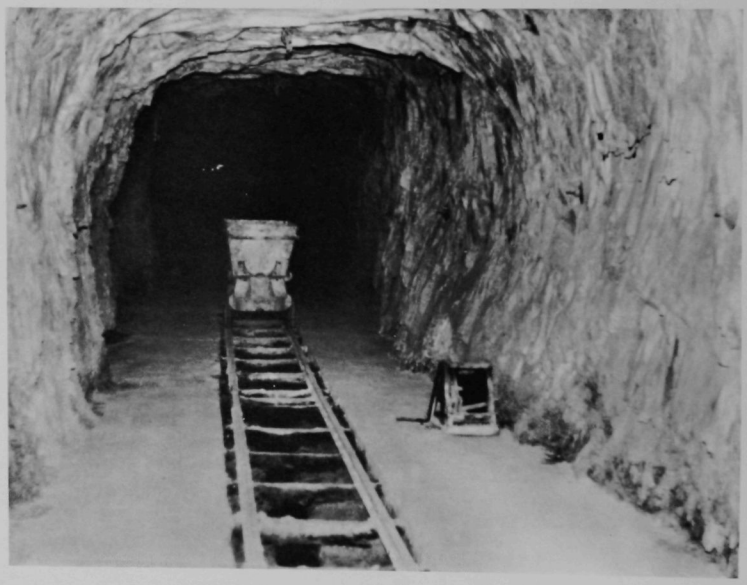


Fig. 3. The Tunnel Prior to Installation of the Detector

Fig. 4. A View of the Equipment Underground

Fig. 5

The Cerenkov Tanks with the Light-tight Covers Removed

Fig. 6. The Cerenkov Sections Plus an End View of the Regular Scintillation Bays

DISCUSSION

YOVANOVITCH (Argonne): Your number should probably be expressed as 8 ± 6 and, together with the uncertainty of your events, perhaps even 8 ± 8, shouldn't it?

REINES: I won't argue about this. I don't know how to take the square root of seven or eight, or even nine, and all I've done here was indicate an approximate doubling of the uncertainty.

COOL (BNL): Eventually, when the statistics are better, how do you plan to disentangle the energy dependence of the cross sections for the ordinary elastic and inelastic events which you wrote down here, in order to make the necessary subtraction to estimate the W production cross section? Is there any hope to disentangle these from the data you can get?

REINES: No, I don't think so. All we can do is first get better statistics. Now if someone sees something that is unequivocally a boson that will help a great deal, obviously. But in the absence of such a happy event, we can improve the statistics and leave it up to the theorists to tell us what one expects of a boson that has a given mass. That limitation applies equally to all such experiments whether cosmic-ray or accelerator.

TELEGDI (U. of Chicago): Leaving aside all these delicate matters of what makes a muon, and taking a very lowbrow view, in this very small and ill-defined number of events, can one find any clue as to why the flux of neutrinos, if you don't assume a W, is anomalously large? There is this uncertainty; you can compute the cosmic flux all you wish, but you can't predict the Crab nebula from Maxwell's equations.

REINES: That's only because you don't know the initial conditions. What we did with these paltry few numbers was to say, "Which way was our telescope pointing as we rode on our well-equipped satellite?" We couldn't find any correlation with anything except that the particles seemed to be horizontal in our frame of reference. Since the earth was certainly whirling about and doing all sorts of wonderful things, it didn't have any correlation with a fixed direction. But it's something that one should look for, and as better angular

resolution and better sensitivity are achieved, one should keep the clock going; it matters what time it is.

PAL (Tata Institute, Bombay): Regarding Telegdi's question, I think that one has some limit on the cosmic neutrino flux from various sources. You see if neutrinos are made, then pions must be made since the neutrinos come from π-decays. If charged pions are made, then neutral pions are made, and so we must have gamma rays. On gamma rays one does have experimental limits, and if one translates them into neutrino limits, then they are of the order of one to a hundred per meter-square per year from various sources. So this is an upper limit. This flux is certainly much smaller than the cosmic flux.

REINES: That's what the gamma-ray astronomers are hanging on, of course. They're hoping for a source of signal that would give neutrinos by Pal's argument. Each year the theorists lower the limit to keep up with the experiment.

LEDERMAN (Columbia): The flux in cosmic rays comes from pions, kaons, and muons. What would be a reasonable conservative estimate of the uncertainty of this flux?

PAL: I think that it's of the order of 20 or 30%. Various calculations give results that fluctuate around this value, and I think most of the calculations agree within that. The chief uncertainty comes from the assumption of how many kaons you have produced at high energies. But since one is working essentially with a horizontal beam here, an uncertainty in kaon ratio doesn't affect the flux. So I would say about 30% is the upper limit.

REINES: The K/π ratio is gotten by polarization measurements.

PAL: I would like to point out that this is really a measured quantity, because one has measured the muons up to 1000 BeV or higher and the neutrino spectrum is related very intimately to the muon spectrum. That's why one says the error is not more than 30%.

GOLDHABER: In your solar neutrino search how do you distinguish background and signal? All individual events would look alike. How can you calculate background?

REINES: In order to answer this, I must make a philosophical remark. If I can get a signal, then I'll test it. Obviously you can always get a signal of some kind, by forgetting a radioactive source in front of one of the photomultiplier tubes. On the other hand, if we ask for a system which requires more than 5 MeV, and if we have a detector which collects so many protons that the statistical fluctuation in the number of protons can be distinguished from contamination by say, ThC; if we know for sure that the total number of muons and anything they are going to produce is negligible on our scale; if we know all this, then if we see a spectrum that looks the way one would expect a spectrum to look from this process, then you say "I think I have a signal," and you can either call it an upper limit or believe it's a signal. If I believe it's a signal, I think I would have some clue as to how to test it. But I couldn't test it with that detector particularly.

WENTZEL (Chicago): I wonder if Professor Pal could give away the number of events that the Kolar mine group has seen up today?

CHAIRMAN: I think Professor Keuffel is going to discuss the Kolar results at some length.

REINES: I refrained from saying anything about the Kolar work because I know that Professor Keuffel is going to present this. So I'm restraining myself to our own small bailiwick.

HILDEBRAND: I think we'd better limit it to about two more questions.

NOVEY (Argonne): Do you imply that the 59 events that you see in a single counter are not from cosmic ray muons? Do you say that you know that the cosmic ray muon intensity is essentially zero? Or is there something else that you think this is a measure of?

REINES: Oh no, that wasn't what I intended to imply. I must clarify this point. As far as we can tell, these are sister muons. These are the only ones that arise in the earth's atmosphere and come down. There is a correction to be made; namely, some of these must be associated with neutrinos, but not very many. After all, it's 30 or so per year out of 150 or more. By the way, this number for the muon intensity underground is in reasonable agreement with an extrapolation which is made from the Kolar gold-field work, when they were doing underground muons and so on. The only startling

thing about it is that they're there, and we've seen them.

SCHWARTZ (Columbia): I wonder if you have calculated in detail the scattering of muons as they come down, and if you can give us some feeling for the extent to which they can scatter into an angle of the order of 90°?

REINES: I have looked at it, yes. It's an electromagnetic process. It is much less than one per year. It just isn't a source of background. I can dig out the exact number, but it is just negligible on our scale.

PARKER (U. of California, Berkeley): There was some other process that you mentioned in your talk at Berkeley. Have you calculated the knock-on electrons from muons? I presume you got a small number for that too.

REINES: Yes.

COSMIC-RAY NEUTRINOS

J. W. Keuffel
University of Utah, Salt Lake City, Utah

I. INTRODUCTION

This paper has three purposes: To introduce to the accelerator physicists at this meeting the subject of high-energy cosmic-ray neutrinos, to survey the experiments which are presently being done in this field, and to give some idea of the type of data which may be expected in the immediate future. Since a report on the Case Institute-University of Witwatersrand experiment in South Africa is included in the program, emphasis will be placed on the University of Durham-Tata Institute-Osaka City University collaboration experiment in the Kolar Gold Fields in India (KGF experiment). Brief mention will be made of the University of Utah detector now in the prototype testing stage.

Since the production of the celebrated intermediate boson (W-particle) seems to be beyond the reach of the CERN and Brookhaven machines, it behooves us to see what can be done with the feeble but energetic cosmic-ray beam. And the first results are certainly encouraging: the rates are higher by a factor of a few than had been anticipated, while background problems seem not too serious. There are hints of possible new phenomena. High-energy neutrino astronomy is being considered as a serious possibility for the not-too-distant future.

II. THE COSMIC-RAY NEUTRINO BEAM

The cosmic-ray neutrino beam may be divided into two components, the atmospheric neutrinos and the cosmic neutrinos. The first component is very likely dominant. We shall touch only briefly on the latter at the end. The atmospheric neutrinos are the decay products of pions, kaons, and muons produced high in the atmosphere by the primary protons. They have a horizontal maximum with the ratio of horizontal to vertical flux ranging from about 2.5:1 to 7:1 in the energy range 10 to 1000 GeV. This behaviour results from the competition between decay and interaction of the parent pions and kaons; the rarer atmosphere encountered by a horizontally-inclined pion, for example, favors the decay process which produces the neutrinos. A horizontal muon also has a much better

chance to decay because of the longer flight path prior to striking the earth. The contributions from the decay of pions, kaons, and muons are comparable over most of the energy range up to 1000 GeV.

Because of the genetic relations between muons and neutrinos, the neutrino flux can be inferred from the cosmic-ray muon spectrum. Calculations of this sort have been carried out by several authors.[1,2,3,4] The resulting neutrino spectra are in agreement within 20%, but all depend on the cosmic-ray muon spectrum, which is beset with uncertainties above 100 GeV. Another systematic uncertainty arises from the poorly-known cosmic-ray K/π ratio. The recent calculations take a K/π ratio of about 20% (all kaon charge states to all pion charge states.) Changing this ratio to zero or to 40% changes the horizontal muon flux by about ± 12% at 100 GeV, but the uncertainties grow larger at higher energies.

A power-law fit to the spectrum of $v_\nu + \bar{v}_\nu$, good to about 10% over the energy range 2 - 100 GeV is given by Cowsik et al[4] as

$$n(E) = 0.058\ E^{-2.89}\ (\mathrm{cm}^2\cdot\mathrm{sec.ster.GeV})^{-1}.$$

At 10 GeV, this is about $0.74 \times 10^{-4} (\mathrm{cm}^2\cdot\mathrm{sec.ster.GeV})^{-1}$. For comparison, the average neutrino flux at the AGS is about 10 $(\mathrm{cm}^2\cdot\mathrm{sec.ster.GeV})^{-1}$ at the same energy, but is of course falling extremely rapidly, with a cut off not much higher than 10 GeV.

III. THE ATTENUATION OF COSMIC-RAY MUON INTENSITY WITH DEPTH

The interpretation of the existing results on natural neutrinos depends critically on a knowledge of the depth and zenith angle dependence of the remanent underground cosmic-ray muons. The situation has been reviewed by Menon and Ramana Murthy.[6] The most recent measurements, at the greatest depths, are those of Miyake, Narasimham and Ramany Murthy.[6a] Their results for the muon intensity as a function of depth are shown in Fig. 1. Also shown in this figure are the results of Castagnoli[7] and of the neutrino experiments themselves. (We shall return to a discussion of the latter points shortly.) Beyond a depth of 4000 mwe, the curve is almost a pure exponential with an attenuation length of 700-800 mwe. This is a consequence of the fact that at an energy of about 1000 GeV, corresponding to a mean range of some 2500 mwe, bremsstrahlung and pair production

losses for muons become of the same order as the ionization losses, and much beyond that, they dominate.

From the vertical depth-intensity curve, it is possible to construct a curve giving the effective angular dependence of the underground remanent muons as a function of zenith angle. Account must be taken of the increased intensity of very high-energy muons arriving at the surface of the earth at large zenith angles, an effect which can amount to about a factor 10 with a curved atmosphere. The result of such a calculation by the KGF group[8] is shown in Fig. 2.

IV. THE KGF EXPERIMENT

The KGF experiment,[9] like the Case-Wits experiment described elsewhere in these proceedings by Reines, takes advantage of the almost-complete shielding obtainable at great depth, and the steep angular distribution of the remanent atmospheric muons. If very few near-vertical muons are observed, a near-horizontal muon can safely be assumed to come from a neutrino interaction in the surrounding rock. Two very-wide-angle scintillator telescopes are used. Each telescope consists of two vertical walls of plastic scintillator 2 m long and 3 m high, separated by 80 cm as shown in Fig. 3. The walls are divided into modules 1 m^2 in area viewed by two photomultipliers. Three neon flash tube arrays separated by two lead walls 2.5 cm thick are located between the scintillator walls. The flash tubes are triggered on fourfold coincidences between any module on one side and any module on the other.

The visual indication afforded by the flash tubes not only permits the determination of the projected zenith angle to a precision of about 1° but also greatly clarifies the interpretation of the events. Electrons can be separated from pions and muons, but the absorber is not thick enough to distinguish π from μ. The effective aperture of the two telescopes together is about 40 m^2.ster for an isotropically-distributed radiation such as the neutrino-induced muons. The effective aperture for a $\cos^8\theta$ distribution is 0.58 m^2.ster.

The apparatus has been operated over a period of about 7 months at a depth of 7500 mwe of standard rock.

A total of 15 events have been recorded as of October 10. The categories are recorded in Table I. The zenith-angle distribution of the 8 events

Table I. KGF Events as of October 10, 1965

Exposure: 6800 m^2.ster for an isotropic radiation

Penetrating particle passing through two scintillators		
(a) Proj. zenith angle $< 60^\circ$	8	
(b) Proj. zenith angle $> 60^\circ$	2	10
Large shower		1
Penetrating particle present, but soft secondary triggered scintillator		3
Event prior to installation of flash tubes (proj. zenith angle $> 37^\circ$		1
Total		15

Note: After flash tubes were operational, no events without flash-tube indications have been seen.

obtained to the end of August is plotted in Fig. 4. The two events with large zenith angles are interpreted by the KGF group as neutrinos with fair certainty, and they estimate that between 2 and 4 of the other events can be attributed to neutrino interactions.

Curve (a) in Fig. 4 results from folding in to the assumed $\cos^8\theta$ dependence on projected zenith angle the geometrical aperture for the apparatus. The 8th-power law is a conservative estimate obtained from Fig. 2. Curve (b) shows the zenith-angle response to an isotropic radiation. Neutrino-induced muons are expected to be nearly isotropic. The argument to be made then is that, were the horizontal muons part of the remanent atmospheric distribution, a very large number of muons would appear between 20° and 40°, and this is not observed.

A similar argument can be made about scattering and the products of nuclear interactions of the muons. All of these would be expected to exhibit a steep zenith-angle distribution. Also, scattering can be ruled out because the remanent muons at this depth have such a high mean energy.

One of the near-horizontal events is especially interesting and is depicted in Fig. 5. There are two tracks, one at a projected zenith angle of 99° and the other at 96°. Both particles travelled ~ 9 radiation lengths without multiplication or large-angle scattering, and are thus not electrons. One of

the particles apparently had a sufficient inclination, viewed from the top, to miss one corner of the flash-tube array. The meeting point of the two tracks could be close to the surface of the rock wall, or up to a distance of one meter inside the rock. The event therefore represents a clear case of the non-elastic interaction of a neutrino, coming from below the horizon.

The event listed as a large shower in Table I is unfortunately too complex to be analyzed with confidence. Both telescopes, which are separated by 20 ft. along the tunnel, were struck and nearly all the flash tubes in the one of them discharged. The KGF group state that the most likely explanation involves an electromagnetic shower of several hundred GeV arising in one wall of the tunnel and travelling with a fairly large zenith angle, though the zenith angle cannot be established with certainty. They mention the event only to indicate the type of phenomena which may be encountered as this area of research expands.

For their best value of the neutrino-induced muon flux underground, the Tata group take 5 events in 6800 m^2.ster.days or a flux of 0.85×10^{-12} $(cm^2.ster.sec)^{-1}$

V. THE CASE-WITS EXPERIMENT

The experiment of Reines et al[10] is described elsewhere in these proceedings. It is similar in approach, with pairs of parallel, vertical scintillator elements set up to detect horizontal muons. The aperture is larger (150 vs. 40 m^2.ster) and the depth is greater (8400 vs 7600 mwe of standard rock), but there is no visual recording of the particles nor absorber between the scintillators.

In 16,000 m^2.ster.days, 7 horizontal muons were observed, or a flux of 0.36×10^{-12} $(cm^2.ster.sec)^{-1}$. The results of the two experiments are in satisfactory agreement, considering the small number of events, and for the moment we may take for the combined value 12 events in 22,800 m^2.ster.days or 0.48×10^{-12} $(cm^2.ster.sec)^{-1}$.

VI. INTERPRETATION OF THE RESULTS

Calculations of the expected rate of muon-induced neutrinos have been made by several authors. .We quote here the results of the KGF calculations as

presented by Menon at the London Cosmic-Ray Conference. Using the neutrinos fluxes of Cowsik et al,[4] and the indicated cross-sections and fractional energy transfers to the muon, the rates are as given in Table II.

Table II. Rates of Neutrino-Induced Muons

Process	Cross Section (cm^2)	Fraction of E_ν retained by muon	Rate $(cm^{-2}.ster.sec)^{-1}$
(a) Elastic $\sigma_{el} = 0.75 \times 10^{-38}$ per n-p pair		1.0	0.065×10^{-12}
(b) Inelastic (i) $\sigma_{inel} = 0.45 \times 10^{-38}$ E_ν (1-10 GeV)		1/2	0.17
	0.45×10^{-37} (10 GeV up)	1	
(ii) $\sigma_{inel} = 0.45 \times 10^{-38}$ E_ν(all E)		1/2	0.29
(c) Boson Production $m_W = 2.5$	Cross-sections of Wu et al[11] up to 20 GeV, joined to Von Gehlen[12] asymptotic expression at 100 GeV	(i) 0.15 (see note)	0.13
		(ii) 0.55	0.46
(d) Experiment (KGF and Case-Wits Combined)			0.48

Note: These are two extreme limits of the combined fraction of E_ν given both to the associated muon and the muon from W-decay (branding ratio $W \rightarrow \mu + \nu / W \rightarrow$ all = 0.4). See London Conference report.[9]

The sum of the contributions from the elastic cross section and the steadily-rising inelastic cross section (ii) is 0.36×10^{-12} $(cm^2.ster.sec)^{-1}$. These two processes can account for the observed rate, in view of the small number of observed events and the uncertainties in the theoretical predictions.

The existence of the boson is not required by the data, although there is certainly room for it. Proof of the existence of the boson, or a better

lower limit on its mass, are probably within reach of cosmic-ray experiments only if the muon spectrum can be measured, or if two-muon events can be established as such by following the tracks of the two particles through many interaction paths of material.

VII. FUTURE PLANS

The KGF group are planning to double their array, and also to add trays of flash tubes at right angles to the existing ones so as to determine the trajectory in two dimensions. This will aid in establishing the vertex of two-prong events coming from deep within the rock, and to check such events for the scattering expected of pion secondaries. It will also help in the search for cosmic neutrino sources. The plans of the Case-Wits group will be discussed elsewhere in these proceedings.

A very large detector is now under construction at the University of Utah, using a quite different approach.[13] The detector will be of area comparable to the Case-Wits set up, but very much thicker ($10 \times 10 \times 6\ m^3$) It will resemble in some respects a multiplate spark chamber such as those used in the Brookhaven or CERN experiments, but scaled up by a factor of 200 in mass. The parallel-plate spark gaps are replaced by trays of cylindrical spark counters of novel design, and the trigger function is provided by water-filled Cerenkov counters

The cylindrical spark counters, resemble giant Geiger tubes 15 cm in diameter by 10 m long. With a filling of 50 cm argon and 25 cm ethylene, the discharge is a sharply-localized corona spike, which may be located by a simple sonic technique to an accuracy of $\pm$ 3 mm. Four Cerenkov counters will trigger an array of 500 spark counters and determine the sense of travel of upward-going muons produced by neutrinos. A counter consists of a water-filled concrete tank $6 \times 10 \times 1\ m^3$ painted black inside. Each $6 \times 10\ m^2$ surface is covered by an array of 113 light-collector elements. By recording separately the pulses from each face, the sense of travel of the muon may be determined.

The detector will be located in a nearby mine at a depth of about 1500 mwe. The expected flux of background muons through the aperture of the instrument is still about $10^6\ yr^{-1}$. However, since the sense of travel of a high-energy muon secondary from a neutrino interaction can be unambiguously determined

(in the most favorable case by four independent Cerenkov measurements and three time-of-flight measurements) the upward-going muons should furnish a background-free signal despite the relatively shallow depth. Also, neutrinos interacting within the detector volume will probably be easy to identify, even for downward-going neutrinos. Data recording will be entirely in digital form on magnetic tape, so that the tape may be fed directly into a computer. The system allows the unambiguous recording of more than one pulse from the same counter and makes for a very compact record on the tape.

The aperture-area factor for upward-going energetic particles is about 160 m^2 ster. For events where the secondary muon range is less than one module ($\sim$ 2 GeV) the effective aperture-area factor is six times this large. The energy spectrum of the secondary muons can be determined by range measurements up to about 5 GeV, and estimated by multiple coulomb scattering to perhaps 100 GeV. The angular resolution of the instrument itself will be about 10^{-6} ster, which will be important for possible neutrino astronomy.

A half-scale prototype detector above ground, with 2 Cerenkov tanks and 110 counters, has just been completed. All elements including the almost-complete electronic system to be used in the mine, are functioning with apparently only minor bugs to be ironed out. The underground detector should be operating by the spring of 1066.

VIII. NEUTRINO ASTRONOMY

With regard to the possible flux of cosmic neutrinos from such sources as supernovae envelopes and quasars, much less can be said. It was once thought that the energetic electrons in the crab envelope were the decay products of the pion-muon chain, in which case one would expect to see neutrinos and γ rays also. However, the present-day experimental limit[5] on high-energy γ rays is so low as to indicate that cosmic sources of any sort do not play a role in current experiments unless there are unknown mechanisms which produce neutrinos without γ rays, or absorb the γ rays before they reach the earth.

Speculation on the detection of high-energy neutrinos from astronomical objects has centered around the Glashow resonance reaction

$$\bar{\nu}_e + \bar{e} \rightarrow W \rightarrow \bar{\nu}_\mu + \bar{\mu}$$

which has a very large cross-section (10^{-30} to 10^{-31} cm^2 when averaged over the

doppler smearing of the target electrons). However, the resonance energy is extremely high: $E_r = m_w^2 \times 10^{12}$ eV, with the boson mass in GeV. It will certainly be of interest to look in the direction of the more exotic astronomical objects with neutrino detectors of high-angular resolution. A few counts per year might be possible in the Utah detector without violating the present γ ray limits.

REFERENCES

1. K. Greisen, Proc. Int. Conf. on Instrumentation for High-Energy Physics, New York, Interscience Publishers, p. 209 (1960).
2. Zatsepin and Kuz'min, Soviet Physics JETP 14, 1294 (1962).
3. Osborne, Said and Wolfendale, Proc. Phys. Soc. 86, 93 (1965).
4. Cowsik, Pal and Tandon, Proc. Ind. Acad. Sci. (to be published)
5. G. Garmire and W. L. Kraushaar, Space Sci. Rev. 4, 123 (1965); See also Cowsik, Pal and Tandon (loc. cit.).
6. M.G.K. Menon and P. V. Ramana Murthy, Progress in Cosmic Ray and Elementary Particle Physics - Vol. IX (in press).

6a. Miyake Narasimham and Ramana Murthy, Nuovo Cimento 32, 1505 (1964).

7. Castagnoli, DeMarco, and Scrimaglio, Nuovo Cimento 33, 722 (1964).
8. A. W. Wolfendale, private communication.
9. Achar, Menon, Narasimham, Ramana Murthy, Sreekantan, Hinotani, Miyake, Creed, Osborne, Pattison, and Wolfendale, Phys. Lett. 18, 196 (1965) and in press; See also Proceedings of the London Cosmic-Ray Conference, September, 1965, papers MU-NU 33 and 34.
10. Reines, Crouch, Jenkins, Kropp, Gurr, Smith, Sellschop, and Meyer, Phys. Rev. Lett. 15, 429 (1965).
11. Wu et al, as quoted by Burns, Goulianos, Hyman, Lederman, Lee, Mistry, Rettberg, Schwartz, and Sunderland, Phys. Rev. Lett. 15, 42-44 (1965).
12. G. von Gehlen, Nuovo Cimento 30, 859 (1963)
13. Bergeson, Hilton, Keuffel, Morris, Parker, Stenerson, and Wolfson, Proceedings of the London Cosmic-Ray Conference, September, 1965.

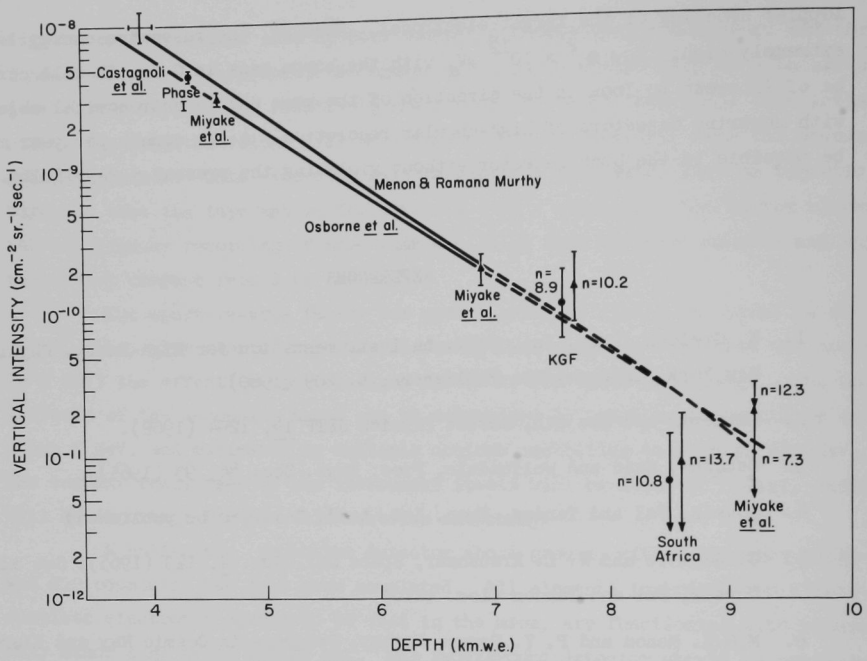


Fig. 1. Vertical Depth-Intensity Curves for muons. The two lines refer to independent surveys by the authors shown.

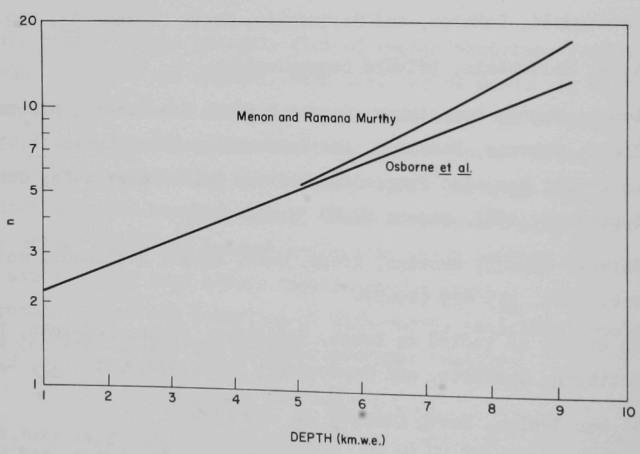


Fig. 2. Depth Dependence of the Exponent, n, of the Zenith-angle Distribution of muons, $\cos^n\theta$. Taken from the two curves of Fig. 1.

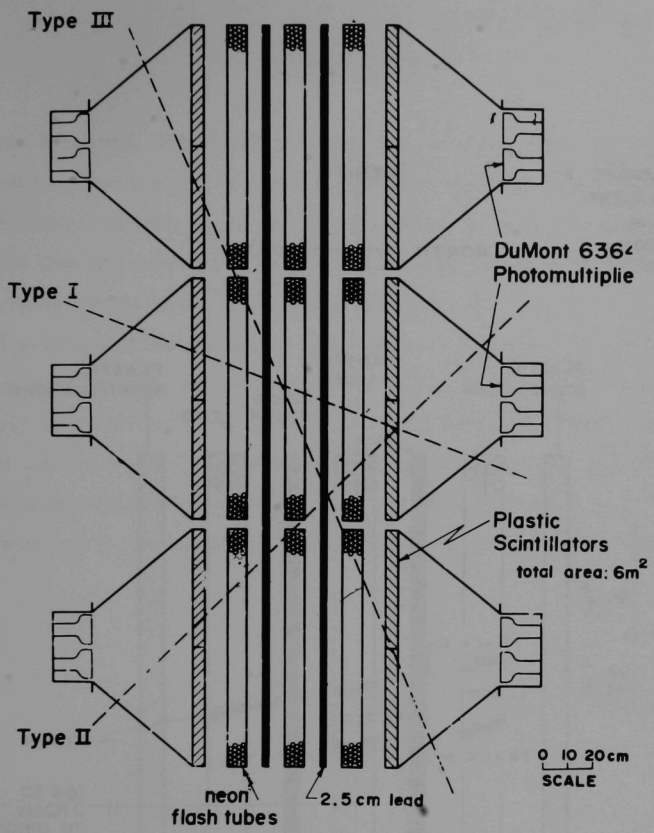


Fig. 3. KGF Neutrino Telescope. (Front View)

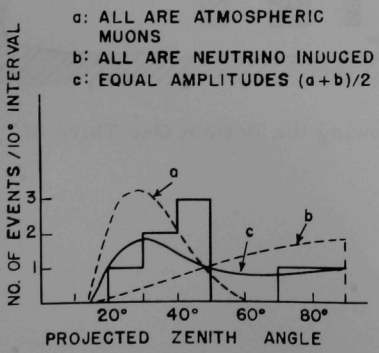


Fig. 4

Zenith-Angle Distribution of KGF Events, Together with Expected Distributions for Atmospheric muons and Neutrino-Induced muons

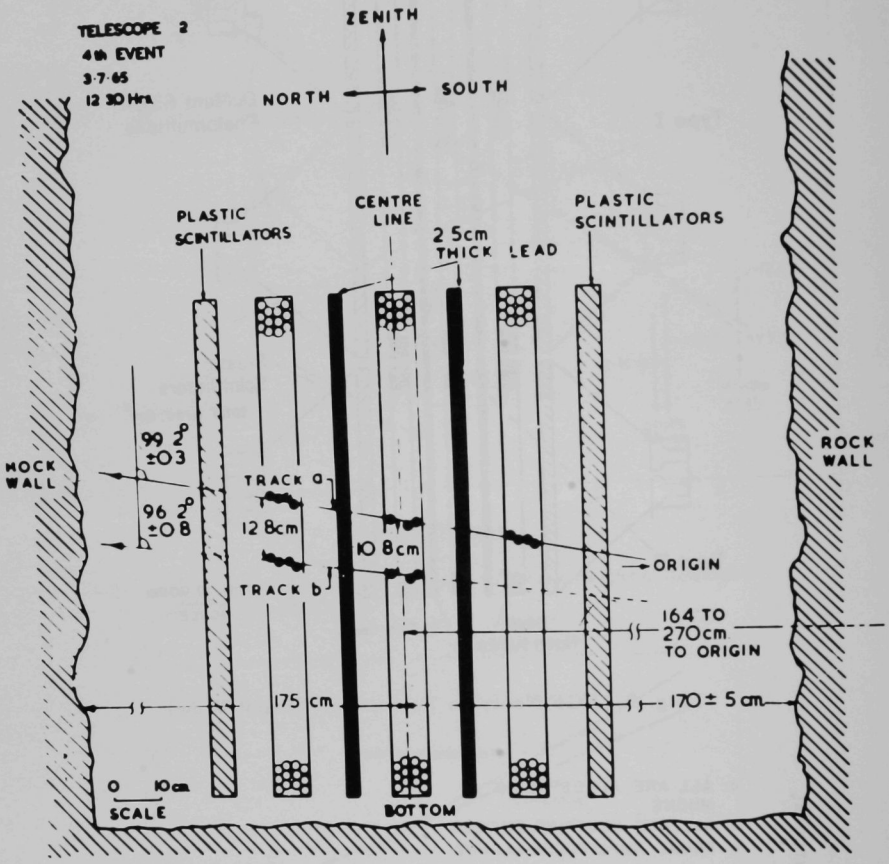


Fig. 5. Double Track Event, Showing the Bottom One Third of Telescope No. 2

DISCUSSION

PAL (Tata Institute, Bombay): I would like to make just one remark which to me seems to summarize the physics one has learned so far from these experiments. A total number of 12 to 13 events have been seen in both experiments. If you said that the neutrino cross section were to saturate around 10 BeV up to which it has been seem to be proportional to the Laboratory energy, the expected number of counts would have been about four. Now if you say that the cross section went on increasing up to 100 BeV at the same rate as it is increasing up to 10 BeV, then the expected number of events would have been eight. If you increase it to 1000 BeV, then of course the expected number of events is about fifteen or sixteen. So it would seem to indicate that the cross section may not be form factor limited at least up to a few hundred GeV.

SESSION VI

THEORETICAL ASPECTS

Wednesday, October 27, 1965

CHAIRMAN: A. Salam
Imperial College of Science and Technology
and International Center for Theoretical Physics

Scientific Secretaries

W. D. McGlinn, University of Notre Dame
B. Sakita, Argonne National Laboratory
K. C. Wali, Argonne National Laboratory

RECENT WORK ON THE RENORMALIZATION OF THE WEAK AXIAL-VECTOR COUPLING CONSTANTS*

by

William I. Weisberger

Stanford Linear Accelerator Center
Stanford University
Stanford, California

I will discuss calculations performed independently[1] by S. L. Adler and the author which seem to give a successful explanation of the ratio of axial-vector to vector coupling constants measured in neutron β-decay. A natural extension of this work to strangeness-changing decays of the hyperons has been performed by several authors[2] and the results are in good agreement with the Cabibbo theory.[3] The $\Delta S = 0$ decays will be discussed first.

The assumptions used in the derivation are: 1) The vector and axial-vector currents measured in the weak interactions obey the equal-time commutation rules of $SU(3) \times SU(3)$ as proposed by Gell-Mann;[4] 2) The axial-vector current is partially conserved, which is a basis for deriving such results as the Goldberger-Treiman[5] relation. From this starting point we are able to relate G_A/G_V to integrals over π-proton total cross sections:

$$1/(G_A/G_V)^2 = 1 + \frac{2M^2}{\pi g_{\pi n}^2} \int_{\mu}^{\infty} \frac{q\,d\nu}{\nu^2} \left[\sigma_{tot}^{\pi^- p}(\nu) - \sigma_{tot}^{\pi^+ p}(\nu)\right] \qquad (1)$$

*Work supported by the U. S. Atomic Energy Commission

where the σ's are total cross sections; ν and q are the pion energy and three momentum in the laboratory system; M = nucleon mass, μ = pion mass, and $g_{\pi n}$ is the π-nucleon coupling constant. All these quantities have been measured and one can make an accurate numerical evaluation of the right-hand side of Eq. (1). The answers obtained are

$$\left|G_A/G_V\right| = \begin{cases} 1.24 \text{ (S. L. Adler)} \\ 1.16 \text{ (W. I. Weisberger)} \end{cases} \tag{2}$$

The difference between these two numbers comes from details of the theoretical formulation of the partially conserved axial-vector current hypothesis and is a reasonable indication of possible theoretical uncertainties in the result. The value of G_A/G_V determined from experimental data is[6]

$$G_A/G_V = -1.18 \pm 0.02 \text{ (C. P. Bhalla and C. S. Wu).} \tag{3}$$

The theory is in good agreement with experiment.

I would like to give an outline of how this result is obtained from the initial assumptions. Let us review briefly some well known facts.[7] Muon-decay and leptonic decays of the strongly interacting particles can be described by an effective current-current interaction. The lepton-neutrino currents occur only in the combination $\gamma_\mu(1-\gamma_5)$, or V-A. The vector coupling constant for neutron β-decay, G_V, is nearly equal to the μ-decay constant, G_μ, and the neutron axial-vector coupling constant, G_A, equals $-1.2\ G_V$.

In order to explain $G_\mu = G_V$, the CVC hypothesis was proposed. There is a universal coupling of the lepton and hadron currents. The vector current of the hadrons is, in fact, just a component of the total isotopic spin density so there is no renormalization of the vector β-decay constant by the strong interactions. Since $G_A/G_V = -1.2$ is close to one, it is tempting to assume that the initial hadron current is V-A like the lepton current, and the 0.2 correction comes from renormalization of the non-conserved axial current. To implement this idea, one must solve two problems.

1) How can one give an unambiguous meaning to a bare V-A coupling for the strongly interacting particles?

2) How can one evaluate the renormalization effects due to the strong interactions?

The isotopic spin is a well defined quantum number for all strongly interacting particles and the strengths of the matrix elements of the vector isospin current are known without appeal to any particular field theoretic model of the current. There is no analogously simple procedure to define a universal axial-vector current for all the baryons and mesons.

A solution to this problem is the algebraic approach proposed by Gell-Mann, which is most elegantly stated in the context of the Cabibbo theory. We restrict ourselves now to stating the result for the algebraic structure of the $\Delta S = 0$ currents. Assume that the $\Delta S = 0$ axial current is a member of an isotopic triplet, a vector in isospin space, and consider the "charges" defined by the space integrals of the time components of the vector and axial-vector currents.

$$\begin{aligned} I_i(t) &= \int d^3x \;\; V_i^o(\underset{\sim}{x},t) \\ I_i^5(t) &= \int d^3x \;\; A_i^o(\underset{\sim}{x},t) \end{aligned} \qquad i = 1,2,3. \tag{4}$$

$\vec{I}$ is the total isotopic spin and $\vec{I}^5$ is called the isotopic chirality. Since the chirality is assumed to be an isovector, these operators obey the following equal-time commutation relations.

$$\begin{aligned} \left[I_i(t),\, I_j(t)\right] &= i\epsilon_{ijk}\, I_k(t) \\ \left[I_i(t),\, I_j^5(t)\right] &= i\epsilon_{ijk}\, I_k^5(t) \end{aligned} \tag{5}$$

Gell-Mann's proposal is that the commutators of components of the chirality close the algebra in a simple manner.

$$\left[I_i^5(t),\, I_j^5(t)\right] = i\epsilon_{ijk}\, I_k(t) \tag{6}$$

This non-linear relation fixes the scale of the axial-vector current relative to the isospin current.

We define right-handed and left-handed charges by

$$I_i^{\pm} = \frac{1}{2}\,(I_i \pm I_i^5) \quad . \tag{7}$$

The three members of each of these triplets of chiral charges when commuted among themselves generate an SU(2) algebra. Two members of different sets commute with each other. This defines a chiral SU(2) × SU(2) algebra. The V-A assumption is that the hadron current measured in the weak interactions is a member of one of these triplets of chiral currents. Of course the algebraic structure does not tell us whether it is V + A or V - A which is found in nature. This must come from experiment.

With these assumptions about the interaction the algebraic relations can be used to determine the relative strength of matrix elements of the vector and axial-vector currents measured in β-decays using the method of Fubini and Furlan.[8] The appropriate commutator to use is

$$2I_3 = \left[I_+^5\,,\ I_-^5\right] \quad . \qquad I_{\pm}^5 = I_1^5 \pm iI_2^5 \quad . \tag{8}$$

Take matrix elements of this commutator between physical one-proton states. The term on the left is the third component of the proton isotopic spin. In the commutator on the right we insert a complete set of intermediate states and isolate the contribution from the one-neutron state

$$\begin{aligned} 1 < P|P > = & \sum_{N\ \text{spins}} < P|I_+^5|N > < N|I_-^5|P > \\ & + \sum_{\alpha \neq N} \left\{ < P|I_+^5|\alpha > < \alpha|I_-^5|P > - (I_+^5 \longleftrightarrow I_-^5) \right\} \end{aligned} \tag{9}$$

The one-neutron matrix elements are given by

$$< P|I_+^5|N > = \int d^3x < P|A_+^o|N > = C\delta^{(3)}(\vec{P} - \vec{N})g_A\bar{u}(P)\gamma_o\gamma_5 u(N) \tag{10}$$

C is a normalization factor.

If the Hamiltonian involves a V ± A current, then $g_A = |G_A/G_V|$, the ratio of axial-vector to vector coupling constants measured in β-decay. We find that we can express the inelastic matrix elements in Eq. (9) in terms of π-nucleon scattering cross sections and thus obtain the sum rule, Eq. (1), which relates g_A to quantities measured independently in the strong interactions. To carry out this program it is necessary to introduce the concept of a partially conserved axial current. This means, in essence, that the Fourier transform of the axial current divergence is dominated by low frequency components. Acting on the vacuum state the divergence leads mainly to a one-pion state. One way to obtain this behavior is to assume that the divergence of the $\Delta S = 0$ axial current, a pseudoscalar isovector operator, is proportional to the pion field,

$$\partial_\mu A_i^\mu(x) = a\varphi_i^\pi(x) \quad . \tag{11}$$

a is the decay constant for charged pions. Taking matrix elements of Eq. (11) between one-nucleon states one also finds

$$a = \frac{i\sqrt{2}\, M\mu^2}{g_{\pi n}}\, g_A . \tag{12}$$

This is one derivation of the Goldberger-Treiman relation. All the results presented here can also be derived from the assumption that matrix elements of $\partial_\mu A^\mu$ obey unsubtracted dispersion relations which are dominated at low momentum transfers by meson poles.[9]

To use the PCAC hypothesis we must relate the inelastic matrix elements of the charges in Eq. (9) to matrix elements of the divergence as shown in the following equation.

$$\begin{aligned} \frac{\partial}{\partial t} < P|I_i^5|\alpha > &= i(E_p - E_\alpha) < P|I_i^5|\alpha > \\ &= \int d^3x < P|\partial_o A_i^o(x)|\alpha > = \int d^3x < P|\partial_\mu A_i^\mu(\alpha)|\alpha > \end{aligned} \tag{13}$$

Dividing through by the energy difference and substituting for $\partial_\mu A^\mu(x)$ from Eq. (11), we express $< P \left| I_\pm^5 \right| \alpha >$ in terms of π-proton scattering amplitudes. The result of these substitutions and further mathematical manipulations is the sum rule of Eq. (1).

Adler has also considered the sum rule which can be obtained by inserting the commutator between one-pion states. In this way g_A is related to integrals over π-π total cross sections. After evaluating the contributions from the known vector resonances, he finds that the sum rule can be satisfied if there is an I = 0, s-wave scattering length, $a_o < -1.20f$. An evaluation of a_o from forward dispersion relations by Roth[10] gives a value in agreement with that required by the algebra.

These ideas can be extended readily to strangeness-changing leptonic decays in the context of Cabibbo theory. The vector currents are assumed to be members of an SU(3) octet and the integrals of their time components are the generators of SU(3). The axial-vector currents are also members of an octet and the commutators of the time-components of these two octets generate a chiral SU(3) × SU(3) algebra. These algebraic relations are supposed to be exact to all orders in the strong interactions even though SU(3) is a broken symmetry. The total hadron current measured in the weak interactions is a component of one of these chiral octets.

$$J^\mu_{HAD} = \cos\theta\,(V^\mu_{1+i2} - A^\mu_{1+i2}) + \sin\theta\,(V^\mu_{4+i5} - A^\mu_{4+i5}) \tag{14}$$

The Cabibbo angle, θ, is a parameter describing the weak interactions. It is the V's and A's which are postulated to obey the simple commutation rules. Because we want to use the algebra to introduce a pure V - A current, we use the same Cabibbo angle for the vector and axial-vector currents. This is equivalent to saying that only left-handed currents appear in the interaction.

If SU(3) were an exact symmetry, there would be no renormalization of any of the vector coupling constants. The axial-vector coupling constants for all the baryon decays could be expressed in terms of two independent parameters.

$$< B_i \left| A^{\mu}_{k} \right| B_j > \propto g_A \left[(1-\alpha)\, f_{ijk} + \alpha\, d_{ijk} \right] \bar{u}_i\, \gamma_\mu \gamma_5 u_j \qquad i,j,k = 1,\ldots,8 \quad (15)$$

f and d are SU(3) Clebsch-Gordan coefficients; $\alpha/(1-\alpha)$ is the d/f ratio.

This SU(3) symmetric description agrees within experimental error with present measurements of semi-leptonic decays despite the fact that SU(3) is a broken symmetry. The reason for the small renormalization effects for the vector currents is suggested by a theorem due to Adomello and Gatto[11] and depends on the fact that these vector currents are the generators of SU(3) transformations. There is no such theorem for the axial-vector currents. However, if we accept the commutation rules as exact, then the axial-vector current transforms exactly as an irreducible octet tensor even in the presence of SU(3) breaking. The success of the Cabibbo description of the axial current matrix elements suggests, therefore, that the one-particle states may be nearly pure octet despite their large mass splittings.

At any rate, we can check the consistency of this description by deriving sum rules for the strangeness-changing currents. The useful commutator is

$$I_3 + 3/2\, Y = \left[I^5_{4+i5},\ I^5_{4-i5} \right] \qquad (16)$$

Two independent sum rules can be obtained by taking matrix elements of this commutator between one-proton states and one-neutron states respectively. In the first case, the one-particle intermediate states are the Σ^0 and the Λ^0. In the second case the one-particle intermediate states is a Σ^-. The procedure is the same as before, and we must extend the PCAC hypothesis to include K-meson pole dominance of the divergence of the $\Delta S = 1$ axial current.

The results are

$$2 = (g_A^{\Sigma^o p})^2 + (g_A^{\Lambda^o p})^2 + \frac{f_K^2}{\pi} \int_{\nu_o}^{\infty} \frac{d\nu}{\nu^2} \left[A^{K^- p}(\nu) - A^{K^+ p}(\nu)\right] \tag{17a}$$

$$1 = (g_A^{\Sigma^- n})^2 + \frac{f_K^2}{\pi} \int_{\nu_o}^{\infty} \frac{d\nu}{\nu^2} \left[A^{K^- n}(\nu) - A^{K^+ n}(\nu)\right] \tag{17b}$$

f_K is the $K \to \ell + \bar{\nu}$ decay constant. The A's are imaginary parts of forward scattering amplitudes. For $\nu > \mu_K$ they can be expressed in terms of total cross sections by the optical theorem. In these integrals, however, there is an unphysical region due to the $\Lambda\pi$ and $\Sigma\pi$ channels which have lower threshold energies than the K-nucleon system. Using measured K-nucleon cross-sections and models for extrapolating below threshold one can evaluate these integrals with ~ 20% accuracy. If we express the baryon decay constants in Eq. (17) in terms of α and g_A, we can determine both α and an independent value of g_A from these two sum rules. The results are[2]

$$\begin{array}{ll} \alpha = 0.73 & \text{(D. Amati, C. Bouchiat, and J. Nuyts)} \\ \alpha = 0.63 \pm 0.12 & \text{(C.A. Levinson and I.J. Muzinich)} \\ \left.\begin{array}{l} |g_A| = 1.24 \pm 0.10 \\ \alpha = 0.75 \pm 0.10 \end{array}\right\} & \text{(W. I. Weisberger)} \end{array} \tag{18}$$

The first two values were actually obtained from Eq. (17a) using g_A as determined from the $\Delta S = 0$ sum rule. Eq. (17a) has also been discussed by L. K. Pandit and J. Schecter. The results in Eq. (18) agree with the values of the d/f ration obtained by fitting Cabibbo theory to experimental data[12]

$$\alpha^{exp} = \begin{array}{l} 0.67 \pm 0.03 \\ 0.63 \end{array} \left\{\begin{array}{l} \text{(N. Brene, B. Hellesen, and M. Roos)} \\ \text{(W. Willis, et.al.)} \end{array}\right. \tag{19}$$

Amati et.al. have pointed out also that the description of all baryon axial decay constants in terms of two parameters implies a consistency condition among the cross-section integrals in the three sum rules. They find good agreement.

In conclusion, it seems we have obtained a consistent theoretical picture of leptonic decays in terms of two fundamental parameters for the weak interactions, G_V and the Cabibbo angle, θ. The evidence that the suppression of the $\Delta S = 1$ decays relative to $\Delta S = 0$ decays by $\tan\theta$ is to be found in the structure of the weak interactions and not explained as a strong interaction renormalization effect, is quite strong. One should expect, however, that more precise measurements of semi-leptonic decays will show departures from complete SU(3) symmetry of the matrix elements. This may be one place to try to achieve a dynamical understanding of SU(3) symmetry breaking.

LIST OF REFERENCES

1. S. L. Adler, Phys. Rev. Letters 14, 1051 (1965); Phys. Rev. (to be published); W. I. Weisberger, Phys. Rev. Letters 14, 1047 (1965).
2. D. Amati, C. Bouchiat, and J. Nuyts (to be published); C. A. Levinson and I. J. Muzinich (to be published); L. K. Pandit and J. Shecter (to be published; W. I. Weisberger (to be published).
3. N. Cabibbo, Phys. Rev. Letters 10, 531 (1963).
4. M. Gell-Mann, Phys. Rev. 125, 1067 (1962); Physics 1, 63 (1964).
5. M. L Goldberger and S. Treiman, Phys. Rev. 110, 1178, 1478 (1958).
6. C. S. Wu (unpublished).
7. A comprehensive review and list of references is given by C. S. Wu, Rev. Mod. Phys. 36, 618 (1964).
8. S. Fubini and G. Furlan, Physics 1, 229 (1965).
9. See W I. Weisberger, reference 2.
10. H. J. Rothe, Phys. Rev. (to be published). Rothe's result is $a_o = -2.4^{+1.8}_{-0.7}$ f.
11. M. Ademollo and R. Gatto, Phys. Rev. Letters 13, 291 (1964).
12. N. Brene, B. Hellesen, and M. Roos, Phys. Letters 11, 344 (1964); W. Willis, et al., Phys. Rev. Letters 13, 291 (1964).

DISCUSSION

OKUBO (U. of Rochester): I want to make two comments. The first one is concerned with the partially conserved axial vector current hypothesis. Some years ago, Professors Haag and Nishijima showed that we can define a local field operator for a bound state. Suppose that a pion is a bound state of quarks, then divergence of the axial vector current satisfies the conditions given by Haag. Hence, the partially conserved axial vector current is simply a definition of a local pion field. Second, I would like to mention that we can derive the Kroll-Ruderman low energy photo-pion production theorem using the current commutators. Also, we may derive an analogous sum rule for G_A in terms of scattering cross-sections of circularly polarized photons on polarized nucleons.

GASIOROWICZ (U. of Minnesota): I understand there is a field-theoretical model of Gell-Mann and Levy, which satisfies PCAC hypothesis. The commutation relations of the current are those of SU(2) (isotopic spin). Can that be extended to SU(3) ?

WEISBERGER: I think so.

GASIOROWICZ: Then how many scalar mesons come in?

WEISBERGER: We can certainly do it by making two octets of mesons, without the parity. One can probably make more economical models, since in the σ model, where you are looking at just the isotopic parts, you need an isovector pseudoscalar meson and a singlet scalar meson. But I'm sure there is a large family of models one can make. Somebody else may know them.

LEVY (Orsay, France): The straightforward extension involves 9 mesons.

NISHIJIMA (U. of Illinois): I would like to make a comment which overlaps Dr. Okubo's comment. The hypothesis of PCAC is not necessary in the derivation of the sum rule, because I think the only purpose of using this relation is to replace the divergence of A_μ by the pion field operator, and then compare this expression with the scattering amplitude. However, there is a theorem in field theory, which has long been known, namely, the correspondence between particle and field is not one to one. For a given particle you can use

a large number of fields satisfying very few conditions - the field operator should have the right transformation property, it should be local, and it should be properly normalized. In such a case divergence of A_μ is equally well qualified as the original pion field operator, provided that it is properly normalized. For the normalization condition, you can take the Goldberger-Treiman relation, so you can replace the PCAC hypothesis by the Goldberger-Treiman condition, which is a much weaker condition.

WEISBERGER: Do I understand that the point is that the divergence of A_μ has the same quantum numbers as the pion field and hence it is as good an interpolating field for the pion as any other?

NISHIJIMA: Yes, as far as on the mass shell elements are concerned, there is no difference.

WEISBERGER: Well, I tried to stay out of the complex plane, but if we are going to worry about continuing in the mass, one can just as well derive those relations by dispersing in the momentum transfer for divergence and replacing by a pion pole on the mass shell. That is essentially the difference between Dr. Adler's number and my number.

ADLER (Harvard U.): I want to say that one uses unsubtracted dispersion relations and assumes they are dominated by the one pion pole and this is essentially equivalent to assuming that when you go off the mass shell things change slowly. If the divergence of A_μ were an interpolating field which changes extremely rapidly when you went from on the mass shell to one pion mass off the mass shell, then it won't work. For example, let us suppose that we have an axial current which satisfies this, then let's change it in such a way that we add to the divergence, $\Box$ to the millionth power of the pion field to normalize it. Then this new divergence is not going to allow us to compare the sum rule with experiment because you either can't write an unsubtracted dispersion relation in the polology point of view, or you cannot assume things change slowly when you go off the mass shell in the field theoretic point of view. Hense, some sort of assumption of slow change when you go off the mass shell or an unsubtracted dispersion relation is necessary. You can make an interpolating field that changes arbitrarily wildly when you go off the mass shell, but then the sum rule will fail.

WEISBERGER: I think essentially what Dr. Adler and I agree about is there are different techniques to evaluate the sum rule. If you get terribly different answers by doing it different ways, you would be terribly unhappy. We're happy that we get almost the same answer.

OKUBO: I agree with the conclusion of Dr. Nishijima. Dr. Marshak and I some years ago have shown that we can derive the Goldberger-Treiman relation without using dispersion relations but instead using the theorem of Haag, which I have mentioned previously.

MARSHAK (U. of Rochester): I also want to comment again, but I'll try to do it much more briefly, on the question of the model that you use in order to justify the current algebra. Adler yesterday used the commutator algebra of the integrated currents, and this you can justify on the basis of a three-field quark model which also makes predictions concerning the strong interactions. He then proceeded to use it for the current densities, justifying it on the basis that there exists a Gell-Mann Levy σ - model. My point is that in seeking models to derive the current algebra, one should try to get the model which makes correct predictions in the weak interactions, as well as in the strong interactions. The three-field model makes definite and very encouraging predictions about the mesons in the strong interactions, and gives the same algebra for the integrated currents, as the one used by Adler and Weisberger. But it does not give any unique answers for the current densities. So I want to add a word of caution about using the current densities with the same confidence as the use of the integrated forms. The Adler-Weisberger result is for the integrated forms and is a very encouraging development in terms of tying in with the strong interaction prediction.

SU(3) and Nonleptonic Weak Interactions

Benjamin W. Lee
University of Pennsylvania
Philadelphia, Pennsylvania

Dr. Adler and Dr. Weisberger have described what I believe to be the most important theoretical contributions in semi-leptonic weak interactions during the past year. Therefore I shall confine myself exclusively to nonleptonic weak interactions. I shall take the attitude that the bulk of nonleptonic weak interactions can be understood in the approximation of CP invariance.

In the current-current interaction picture of weak interactions the nonleptonic decays of hadrons are mediated by the term bilinear in hadron currents:

$$g_{\mu\nu}\, j_i^{\mu} j_j^{\nu} \times \begin{pmatrix} \cos\theta \ \sin\theta \\ \cos^2\theta \\ \sin^2\theta \end{pmatrix} \begin{matrix} \Delta S = \pm 1 \\ \left.\begin{matrix} \\ \\ \end{matrix}\right\} \Delta S = 0 \end{matrix} \tag{1}$$

where we assume j_i^{μ} is the sum of vector and axial vector currents according to the prescription of Cabibbo's theory which transforms like the i-th member of an octet. We assume in particular

1. $CP\ j_i^{\mu}\ (CP)^{-1} = g^{\mu\mu} \epsilon_i\, j_i^{\mu}\ (-x\ ,\ t)$

   $\epsilon_i = -1,\ i = 2,\ 5,\ 7;\ \epsilon_i = +1$ otherwise
   (absence of the second class currents)

2. that j_{μ}^{i}'s belong to the same octet.

The bilinear term of octet currents transform like a product of 8 x 8 under SU(3). Since the currents belong to the same octet, however, only the symmetric parts of 8 x 8 occur, i.e. 1, 8_s and 27.

Experimentally the rule $\Delta S = \pm 1$, $\Delta T = 1/2$ for nonleptonic processes seem to be good to within, say, 10%. This rule would follow if the weak Lagrangian responsible for these phenomena transformed effectively like an octet. There are at least two ways in which this could happen. One is that the Lagrangian is built up so as to effect this transformation property. The second is that strong interactions enhance the effects of the octet part of the weak Lagrangian. The second possibility is called the "octet enhancement". We shall discuss these possibilities in more detail later.

In any case let us assume that the nonleptonic weak interaction transforms effectively like an octet. Then there are two possibilities. It may transform like either

$$d_{6ij}\, j_i\, j_j \sim K_o + \overline{K}_o \sim \lambda_6$$

or

$$i d_{7ij}\, j_i\, j_j \sim i\,(K_o - \overline{K}_o) \sim \lambda_7$$

under SU(3). This ambiguity is removed, however, once we demand CP invariance of the nonleptonic weak interaction. It turns out that only the first is CP invariant, under the assumption (1) made above (absence of the second class currents). This was noted independently by Gell-Mann[1] and Okubo[2].

Knowing that the interaction transforms like the sixth member of an octet, and assuming CP is conserved, we can write down phenomenological $Y \to B + \pi$ vertices. A detailed analysis[3] shows that there are 3 linearly independent terms for the s-wave decays (p. v.) while there are 4 for the p-wave (p. c.). Under the $\Delta T = 1/2$ rule along (which is now a consequence of the octet rule), there are 4 observable, independent amplitudes. They are:

$$\Lambda \to N + \pi$$

$$\Sigma \to N + \pi \ (T = 1/2)$$

$$\to N + \pi \ (T = 3/2)$$

$$\Xi \to \Lambda + \pi$$

Since the p. v. interaction is described in terms of 3 parameters, we get a sum rule in this case, which is

$$2A(\Xi_-^-) = A(\Lambda_-) + \sqrt{3}\, A(\Sigma_o^+) \qquad (2)$$

where A stands for the p. v. amplitude[4]. Dr. Samios has shown you the experimental confirmation of this sum rule. He presented an A-B plane plot of the quantities Λ_-^o, $\sqrt{3}\,\Sigma_o^+$ and $2\,\Xi_-^-$. The sum rule above means that the horizontal projections of these vectors satisfy the equality. This is borne out experimentally.

Another point to notice here is that the triangle closes, i. e. it appears that the p. c. amplitudes also satisfy the sum rule

$$2B(\Xi_-^-) = B(\Lambda_-) + \sqrt{3}\, B(\Sigma_o^+) \qquad (3)$$

There were many justifications offered for the validity of (3) but none were too convincing. In a recent paper, S. P. Rosen[5] derives a necessary and sufficient condition for the validity of Eq. (4). To construct the octet interaction, we may first combine $\overline{B}$ and B to form irreducible tensors n = 1, 8_a, 8_s, 10, 10*, and 27. To this we add π to form an octet, i. e.

$$H_w = \sum_n C_n \left[[\overline{B} \times B]_n \times \pi \right]_8$$

Rosen shows that the necessary and sufficient condition for Eq. (4) is that $C_{10} = C_{10}^*$. To effect this the following possibilities have been proposed

1. RP invariance[6]
2. R invariance[7]
3. H_w transforms like λ_7[8]

The last possibility seems to violate CP invariance from what I have said; but I want you to keep this in mind until I come back to this point later. The first two possibilities could be more attractive if currents had definite R-conjugation parities (for instance, the pure F type vector currents and pure D type axial vector currents for RP. There is no lack of theories that predict this.) It may be of some interest to note that the first of these possibilities gives an additional rule[9]:

$$A(\Sigma^+_+) = 0$$

i.e. $\Sigma^+ \to n + \pi^+$ is pure p-wave.

Let us now consider how the octet rule can be implemented into the weak Lagrangian. The bilinear combination of currents that transform like the $\Delta S = \pm 1$, $\Delta T = 1/2$ member of an octet is

$$K^+\pi^- - \frac{1}{\sqrt{2}} K^o (\pi^o + \frac{1}{\sqrt{3}} \eta^o) + h.c. \tag{4}$$

where I have represented the currents by the meson symbols of the corresponding transformation properties. In the Cabibbo theory this term is of order of $G \cos\theta \sin\theta$. We see that the octet implementation requires 2 additional neutral currents, K_o and $Q \equiv \pi^o + \frac{1}{\sqrt{3}} \eta^o$ (electromagnetic current!) which lack, apparently, leptonic weak interactions. The above scheme can be realized by a very minor modification of the old schezon scheme. If we couple W^+, W^-, W^o and $\overline{W}^o$ to K^+, K^-, and $\overline{K}^o$ as in the old scheme and $\frac{W^o + \overline{W}^o}{\sqrt{2}}$ to $\pi^o + \frac{1}{\sqrt{3}} \eta$ (instead of to π^o), we get the effective current-current Lagrangian (4). Thus the octet rule for $|\Delta S| = 1$ decays require 4 vector bosons, the number that's required to just implement the isospinor rule. The $|\Delta S| = 0$ part of the effective current-current interaction has, however, no simple transformation property under SU(3) in this theory.

A more appealing possibility, from the SU(3) viewpoint, is the scheme of d'Espagnat[10], in which the vector bosons form a triplet under SU(3) and are coupled to the octet of currents so as to make the semi-weak Lagrangian transform like a triplet. The current-current interaction then transforms like an octet and a singlet.

In the octet enhancement argument, it is assumed that the weak coupling is of the form

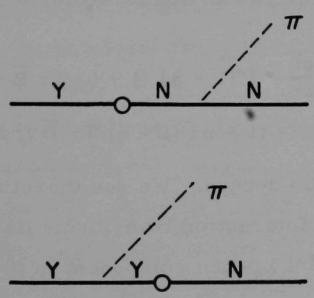
$$\frac{G}{\sqrt{2}} J_\mu \cdot J_\mu^+$$

and J_μ is a sum of leptonic and charged hadronic currents. As we have discussed earlier, it transforms like 1 + 8 + 27. To account for the octet rule, and in particular, the $\Delta I = 1/2$ rule, one assumes that the octet part is enhanced selectively by the intervention of strong interactions, just as the

same mechanism can enhance the octet part of the elctromagnetic mass splittings in various SU(3) multiplets, as suggested by Coleman and Glashow[8]. Since, in Cabibbo's theory, the term (4) is multiplied by $G \cos\theta \sin\theta$, some sort of enhancement is in any case necessary to compensate for the suppression by the factor $\sin\theta$, as pointed out by Salam some time ago. A detailed study along this line, incorporating the "bootstrap" philosophy, has been carried out by the Pasadena school, notably by Dashen and Frautschi[11]. In the case of the p.v. decays of hyperons, they verify the rule (2) and get the experimentally favored result[9,12]:

$$A(\Sigma^+_+) = 0.$$

Lastly I would like to discuss a difficulty associated with applying the symmetry argument too naively to the parity conserving decays. This difficulty will be pointed out in the context of a very simple model, but I believe it to be general. We consider the baryon pole dominance model of Feldman, Matthews and Salam, depicted in the figure below:



Typically these amplitudes are proportional to the factor $(m_Y - m_N)^{-2}$ and we see that the mass splittings are crucial in determining the amplitudes. Because of this fact, the amplitudes corresponding to these diagrams cannot be computed directly from the λ_6-like transformation property of the weak spurion. We can write down a phenomenological Lagrangian which generates these diagrams. It may be taken to be

$$L = L_{free}^{SU(3)\ symmetric} + \Delta m\left[\bar{\Psi}^i F_{8ij} \Psi^j + \alpha \bar{\Psi}^i D_{8ij} \Psi^j\right]$$
$$+ f\left[\bar{\Psi}^i F_{6ij} \Psi^j + \beta \bar{\Psi}^i D_{6ij} \Psi^j\right]$$
$$+ g\left[\gamma \bar{\Psi}^i F_{kij} \Psi^j + \bar{\Psi}^i D_{kij} \Psi^j\right] \pi^k$$
$$+ \text{meson mass splitting term, etc.}$$

If $\beta = \alpha$, the term proportional to f can be transformed away by a unitary transformation completely without affecting the invariant πBB couplings. This is what happens in the tadpole model, as pointed out by Coleman and Glashow[8], if the weak tadpole and the mass splitting tadpole belong to the same octet. Let us assume that this is not the case.

The parameter α characterizes the ratio of $M_\Sigma - M_\Lambda$ to $M_\Xi - M_N$ and is a small number. To facilitate our discussion, let us assume it to be zero. In this case the term proportional to f can be transformed away by a unitary transformation, but the πBB couplings are not invariant under the transformation. It acquires an additional term of the form [to lowest order in f]

$$i\frac{2}{\sqrt{3}}\frac{gf}{\Delta m}\ \{ (1+\beta)(1+\gamma)\ \mathrm{Tr}\ \bar{B}\gamma_5\ [\lambda_7, M]\ B$$
$$- (1-\beta)(1-\gamma)\ \mathrm{Tr}\ \bar{B}\gamma_5\ B\ [\lambda_7, M]\}$$

which mediates the hyperon decays. We see therefore that even if the effective current-current interaction transforms like λ_6, there will be a large, perhaps predominant λ_7-like component in the hyperon decay amplitudes due to the medium strong mass splittings in SU(3) multiplets[12] We have already seen that the phenomenological hyperon decay interaction that transforms like λ_7 gives the sum rule. It may be noted that the D-type mass splitting (the term proportional to α) induces a small term in the hyperon decay amplitudes that transforms like $\underline{27}$.[13]

References

1 M. Gell-Mann, Phys. Rev. Letters 12, 155 (1964).

2 S. Okubo, Phys. Letters 8, 362 (1964).

3 See for example S. Coleman, S. Glashow and B. W. Lee, Ann. Phys. 30, 348 (1964).

4 We write

$$\langle B'\pi \,|Hw|\, B\rangle = (2\omega)^{-1}\left(\frac{m'}{E'}\right)^{1/2} \bar{u}_{B'}\,(A + \gamma_5 B)\, u_B$$

where ω is the c. m. energy of the decay pion, m' and E' are the mass and c. m. energy of the decay baryon. In Σ_o^+, etc., the superscript refers to the charge of the parent, the subscript to that of the decay pion.

5 S. P. Rosen, Phys. Rev. 140, B326 (1965).

6 B. W. Lee, Phys. Rev. Letters 12, 83 (1964).
B. Sakita, Phys. Rev. Letters 12, 379 (1964).
S. P. Rosen, Phys. Rev. Letters 12, 408 (1964).

7 H. Sugawara, Progr. Theor. Phys. (Kyoto) 31, 213 (1964).

8 S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964).
S. Coleman and S. L. Glashow and B. W. Lee, reference 3.

9 A sufficient condition for this additional rule is that $C_n = 0$ except for $n = 8_a, 8_s$. RP invariance requires this: the bootstrap theory of Dashen et al (reference 11) predicts this.

10 B. d'Espagnat, Phys. Letters 7, 209 (1963).
R. Dashen, S. Frautschi and D. Sharp, Phys. Rev. Letters 13, 777 (1964) and papers quoted therein.

11 For the implications of the octet enhancement to the strangeness conserving weak interactions in nuclear physics, see Professor H. Primakoff's summary talk.

12 B. W. Lee, Phys. Rev. 140, B152 (1965). This was anticipated in reference 7.

13 A similar circumstance will presumably occur in a bootstrap calculation.

DISCUSSION

ROSEN (Purdue U.): I would like to point out that the sum rule follows if you assume that the baryon, anti-baryon system is coupled to an octet - irrespective of the overall transformation properties of the Hamiltonian A corollary of this is that you will not get $\Sigma^+ \rightarrow N + \pi^+$, since $\overline{\Sigma}^+ N$ has $T = 3/2$. One other point, I assume that when you write down your effective interactions you are taking S + P type interaction.

LEE : Everything I have said is independent of whether I choose to write this phenomenological coupling in terms of S + P or V + A.

ROSEN: I am afraid I must disagree with you there. I do not think that is the case unless you take your coupling constants to be functions of masses with particular symmetry properties.

LEE: I guess we will have to resolve this later.

SUDARSHAN (Syracuse U.): You made the remark that if you consider the current-current interaction with only charge currents, you do not expect to find a unique transformation property for the effective Hamiltonian. The same situation prevails if you assume $\Delta I = 1/2$ rule for the strangeness changing current and current-current type picture for the non-leptonic decays. One would have a superposition of $\Delta I = 1/2$ and $\Delta I = 3/2$ amplitudes. If you look at the experimental data that was presented earlier, it is quite clear that the sum rule you presented seems to be better satisfied than the $\Delta I = 1/2$ sum rule for Σ - decay. It is worthwhile, therefore, to ask the question whether in non-leptonic decays there is any evidence for the presence of both $\Delta I = 1/2$ and $\Delta I = 3/2$ amplitudes. Now in general it is very difficult to test this because of the presence of both S and P amplitudes. There is however one case when you can test it and this is in 2π decay of K-mesons. In this case as there is only S-wave, there exists the following sum rule for the amplitudes:

$$2M\,(K^+ \rightarrow \pi^+\pi^0) = M\,(K_1^{\,0} \rightarrow \pi^+\pi^-) - \sqrt{2}\,M\,(K_1^{\,0} \rightarrow \pi^0\pi^0)$$

This sum rule is a consequence of assuming that there are no transitions in which $\Delta I = 5/2$. In other words, you have a current-current interaction that contains currents that transform like $I = 1$ and $I = 1/2$. Around 1957-58 when such sum rules were discussed, the numbers were not good enough to make a meaningful comparison. I am told by Professor Mahanthappa that with the presently available numbers the above sum rule is satisfied very well.

LEE : This is in answer to Dr. Rosen's comment. You are right. What I have said is correct in the case of V + A coupling if you assume that the parameter alpha is set equal to zero.

PATI (U. of Maryland) : I would like to say that I disagree with your comment for the parity conserving case. The sum rule is not satisfied if you take into consideration $\Sigma - \Lambda$ mass difference - L. H. S ~ 8 and R. H. S ~ 5. I also think we should wait and see if the sum rule is really valid experimentally.

LEE: Dr. Samios showed the slides for the sum rules. They seem to be good. Very good in fact, more than we have any right to expect, and secondly if you do not assume that the alpha is equal to zero but use the physical value for alpha, then the phenomenological coupling transforms no longer purely as an octet, it has a small admixture of 27, but, it is small.

THEORETICAL REMARKS ON CP NON-INVARIANCE*

T. D. Lee
Columbia University
New York, N. Y.

I wish to make a few remarks on the theoretical implications of the important discovery of CP non-invariance in $K_2^o \to \pi^+ + \pi^-$ by Christenson, Cronin, Fitch and Turlay,[1] since almost none of these theoretical ideas has been discussed, as yet, in this conference.

1. The decay $K_2^o \to \pi^+ + \pi^-$ implies CP non-invariance; i.e.,

$$[H, CP] \neq 0, \tag{1}$$

where H represents the total interaction. In this decay, both the initial and the final states are eigen-states of $H_{st} + H_\gamma$ and the transition is due to H_{wk}, where H_{st}, H_γ and H_{wk} refer, respectively, to the strong, electromagnetic and weak interactions. This means that the CP violation could be due to[2] H_{st}, or due to[3] H_γ, or due to[4] H_{wk}, or a combination of these interactions, or the presence of some new interactions, such as the super-weak interaction.[5] From this single experiment, it is not possible to decide which interaction is responsible for this violation.

Of course, so far as the decay of the neutral K meson is concerned, its behavior can be easily characterized phenomenologically by a 2 X 2 matrix.[6] Such description is independent of the underlying mechanism of CP non-invariance and is independent of the assumption that H_{st} and H_γ are invariant under C and T; the phenomenological description of the $K_1^o - K_2^o$ complex can also be readily extended to include possible CPT non-invariance. Some of these phenomenological analyses were summarized by Dr. Yang on Monday.

2. The amount of the observed CP violation in the K_2^o decay is a small one, characterized by a parameter

$$|\varepsilon| = \left| \frac{\text{Rate } (K_2^o \to \pi^+ + \pi^-)}{\text{Rate } (K_1^o \to \pi^+ + \pi^-)} \right|^{\frac{1}{2}} \sim 2 \times 10^{-3} .$$

The smallness of this parameter is, perhaps, one of the most puzzling features of this new discovery. To explain ε, we may invoke a small C non-invariant term in H_{st}, or, if ε is a typical example of CP non-invariant amplitude, a

* This research was supported in part by the U. S. Atomic Energy Commission.

small CP non-invariant term in H_{wk}. There is no difficulty in doing either of these; one is only puzzled by the smallness of such violation and by the multitudes of different ways to construct such a violation.

If it is due to the super-weak interaction, then, for all practical purposes, independent of the underlying theory of the super-weak interaction, all the observable CP violating phenomena can be characterized by one parameter ε and, apart from a $\pm$ sign, this parameter has already been measured.[5] In this case, we can (almost) literally all stop working on the CP problem.

The last possibility is that H_γ may have large violations of C, where

$$C = C_{st}, \text{ (= particle anti-particle conjugation).}$$

In this case, $e \cong \alpha/\pi$, and it gives a natural explanation of the smallness of the CP non-invariant amplitude in K_2^o decay.

3. Two problems, naturally, arise:

(i) Is the possibility of H_γ being non-invariant under C_{st} in contradiction with any known experiments? In an extensive study made in collaboration with Bernstein and Feinberg, we found that there exists at present no evidence that H_γ of the non-leptons is, or is not, invariant under C.

(ii) The H_γ of the leptons are known to be invariant under the charge conjugation C_γ, and it is attractive to assume that all electromagnetic interactions, leptonic and non-leptonic, are invariant under

$$C_\gamma = \text{charge conjugation.}$$

Under C_γ, all electromagnetic currents change sign. Under C_{st}, $p \to \bar{p}$ and $n \to \bar{n}$, and we may, e.g., view C_{st} as the "baryon number conjugation." The question whether H_γ is invariant under C_{st} is identical with the question whether

$$C_{st} \stackrel{?}{=} C_\gamma .$$

If $C_\gamma \neq C_{st}$, then we can attribute the observed CP non-invariance as due to either the violation of C_γ by H_{st} or the violation of C_{st} by H_γ.

The possibility that $C_\gamma \neq C_{st}$ is, of course, only a theoretical speculation, since it is based on just one experimental result: $\varepsilon \cong (\alpha/\pi)$. Nevertheless, the fact that there exists, at present, no evidence that H_γ is, or is not, invariant under C_{st} and T_{st} should provide sufficient incentive for

further experimental efforts in this direction. Various tests have been proposed, and some of these are already in progress.

References

1. J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964). See also A. Abashian et al., Phys. Rev. Letters 13, 243 (1964).

2. T. D. Lee and L. Wolfenstein, Phys. Rev. 138, B1490 (1965); J. Prentki and M. Veltman, Phys. Letters 15, 88 (1965); L. B. Okun (preprint).

3. J. Bernstein, G. Feinberg and T. D. Lee, Phys. Rev. 139, B1650 (1965).

4. See, e.g., R. G. Sachs and S. B. Treiman, Phys. Rev. Letters 8, 137 (1962). Since the discovery of $K_2^o \rightarrow \pi^+ + \pi^-$, there have been may publications on the various possible ways to violate the CP invariance in the weak interaction. We list but a few of these references: R. G. Sachs, Phys. Rev. Letters 13, 286 (1964); N. Cabibbo, Phys. Letters 12, 137 (1964); S. Glashow, Phys. Rev. Letters 14, 35 (1965), etc.

5. L. Wolfenstein, Phys. Rev. Letters 13, 562 (1964). A general discussion of the consequences of the super-weak interaction is given by T. D. Lee and L. Wolfenstein, loc. cit.

6. The K_1^o - K_2^o system was first predicted and discussed under the assumption of charge conjugation invariance by M. Gell-Mann and A. Pais, Phys. Rev. 97, 1387 (1955). The phenomenological analysis of the K_1^o - K_2^o problem without any assumption of separate C, P, T invariances, but assuming CPT invariance, was first made by T. D. Lee, R. Oehme and C. N. Yang, Phys. Rev. 106, 340 (1957).

   For a summary of the various discussions prior to the discovery of $K_2^o \rightarrow \pi^+ + \pi^-$, see the review article by R. G. Sachs, Ann. Phys. 22, 239 (1963). Since the discovery of $K_2^o \rightarrow \pi^+ + \pi^-$, there have been many new papers on the extensions and elaborations of the same phenomenological analysis. Cf., e.g., the detailed discussion given by Dr. Yang (this conference).

DISCUSSION

VELTMAN (CERN): I have several questions that I would like to ask in succession. First, do you expect an asymmetry in the momentum distribution of π^+, π^- in $\eta \to \pi^+ \pi^- \pi^o$?

LEE: Thank you very much for the question. I assure you that it was not prearranged. Now it is surprising to find that there exists no experimental proof whether C_{st} is or is not the same as C_γ; whether electromagnetic interaction is or is not invariant under C_{st}. Perhaps what is equally surprising is the fact that after considerable thought we could find very few practical tests, one of which is that referred to by Dr. Veltman. Eta-decay, which is forbidden by strong interactions, proceeds through electromagnetic interactions and hence is a natural choice for testing these ideas. The test in principle is simple. You look for asymmetry in the energy distribution of π^+ and π^- in $\eta \to \pi^+ + \pi^- + \gamma$ and $\eta \to \pi^+ + \pi^- + \pi^o$. However, it is difficult to make a reliable estimate of the magnitude of the asymmetry even if the electromagnetic interaction has large C_{st} violation.

Thus in the case of $\eta \to \pi^+ + \pi^- + \gamma$, even if we assume that the reduced amplitudes that are even and odd under C_{st} are comparable in magnitude, we expect, based on rather a crude estimate of the centrifugal barrier effects, an asymmetry of the order of only 10%. In $\eta \to \pi^+ + \pi^- + \pi^o$, the final isotopic spin state can be I = 0, 1, or 2. If H_γ is invariant under C_{st}, the final state can be only I = 1. However, if C_{st} is violated, in addition I = 0 or I = 0, 2 can be present depending on whether the violating part conserves isotopic spin or not. Again, due to centrifugal barrier effects, you get different answers in the two cases. For I = 0, a factor $(kR)^6$ enters. If one uses for the range of interaction R, $R \sim 1/m_\pi$ then one finds that the asymmetry can be, at most, of the order of 5%. If $R \sim 1/m_\eta$ the asymmetry would be extremely small. For I = 2, $(kR)^2$ enters and one might expect a sizeable asymmetry.

VELTMAN: Then let's assume that there is an isospin 2 contribution. That would mean that in your C-violating electromagnetic interaction, I have also $\Delta I = 1$. Now the conserved vector current hypothesis tells me that the weak interaction vector current is related to the isovector current of electromagnetic interaction. For that reason I would therefore find the same C-violating current K_μ, as you called it, in the weak interactions and thus expect in the weak interaction large violations instead of the .2 percent that we have seen. So in such a case will you reject the conserved vector current hypothesis?

LEE: No, not totally. As demonstrated by π-decay, and B^{12} - N^{12} experiments, you would say that CVC applies only to the isovector current that is invariant under T_{st}.

VELTMAN: Well, let's come down to another question. There have been certain schemes of intermediate bosons in which $\Delta I = 1/2$ rule holds exactly for the nonleptonic interactions. Now if you take this point of view, then the $K^+ \rightarrow \pi^+ \pi^o$ decay is due to electromagnetic perturbations. This decay has an amplitude of 5%, and if the C violation is in the electromagnetic interaction, I would expect that in the K_2^o decay we would get $K_2^o \rightarrow 2\pi$, on the order of 5% CP violation, instead of 0.2, unless there is an accidental cancellation. That is, if the $\Delta I = 1/2$ rule is broken electromagnetically only, then I'm puzzled by the smallness of the Fitch-Cronin effect in the scheme of CP violation in electromagnetic interactions.

LEE: Let me just make a statement and then leave this point. In the K^+ decay the presence of the $\Delta I = 3/2$ amplitude has always been a problem but that is quite independent of the testing C or CP nonconservation.

VELTMAN: Then I have one final question, if that is all right. I am told that there has been a private meeting on the question of experimental asymmetry in the η decay. Do you know any details?

LEE: Since I did not do the experiment, it would not be proper for me to present the results.

CRAWFORD (Lawrence Radiation Lab): In June, 1965, a meeting was held in Berkeley to compile all available η decays in order to look for possible C-violation in the form of a charge asymmetry in the Dalitz plot of $\eta \rightarrow \pi^+ \pi^- \pi^o$. The meeting was motivated by the theoretical speculations of T. D. Lee and others, and by the results of a previous compilation by P. Franzini and M. Schwartz. At the meeting we realized that further work was necessary in order to correct for a bias due to ambiguity in distinguishing two different final states which both have π^+ mesons. These are $\pi_1^+ + \rho^-$ $(= \pi^- \pi^o)$ and η $(= \pi_2^+ + \pi^- + \pi^o)$; and also in order to systematize the background subtractions. We now have a total of about 1300 events above background, with backgrounds subtracted and biases corrected, compiled from hydrogen bubble chamber experiments by groups at Columbia, LRL, Wisconsin, and Yale. The preliminary results are as follows: (1) If we test the hypothesis "C is conserved" we find a good fit, namely a 16% chi square probability. (2) The Dalitz plot shows an asymmetry $(N_+ - N_-) / (N_+ + N_-) = 0.06 \pm 0.03$, where N_+ means the number of events with $E(\pi^+) > E(\pi^-)$. (3) If we parametrize in terms of a C-violating theory, we find a two-standard deviation result for the C-violating parameter. We regard these results as inconclusive.

LEE: I would like to comment again that even if one assumes as big a radius as $R \sim 1/m_\pi$, one expects only 5% asymmetry if $\Delta I = 0$ for C-violating part. This is certainly consistent with presently available experimental information. To settle this question, one really needs better statistics, I would say - 10,000 events in the case of 3π mode and 2000 events for the $\pi\pi\gamma$ mode.

TELEGDI (U. of Chicago): I want to ask you whether the experiment on $\eta \rightarrow \pi^o e^+ e^-$ rules out the possibility of C violation in electromagnetic interaction.

LEE: In this case, in the single photon approximation, C_{st} is violated by the electromagnetic current, but again the question is regarding the magnitude. Let us analyze the current of the C-violating part into various SU_3 multiplets. Let's assume that it contains only 27 multiplet. Then you would have

$R(\eta^o \to \pi^o e^+ e^-) / R(\eta^o \to 2\gamma) \approx 4\% (m_\eta R)^2$. [For the precise number, see Bernstein, Feinberg, and Lee.] Now the radius involved is the charge radius. If you take R to be $1/m_\eta$ then you get 4%. But if you assume, as it is quite reasonable, that the current for both the C invariant and non-invariant part behaves like an octet and a singlet under SU(3), then this would be mutiplied by an additional factor of 10^{-2}. If the current behaves only like a singlet for C noninvariant part, such as would follow from the dynamical theory of the A article, then the ratio will be down by 10^{-4}, because it would be restricted by isospin. Recently there has been another calculation that puts the 4% down to 0.4%. Therefore, I must conclude that the present limits on the $\eta \to \pi^o e^+ e^-$ throw no light whatsoever.

NAUENBERG (SLAC): I just want to mention that as a consequence of the CPT theorem the magnitude of the $\pi^+ \pi^-$ asymmetry in the two η decays described depends directly on the $\pi - \pi$ interaction. Since not much is known at present about it, it would be difficult to give a correct estimate.

LEE: There is no correct estimate. The estimate is always an order of magnitude. For the $\pi\pi\gamma$, there are reasonable models on the basis of which one my anticipate that the effect may not be small. For $\pi\pi\pi$ case, it's a bit uncertain, but what you say is certainly right.

TOUSCHEK (Frascati National Lab): I think you would help me very much in understanding this theory if you could tell me what C_γ applied to a proton state could be.

LEE: C_γ applied to a bare proton makes it a bare, anti-proton. However, if C_γ is not the same as C_{st}, the strong interaction is not invariant under C_γ. Therefore, C_γ on a physical proton is what we are not familiar with.

SUMMARY

H. Primakoff
University of Pennsylvania
Philadelphia, Pennsylvania

I do not have much time to summarize the results of this remarkable conference so that I shall merely comment in an impressionistic, but I hope not a non-objective way, on certain of the high points that have been stressed by the speakers we have heard. I shall also comment, from the point of view of the general framework of the theory of weak interactions, on several important questions that have been mentioned only too briefly.

We all have in the forefront of our minds the now familiar expression for the current-current, V-A, P- and C-violating, effective Hamiltonian of the weak interactions; in this Hamiltonian there appears first of all the basic weak-interaction coupling constant G. You will recall that Gm_p^2 is, empirically, about 10^{-5} (on the basis of an analysis of muon decay) and I think that it is worth reminding oneself occasionally that this value of 10^{-5} is as much a mystery as the value (1/137) for e^2, etc. Thus, no understanding whatever is available at present of the scale of strength of the weak interactions and it is obvious that no prospect of obtaining such an understanding exists within the context of a description where the weak, electromagnetic and strong interactions are treated in an essentially non-unified way.

A second fundamental question that I wish to mention is the matter of invariance under CPT. We heard from various speakers that a very important reason for belief in CPT invariance is the observed equality of particle and antiparticle masses to an extremely high accuracy (particularly in the K, $\overline{K}$ case). On the other hand, appeals were voiced from the floor regarding the desirability of "dynamic" tests of CPT, i.e., of experimental comparisons of rates of particle-reactions which are predicted to be equal if CPT invariance holds. Such dynamical tests are perhaps not wholly superfluous since it is conceivable that the equality of particle and antiparticle masses is a manifesta-

tion of a physical principle less restrictive (of particle-reaction rates) than CPT; unfortunately very difficult experiments would be involved. Thus, as mentioned by Yang, one might, for example, investigate whether the leptonic decay rates of a fresh K and a fresh $\bar{K}$ beam are identical. We should also emphasize that such an identity, while predicted from CPT invariance, does not necessarily imply an absence of lepton charge asymmetry in the decay of K_2^0- for this, CP invariance is also necessary. With regard to the CP non-invariance exhibited by the coexistence of the reactions $K_2^0 \to \pi^+ + \pi^-$ and $K_2^0 \to \pi^+ + \pi^- + \pi^0$, (and no certain experimental evidence exists for a CP violation in any other reaction) we are still in the dark regarding which of the elementary-particle interactions is to blame; in particular, either the hadron electromagnetic interaction (T. D. Lee) or a $\Delta S = 2$ superweak interaction (Wolfenstein) may fail to commute with CP.

We proceed to discuss the status of several other of the cherished principles on which the treatment of the weak interactions is based, and which are all incorporated into the effective weak-interaction Hamiltonian; the situation as painted at the Conference was on the whole very favorable to these principles: thus there is no evidence for the existence of neutral lepton currents, no evidence for the violation of lepton-number conservation, no evidence for the violation of muon-electron symmetry. Of course, by no evidence I mean no statistically firm evidence, interpreted not only quantitatively on the basis of some confidence limit, but also qualitatively on the basis of the consensus of opinion of experts in the field. In addition, the balance of the testimony of experiment favors the $\Delta I = \frac{1}{2}$ rule in both the hadron leptonic decays and the hadron non-leptonic decays; further, there is no convincing evidence against the $\Delta S = \Delta Q$ rule in hadron leptonic decay though the evidence in its favor obtained from an analysis of K and Σ leptonic decays is far from completely compelling-a similar remark may be made regarding the possibility of a $\{\Delta S = -\Delta Q\}$ -associated CP violation ($|\mathrm{Re}\chi| \lesssim 0.20$, $|\mathrm{Im}\chi| \lesssim 0.25$; $\chi \equiv \mathrm{Amp}(\bar{K}^0 \to \pi^- + e^+ + \nu_e)/\mathrm{Amp}(K^0 \to \pi^- + e^+ + \nu_e)$. A very interesting new experimental evidence was presented regarding the V-A character of the hadron current; thus it was shown that the $(K \to e + \nu_e)/(K \to \mu + \nu_\mu)$ branching

ratio is inconsistent with the presence of even a small pseudoscalar lepton current (Pennsylvania-Princeton group) while the shapes of the electron momentum spectra in $K \rightarrow \pi + e + \nu_e$ are incompatible with any appreciable admixture of a scalar or a tensor lepton current (Illinois group). On the other hand, there was, of course, no evidence reported for or against the principle of locality "within the lepton current", i.e., for or against the idea that the ℓ and ν_ℓ field operators in this current are to be taken at the same point of space-time; the validity of this locality principle can be tested by describing high energy neutrino cross sections in terms of the usual form-factors and then testing whether the values of these form-factors as deduced from experiment are numerically the same for two values of momentum transfer equal one to the other but corresponding to different neutrino energies and muon production angles. With respect to the other much discussed type of non-locality, the non-locality associated with the transmission of the weak interactions by an intermediate boson W, two negative results relating to W production in nucleon-nucleon collision were presented; in view of these, and of the previous negative results on W production in neutrino-nucleon collisions, I think that it is fair to say that if there is a boson, its mass is more than something like 4 or 5 m_p. In fact, if I guage public sentiment correctly, I think that it is not too inaccurate to assert that many people are losing faith in the existence of the boson. I might also comment that it is not all obvious that an intermediate boson is necessary to prevent the unitarity catastrophe which is associated with the monotonic growth with neutrino energy of the Born-approximation neutrino-electron scattering cross section; this follows since it may well be that higher order effects of a sans-boson weak interaction (and/or the electromagnetic interaction) make the actual neutrino-electron scattering cross section flatten out at high neutrino energies.

With regard to the detailed character of the V-A hadron currents we heard the impressive contributions of Adler and Weissberger who showed that specification of the $\Delta S = 0$ axial hadron current in an implicit way through appropriate equal-time commutation relations yields the numerical value of the axial form-factor at zero momentum transfer for the neutron

leptonic decay; analogous calculations, based on the corresponding commutation relations for the $\Delta S = 1$ axial hadron current, yield numerical values of the axial form-factors at zero momentum transfer for the Λ and Σ leptonic decays. These calculations are of great interest since, together with the CVC-based calculations of zero-momentum-transfer polar form-factors, they permit at least in principle the calculation of the various matrix elements of the whole hadron current, and so the unequivocal determination of the Cabibbo angle θ. With regard to θ, a value of 0.20 is obtained from the analysis of $\Delta S = 0$ polar superallowed nuclear leptonic decays while a value of 0.24 is deduced from a corresponding treatment of $\Delta S = 1$ polar $K \to \pi + e + \nu_e$ leptonic decay; corrections to the value of the last form-factor arising from the circumstance that $|\pi>$ and $|K>$ are imperfect octet states are considered very small (Gatto-Ademollo theorem). The discrepancy between the two values of θ may be caused by the neglect of the above mentioned SU3-breaking corrections or, alternatively, from an inadequate treatment of the electromagnetic radiative correction. The second of these possibilities is of especial interest since the assumption that hadrons are composite structures built of "quarks", together with a quark-mass rather than a nucleon-mass cut-off in the ultraviolet divergent integrals of the electromagnetic radiative correction, renders the $\Delta S = 0$ and $\Delta S = 1$ θ-values consistent (A similar remark has been made by T. D. Lee in an intermediate-boson context).

Additional results on the form-factors associated with the hadron current have been obtained on the basis of analysis of several types of experimental data. Thus, from a study of $\nu_\mu + n \to p + \mu^-$ it has been concluded that the form-factors $F_V(q^2)_{n \to p}$ and $F_A(q^2)_{n \to p}$ fall off with momentum-transfer q^2 in essentially the same way. Assuming that this result holds with some quantitative accuracy, and parametrizing each form-factor by means of pole terms associated with 1_1^{++} and 1_+^{+-} (J_I^{PG}) vector mesons, one can conclude that the spectra of masses and nucleon coupling constants of the two types of vector mesons are very similar. In the study of $F_V(q^2)_{K^+ \to \pi^0}$ and $F_V(q^2)_{K_2^0 \to \pi^\pm}$ form-factors associated with $K \to \pi + e + \nu$ decays a discrepancy was reported in that a somewhat different q^2 dependence appeared to characterize the two form-factors. This is, of course, contradictory to the $\Delta I = \frac{1}{2}$ rule which

otherwise holds very well in the description of $K \to \pi + e + \nu$ decays, and more particularly, is contradictory to the idea that the $K^+\pi^0$ and $K^0\pi^-$ vertices are dominated by one and the same $(K^*)^+$ vector meson; clearly, more precise experimental data is desirable in this connection. Preliminary information, both experimental and theoretical, was presented on hadron-hadron transitions with the initial and final hadrons members of different SU3 multiplets, in particular $(N^*)^+ \to n + \ell + \nu_\ell$. Here a calculation was presented by Adler which, employing methods analogous to those used in the description of $\gamma + p \to (N^*)^+$, related the $F_A(q^2)_{(N^*)^+ \to n}$ and $F_A(q^2)_{n \to p}$ form-factors ($F_V(q^2)_{(N^*)^+ \to n}$ is given directly by CVC in terms of the $\gamma + p \to (N^*)^+$ form factors). This theory yields rather good agreement with the CERN experiments on the cross section for $\nu_\mu + n \to (N^*)^+ + \mu^-$ as does (1): an alternative theory due to Albright and Liu (not reported to the Conference) which relates $F_A(q^2)_{(N^*)^+ \to n}$ and $F_A(q^2)_{n \to p}$ via SU6 considerations or (2): a treatment based on the Goldberger-Treiman relation which connects $F_A(q^2)_{(N^*)^+ \to n}/F_A(q^2)_{n \to p}$ with the ratio of the corresponding $(N^*)^+$, n and n, p pion coupling constants. Such a treatment is also involved in a theory of pion exchange effects in nuclear leptonic decay where, as shown by a student of mine, Cheng, the $n \to n + \pi^+ + e^- + \bar{\nu}_e$ vertex is dominated by the vertices $n \to (N^*)^+ + e^- + \nu_e$; $(N^*)^+ \to n + \pi^+$; Cheng's calculation on this basis of the pion exchange correction ($n_1 \to n_1 + \pi^+ + e^- + \bar{\nu}_e$; $n_2 + \pi^+ \to p_2$) to the $H^3 \to He^3 + e^- + \bar{\nu}_e$ axial hadron-current matrix element removes a long standing discrepancy between the computed and the observed H^3 decay rates.

Finally, I should like to mention the non-leptonic weak decays of the hadrons. Here, as elegantly described by my colleague B. Lee, one replaces the $H_{ini} \to H_{fin}$ matrix elements of the product of two V-A hadron currents by the corresponding matrix elements of an effective transition operator of suitable SU2 and SU3 transformation properties, i.e., by an effective transition operator which has the SU2 transformation properties of an isospinor ($\Delta I = \frac{1}{2}$ rule) and the SU3 transformation properties of an octet; such a treatment, together with certain auxiliary assumptions clearly categorized with respect to necessity and sufficiency by Rosen, leads to a deduction of the $\Sigma^+ \to p + \pi^0$, $\Sigma^- \to n + \pi^-$ Lee-Sugawara triangle which, parenthetically,

is in as good agreement with experiment as the $\Sigma^+ \to p + \pi^0$, $\Sigma^- \to n + \pi^-$, $\Sigma^+ \to n + \pi^+$ Gell-Mann-Rosenfeld $\Delta I = \frac{1}{2}$ triangle. On the other hand, no really satisfactory dynamical account has yet been given of the enhancement of the SU3 octet component (and so the SU2 isospinor component) of the product of the $\Delta S = 0$ and $\Delta S = 1$ V-A hadron currents; an associated prediction by Gell-Mann and collaborators of the enhancement of the $\Delta I = 0$ component of the product of the two $\Delta S = 0$ V-A hadron currents has not so far been tested though G. Goldhaber described to the conference an intriguing experiment which indicates the existence of imperfect parity-eigenstates in a certain nucleus. Such an effect is to be anticipated on the basis of the presence of this last product of currents in H weak and its further investigation is of great interest.

In closing I may recall, in order to convey some sense of a historical perspective that, say twenty years ago, the only elementary-particle weak-interaction processes that were known experimentally were the leptonic decay of the neutron and the leptonic decay of what was then believed to be the pion but was in fact the muon. As regards weak-interaction theory, the current-current effective hamiltonian was already familiar but its V-A and P- and C-violating properties were, of course, unknown. If progress in the field of weak interactions in the next twenty years involves as much of an expansion of our knowledge as that in the last twenty, I think I had best leave the results to your imagination.

ATTENDEES AT THE INTERNATIONAL CONFERENCE ON WEAK INTERACTIONS, ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS, OCTOBER 25-27, 1965

CONFEREES

Name	Affiliation
Abashian, A.	University of Illinois
Adair, R. K.	Yale University
Adler, S. L.	Harvard University
Aitken, A. H.	Naval Research Laboratory
Albright, C. H.	Northwestern University
Ammar, R. G.	Northwestern University
Anderson, H. L.	University of Chicago
Ashkin, J.	Carnegie Institute of Technology
Aubert, B.	Orsay (France)
Bacon, T. C.	Vanderbilt University
Baillon, P.	Ecole Polytechnique (France)
Baldo-Ceolin, M.	University of Padova (Italy)
Baltay, C.	Columbia University
Bartlett, D.	Princeton University
Beg, M. A. B.	The Rockefeller Institute
Behr, L.	Ecole Polytechnique (France)
Behrends, R. E.	Yeshiva University
Berley, D.	Brookhaven National Laboratory
Berman, S.	Stanford Linear Accelerator Center
Bernstein, J.	New York University
Bernstein, S.	University of Illinois, Chicago Circle
Bietti, A.	California Institute of Technology
Bjorken, J. D.	Stanford Linear Accelerator Center
Blair, I. M.	Rutherford Laboratory (England)
Block, M. M.	Northwestern University
Bodmer, A. R.	Argonne National Laboratory
Bouchiat, C.	Orsay (France)
Brene, N.	Institute for Theoretical Physics (Denmark)
Bronzan, J. B.	Massachusetts Institute of Technology
Brown, L. M.	Northwestern University
Brunet, R. C.	Argonne National Laboratory
Burleson, G. R.	Northwestern University
Burnstein, R. A.	Illinois Institute of Technology
Byers, N.	University of Colorado
Camerini, U.	University of Wisconsin
Capps, R. H.	Northwestern University

Name	Affiliation
Carhart, R. A.	Brookhaven National Laboratory
Chadwick, G. B.	Stanford Linear Accelerator Center
Charpak, G.	CERN (Switzerland)
Chilton, F.	Argonne National Laboratory
Chiu, H. Y.	Columbia University
Christenson, J. H.	Columbia University
Cline, D. B.	University of Wisconsin
Coester, F.	Argonne National Laboratory
Coleman, S. R.	Harvard University
Commins, E. D.	University of California - Berkeley
Cool, R. L.	Brookhaven National Laboratory
Courant, H. W.	University of Minnesota
Crawford, F. S., Jr.	Lawrence Radiation Laboratory
Cronin, J. W.	Princeton University
Crowe, K. M.	Lawrence Radiation Laboratory
Cundy, D. C.	CERN (Switzerland)
Curtis, R. B.	Indiana University
Cushing, J.	Argonne National Laboratory
Cutkosky, R. E.	Carnegie Institute of Technology
Dalitz, R. H.	Oxford University (England)
Derrick, M.	Argonne National Laboratory
Deser, S.	Brandeis University
Deutsch, M.	Massachusetts Institute of Technology
Di Capua, E.	University of Roma (Italy)
Doede, J. H.	Argonne National Laboratory
Domokos, G.	Hungarian Academy of Sciences (Hungary)
Drijard, D.	Harvard University
Ebel, M. E.	University of Wisconsin
Edelstein, R. M.	Carnegie Institute of Technology
Ekstein, H.	Argonne National Laboratory
Engler, A.	Carnegie Institute of Technology
Feinberg, G.	Columbia University
Feshbach, H.	Massachusetts Institute of Technology
Fetkovich, J. G.	Carnegie Institute of Technology
Fields, T. H.	Argonne National Laboratory
Filthuth, H.	University of Heidelberg (Germany)
Fitch, V. L.	Princeton University
Fowler, E. C.	Duke University
Frankel, S.	University of Pennsylvania
Franzinetti, C.	CERN (Switzerland)
Franzini, P.	Columbia University
Frauenfelder, H.	University of Illinois
Frazer, W. R.	University of California - La Jolla
Freeman, J. M.	Harwell Laboratory (England)

Name	Affiliation
Freund, P. G. O.	University of Chicago
Frisch, D. H.	Massachusetts Institute of Technology
Fry, W. F.	University of Wisconsin
Fubini, S.	Institute for Advanced Study
Fulton, T.	Johns Hopkins University
Gasiorowicz, S. G.	University of Minnesota
Geffen, D. A.	University of Minnesota
Gelfand, N. L.	University of Chicago
Gerhart, J. B.	University of Washington
Giacomelli, G. M.	Brookhaven National Laboratory
Glasser, R. G.	University of Maryland
Goldhaber, A. S.	Lawrence Radiation Laboratory
Goldhaber, G. S.	Brookhaven National Laboratory
Goldhaber, M.	Brookhaven National Laboratory
Goldwasser, E. L.	University of Illinois
Good, M. L.	University of Wisconsin
Good, R. H., Jr.	Iowa State University
Goulianos, K.	Princeton University
Greenberg, J. S.	Yale University
Gregory, B. P.	Ecole Polytechnique (France)
Griffiths, D.	Argonne National Laboratory
Grodzins, L.	Massachusetts Institute of Technology
Guidoni, P.	Brookhaven National Laboratory
Hahn, B.	CERN (Switzerland)
Hamermesh, M.	University of Minnesota
Hanson, A. O.	University of Illinois
Henley, E. M.	University of Washington
Hildebrand, B.	U. S. Atomic Energy Commission
Hildebrand, R. H.	University of Chicago
Hoang, T. F.	Argonne National Laboratory
Hopkins, H. W. K.	Vanderbilt University
Horn, D.	Argonne National Laboratory
Hughes, E. B.	Princeton University
Hughes, V. W.	Yale University
Hutchinson, D. P.	Princeton University
Hyman, L. G.	Argonne National Laboratory
Jackson, J. D.	University of Illinois
Jacobsohn, B. A.	University of Washington
Jenkins, D. A.	Lawrence Radiation Laboratory
Johnson, W. R.	University of Note Dame
Jones, P. B.	Oxford University (England)
Jovanovic, D. D.	Argonne National Laboratory

Name	Affiliation
Kadyk, J. A.	Lawrence Radiation Laboratory
Kernan, A.	Lawrence Radiation Laboratory
Kerth, L. T.	Lawrence Radiation Laboratory
Keuffel, J. W.	University of Utah
Kim, J. K.	Yale University
Kinoshita, T.	Cornell University
Konopinski, E. J.	Indiana University
Krohn, V.	Argonne National Laboratory
Lamb, R. C.	Argonne National Laboratory
Lande, K.	University of Pennsylvania
Lederman, L. M.	Columbia University
Lee, B. W.	University of Pennsylvania
Lee, T. D.	Columbia University
Lee, W. Y.	Columbia University
Lee-Franzini, J.	Stony Brook
Leipuner, L. B.	Brookhaven National Laboratory
Leitner, J.	Syracuse University
Lévy, M. L.	Orsay (France)
Lewis, R. R.	University of Michigan
Lichtenberg, D. B.	Indiana University
Loken, J. G.	Argonne National Laboratory
London, G. W.	Brookhaven National Laboratory
Lundy, R. A.	Argonne National Laboratory
MacDowell, S. W.	Yale University
Madansky, L.	Johns Hopkins University
Mann, A. K.	University of Pennsylvania
Manner, W. E.	Argonne National Laboratory
March, R. H.	University of Wisconsin
Marshak, R. E.	University of Rochester
Marshall, L. W.	University of Colorado
Masek, G. E.	University of California - La Jolla
Matthews, P. T.	Imperial College (England)
Mayer, M. E.	Indiana University
McFarlane, W. K.	University of Pennsylvania
McGlinn, W. D.	University of Notre Dame
McLeod, D. W.	Argonne National Laboratory
Merrison, A. W.	University of Liverpool (England)
Meshkov, S.	National Bureau of Standards
Meyer, D. I.	University of Michigan
Meyer, S. L.	Rutgers University
Moffat, J. W.	University of Toronto (Canada)
Morellet, D.	Orsay (France)
Murphy, C. T.	University of Michigan

Name	Affiliation
Nambu, Y.	University of Chicago
Natali, S.	University of Bari (Italy)
Nauenberg, M.	Stanford Linear Accelerator Center
Nefkens, B. M. K.	University of Illinois
Nishijima, K.	University of Illinois
Novey, T. B.	Argonne National Laboratory
Oakes, R. J.	Stanford University
Oehme, R.	University of Chicago
Okubo, S.	University of Rochester
Oneda, S.	University of Maryland
O'Neill, G. K.	Stanford University
O'Raifeartaigh, L.	Syracuse University
Overseth, O. E.	University of Michigan
Pal, Y.	Tata Institute (India)
Parker, S. I.	University of California - Berkeley
Pati, J. C.	University of Maryland
Perkins, D. H.	Oxford University (England)
Peshkin, M.	Argonne National Laboratory
Pevsner, A.	Johns Hopkins University
Piccioni, O.	University of California - La Jolla
Pondrom, L. G.	University of Wisconsin
Prentki, J.	CERN (Switzerland)
Primakoff, H.	University of Pennsylvania
Radojicic, D.	Brookhaven National Laboratory
Ratner, L. G.	Argonne National Laboratory
Ravenhall, D. G.	University of Illinois
Reay, N. W.	University of Rochester
Reines, F.	Case Institute of Technology
Riazuddin	University of Pennsylvania
Roberts, A.	Argonne National Laboratory
Robinson, D. K.	Brookhaven National Laboratory
Roe, B. P.	University of Michigan
Romanowski, T. A.	Argonne National Laboratory
Rosen, J. L.	University of Rochester
Rosen, S. P.	Purdue University
Ross, M.	University of Michigan
Roth, R. F.	Princeton University
Rubbia, C.	CERN (Switzerland)
Ruderman, M. A.	New York University
Sachs, R. G.	University of Chicago
Sakita, B.	Argonne National Laboratory
Salam, A.	International Center for Theoretical Physics (Trieste, Italy) and Imperial College (England)

Name	Affiliation
Salzman, F.	University of Massachusetts
Salzman, G.	University of Massachusetts
Samios, N. P.	Brookhaven National Laboratory
Sandler, C. L.	Argonne National Laboratory
Sard, R. D.	University of Illinois
Sawyer, R. F.	University of California - Santa Barbara
Schlein, P. E.	University of California - Los Angeles
Schluter, R. A.	Argonne National Laboratory
Schneps, J.	Tufts University
Schulke, L.	University of Heidelberg (Germany)
Schult, R. L.	University of Illinois
Schultz, C.	Columbia University
Schwartz, M.	Columbia University
Schweber, S. S.	Brandeis University
Seeman, N.	Naval Research Laboratory
Segar, A. M.	Rutherford Laboratory (England)
Selove, W.	University of Pennsylvania
Siegel, R. T.	College of William and Mary
Sinclair, D.	University of Michigan
Sirlin, A.	New York University
Socolow, R. H.	University of California - Berkeley
Soergel, V.	CERN (Switzerland)
Stafford, G. H.	Rutherford Laboratory (England)
Steiner, H.	Lawrence Radiation Laboratory
Stevenson, M. L.	Lawrence Radiation Laboratory
Stichel, P.	University of Hamburg (Germany)
Stiening, R. F.	Lawrence Radiation Laboratory
Sucher, J.	University of Maryland
Sudarshan, E. C. G.	Syracuse University
Tanaka, K.	Ohio State University
Taylor, J. C.	Oxford University (England)
Telegdi, V. L.	University of Chicago
Thevenet, B.	Saclay (France)
Ticho, H. K.	University of California - Los Angeles
Ting, S. C.	Columbia University
Touschek, B.	Frascati National Laboratory (Italy)
Treiman, S. B.	Princeton University
Trilling, G. H.	Lawrence Radiation Laboratory
Truong, T. R.	Brown University
Turlay, R.	Saclay (France)
Uretsky, J. L.	Argonne National Laboratory
Valk, H. S.	National Science Foundation
Vander Velde, J. C.	University of Michigan

Name	Affiliation
Veltman, M.	CERN (Switzerland)
Voyvodic, L.	Argonne National Laboratory
Wales, W. D.	University of Pennsylvania
Wali, K. C.	Argonne National Laboratory
Ward, J. C.	Johns Hopkins University
Warnock, R. L.	Argonne National Laboratory
Wattenberg, A.	University of Illinois
Weisberger, W. I.	Stanford Linear Accelerator Center
Welling, D.	Argonne National Laboratory
Wentzel, G.	University of Chicago
White, D. H.	Cornell University
Wick, G. C.	Columbia University
Willis, W. J.	Yale University
Willmann, R. B.	Purdue University
Wilson, R.	Harvard University
Winston, R.	University of Chicago
Winter, K.	CERN (Switzerland)
Wolfenstein, L.	Carnegie Institute of Technology
Wong, D. Y.	University of California - La Jolla
Wood, L. A.	Air Force Office of Scientific Research
Wu, C. S.	Columbia University
Wyld, H. W.	University of Illinois
Yamamoto, S. S.	University of Massachusetts
Yang, C. N.	Institute for Advanced Study
Yokosawa, A.	Argonne National Laboratory
Zachariasen, F.	California Institute of Technology
Zdanis, R. A.	Johns Hopkins University
Zorn, G. T.	University of Maryland
Zweig, G.	California Institute of Technology

AUDITORS

Name	Affiliation
Arnold, R. C.	Argonne National Laboratory
Atkinson, R.	Tufts University
Auerbach, L. E.	University of Pennsylvania
Auvil, P. R.	Northwestern University
Balachandran, A. P.	Syracuse University
Barbour, I. M.	University of Illinois
Barger, V. D.	University of Wisconsin

Name	Affiliation
Callahan, A. C.	University of Wisconsin
Carpenter, D. W.	University of Illinois
Cason, N. M.	University of Notre Dame
Chang, C. Y.	Syracuse University
Chew, H. W.	Western Reserve University
Chu, W. T.	Ohio State University
Clark, A. R.	Lawrence Radiation Laboratory
Cook, V.	University of Washington
Cooper, W. A.	Argonne National Laboratory
Crouch, M. F.	Case Institute of Technology
Davis, R. E. P.	Northwestern University
Derado, I.	University of Notre Dame
Dietz, K.	University of Illinois
Eisenstein, B.	Harvard University
Ernst, F. J.	Illinois Institute of Technology
Ginsberg, E. S.	University of Pennsylvania
Glaubman, M. J.	University of Illinois
Gluckstern, R. L.	University of Massachusetts
Goldberg, M.	Syracuse University
Groves, T. H.	Purdue University
Hoff, G.	University of Illinois, Chicago Circle
Holladay, W. G.	Vanderbilt University
Jabbur, R. J.	Argonne National Laboratory
Kane, G. L.	University of Michigan
Kantor, P. B.	Stony Brook
Kim, C. W.	University of Pennsylvania
Kuo, T. K.	Purdue University
Leacock, R. A.	Iowa State University
Lee, Y. K.	Johns Hopkins University
Malhiot, R. J.	Illinois Institute of Technology
Margulies, S.	University of Illinois, Chicago Circle
Massimo, J. T.	Brown University
Mathur, V. S.	University of Rochester
McKenzie, J.	Carnegie Institute of Technology
Meltzer, C.	Carnegie Institute of Technology
Meyer, J. W.	University of Minnesota
Mistry, N. B.	Cornell University
Mo, L. W.	Stanford Linear Accelerator Center
Month, M.	University of Illinois
Moscati, G.	University of Illinois
Nissim-Sabat, C.	University of Chicago

Name	Affiliation
Oswald, L. O.	Argonne National Laboratory
Pakvasa, S.	Syracuse University
Palmer, R. B.	Brookhaven National Laboratory
Pandit, L. K.	University of Rochester
Pappademos, J. N.	University of Illinois, Chicago Circle
Peoples, J.	Columbia University
Perdrisat, C. F.	University of Illinois
Pewitt, E. G.	Argonne National Laboratory
Prentice, J. D.	University of Toronto (Canada)
Ram, M.	Johns Hopkins University
Reibel, K.	Ohio State University
Ringo, G. R.	Argonne National Laboratory
Ryan, C. P.	University of Rochester
Sankaranarayanan, A.	Iowa State University
Sarker, A. Q.	The Rockefeller Institute
Schiff, M.	Yale University
Schima, F. J.	Indiana University
Sciulli, F. J.	University of Pennsylvania
Sechi-Zorn, B.	University of Maryland
Shrauner, E. J.	Washington University
Spejewski, E. H.	Indiana University
Strelzoff, A.	University of Wisconsin
Stump, R.	University of Kansas
Suura, H.	University of Minnesota
Teiger, J.	Brookhaven National Laboratory
von Hippel, F. N.	Cornell University
Wada, W. W.	Ohio State University
Welsh, R. E.	College of William and Mary
White, T. O.	Northwestern University
Winsberg, L.	University of Illinois, Chicago Circle
Young, K.	University of Michigan

LISTENERS

Name	Affiliation
Abrams, R. J.	University of Illinois
Bart, G.	Illinois Institute of Technology
Beier, E. W.	University of Illinois
Bookstein, A.	Lawrence Radiation Laboratory
Chang, T. H.	University of Chicago

Name	Affiliation
Chen, H.	University of Minnesota
Chiu, Y.	University of Chicago
Cho, Y.	Carnegie Institute of Technology
Clavelli, L. J.	University of Chicago
Cook, T. T.	Argonne National Laboratory
Cronin, J. A.	University of Chicago
Delaney, R. M.	Argonne National Laboratory
Ehrlich, R.	University of Chicago
Einschlag, M.	University of Maryland
Elwyn, A. J.	Argonne National Laboratory
Eoll, C.	University of Toronto (Canada)
Fryberger, D.	University of Chicago
Fukui, S.	University of Chicago
Goldstein, G. R.	Argonne National Laboratory
Graham, R. H.	Purdue University
Greenberg, D. F.	University of Chicago
Gupta, S. N.	Illinois Institute of Technology
Hassenzahl, W. V.	University of Illinois
Hoffman, E.	Northwestern University
Hwang, C. F.	Northwestern University
Jensen, D.	University of Chicago
Keller, L. P.	Argonne National Laboratory
Kenny, B.	University of Chicago
Kimel, I.	University of Chicago
Knop, R. E.	University of Maryland
Koberle, R.	University of Chicago
Lai, C. S.	University of Chicago
Lo, S.	University of Chicago
Mantsch, P. M.	University of Illinois
Marmer, G. J.	Argonne National Laboratory
McDaniel, H. S.	Illinois Institute of Technology
Michael, D.	University of Chicago
O'Donovan, P.	University of Chicago
Panchapakesan, N.	University of Chicago
Phelan, J. J.	Argonne National Laboratory
Powers, R. J.	University of Chicago
Ragusa, S.	Argonne National Laboratory
Rhode, R. E.	Argonne National Laboratory
Rudnick, S. J.	Argonne National Laboratory
Schlecter, J.	University of Chicago
Schweingruber, F. L.	Argonne National Laboratory
Sherwood, B. A.	University of Chicago
Simmons, W. A.	Purdue University

Name	Affiliation
Simpson, J.	Argonne National Laboratory
Stutzke, R.	University of Illinois
Swallow, E.	Argonne National Laboratory
Thatcher, R.	University of Illinois
Ueda, Y.	Indiana University
Venturi, G. A.	University of Chicago
Verhey, L. J.	University of Illinois
Wangler, T.	Brookhaven National Laboratory
West, E.	University of Toronto (Canada)

ARGONNE NATIONAL LAB WEST
3 4444 00015007 8