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PHYSICS DIVISION SUMMARY REPORT

June 1963

Annual Review

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PHYSICS DIVISION SUMMARY REPORT

June 1963

Annual Review

Lowell M. Bollinger, Division Director

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FOREWORD

This issue of the ANL Physics Division Summary Report presents a comprehensive picture of the work of the Division in the year ending in the spring of 1963. Instead of the usual small selection of relatively full accounts of individual researches reported at the random times at which they become available, this issue offers a complete and systematic overview of what is going on. Much of what is indicated briefly here has been described more fully in earlier issues of the Summary; most of the rest will appear in forthcoming issues.

In addition, the papers published in the 1-year period from 1 April 1962 through 31 March 1963 are listed immediately after the reports on the research. This list accounts for much the same effort but from a different point of view.

Still another picture of the relative emphases on the different programs of the Division is supplied by the roster of personnel, in which the staff members are grouped by program. (It must be understood, however, that staff members frequently do part of their work in another program.) This roster forms the last section of the report.

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I. NUCLEAR PHYSICS

I - 1. INTRODUCTION

The general objective of the program remains unchanged: it is to contribute to the advance of nuclear physics by studying the properties of light nuclei — particularly the energies, quantum numbers, and lifetimes of nuclear energy states. Experimenters and theorists work closely together so that new results in one area may suggest new approaches in the other. An effort is made to stress work that can be done more advantageously at Argonne than elsewhere because of the special facilities available. In view of the history and tradition of the Laboratory, it is natural that much of the work involves interactions between nuclei and neutrons; but this is balanced by a well diversified program of other nuclear investigations.

The experimental part of the program is most easily outlined by subdividing the work into various categories for which a major piece of equipment or an important experimental technique is the unifying factor. The categories formed in this way are the following:

(1) Studies of the neutron and of neutron-induced reactions at the reactor CP-5.

(2) Neutron and charged-particle-induced reactions at the 4.5-MeV Van de Graaff.

(3) Charged-particle reactions at the tandem Van de Graaff accelerator.

(4) Charged-particle reactions at the 60-in. cyclotron.

(5) Various experiments that use the Mössbauer effect.

(6) Atomic-beam studies.

(7) Studies of the decay of short-lived radionuclides.

Some physicists restrict their efforts to the use of a single machine or technique, whereas others investigate related problems with several systems of apparatus.

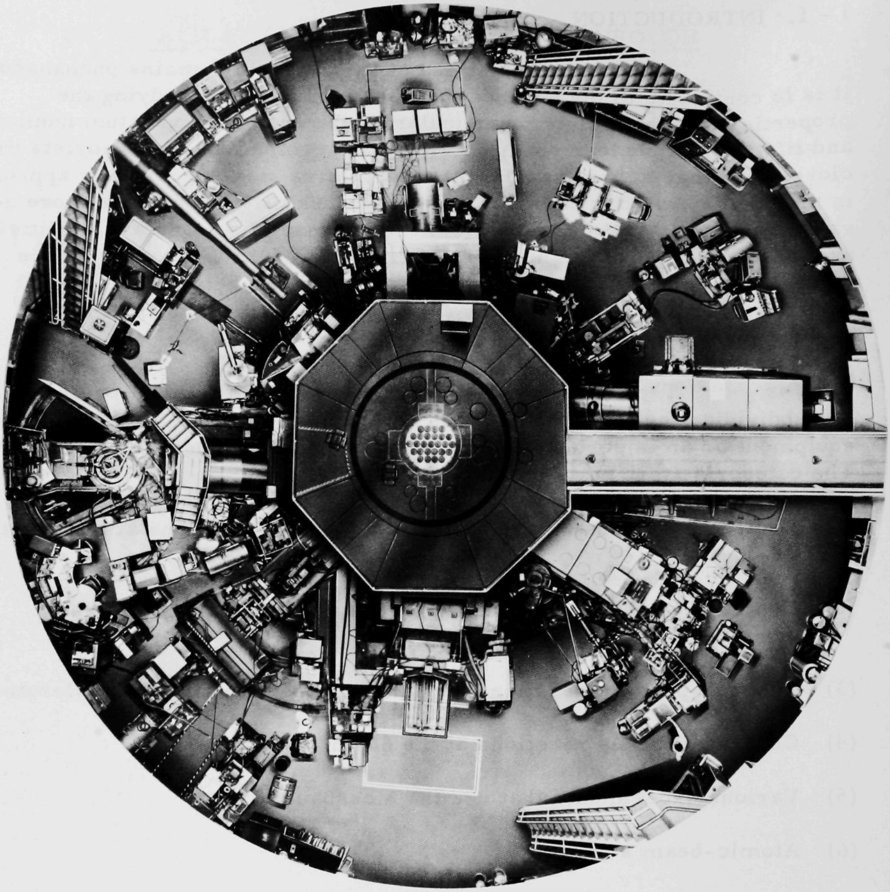


Fig. 1. Equipment in the experimental area around the reactor CP-5. The physics equipment, identified by its angular position measured clockwise from the top of the figure and by the pages on which the work is described in this report, comprises (135°) the scintillation spectrometer and neutron polarizer (pp. 14-15); (150°) the apparatus for measuring the lifetimes of states formed by neutron capture (pp. 7-8); (175°) the bent-crystal spectrometer (pp. 10-12); (225°) the fast chopper (pp. 5-7, 8-10); (325°) the neutron polarizer (pp. 3-4); and (350°) the magnetic Compton spectrometer (pp. 13-14).

I - 2. RESEARCH AT THE REACTOR CP-5

The program of the Physics Division at the reactor CP-5 is devoted entirely to nuclear physics. The experiments fall into three broad categories — experiments on the fundamental properties of the neutron itself, studies of neutron cross sections, and a variety of experiments with neutron-capture gamma rays.

The first category includes an investigation of the neutron-electron interaction and studies of the decay of polarized neutrons.

Neutron cross sections are measured by the time-of-flight method with a fast chopper. During the past year, this system was used to measure total and fission cross sections and especially to study the gamma-ray spectra that result from the capture of neutrons in resonances.

The largest area of investigation is concerned with the gamma rays from capture of thermal neutrons. The program centers around two precision instruments. For the range of energy up to about 2 MeV, the bent-crystal spectrometer is used; at higher energy the recently completed Compton spectrometer is more suitable. In addition to the measurements made with these precision instruments, many useful studies are performed with NaI scintillation spectrometers of various kinds. These studies include measurements with an anticoincidence spectrometer to obtain the capture gamma-ray spectra for materials having exceptionally small neutron cross sections, delayed-coincidence measurements of the lifetimes of excited states formed by neutron capture, coincidence measurements to determine nuclear decay schemes, and angular-correlation measurements to determine spins and parities of excited states.

In addition to the above experiments that are now in progress, during the coming year a program of measurements on the resonant scattering of neutron-capture gammas will be started.

I - 2.1. Instrumentation for Measurements of the Symmetry Properties of Neutron Decay (Project 123)

M. T. Burgy and G. R. Ringo

For the next phase of the experiment on the symmetry properties of neutron decay, it is necessary to know the polarization of the neutrons with an accuracy of about ±2%. The work of the past year has been largely devoted to this end. It now seems likely that this can be done by using reflection off two (parallel) mirrors in succession at both the polarizer and analyzer positions. This has given polarizations apparently as high as 97%, but more work is needed to get the measurements entirely under control. When this has been done, a new measurement of the decay asymmetries will be undertaken. To do this well, a new polarizer mirror will be needed.

I - 2.2. Electron-Neutron Interaction (Project I-135)

V. Krohn and G. R. Ringo

The electron-neutron interaction must be explained by any satisfactory theory of nucleon structure and hence is of considerable theoretical importance. It is desirable that this interaction be precisely measured by more than one experimental method and with a number of elements (since the results of all methods depend strongly on the assumption that the nuclear scattering amplitudes involved in the experiments are well understood).

During the past year, the program to measure this interaction by observing the asymmetry (ratio of counting rate at 45° to that at 135°) in the scattering of thermal neutrons (from CP-5) by noble gases has been revived. The contribution of the center-of-mass motion to the observed asymmetry is being precisely evaluated by a new computer program. Calculations from this computer program have been combined with existing data and the results will provide a useful guide in the continuing effort to obtain highly precise measurements. The results indicate that the angular divergence of the incident beam in the earlier measurements was satisfactory; but in the course of analyzing the data it has become evident that the scattering should be measured (in order to establish the "effective" atomic weights to be used in calculating the asymmetry associated with the motion of the center of mass). In addition, more reliable neutron counters are needed if the precision of the measurements is to be improved.

A new system for handling and cleaning the noble gases is now under construction. This system will also be used in a program to develop large-diameter He^3 proportional counters suitable for the scattering measurements. A new scattering chamber will be built in the near future. Separated isotopes of the noble gases to be used in the measurements are scheduled to be available by November 1963.

I - 2.3. Cross Sections for Slow Neutrons (Project I-3)

L. M. Bollinger, R. E. Coté, H. E. Jackson, J. P. Marion, and G. E. Thomas

The fast chopper at CP-5 was used with various targets to measure the total cross section for neutrons in the energy range from 10^{-2} to 10^3 eV. The neutrons were detected with a newly developed array of boron-loaded liquid scintillators. The large size and high efficiency of this system results in an exceptionally high counting rate. Consequently, the statistical accuracy of our recent work sets a new standard of excellence and small effects that were previously undetectable can now be studied.

Transmission measurements were made on targets of Cm^{244}, Th^{232}, Se, and Mo. Resonance parameters were determined for Cm^{244}, a target which had not been studied previously. This target was prepared by H. Diamond of the Chemistry Division. In Th^{232}, Se, and Mo, all of which had been studied previously, many tiny new transmission dips were detected. These dips are most readily interpreted as resulting from the p-wave resonances that are expected to be present even at very low neutron energies. A systematic study of the small resonances is continuing. It seems probable that the work will lead to reliable values of the p-wave strength function for Th^{232} and U^{238}, a result which would be important to both nuclear physics and reactor physics.

Another experiment that required a special detector was a measurement of the fission cross section of Th^{229}, the lightest nuclide that is known to be fissionable by thermal neutrons. The sample was prepared by H. Diamond and J. Gindler of the Chemistry Division. A Th^{228} impurity in the sample gave an alpha activity of 2×10^9 particles/sec. In spite of this intense background, it proved possible to detect fission fragments efficiently with a special gaseous scintillation chamber. With this chamber, the resonance structure of Th^{229} was studied at the Harwell electron linac by one of the group (L. M. B.). These data were then extended to sub-thermal energies by measurements with the Argonne fast chopper. These data will be combined with the results of previous measurements of the total cross section to give resonance parameters.

Two major improvements in the apparatus for cross-section measurements are planned for the coming year. First, the present 1024-channel analyzer, which is inadequate and obsolete, will be replaced by a new instrument with 4096 channels. Second, an effort will be made to eliminate background counts in the boron-loaded liquid scintillation detectors by pulse-shape discrimination.

I - 2. 4. Excitation of Low-Energy States by Resonant Neutron Capture

R. T. Carpenter, R. E. Segel, and R. K. Smither

The fast chopper at the reactor CP-5 was used in a study of the low-energy states of Hg^{200} that are excited by capture of neutrons in resonances of Hg^{199}. The gamma rays associated with radiative transitions to and from the low-energy states were detected by large NaI scintillators. The three-parameter tape-recording analyzer was used to store the spectral information. By examining the spectra for several resonances of Hg^{199}, it was possible to detect two new low-energy states in Hg^{200}. These states were tentatively identified with those expected from a nuclear model.

I - 2.5. Angular Correlation of Neutron-Capture Gamma Rays

R. E. Coté, H. E. Jackson, L. L. Lee, Jr., and J. P. Schiffer

A series of angular correlations of two-step cascade gamma rays following thermal-neutron capture in Fe^{54}, Ni^{58}, Ni^{60}, and Ni^{62} was measured. The aim was to determine the spins of some of the $\ell = 1$ levels, found through stripping measurements, in an attempt to relate these levels to the gross structure observed in (d, p) reactions. The measurements, which were performed at the 25-meter detector station of the chopper, used the three-parameter analyzer to record the data. For most experiments the read-out time is too long. Modifications of the system to allow more rapid read-out have been designed and will be installed in the summer of 1963.

I - 2.6. Lifetimes of Energy Levels Excited by Slow-Neutron Capture; Lifetimes and Nuclear-Structure Parameters of Levels Populated by Beta Decay (Project I-9)

H. H. Bolotin

An electronic system has been assembled for the study of the lifetimes of excited nuclear states by the delayed-coincidence method. In the first experiment with this system, double isomerism was observed in As^{73} states populated by the decay of 7.1-hr Se^{73}. Preliminary work of a similar character has begun on the nuclear states of Ga^{66}.

In further measurements with the same apparatus, the lifetimes of excited states of nuclei resulting from neutron capture are being studied at the CP-5 reactor. Relatively little is known of the details of levels in odd-odd nuclei, and thermal-neutron capture is a convenient and direct method of populating these levels. The low-lying states both in naturally-occurring samples and in separated isotopes of selected elements will be studied.

To improve and facilitate future measurements, the present electronic system is being enlarged and refined. With the new system, it will be possible to perform varied and simultaneous experiments such as the recording of prompt and delayed coincidence data, simultaneous "self-comparison" lifetime studies, detailed investigations of nuclear level schemes, and simultaneous measurements of lifetimes of two or more levels.

I - 2. 7. Gamma-Ray Spectra from Capture in Neutron Resonances (Project I-7)

L. M. Bollinger, R. T. Carpenter, R. E. Coté, H. E. Jackson, and J. P. Marion

The fast chopper at the reactor CP-5 was used in a series of measurements of the spectra of high-energy gamma rays resulting from the capture of neutrons in resonances. The spectra were observed with large (8-in. diameter by 6-in. thick) NaI scintillators. The pulse-height and time-of-flight information were stored in the three-parameter tape-recording analyzer.

A study of the distribution of partial widths for high-energy radiative transitions was continued. Measurements on eight heavy nuclides have been analyzed. All of the data are consistent with what is expected from a purely statistical description of the emission process; that is, the distribution of partial radiation widths is found to be indistinguishable from the distribution of reduced neutron widths.

A study of the dependence of the average partial radiation widths on nuclear mass was completed. The results were found to be in surprisingly good agreement with a relationship that has recently been inferred by Axel from the behavior of the photonuclear cross sections.

A systematic effort was made to use high-energy gamma rays to identify p-wave resonances. Many of these resonances were identified in Zr^{91}, Nb^{93}, and Mo^{95}.

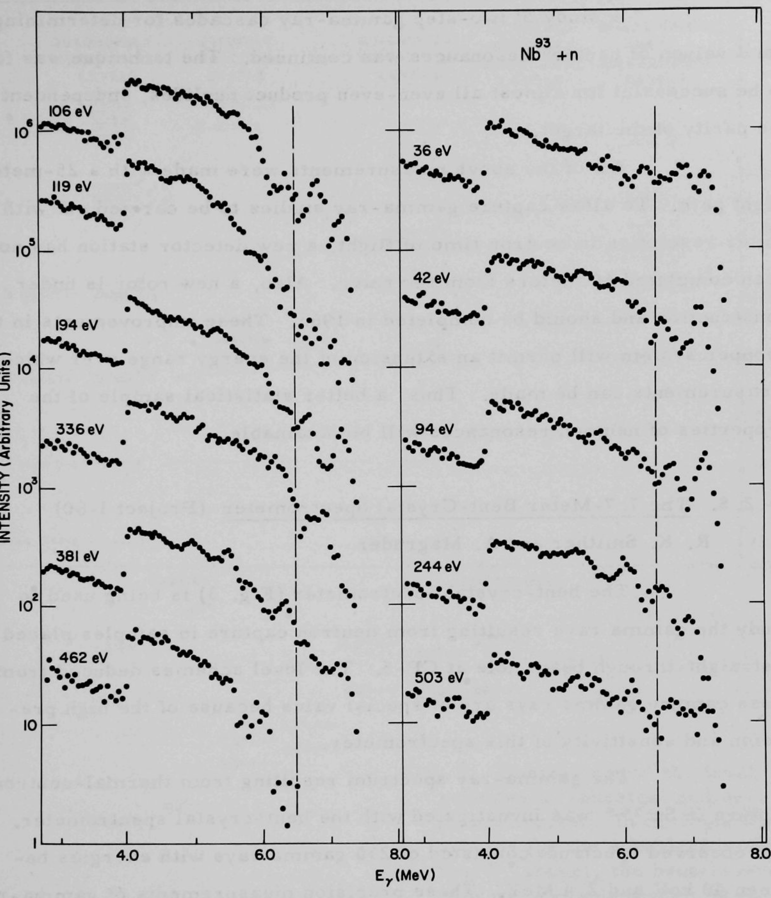


Fig. 2. Gamma-ray spectra from resonance capture in Nb^{93}. For p-wave resonances, the intensity of transitions to states within 700 keV of the ground state is expected to be much stronger than for s-wave resonances. This prediction is verified in these spectra. Events with photon energies greater than that at the dashed line represent such transitions. In the group of spectra on the left, the total relative intensity of transitions in this class is in the range 0.0—0.3; in the group on the right, it is in the range 0.8—1.2. The latter group is therefore interpreted as consisting of p-wave resonances.

A study of two-step gamma-ray cascades for determining the J values of neutron resonances was continued. The technique was found to be successful for almost all even-even product nuclides, independent of the parity of the target.

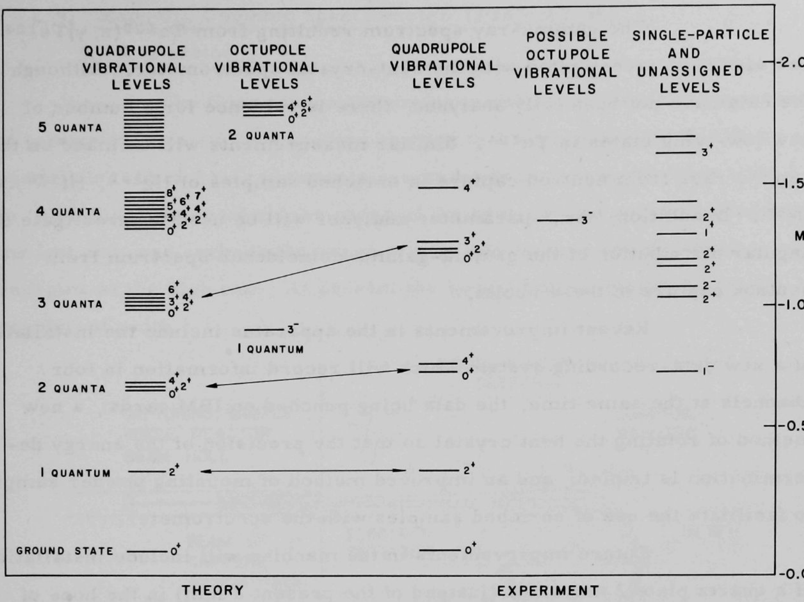
All of the above measurements were made with a 25-meter flight path. To allow capture gamma-ray studies to be carried out with better resolution in neutron time of flight, a new detector station has now been completed 60 meters from the rotor. Also, a new rotor is under construction and should be completed in 1963. These improvements in the chopper system will permit an extension of the energy range over which measurements can be made. Thus, a better statistical sample of the properties of neutron resonances will be obtainable.

I - 2.8. The 7.7-Meter Bent-Crystal Spectrometer (Project I-60)

R. K. Smither and A. Magruder

The bent-crystal spectrometer (Fig. 3) is being used to study the gamma rays resulting from neutron capture in samples placed in a straight-through beam hole at CP-5. The level schemes deduced from these capture gamma rays are of special value because of the high precision and sensitivity of this spectrometer.

The gamma-ray spectrum resulting from thermal-neutron capture in Sm^{149} was investigated with the bent-crystal spectrometer. The observed spectrum consisted of 230 gamma rays with energies between 40 keV and 2.4 MeV. These precision measurements of gamma-ray energies and intensities were combined with a set of γ-γ coincidence and angular-correlation studies (performed with the 3-parameter analyzer built for use with the chopper) to modify and extend the level scheme of Sm^{150}. Of particular interest in this new level scheme are the presence of three levels that may be associated with 3-phonon excitations of the nucleus. Very few states of this character have been identified to date.



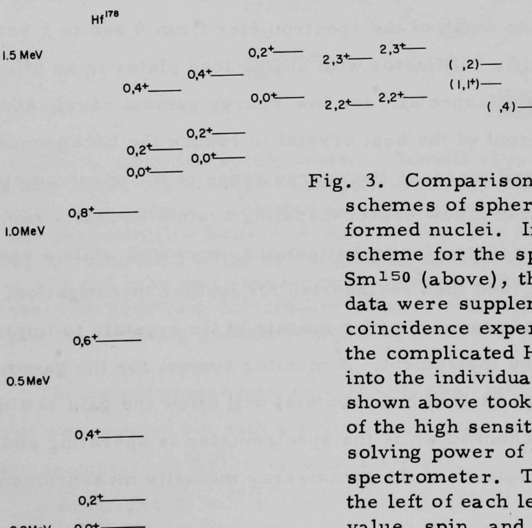


Fig. 3. Comparison of the level schemes of spherical and deformed nuclei. In deriving the scheme for the spherical nucleus Sm^{150} (above), the bent-crystal data were supplemented by γ-γ coincidence experiments. Sorting the complicated Hf^{178} spectrum into the individual rotation bands shown above took full advantage of the high sensitivity and resolving power of the bent-crystal spectrometer. The numbers at the left of each level are the K value, spin, and parity.

The gamma-ray spectrum resulting from $Te^{123}(n,\gamma)Te^{124}$ has also been investigated with the bent-crystal spectrometer. Although the data have not been fully analyzed, there is evidence for a number of new low-lying states in Te^{124}. Similar measurements will be made on the gamma rays from neutron capture in enriched samples of Hg^{199}, Hf^{179}, and U^{238}. In addition, the 3-parameter analyzer will be used to investigate the angular distribution of the gamma-gamma coincidence spectrum from neutron capture in these nuclei.

Recent improvements in the apparatus include the installation of a new data-recording system which will record information in four channels at the same time, the data being punched on IBM cards; a new method of rotating the bent crystal so that the precision of the energy determination is tripled; and an improved method of mounting powder samples to facilitate the use of enriched samples with the spectrometer.

Future improvements in the machine will include installation of a quartz plate 2 mm thick (instead of the present 4 mm) in the hope of reducing the line width of the spectrometer from 9 sec to 5 sec of arc, rebuilding the baffle collimator with stiffer lead plates in an effort to increase the counting rate (especially for low-energy gamma rays), addition of a collimator in front of the bent crystal to reduce the background in the spectrometer and increase the energy range of the spectrometer to 3.5 MeV, and installation of a new source-handling system so that a sample can be inserted in the reactor for investigations, removed while a second sample is investigated, and then re-inserted for further investigation. An attempt will also be made to construct a mosaic of Ge crystals to improve the sensitivity of the instrument. A monitor system for the gamma-ray detector system (a bank of NaI crystals) will allow the gain setting of the detector to be checked while the spectrometer is operating and thereby improve the precision of the gamma-ray intensity measurements.

I - 2.9. Magnetic Compton Spectrometer (Project I-56)

R. S. Preston

The Compton spectrometer is used to measure the spectrum of gamma rays that follow neutron capture in a source located in a CP-5 beam hole. Useful measurements can be made in the region from 1 MeV to 15 MeV. This overlaps the range of the bent-crystal spectrometer at the low end, and exceeds the range of possible capture gamma-ray energies at the high end. At present the instrument is operated at 0.6% resolution width.

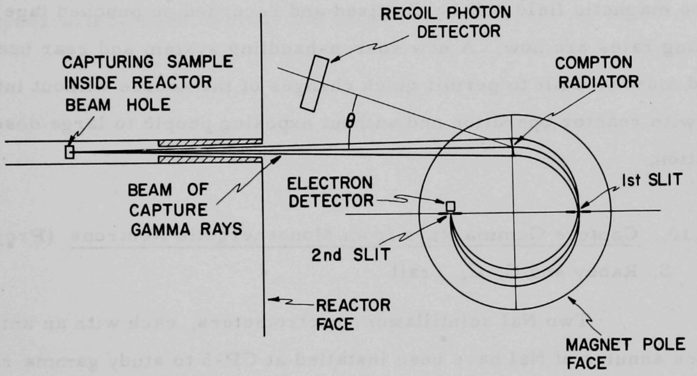


Fig. 4. The magnetic Compton spectrometer. Gamma rays from the capturing sample in the reactor eject Compton electrons from the radiator. The electrons emerging in a selected direction from any part of the radiator are magnetically focused on the 1st slit. For a given magnetic field, the electrons of the corresponding energy are refocused on the second slit and pass on to the electron detector. Background can be suppressed by requiring coincidence between a detected Compton electron and the recoiling gamma photon that produced it.

The spectrometer was put into operation late in 1962. A calibration run was carried out with a sodium capturing sample, and measurements on capture in Dy^{164} have been started.

Measurements will be made on the spectrum of gamma rays from neutron capture in Sn^{149} to complement measurements that have already been made with the bent-crystal spectrometer. Other measurements will doubtless be made in conjunction with the bent-crystal spectrometer.

Certain elements, starting with germanium, will be studied to determine the binding energy of the last neutron in several adjacent isotopes. The purpose is to see if the spectrometer can provide some precise mass links for mass spectroscopy.

Improvements will include a new electron-detection system to reduce the background counting rate. The output of the control probe for the magnetic field will be digitized and recorded on punched tape, as counting rates are now. A new source-handling system and rear beam shield must be built to permit quick changes of the source without interference with reactor operation and without exposing people to large doses of radiation.

I - 2.10. <u>Capture Gamma Rays from Monoenergetic Neutrons</u> (Project I-55)
S. Raboy and C. C. Trail

Two NaI scintillation spectrometers, each with an anticoincidence annulus of NaI have been installed at CP-5 to study gamma rays from capture of monoenergetic neutrons. A cobalt mirror is used to give an intense polarized neutron beam relatively free of gamma radiation. The energy of the neutrons is about 0.01 eV.

An attempt was made to study the conservation of parity in strong interactions by measuring the ratio of the yield of gamma radiation parallel and antiparallel to the direction of neutron polarization from capture of polarized neutrons by hydrogen. An inconclusive result was obtained, probably because of electronic difficulties. Further work is planned.

The $He^3(n, \gamma)He^4$ capture cross section has been studied. No gamma ray was seen; an upper limit will be placed on the cross section. If the transition is $0 \rightarrow 0$, gamma radiation is forbidden but electron-positron pairs should be emitted. We plan to look for these in the coming year.

Neutron capture by C^{12} and H^2 has been observed. It now appears that our apparatus can be used for capture gamma-ray spectroscopy in many cases in which the capture cross section is around a millibarn or less. A general survey of nuclei with these small cross sections is planned.

The gamma-ray spectrum from neutron capture by Ca^{44} has been observed and over 20 gamma rays have been identified. The 2-D analyzer will be used to study the decay scheme.

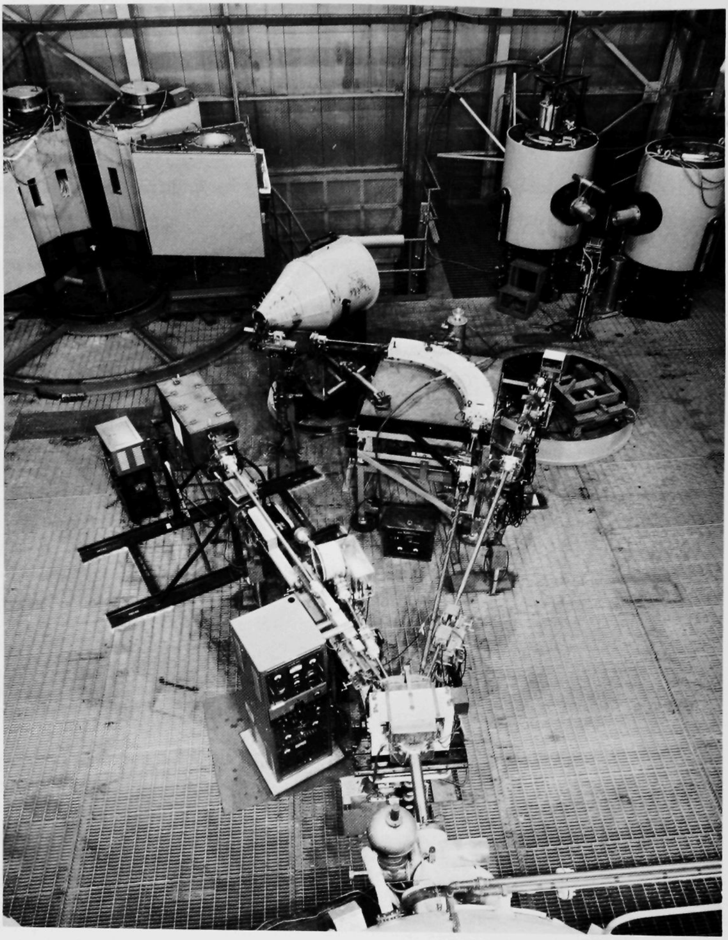


Fig. 5. Equipment at the 4.5-MeV Van de Graaff accelerator. The experiment set up on the left-hand beam line is the beam pulser and the apparatus to measure the lifetimes of nuclear excited states (pp. 22-24). Beyond it in the upper left corner is the circular track and the array of neutron detectors for the measurement of neutron polarization and differential cross section (pp. 17-21). One of the right-hand beam lines goes through the 90° electrostatic analyzer to the neutron detector in the cylindrical shield with conical nose (upper center) used to study neutron scattering in the keV region (pp. 21-22). The large tanks in the upper right-hand corner are the two shielded neutron detectors for measurement of scattering and capture cross sections.

I - 3. RESEARCH AT THE 4.5-MEV VAN DE GRAAFF ACCELERATOR

The experimental program with the 4.5-MeV Van de Graaff accelerator is continuing along much the same lines as in previous years. Experiments with fast neutrons are emphasized, especially measurements of the polarization of scattered neutrons. Other experiments include pulsed-beam measurements of the lifetimes of excited states, studies of Coulomb excitation by heavy ions, studies of nuclear reactions induced by charged particles, and measurements of total neutron cross sections. A continuing program is directed toward the improvement of the accelerator.

I - 3.1. Neutron Polarization and Differential Cross Section (Project I-18)

A. J. Elwyn, R. O. Lane, and A. Langsdorf, Jr.

In the measurements of the polarization of neutrons scattered from various nuclides, the polarized neutrons are produced in the $Li^7(p,n)Be^8$ reaction. Those selected for use are emitted at 51° to the beam direction. The neutron spins can be turned through 180° in a spin-precessing electromagnet. After scattering, the neutrons are detected by banks of oil-moderated BF_3 counters enclosed in large shielding tanks. With this system we are able to measure both the polarization and the un-polarized differential cross sections at five angles simultaneously.

Using the previously measured polarization of neutrons emitted at 51° in the $Li^7(p,n)Be^7$ reaction, we have investigated the polarization and differential cross section in scattering from Si. At energies from 0.2 to 0.7 MeV, the differential cross sections were analyzed in terms of the properties of the resonance levels in Si^{29}. Two states at $E_n = 0.536$ MeV and 0.571 MeV were assigned the characters $D_{5/2}$ and $D_{3/2}$, respectively, as a result of this analysis. The measured polarization as a function of angle agreed with theoretical predictions. The usefulness of silicon as an energy analyzer is restricted, however, by the necessity for a very narrow energy spread in the neutron beam.

By use of the same equipment, the polarization and differential cross section in n-d scattering with scatterers of deuterated polyethylene were measured with high precision. Results at neutron energies of 0.5 and 1.0 MeV gave polarizations that were zero to within 2 — 3%. At 1.95 MeV small positive polarizations (about 4% maximum) were observed. Phase-shift analyses of the differential cross sections led to the conclusion that, at least near 2 MeV, D-wave neutrons were contributing to the interaction.

The polarization in the scattering of neutrons from other light nuclei has been studied below $E_n = 2$ MeV. Attempts to analyze these results in terms of individual levels in the compound nuclei involved are continuing. (1) The scattering and polarization data for Mg in the region between 80 and 500 keV have been analyzed in terms of levels in Mg^{25}. In this region the polarizations are large and change only gradually so that Mg is quite useful as a polarization analyzer. (2) The scattering and polarization from Li^6 and Li^7 are being studied in an attempt to understand the large and constant polarization in both these nuclei up to energies near 2 MeV in terms of only a few known levels in Li^7 and Li^8 and/or in terms of the optical model. (3) The scattering and polarization from Be^9 has been measured in the region of the 7.37-MeV state in Be^{10}. The parity of this level is not experimentally established. Indications from preliminary analysis of our results favors the assignment 3^- for this state, in agreement with a recent report by Altman, MacDonald, and Marion.

Neutron beams with large energy spreads are being used to study the scattering from F, Na, Al, P, and K (Fig. 6). Although the purpose was to study gross-structure effects, the results seem to indicate that the properties of individual levels or groups of levels are very important at energies up to 2 MeV [even with the broad energy spread (100 — 150 keV) of the incident beam.] Similar studies on targets of Zr, Nb, Cd, and Mo have been made. In this region (near A = 100) a description of the results in terms of an optical model appears to be very promising even at energies below 1 MeV. Analysis in terms of the

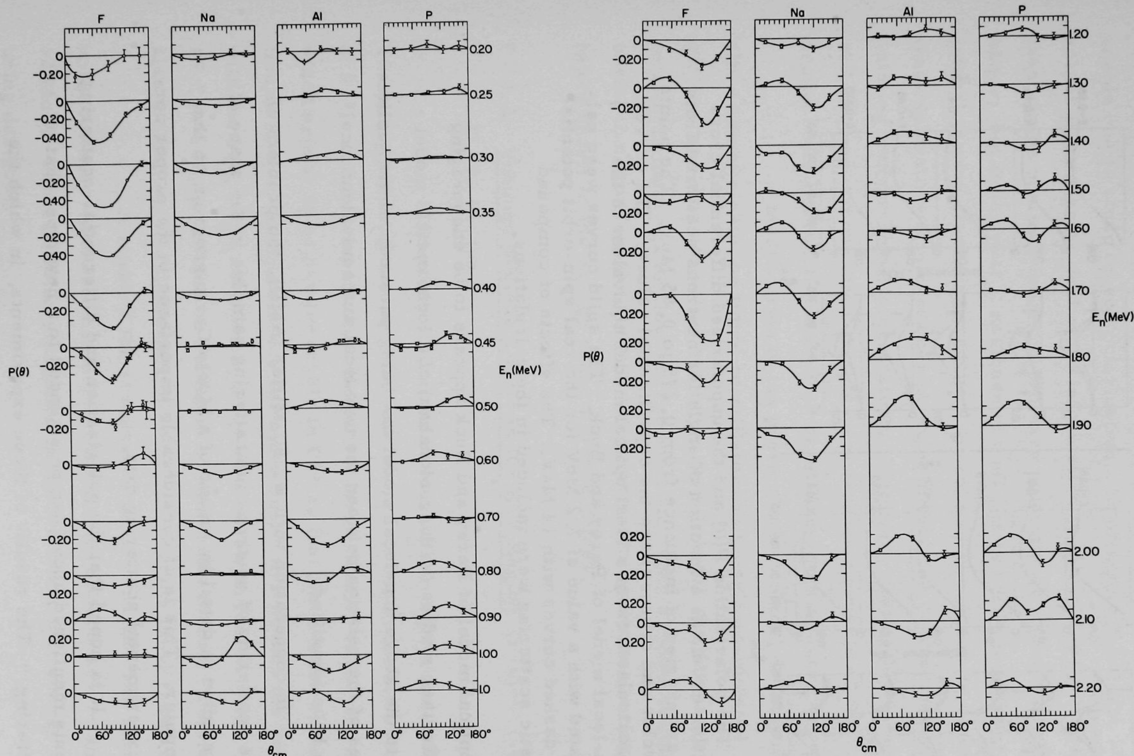


Fig. 6. The polarization as a function of angle for neutrons scattered from F, Na, Al, and P at energies of incidence (a) from 0.2 to 1.09 MeV and (b) from 1.2 to 2.2 MeV. The errors indicated are statistical only.

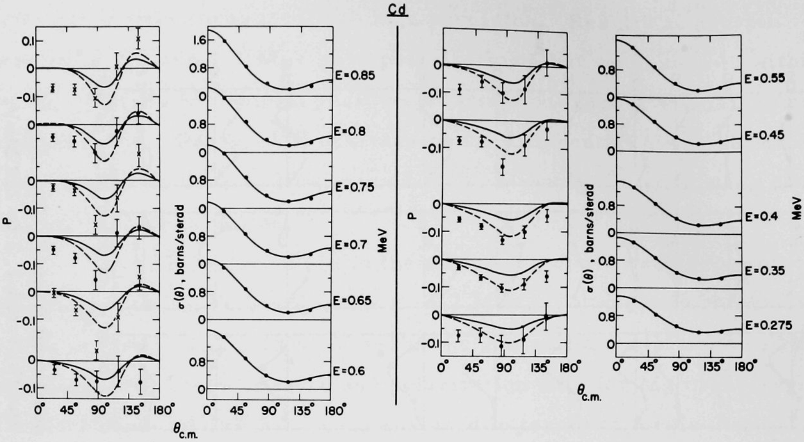


Fig. 7. The polarization P(θ) and the unpolarized differential cross section $d\sigma/d\Omega$ as a function of angle for neutrons scattered from Cd at energies of incidence from 0.275 to 0.85 MeV. The points (circles and crosses) are the experimental values. The curves are calculated from a local optical model equivalent to the non-local model of Perey and Buck. The solid curves were calculated with a value of 7.2 MeV for the real spin-orbit potential, the dashed curves with 14 MeV. The effects of compound elastic scattering were included in the calculations.

non-local optical model of Perey and Buck appears to be encouraging (Fig. 7). Further studies (with J. Monahan) of a local optical model equivalent to the above non-local model are being pursued; some qualitative features of the relation between the non-local and equivalent local model have been identified.

In cooperation with W. F. Miller (AMD), the problem of the multiple scattering of neutrons in scattering samples in the shape of plates was studied in detail by means of a Monte Carlo program on the George computer. This is of considerable importance in the proper correction of experimental scattering data.

It is hoped that the polarization and differential-scattering measurements mentioned above can be extended to a new type, that of "triple scattering." The results of these experiments, in which the neutrons undergo three successive interactions before being detected, would enable one to study tensor polarization. In principle, this type of interaction gives a great deal more information on the nuclear forces involved than can be obtained from the ordinary polarization experiments described above; but in the past it has been virtually impossible to obtain sufficient intensities for significant results. By careful design it now seems possible that exploratory triple-scattering experiments can be undertaken with existing Van de Graaff accelerators. However, reasonably accurate results will require (among other things) an accelerator capable of delivering proton beam currents of the order of milliamperes at energies of 3 — 6 MeV.

Modification of the present experimental arrangements to allow use of plastic or liquid scintillators is being contemplated. With pulse-shape discrimination against γ rays and with the detectors biased to discriminate against low-energy neutrons, such a modification would be useful in continuing the study of the polarization in the scattering from heavy nuclei in the energy range 1.0 — 2.5 MeV.

I - 3.2. Unbound Nuclear Levels in the KeV Region (Project I-98)

C. T. Hibdon

The study of neutron resonances in light nuclei has continued. The principal study for the last year was concerned with the resonances of F^{19}. The curves obtained indicate a large density of levels, most of which appear to be p-wave levels in F^{20} so that the p-wave strength function is large. Additional data for other nuclei are needed for comparison with the $P_{3/2}$, $P_{1/2}$ doublet in the p-wave strength function for $15 < A < 32$, predicted on the basis of spin-orbit forces. This study will also include a careful recheck of some small peaks in Al^{27} and F^{19}.

A study of the resonances in Li^6 and Li^7 has started and will continue. Measurements will extend from about 1 keV to about 12 MeV. The additional equipment needed to cover this energy region is being designed.

A method of analyzing resonance levels by use of flat- and self-detection data has been developed by C. Hibdon and J. E. Monahan and is applicable in the present work. It removes much of the uncertainty associated with the finite resolution of the measurements. An attempt is being made to extend the method to multiple-level analysis.

The neutron background from scattering by the tantalum backing of lithium targets used to produce neutrons by the $Li^7(p, n)$ reaction was measured at 120° from the direction of the proton beam. The results obtained up to 300 keV are being used in correcting data near the peaks of resonances.

I - 3.3. Coulomb Excitation of Levels in K^{40}

R. E. Holland and F. J. Lynch

We have begun the measurement of the Coulomb-excitation cross section of three low-lying levels in K^{40}. The lowest level (at 30 keV) has been observed with $(He^4)^+$ ions at the 4.5-MeV Van de Graaff accelerator. We expect to be able to excite the two higher levels (at 800 keV and 890 keV) with a heavy-ion beam (possibly Cl^{35} or A^{40}) from the tandem machine.

These levels in K^{40} are well explained by a j-j coupling model. The model also predicts the reduced matrix element B(E2) measured in Coulomb excitation, but with two parameters depending on nuclear effective charge which should be the same for all of the levels. Thus, with three measurements the system is over-determined and one can check the self-consistency of the model.

I - 3.4. Pulsed-Beam Measurements of Lifetimes of Nuclear Excited States (Project I-14)

R. E. Holland, F. J. Lynch, and E. N. Shipley

We have used a pulsed-beam technique with the 4.5-MeV Van de Graaff accelerator to measure lifetimes of nuclear excited states.

With the older techniques which use radioactive sources, the lack of a suitable parent had often prevented lifetime measurements.

A series of measurements on excited states in V^{51}, Ga^{73}, As^{75}, Rb^{85}, and Sb^{123} has been completed. The levels were formed by Coulomb excitation; the measurement of their lifetimes gives the partial decay rates for emission of E2 and M1 radiation and the ratio between the two.

Two closely spaced levels in Se^{77} have been investigated in detail (by Lynch and Shipley). The levels are so closely spaced that they are inseparable by ordinary methods. However, they are easily distinguished by their lifetimes (Fig. 8). In this way the lifetimes of the two levels and the relative intensities of the de-excitation gamma rays were determined.

Plans for improving the electronic equipment include a circuit for correction of the time shift associated with changes in energy

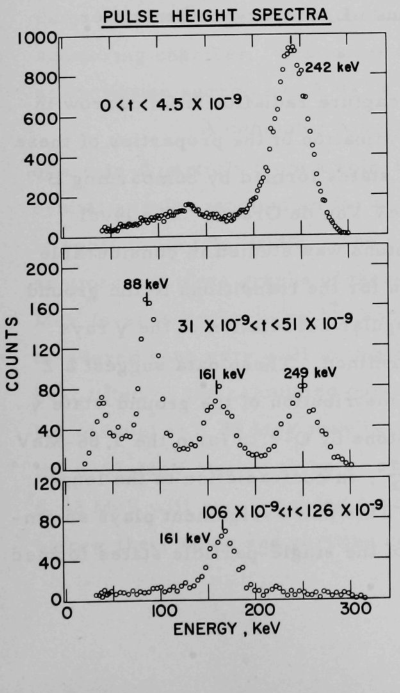


Fig. 8. Scintillation pulse-height spectra obtained at different times after formation of the excited states in Se^{77}. The upper curve shows the spectrum associated with the fast component, the middle curve that associated with the slow component, and the lower curve that associated with the random component (very long times).

of the scintillation event, a new time-to-pulse-height converter which will use an Esaki diode flip flop, and newer, more reliable gating circuits.

We also plan to extend these measurements to the tandem accelerator. A system for obtaining a pulsed beam from the tandem by velocity modulation of the beam was recently completed. Six times the present beam intensity should be obtainable with a change now being studied. This requires a parabolic voltage for velocity modulation rather than the present sinusoidal voltage. This parabolic drive will be worth while only if the spread in ion velocities from the ion source can be made much smaller than now obtainable with our machine. However, recent work at the High Voltage Engineering Corporation indicates that direct extraction of negative ions from the ion source may greatly reduce the spread in ion velocity.

I - 3.5. (p, γ) Properties of Individual Unbound Levels (Project I-21)

R. Allas, M. Grace, S. S. Hanna, L. Meyer-Schützmeister, R. E. Segel, and P. P. Singh

The study of the proton-capture radiation from narrow individual levels can often lead to a determination of the properties of these levels. We have studied several of the states formed by bombarding B^{11} with 1 — 4-MeV protons from the 4-MeV Van de Graaff. The level formed by the capture of 3.13-MeV protons was studied in considerable detail; angular distributions were taken for the transitions to the ground state and first excited state, and the angular correlation of the γ rays through the first excited state was determined. These data suggest a 2^- assignment for the state. The angular distribution of the ground-state γ rays from the capture of 3.48-MeV protons by O^{16} to form the 3.86-MeV level in F^{17} has shown that this state is $\frac{5}{2}^-$, in contradiction to the long-accepted $\frac{7}{2}^-$ assignment of this state. This new assignment plays an important role in assigning the positions of the single-particle states formed by a proton orbiting an O^{16} core.

I - 3.6. The $B^{11}(p, \alpha)Be^8$ Reaction (Project I-21)

R. G. Allas, D. von Ehrenstein, J. R. Erskine, Luise Meyer-Schützmeister, and J. A. Weinman

Angular distributions were taken at 25-keV intervals and at more closely spaced energies (about 10 keV apart) in the vicinity of narrow resonances. Several resonances were seen, but the very prominent (p, α) resonance at a proton energy of 3.13 MeV was not observed in this alpha experiment. The absence of alphas establishes this state as T = 1.

I - 3.7. Alpha Scattering from Li^6

D. S. Gemmell and P. P. Singh

A preliminary investigation of this reaction has been made at alpha-particle energies from 2.4 to 4.6 MeV. Scattered alphas were detected at six angles by mounting six semiconductor counters in an 18-in. scattering chamber. Scattering anomalies corresponding to states in B^{10} at excitation energies of 5.93, 6.16, 6.42, and 6.57 MeV were observed.

A computer program was written to calculate the scattering of a spin-0 particle from a spin-1 target for the case of a conserved orbital angular momentum for a single level whose elastic scattering width is equal to its total width. The program computes differential cross sections and plots graphs of these values at specified angles. The 5.93-MeV level is known to be 2^+, and the computed cross sections fit the measured ones very well in this case. The broad level at 6.57 MeV is best fitted by the calculated curves for a 4^- level. However, another broad level at 6.88 MeV may be interfering with this level, in which case the 6.57-MeV state may be 1^- or 4^-. The narrow levels at 6.16 and 6.42 MeV will require more careful experimental data with thinner targets before their spins and parities can be assigned.

At higher energies, the three approximations mentioned above are expected to break down. Hence the plan is to write a computer code for the more general (and complex) scattering formula for the case in which other reaction channels are open, orbital momentum changes can occur, and more than one level is involved.

It is planned to carry out further measurements on this reaction in finer energy steps and also at higher bombarding energies with the tandem Van de Graaff.

I - 3.8. <u>Operation of the 4.5-MeV Van de Graaff Accelerator</u> (Project I-11)

R. L. Amrein and J. R. Wallace

The 4.5-MeV Van de Graaff accelerator has operated over 4800 hours since January 1962. It has been running on a 90-hr/week schedule with six operating technicians and one chief technician. There are tentative plans to increase this schedule to 120 hr/week. The accelerator has operated from 700 keV to 4.5 MeV and it is currently capable of delivering 40 μA of proton beam current.

Approximately 20 scientists have used this accelerator for research in the past year.

A long-range program to increase the beam current of the accelerator and to improve the energy stability has been pursued without interfering with the very active research program being carried on at this Van de Graaff. It will continue because its success will make possible certain scattering experiments that are marginal at present.

For experiments employing scintillators and other detectors sensitive to x rays, it usually is necessary to shield the detectors against x rays from the accelerator. However, shielding around the accelerator is preferable to shielding around the various individual experimental assemblies. Therefore it is planned to shield the open top and grounded end of this accelerator when it is moved back to provide for beam steering.

I - 3.9. Modifications of the 4.5-MeV Van de Graaff Accelerator

A. Langsdorf, Jr.

Completed improvements. (1) A new induction system to place charge on the belt has operated very well for about 8 months. A steady charging rate is maintained more easily than before and the lifetime of the belt seems to be increased (to more than 1200 hours for the present one). (2) Sparking in the machine has been reduced by halving the number of corona gaps in the voltage divider and correspondingly doubling the voltage across each gap. (3) The intermediate shells between the pressure tank and the high-voltage electrode were found to contribute little or nothing to operation of the machine. The space freed by their removal allows the machine to be moved so that beam-steering equipment can be installed. This will save operating time and will improve both the precision of experiments and the reliability of the results.

Improvements initiated. (1) The use of grooved pulleys is being tested. (2) It is hoped that voltage fluctuations (now about 1000 volts in an operating voltage of 2 million volts) can be significantly reduced by redesign of the electronic control circuits. (3) Circuit changes in the power supplies for the focus voltage, etc. should also help to improve the voltage stability of the machine. (4) The machine will be moved back about 10 feet farther from the experimental floor to make room for a beam-steering system and additional quadrupole lenses.

Studies of corona (with R. B. Wehrle [RC]). Because of the great importance of corona discharge in Van de Graaff operation, studies of it have been re-initiated. A pressurized test setup is needed for measurement of different corona and breakdown characteristics in various gases and mixtures over the useful range of pressures. The objective is to find a usable gas mixture whose spark-over voltage is higher than that in the mixtures now used.

Voltage analyzer. Electrostatic analyzers are used to measure the beam energy and regulate the accelerator voltage. The larger and more precise one, which deflects the beam through 90°, has a maximum resolution of roughly 10 000. Its power supply (to set its deflecting plates at up to 25 000 volts above and below ground) should be resettable and stable to an accuracy approaching 1 part in 100 000 to reach the achievable precision of measurement. Such a supply has now been designed and is being built by the Electronics Division.

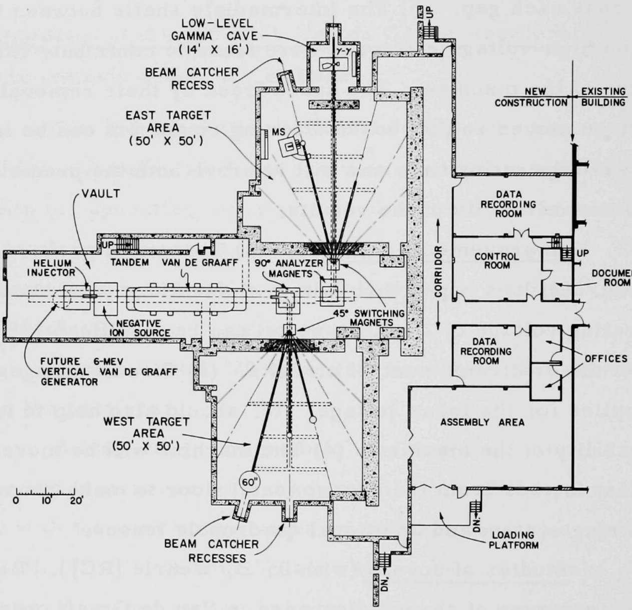


Fig. 9. Floor plan of the experimental level of the Tandem wing. With two target areas, equipment can be set up in one while the beam goes to the other. Each target area is connected to its own data-recording room. In the east target area, MS is the broad-range magnetic spectrograph (pp. 39-40) and γ-γ in the gamma cave is the angular-correlation apparatus (pp. 41-42). In the west target area, the circle marked 60" is the 60-in. scattering chamber (p. 38) and the small circles are small scattering chambers used in several experiments.

I - 4. RESEARCH AT THE 12-MEV TANDEM VAN DE GRAAFF

The character of the program of nuclear research changed significantly in June of 1962 when the tandem Van de Graaff generator started routine operation. Since then, about fifteen physicists have devoted their time to experiments at the Tandem so that this is the largest single program in the division. When funds become available, the program will be expanded further by scheduling the accelerator for continuous operation and by adding several staff members to the program.

During the initial year of operation, most of the experiments at the Tandem were performed with relatively simple apparatus. Now, however, major pieces of equipment are being put into service as a base on which to build an effective long-range program. The new installations include a uniform-field magnetic spectrometer, angular-correlation equipment for γ-ray studies, a 60-in. scattering chamber, and terminal bundhing equipment. Also, an ASI-210 computer and various accessory equipment is soon to be installed on line at the Tandem to perform various functions of data storage and analysis. The ASI-210 will, in turn, be tied directly to the CDC-3600.

I - 4.1. Installation and Operation of the Tandem Van de Graaff Accelerator

W. F. Evans, F. P. Mooring, and J. R. Wallace

The installation of the tandem Van de Graaff was completed in January 1962. The acceptance tests of the accelerator took place in February 1962. It has been on a steady operating schedule to date except for two periods. A four-week period was required for changing of the 90^{o} analyzer magnets and for re-alignment. A one-week period was required for installation of a beam buncher. The Tandem was operated on a 90-hr/week schedule until February, 1963. At this time the research schedule had become so heavy that it was deemed advisable to increase the operating time to 120 hr/week. The Tandem has been operated for over 4100 hours to date. The present operating schedule has required eight operating technicians and one chief technician.

The accelerator has been used to accelerate protons, deuterons, singly-charged alphas, and doubly-charged alphas. One group of experimenters is currently working on a project to accelerate still heavier ions. Research has been done with proton and deuteron energies as high as 13.9 MeV. The major items of experimental equipment in use or being installed at the Tandem are: (1) an 18-inch scattering chamber (Braid), (2) angular-correlation equipment (Braid), (3) a buncher and pulser for lifetime and time-of-flight measurements (Lynch), (4) a broad-range magnetic spectrometer (Erskine), and (5) a 60-inch scattering chamber (Yntema).

Approximately 20 scientists (including some from outside the Physics Division) are now using the Tandem facilities for research problems.

Plans for the coming year include (a) completing the installation of items (4) and (5) mentioned above, (b) installing new inclined-field accelerating tubes which should increase the beam current and also allow operation at a higher accelerating voltage, (c) a program for producing heavier ions for acceleration, (d) a small computer for multiparameter analysis and on-line data reduction and to feed partially processed data directly to the CDC-3600, (e) a fast card read-out system for tabulating and plotting data from multichannel analyzers, and (f) a second 18-in. scattering chamber.

I - 4.2. Charged-Particle Reactions at the Tandem

R. G. Allas, D. von Ehrenstein, J. R. Erskine, D. S. Gemmell, L. L. Lee, Jr., Luise Meyer-Schützmeister, J. P. Schiffer, P. P. Singh, J. A. Weinman, and B. Zeidman

The proton, deuteron, and alpha-particle beams from the tandem Van de Graaff are being used to study a wide variety of reactions. Much the same equipment is used in all of the studies by various combinations of the workers listed above. Most of the work to date has been done with semiconductor counters in the 18-in. scattering chamber designed by T. H. Braid. The standard counting electronics at the tandem has been used, including multiple-coincidence circuits, various multichannel pulse-height analyzers, and the IBM-1620 computer. This program started with the first beams from the tandem in May 1962 and is continuing with ever-increasing activity. (At present it takes about 30% of the tandem time.)

A. The $B^{10}(d,Li^6)Li^6$ Reaction

D. S. Gemmell, J. P. Schiffer, and J. R. Erskine

Differential cross sections have been measured for this reaction at E_d = 8, 10, 12, and 13.5 MeV at the tandem generator. To detect the Li^6 nuclei, two semiconductor counters were placed at the appropriate pair of angles defined by the reaction kinetics and then the pulses from the two counters were displayed on a 2-dimensional Nuclear Data analyzer (operated in its 32 × 32-channel mode), gated by a coincidence between the two counters. This technique was quite successful. At the higher energies used in this experiment, there is good reason to believe that the reaction proceeds via a direct mechanism involving the pickup of an ℓ = 2 alpha particle. The present differential cross section at 12 MeV has been compared with a DWBA calculation by G. R. Satchler. The calculation reproduces the main features of the data—viz., prominent peaks at 40° and 140°. A computer program was coded to calculate the angles at which to place the counters, the solid-angle correction factors, the center-of-mass angles, and the Li^6 energies. The targets were self-supporting B^{10} foils prepared by an electron-bombardment technique recently developed by J. R. Erskine and D. S. Gemmell.

B. Studies of (p,α) and (d,α) Reactions (Project I-21)

R. G. Allas, D. von Ehrenstein, J. R. Erskine, Luise Meyer-Schützmeister, and J. A. Weinman

$K^{39}(p,\alpha)Ar^{36}$. In this reaction, eleven reasonably well resolved alpha-particle groups have been observed. These alpha groups lead to different levels in Ar^{36}, of which only seven were previously known. The angular distribution (eight different angles) of each of these alpha-particle groups was measured as a function of the proton energies.

When the analysis is completed, the study will be extended to (a) fluctuations of the total cross section and the partial cross sections and (b) averages of the total cross section and of the partial cross sections over different ranges of proton energies. In addition, the levels will be determined with higher precision by studying the different alpha groups with the magnetic spectrometer. And the alpha-gamma correlation will be measured to determine gamma-ray ratios and, wherever possible, the spins and particles of levels in Ar^{36}

$C^{12}(d, \alpha)B^{10}$. This reaction should excite only T = 0 states in B^{10} if the isotopic-spin selection rule holds. The first step was therefore to look for the alpha group that leads to the first T = 1 state in B^{10} since its yield is a good indication of the isotopic-spin violation in this reaction. In the partly finished measurements, this alpha group was definitely observed. At certain angles and deuteron energies its intensity is about 7% of the other observed alpha group leading to one of the T = 0, J = 1 states and, since formation of this state is statistically inhibited, the isotopic-spin violation is actually larger than this indicates.

Preliminary analysis of the data shows that the isotopic-spin violation varies with deuteron energy; at certain deuteron energies this particular alpha group is not visible at all. This problem will be studied carefully.

$C^{13}(p, \alpha)B^{10}$. For this reaction, the proton energies applied must excite the compound nucleus N^{14} into the same region of excitation energies as in the case of the $C^{12}(d, \alpha)B^{10}$ reactions. The yields of these two reactions leading to the T = 0 and T = 1 states in B^{10} will be compared. It is hoped that this comparison will give information about the relative level density of T = 0 and T = 1 states in the highly excited compound nucleus N^{14} and about the variation of these level densities as a function of the excitation energy.

C. The $Ca^{40}(d, d)Ca^{40}$ and $Ca^{40}(d, p)Ca^{41}$ Reactions

L. L. Lee, Jr., J. P. Schiffer, and B. Zeidman

Angular distributions and absolute differential cross sections have been measured at the Tandem for the elastic scattering of deuterons from Ca^{40} and for $Ca^{40}(d, p)Ca^{41}$ reaction to four prominent levels at 0, 1.95, 2.47, and 3.95 MeV excitation. These results (Fig. 10) have been used to test Distorted-Wave Born Approximations (DWBA) of the (d, p) reactions which, if accurate, should be a powerful tool in studies

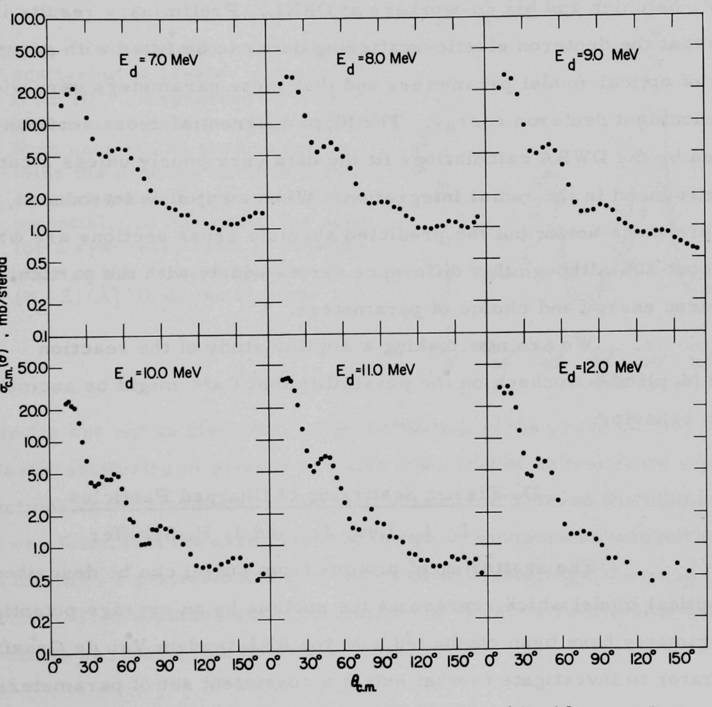


Fig. 10. Angular distributions from the $Ca^{40}(d, p)Ca^{41}$ ground-state reaction. Data such as these are being used to determine the reliability of the distorted-wave Born approximation in giving absolute spectroscopic factors for nuclear states.

of nuclear structure. Since Ca^{40} is a doubly-magic nucleus, the levels observed in Ca^{41} should be described accurately as a single neutron added to an inert Ca^{40} core. The DWBA calculations should then be able to predict both the absolute cross sections and the angular distributions for the proton groups studied. How well this prediction succeeds is a measure of the validity and accuracy of the DWBA approach.

Measurements were made at 1 MeV intervals for deuteron energies from 7 to 12 MeV. The DWBA calculations are being made by G. R. Satchler and his co-workers at ORNL. Preliminary results indicate that the deuteron elastic-scattering data can be fitted with several sets of optical-model parameters and that these parameters vary widely with incident deuteron energy. The (d, p) differential cross sections predicted by the DWBA calculations fit the data very poorly unless a cutoff is introduced in the radial integration. When a cutoff is introduced, the fits are much better but the predicted absolute cross sections are wrong by about 20% although this difference varies widely with the particular deuteron energy and choice of parameters.

We are now making a similar study of the reaction $Fe^{54}(d,p)Fe^{55}$ to check on the possibility that Ca^{40} might be anomalous in its behavior.

D. Elastic Scattering of Charged Particles

L. L. Lee, Jr. and J. P. Schiffer

The scattering of protons from nuclei can be described by the optical model which represents the nucleus by an average potential. Experiments have been conducted with the ANL tandem Van de Graaff generator to investigate to what extent a consistent set of parameters can describe this interaction over a series of incident-particle energies. It was found that in the scattering of deuterons from Ca^{40} the parameters changed rather drastically with energy between deuteron energies of 7 and

12 MeV. For elastic scattering of protons from Ni and Cu, rather good agreement was found with a consistent set of parameters. The scattering of 12-MeV protons, deuterons, and alpha particles from four isotopes of Ni has also been studied (Fig. 11) in order to investigate the dependence of the potential parameters on neutron excess. The results were in good agreement with expectations for protons; the deuteron and alpha particle

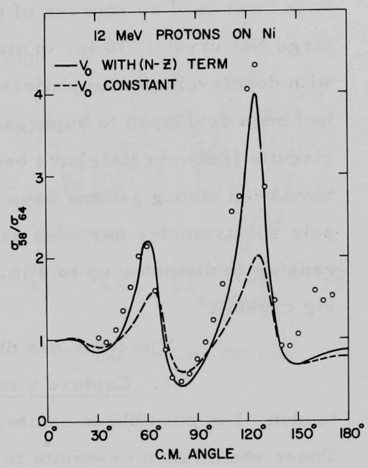


Fig. 11. Cross sections for elastic scattering of 12-MeV protons from Ni^{58}, expressed as a ratio to the same cross section for Ni^{64}. Such data can be used to determine the need for various small corrections to the optical-model potential. In this case, the need for a symmetry term [a dependence on the neutron excess (N - Z)/A] is demonstrated.

results are not so clear cut. The fluctuation in the cross section for elastic scattering of protons has also been studied to test certain predictions of the statistical model, the so-called "Ericson fluctuations." It was found that the assumption of complete randomness was not valid in the Ni^{58} + p system and that non-random clusterings of strong levels occur. Thus a rather basic assumption of the statistical model has been found to be invalid in a particular case.

I - 4.3. Gamma Rays from Proton-Induced Nuclear Reactions (Project I-21)

R. Allas, S. S. Hanna, L. Meyer, P. P. Singh, R. E. Segel, and M. Grace

An extensive program has been undertaken to study the gamma rays produced in nuclear reactions initiated by the proton bombardment of nuclei. Both the 4.5-MeV Van de Graaff and the tandem have been used as sources of protons. The main detector has been a large NaI crystal (10 in. in diameter and 8 in. thick) used in conjunction with double-clipped amplifiers and multichannel analyzers. Circuitry has been developed to suppress pileup. Where appropriate, coincidence circuits (commercial) have been used. In some cases in which there have been strong gamma rays in the 2—10-MeV range, a three-crystal pair spectrometer has been used. Finally, various small crystals ranging in diameter up to 4 in. have been used in conjunction with the big crystal.

The work has divided itself into the following general areas.

1. Capture γ rays from the giant resonance. With the tandem it is possible to excite nuclei in the giant-resonance region. These should then de-excite to the ground state with a strong electric-dipole γ ray. Because of the poor resolution, work done with betatrons does little to settle the question of the degree of fine structure in the giant resonance and therefore the inverse (p,γ) reaction is being studied with the high resolution available with the tandem. Yield curves [Fig. 12(a)] and angular distributions for the $B^{11}(p,\gamma)C^{12}$ reaction have shown that the main feature of this reaction is indeed a broad peak centered at a bombarding energy of about 7 MeV. However the yield curve is by no means Gaussian, showing many small deviations from a smooth shape. However, the angular distributions vary but little—even where there are sharp breaks in the yield curves. The γ rays to the first excited state of C^{12}, which is presumably below the giant-resonance region, show even

more structure; and here the angular distributions do vary considerably. Capture γ rays from bombardment of B^{10}, Al^{27} [Fig. 12(b)], and Be^9 have been surveyed and a more detailed study of some of these is planned for the coming year.

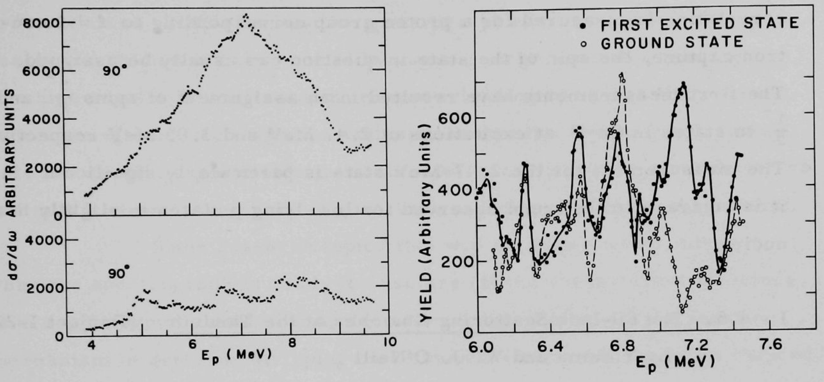


Fig. 12. Yield curves of (a) the $B^{11}(p,\gamma)C^{12}$ reaction and (b) the $Al^{27}(p,\gamma)Si^{28}$ reaction.

2. Gamma rays following inelastic scattering. With the tandem it is possible to cleanly and strongly excite some bound levels of nuclei which are rather inaccessible by other means. This is being put to use in studying the energy levels of B^{10} by observing γ-γ coincidence following the bombardment of B^{10} with protons from the tandem. The various levels have been measured and their decay properties determined. Several of the more subtle properties of the decay schemes, which were unresolved in former studies, have now been cleared up.

I - 4.4. Spins of Excited Nuclear States by p-γ Angular Correlations

D. S. Gemmell, L. L. Lee, Jr., and J. P. Schiffer

As part of a continuing program to study the neutron single-particle states in medium-weight nuclei, a program to measure (d, pγ) angular correlations has been started. When this proton-gamma angular correlation is measured for a proton group corresponding to $\ell = 1$ neutron capture, the spin of the state in question can usually be assigned. The first measurements have resulted in an assignment of spins $\frac{3}{2}^-$ and $\frac{1}{2}^-$ to states in Ca^{41} at excitations of 2.47 MeV and 3.95 MeV respectively. The measurement for the 2.47-MeV state is particularly significant since it is contrary to the trend observed for low-lying p states in slightly heavier nuclei.

I - 4.5. The 60-Inch Scattering Chamber at the Tandem (Project I-22)

J. L. Yntema and W. J. O'Neill

A second 60-in. scattering chamber (in some respects similar to the one currently in successful operation at the cyclotron, but incorporating several improvements and additional features) is being installed at the Tandem. The basic structure of the new instrument is nearly complete. The design of the mechanism to move a detector throughout the upper hemisphere will be started when the present (d, p) and (p, p) experiments on Ti^{46}, Ti^{47}, Ti^{48}, Ti^{49}, and Ti^{50} have been completed.

A three-dimensional television system has been constructed to enable the experimenter to keep the detector that moves in the upper hemisphere from colliding with those in the horizontal plane. This design is a considerable improvement over previous 3-D television systems since it does not require as intense illumination and it eliminates ghosts and cross talk.

I - 4.6. Broad-Range Magnetic Spectrograph

J. R. Erskine

This magnetic spectrograph, now being installed in the east target room of the tandem Van de Graaff, will be one of only a few such instruments for which bombarding energies up to 13.5 MeV are available. At this energy the spectrograph can be used for high-resolution studies of heavy nuclei by use of charged-particle reactions. The high resolution and freedom from overloading at high particle fluxes, which are intrinsic to magnetic analysis, enable the spectrograph to be used for certain experiments that cannot be done with solid-state detectors and multichannel analyzers. Figure 13 is a photograph of the instrument.

Some research topics that will be of particular interest when the spectrograph is ready for use are (1) the energy-level structure of heavy deformed nuclei and nuclei near closed shells, (2) the reaction mechanism of deuteron stripping on deformed nuclei, (3) reactions induced by bombardment with complex nuclei, (4) coincidence experiments in which the spectrograph serves as a high-resolution spectrometer, and (5) measurements of reaction products emitted very near the beam direction where solid-state detectors cannot be used because of the very high flux of elastically scattered particles.

I - 4.7. Beam Pulser for the Tandem Accelerator

F. J. Lynch

The beam-pulsing system recently constructed at the Tandem accelerator is similar to that at the University of Wisconsin. The ion beam is bunched by velocity modulation in a 3-gap modulator placed between the negative-ion source and the accelerator. After acceleration, the beam is chopped by sweeping it vertically across a slit by means of a 3.75-Mc/sec rf field.

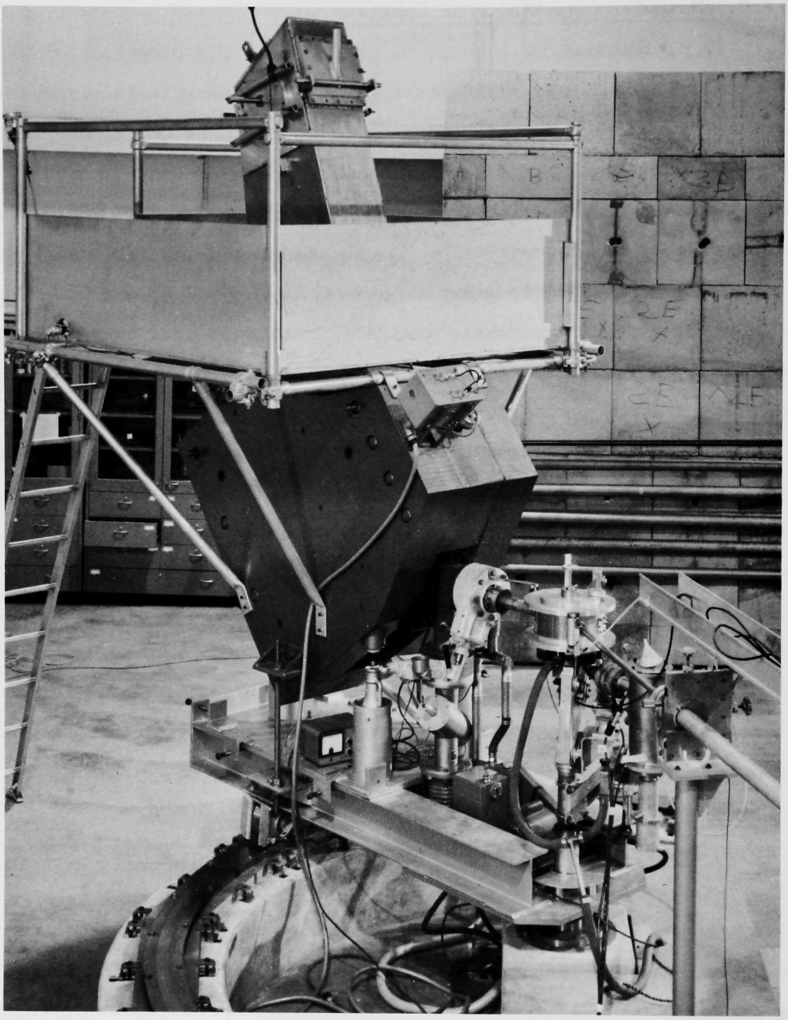


Fig. 13. Broad-range magnetic spectrograph. Nuclear track plates located in the focal plane of the magnet are the primary means of studying reaction products. The camera that holds the plates during a bombardment extends above the experimenter's platform at the top. In an alternative mode of operation, in which the magnet serves as a spectrometer, a quadrupole lens is mounted between the target chamber and the magnet; and a semiconductor particle detector is placed at the focal point.

The phase difference between the buncher and chopper is accurately maintained and monitored so that the chopper transmits the peak of the bunched beam. Electrodes ahead of the buncher deflect the beam away from the entrance of the accelerator during the nonbunching part of the rf cycle.

The measured ion current at the peak of a bunch is 8 times the current in the unbunched beam. The duration of a pulse is less than 2 nsec.

I - 4.8. Gamma-Gamma Angular-Correlation Apparatus

T. H. Braid and J. T. Heinrich

A facility for conducting three-dimensional gamma-gamma correlation experiments is now being completed in the east target room. Figure 14 shows the apparatus in its low-background cave before the shield wall was erected in front of the cave opening. The apparatus provides three arms on which detectors may be mounted: a primary, a secondary, and a "space" arm. All three may be rotated about a common vertical axis by remote control from the east data room. In addition, the counter carriage on the curved "space" arm can be positioned from 8° below to 90° above the horizontal scattering plane. The primary arm was designed to support a 1000-lb detector with its face at a radius of 4 — 27 in., the secondary arm for a 100-lb load at a radius of 2 — 16 in., and the space arm for 250 lb. at 4 — 24 in. The horizontal circle that just clears the support columns of the space arm has a radius of 44 in., but the entire space arm and its supporting bridge structure may be removed so that the distance from target to counter can be extended. A number of vacuum-tight target chambers are being provided. One has a target wheel, remotely controlled from the east data room, so that any one of eight targets may be selected for use. Remotely controlled horizontal and vertical motions of the whole system are provided so that the center of rotation of the arms can be placed on the Tandem beam.

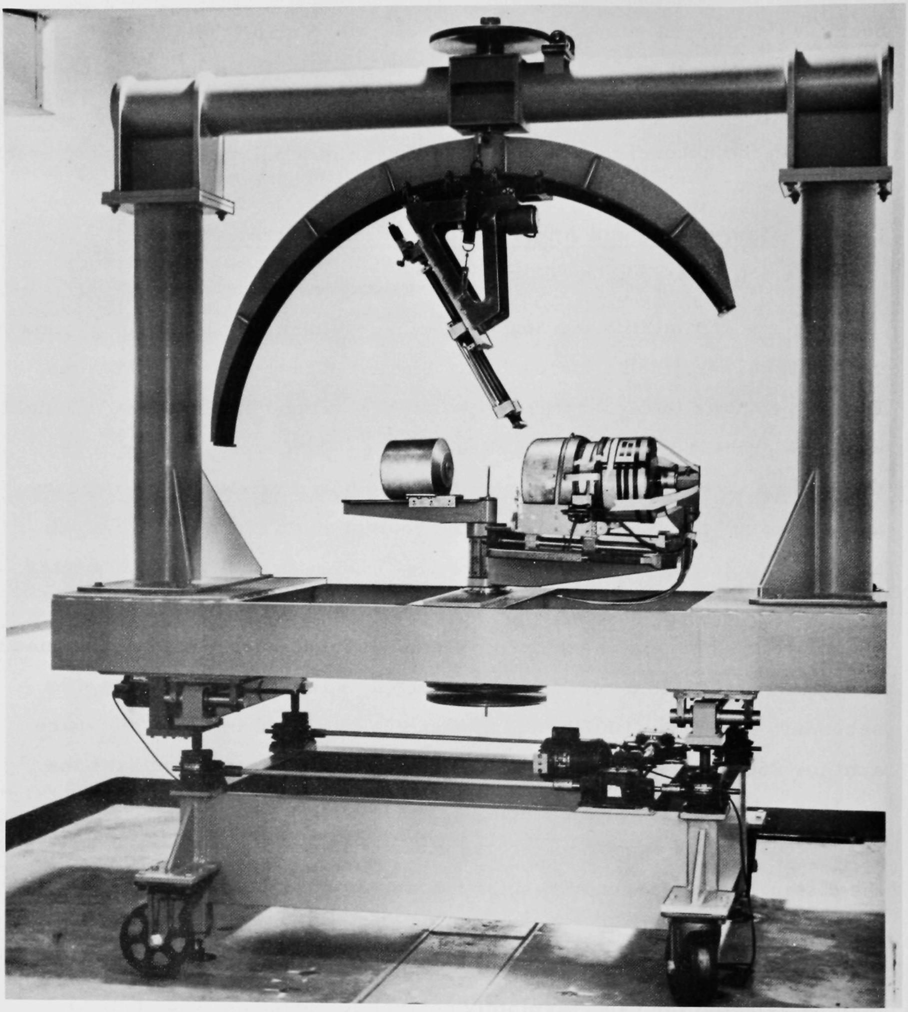


Fig. 14. The angular-correlation apparatus at the Tandem accelerator.

I - 5. RESEARCH AT THE 60-IN. CYCLOTRON

The 60-in. cyclotron is one of the low-energy accelerators operated by the Chemistry Division. It accelerates α particles to 43.2 MeV, deuterons to 22.6 MeV, and protons to 10.8 MeV. For all three of these projectiles, it can produce external beams at the shutter in excess of 0.1 ma. In addition, it accelerates Li^6 to an energy of 66 MeV with usable external beams of the order of 0.01 μa. Modifications to be made in the fall will enable the machine to accelerate He^3 to 28 MeV and (probably) Li^7 — in addition to the nuclei now accelerated.

The beam-handling equipment currently consists of a beam squeezer, three sets of quadrupole lenses, and two sets of left-right and up-down deflection magnets. A switching magnet permits the use of five different experimental stations. The energy of the incident particles can be lowered by use of a remotely controlled foil changer at the focal point of the first set of quadrupole lenses.

Now that a second experimental area is being built, it has become feasible to install a beam-analyzing magnet system. It is anticipated that this system will be ready near the end of 1963 and will provide a resolution width of 0.1% or less. The cyclotron is in operation approximately 80 hr/week. On the average, the Physics Division uses 25-30% of the operation time of the machine.

I - 5.1. The 60-In. Scattering Chamber at the Cyclotron (Project I-22)

J. L. Yntema and H. W. Broek

The elastic and inelastic scattering of 43-MeV alpha particles by nuclei in the region from Ca^{40} to Zn^{68}, by four stable isotopes of Zr, and by Pb^{208} were studied. The alphas were detected by silicon surface-barrier detectors. In all targets studied, alpha groups corresponding to $\ell = 2$ were seen at about 1 MeV excitation and others corresponding to $\ell = 3$ were seen at about 4 MeV — more strongly excited in even-even than in odd-A targets. The 3^- cross section increases with A, but the 2^+ cross section varies irregularly with A.

The elastic scattering of 21.4-MeV deuterons by the five stable isotopes of Ti, and by Pb^{208}, Pb^{206}, and Ca has been measured. The diffraction pattern clearly shows the effect of shell closure in Ca^{40},

Ti^{50}, and Pb^{208}. The inelastic scattering to the 2^+ states of Ti^{46} and Ti^{48} has a considerably larger cross section than the one to the 2^+ state of Ti^{50}. The angular distributions of the transitions to the 4^+ states do not give a clear diffraction pattern.

The (d, t) reaction on the Ti isotopes was studied at a deuteron energy of 21.4 MeV. The results show conclusively that seniority mixing occurs in the Ti isotopes. Some admixture of 2p neutrons was detected in the ground-state wave functions of Ti^{50} and Ti^{48}.

The (d, p) reaction on five stable isotopes of Ti, three of Pb, and four of Zr was also investigated at an incident-deuteron energy of 21.4 MeV. Contrary to the expectations from the simple theory, it is possible to identify the ℓ value of transitions in a number of cases. Distorted-wave Born-approximation calculations have been used to extract the spectroscopic factor for a number of transitions in the Ti isotopes. In some cases these calculations can be compared with the spectroscopic factors derived from the (d, t) reaction. This comparison shows that the assumptions used in most DWBA calculations are not justified in all cases.

The $Ti^{49}(d, p)Ti^{50}$ transitions to the 1.56- and 2.76-MeV levels also show conclusively that seniority mixing occurs in Ti^{49}. The (d, He^3) reaction has been measured for 21.4-MeV deuterons incident on Ca and the stable isotopes of titanium. It was found that the $1d_{3/2}$ hole state in Sc^{45} is less than 100 keV from the ground state, that there is at least one d hole state at less than 100 keV from the ground state of Sc^{46} and another near 400 keV excitation, but that in Sc^{48} and Sc^{49} the $d_{3/2}$ hole state moves to excitation energies higher than the excitation energy of the $2s_{1/2}$ hole state. The separation of the ground state and $2s_{1/2}$ hole state varies from about 1 MeV in Sc^{45} to about 2.4 MeV in Sc^{49}; in all instances it is smaller than the measured $2d_{3/2}$-$2s_{1/2}$ separation of 2.60 MeV in K^{39}.

The gas scattering system has been used for studies of the (d, d) and (d, p) reactions on He^4. Similar experiments on O^{16} and He^3 are planned when a system with a smaller and grease-free volume is completed.

The data-handling system will be redesigned in order to speed up the read-out and to make better use of the computer facilities. The scattering chamber will very probably be moved to the second experimental area when the magnetically analyzed beam becomes available.

I - 5.2. Studies of Pickup Reactions (Project I-24)

T. H. Braid and B. Zeidman

The 21.5-MeV deuteron beam of the 60-in. cyclotron is being used to study nucleon pickup reactions by means of (d, t) and (d, He^3) reactions. These reactions provide a sensitive probe for the examination of the nuclear structure of the target nuclei and residual nuclei. The presence of several groups involving f-neutron pickup in the spectra from (d, t) reactions on targets containing 28 neutrons (e.g., Cr^{52} and Fe^{54}) is conclusive evidence for seniority mixing in these nuclei. In Fe^{54}, the observation of precisely four strong groups and their excitation energies shows the presence of the state whose isotopic spin is the analog of that of Mn^{53}. The (d, He^3) reaction on Ca^{40} yields the location of the single-particle hole states in K^{39}, where the $2s_{1/2}$ state is shown to be about 2.6 MeV above the $1d_{3/2}$ state. The (d, He^3) reactions on F^{19} and Sc^{45}, each of which has one proton outside a presumably closed shell, show strong configuration mixing in both nuclei. The nuclei studied have included F^{19}, Al^{27}, Ca^{40}, Sc^{45}, Ti^{48}, V^{51}, Cr^{52}, Fe^{54}, Fe^{56}, Mn^{55}, Ni^{58}, and Ni^{60}.

The measurements will be extended to other nuclei in this region and to larger scattering angles in order to provide more complete information concerning the reaction mechanisms and nuclear structure. Improvements in experimental technique through the use of faster and more versatile electronics will provide improved energy resolution at higher counting rates and also permit the simultaneous detection of more than one type of particle.

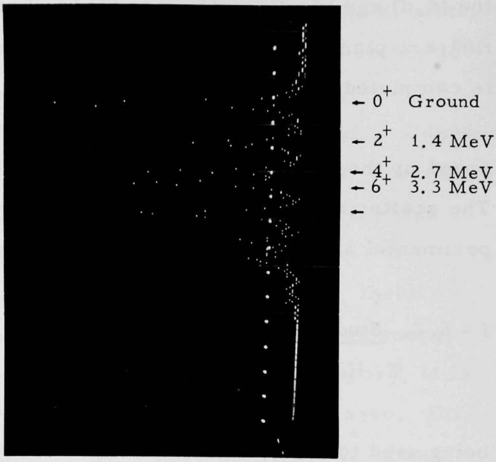


Fig. 15. Raw data (from the display on the multichannel analyzer) from the $V^{51}(d, He^3)Ti^{50}$ reaction at 20^o lab. The peaks shown correspond to pick-up of $1f_{7/2}$ protons to leave the Ti^{50} in the 0^+, 2^+, 4^+, and 6^+ states, respectively. The fifth peak and others to the left correspond to pick-up of particles from the 1d-2s shell.

I - 5.3. <u>Measurements of Deuteron Polarization</u> (Project I-22)

B. Zeidman and J. L. Yntema

Since the deuteron has spin 1, the study of deuteron polarization is complicated by the presence of tensor polarization in addition to the vector polarization characteristic of particles with spin 1/2. For a vector polarized beam, the polarization in a reaction may be measured by the asymmetry in scattering in the plane perpendicular to the incident polarization. If tensor polarization is present, it is also necessary to investigate the scattering out of this plane. The 21.5-MeV deuteron beam of the 60-in. cyclotron is therefore being scattered twice, the first (polarizing) scattering providing a beam for the second (analyzing) scattering in order to measure deuteron polarizations.

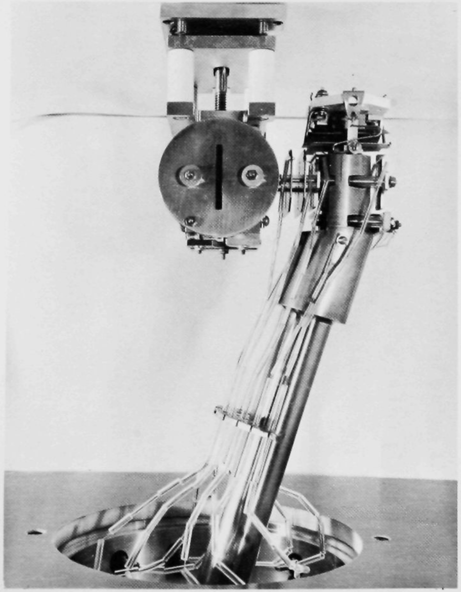
A device has been constructed to measure the asymmetry in counting rate at equal angles on either side of the second beam. This device has been temporarily installed in the 60-in. scattering chamber, where preliminary measurements in the plane of the first scattering have been made. Asymmetries have been observed, but much additional work is required to determine their origin. A scattering chamber which is nearing completion will allow measurements to be made as theplane of the second scattering is rotated about the second beam direction.

I - 5.4. Fission of Cf^{252}

T. H. Braid and H. Diamond (CHM)

Rare modes of spontaneous fission of Cf^{252} have been measured in a continuing study. The long-range alpha spectrum was measured some time ago and an effort to detect triple fission is in progress.

Plans for the future include attempts to obtain the angular distribution of the long-range alphas with respect to the fission direction, and to measure the spectra of other light particles emitted in the fission process. The 3-parameter analyzer is used for these experiments, and it is hoped that spark-chamber techniques can be used with profit. A study of the fission induced in various targets by inelastic scattering of the Li beam from the cyclotron is being tentatively planned in cooperation with A. Friedman (CHM).



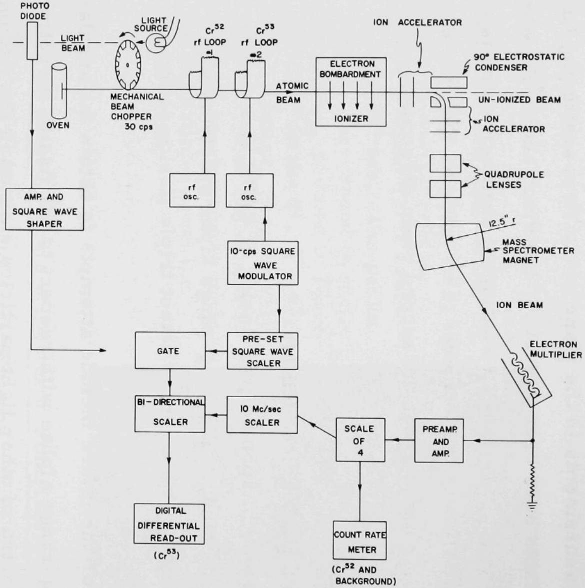


Fig. 16. Ion source of the electron-bombardment universal detector of the Mark II atomic-beam machine. To detect the neutral atomic beam which passes through the apparatus from left to right, electrons are shot up through the beam from the Pierce gun at the bottom left of the figure. The ions formed are drawn to the right, deflected through 90°, accelerated out of the plane of the page, and focused into a mass-spectrometer magnet. The ions are counted individually after detection with an electron-multiplier tube. The ion-box assembly is kept at liquid-nitrogen temperature to reduce the background of ions not originating in the bombardment of the beam.

Fig. 17. Schematic diagram of the electronic circuitry for synchronous detection of the atomic beam as used for the Cr^{53} experiment. The atomic beam is represented schematically near the top of the figure.

I - 6. OTHER NUCLEAR EXPERIMENTS

Several experimental nuclear investigations in the Physics Division are not closely associated with any of the major sources of neutrons or charged particles. These independent studies are collected for convenience in this section.

I - 6.1. Atomic-Beam Research (Project I-80)

W. J. Childs, L. S. Goodman, and J. Dalman

Efforts in the atomic-beam magnetic-resonance project have recently been focused on completion and operation of the new (Mark II) apparatus. Investigation of the hyperfine structure of Cr^{53} has been completed and Fe^{57} is under study.

The newly-installed universal detector of the Mark II atomic-beam machine is capable of unusually high sensitivity. This is achieved by the use of the liquid-nitrogen-cooled ion source (Fig. 16) and novel synchronous counting techniques (Fig. 17). The number of isotopes whose hyperfine structure can be quantitatively examined is thereby increased considerably.

While such measurements on stable isotopes are of great interest, the machine will also make measurements on radioactive isotopes much more straightforward. Although the detector cannot be used to observe resonances in radioactive atoms (because of lack of intensity), it can be used for oven alignment and monitoring of the beam stability. Collection of data should therefore be much more efficient.

In the previous work in this program, research on radioactive atoms has frequently been hampered by a lack of knowledge of the electronic g factor or of the magnetic field which the atomic electrons produce at the position of the nucleus. The Mark II machine, which can make such measurements on stable atoms, will end the dependence on other laboratories or on tedious measurements with radioactive nuclei. Measurements on the nuclear properties of radioactive atoms will thus be shorter and more productive than in the past.

When the Mark II machine is equipped for measurement of the properties of radioactive atoms, the Mark I machine will be retired. The plan is to replace it with a Mark III apparatus, a versatile atomic-beam machine which could be used for high-precision radiofrequency spectroscopy of atomic beams and for novel experiments that would directly determine the magnitudes and signs of nuclear moments.

I - 6.2. Decay of Short-Lived Radionuclides (Projects I-36, 37, 38)

S. B. Burson and E. Brooks Shera

Beta-Ray Spectrometer. The radionuclides studied were Ho^{166}, Re^{188}, and W^{188}. The observed parameters of the decay of W^{188} help to confirm the 1^- assignment of the ground state of Re^{188} and aid in developing the total decay scheme of W^{188}.

Experiments on various baffle systems within the spectrometer showed that the present instrument is inadequate for studying detailed spectral shapes of beta-ray distributions (to study beta-decay interactions and nuclear matrix elements). However no changes are planned since it is extremely stable and precise in determining endpoint energies and internal-conversion coefficients.

Solid-state detectors were installed in the beta-ray spectrometer to provide energy distributions useful in the study of baffle systems. A second purpose was to start a library of spectral shapes so that solid-state devices can be used as quantitative beta-ray detectors.

Angular-Correlation Apparatus. A fully automated system for measuring gamma-gamma directional correlations has been constructed. We have started to measure the gamma-gamma correlation in the 230 — 63-keV cascade in W^{188} as an aid in assigning parameters to the excited states of the odd-odd nucleus Re^{188}.

Use of solid-state detectors will permit measurement of other types of correlations such as beta-gamma or electron-electron coincidences.

Fig. 18. Fully automated suspension for the two scintillation detectors of the angular-correlation apparatus. The yoke supporting the movable detector pivots about a vertical axis. It is driven by a reversible motor and gear train and is precisely indexed at pre-set positions by means of a tapered pin and set of V-blocks clamped to the protractor plate. The complete sequence of operations needed to locate the yoke at any pre-scribed position is initiated by a single pulse on any one of the 21 address lines. Such an address pulse can be provided either from a symbol on the punched tape in the programming unit or from one of a set of buttons on the control console of the system.

Gamma-Ray Detection System. Scintillation techniques have been used for precise measurements of the gamma-ray spectra of radionuclides, particularly odd-odd nuclides such as W^{188}. The principal decay mode of the latter is a 342-keV beta transition to the ground state of Re^{188}; but somewhat less than 0.1% go to two excited states.

Computer Programs for Data Analysis. We have developed and tested several programs. (a) A program to analyze continuous complex beta-ray spectra has been successfully applied and is being published. It is the first one that simultaneously fits the descriptive parameters to an experimental beta-ray spectrum. It has replaced the older "stripping" method in the analysis of the spectra of Re^{188}, W^{188}, Tm^{172}, and Cu^{61}. (b) Several small programs have been developed to process the voluminous data from the automated angular-correlation system. (c) We have written and tested several programs that determine the best fits to experimental data and thereby derive the correlation coefficients in gamma-gamma experiments, and that interpret such data to ascertain the mixing ratios of the transitions.

I - 6.3. Measurement of Gyromagnetic Ratios by γ-γ Angular Correlation (Project I-70)

S. Raboy and C. C. Trail

The angular-correlation apparatus is being tested and preparations are being made for measuring the gyromagnetic ratio of the 6-nsec 81-keV first excited state of Cs^{133}. The source is 7.2-yr Ba^{133}.

This measurement will be the beginning of a series of measurements on other isotopes.

I - 6.4. Pattern Recognition for Nuclear Events

J. A. Gregory (AMD) and G. R. Ringo

The mechanization of the identification of interesting events is a problem of increasing importance in nuclear and particle physics. It is particularly critical in the case of emulsions for which it is desirable to scan large volumes of material with microscopes showing volumes of 10^{-8} cc or less in a view. A general-purpose computer has been programmed to simulate a three-layer random-connection network similar in its general character to the Perceptron of F. Rosenblatt. This program is designed to separate patterns presented in the form of 80-bit words into wanted and unwanted classes after a learning phase using 100 cases of each. The approach differs from the original Perceptron in that in the original the random connections are reinforced or weakened on the basis of the learning performance. In the version here, many completely different sets of connections are tried and the most useful (in the learning phase) kept.

Preliminary results show significant but not yet useful discrimination in a realistic but difficult case approximately equivalent to distinguishing X's from Y's of random position, size, orientation, and opening angle.

The next phase would involve the construction of at least a 40-bit tally counter for GEORGE or the CDC-3600 and the trial of a radically larger field of random connections.

I - 6.5. Study of Mesic X Rays (Project I-57)

C. C. Trail and S. Raboy

Precise measurements of the energies of the K_α μ-mesic x rays in N, O, F, Mg, Ca, Zn, Cu, Ti, and Ni were made at the frequency-modulated cyclotron of the University of Chicago. These measurements yield information about the electric charge distribution in the nucleus of the atom. The scintillation spectrometer with the anticoincidence annulus of NaI(Tl) lends itself nicely to such measurements.

In addition, the energy of the L_α μ-mesic x rays of Zn, Cu, Ni, and Ti were measured and found to be higher than the theoretical values. The isotope shift of the K_α line of Ca was determined by measuring the energies of the K_α lines of natural Ca and of Ca^{44}.

It turns out that earlier measurements by laboratories at Columbia University and at CERN in Geneva are lower than our results. Both their techniques and ours need critical examination.

In addition to such energy determinations, plans include a search for μ-capture γ rays from the nucleus and for quadrupole splitting in the heavy nuclei, and studies of isotope shifts in Ca and U.

Further refinements in the counting system are required to permit identification of μ-mesic events in the presence of pions and electrons.

I - 6.6. Mössbauer Measurements (Project I-19)

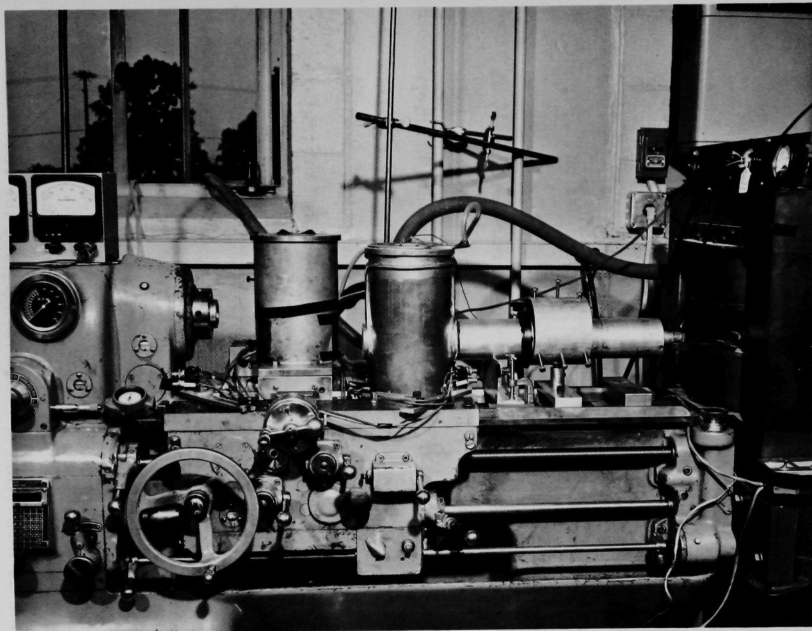
Mössbauer's discovery of the recoilless emission and absorption of nuclear gamma radiation has provided a powerful means of investigating many phenomena in nuclear and solid state physics. Because of the great sensitivity of the effect ($\Delta E/E \approx 10^{-13}$), it is possible to resolve magnetic and electric hyperfine structure of nuclear levels, to make accurate measurements of very small level shifts resulting from thermal motion of the atoms or from interaction of the nuclei with the atomic electrons, and to determine intensities of nuclear absorptions. The method has had its most striking successes in the case of the first excited state of Fe^{57} at 14.4 keV. The importance of the effect in Fe^{57} is due to its great strength and sensitivity and to the propitious circumstance that iron and many of its compounds and alloys are ferromagnetic. Isotopes of tin and gadolinium are also being studied in detail. Recently an intensive study of xenon and its very interesting compounds has been undertaken with the Mössbauer effect.

A. Mössbauer Effect in an External Magnetic Field

J. Heberle and S. S. Hanna

A liquid-helium cryostat suitable for testing magnets has been built. Two beryllium windows have been incorporated so that this cryostat can be used for studies of the Mössbauer effect.

Seven superconducting coils have been wound and tested. The last one, M7, is capable of producing 50 kG on a Mössbauer absorber with a diameter of 0.540 in. It is to be noted that commercial magnets with comparable performance are considerably larger and therefore would not fit into our cryostat.



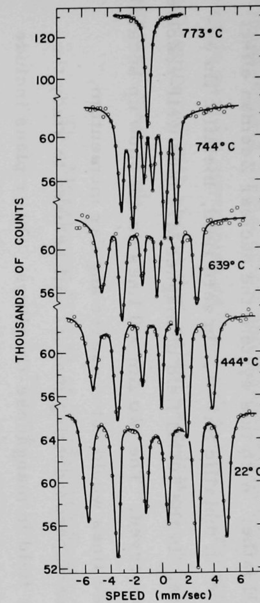


Fig. 19. Lathe setup used in Mössbauer research. The source of radiation is kept cold in the cylindrical Dewar mounted at the left on the lathe carriage. An iron absorber is mounted in the cylindrical oven in the center. When the source moves at speeds between 0 and 7 mm/sec, the nuclear hyperfine spectra in the graph are recorded by means of the scintillator in the horizontal cylinder at the right. The graph shows that the magnetic splitting in the Fe^{57} spectrum decreases as the sample is warmed from room temperature to the Curie temperature (768°C), in accordance with the change in the saturation magnetization of iron.

The cryostat and magnet M7 have been mounted on the older Monarch EE lathe. With this system the nuclear Zeeman effect have been observed in metallic Sn^{119}. In zero field, metallic tin exhibits a single line. In the 50-kG field of magnet M7, four well-resolved lines have been observed. The two $\Delta m = 0$ lines do not show up because absorption in these lines would not conserve angular momentum.

The superconducting magnet will be used to study the internal magnetic field in manganese-tin alloys. Other plans include building a larger magnet and a larger cryostat to hold it. If superconducting magnets capable of producing fields of 100 kG become available in the near future, these experiments can take advantage of them.

B. Mössbauer Effect in Iron

R. S. Preston and S. S. Hanna

The series of Mössbauer measurements on metallic iron has extended over a wide temperature range. The results have recently been published. Continuing measurements along these lines seek to determine the effective Debye temperature in iron more precisely as a function of the actual temperature. Plans for further work include more precise measurements on the variation of the internal magnetic field with temperature just below the Curie point, and on the nature of the discontinuity in the temperature shift at the Curie point. A study of the isomer shift in certain alloys and in externally applied magnetic fields is also contemplated.

C. Mössbauer Effect for Impurities

J. P. Schiffer

The Mössbauer effect has been studied for Fe^{57} as an impurity in various metal lattices. Sources were prepared by diffusing Co^{57} into Be, Cu, W, and Pt. The temperature shift (the displacement of the absorption line as a function of temperature) and the recoilless fraction as a function of temperature have been measured. From this the mean-square displacement and mean-square velocity of the Fe^{57} atoms in various environments can be deduced. These results have been compared with recent theoretical calculations; except for Pt, good agreement was found.

D. Mössbauer Studies of Solid-State Properties

G. J. Perlow

Quadrupole coupling in salts. This is a continuation of work done while on leave at Harwell. The sign and magnitude of the quadrupole coupling in ferrous salts leads to knowledge of the ground-state wave function of the ferrous ion in various ligand fields and to further understanding of the nature of the chemical bond.

Relationship between the electric field gradient and the dipole field at an iron impurity in hexagonal cobalt. This is an effort to experimentally evaluate one of the terms in the hyperfine interaction in ferromagnets, namely the term due to the magnetic field contributed directly by electron spins adjacent to the nuclear site. This contribution is related to the distribution of neighboring charge and therefore to the gradient of the electric field. The dipole field and the gradient of the electric field were measured separately. Their ratio was different from the predicted value; it is not yet certain why.

Mössbauer effect in xenon compounds. The Mössbauer effect has been seen in Xe^{129} formed in the beta decay of I^{129} in NaI. Absorbers of xenon clathrate (hydroquinone), sodium xenate, XeF_4, and XeF_2 have been used, all at the temperature of liquid helium. The results are being analyzed to get some nuclear parameters of xenon and to study the nature of the bonding. Additional compounds will be tried as this program continues.

E. Search for an Effect of Magnetic Fields on Electromagnetic Radiation

S. S. Hanna, G. J. Perlow, J. P. Schiffer, and J. A. Weinman

The effect of magnetic field on the frequency of electromagnetic radiation was studied. It was found that for fields of the order of a few thousand oersteds over distances of a few centimeters, the frequency of the radiation was shifted by less than about four parts in 10^{15}.

I - 7. THEORETICAL NUCLEAR PHYSICS

The theoretical nuclear research in the Physics Division comprises a continuing study of the structure and reactions of light nuclei, an expanding investigation of the collective model of nuclear structure, and increasingly interesting and useful problems in the statistical properties of nuclei. An important theoretical development currently taking form is a major effort to obtain exact solutions to shell-model problems by using new techniques of machine calculation. The CDC-3600 computer, when it becomes available, will greatly benefit this major program of calculations.

The theoretical section continues to attract a large number of temporary appointees; the number of applications exceeds the available positions by an order of magnitude. An outstanding series of seminars provides for mutually beneficial exchanges of ideas between temporary and permanent members of the theoretical group, visitors from other laboratories, and experimenters. These formal programs are supplemented by a variety of informal contacts.

I - 7.1. Strong M1 Transitions in Light Nuclei (Project V-2)

Dieter Kurath

The nature of strong M1 transitions, particularly those observed by inelastic scattering at backward angles, was investigated. Calculations of particular cases revealed a tendency to concentrate the transition strength in a few levels, in some respects similar to the familiar giant E1 resonance. The energy-weighted sum rule for such transitions was examined, and an approximation was developed which exhibited the qualitative behavior to be expected in 4N nuclei whose ground states have I = 0 = T. The results were compared with experiment.

In order to carry out more detailed calculations for this effect and for other properties, one needs good wave functions. These can be obtained either by diagonalizing some shell-model Hamiltonians, or by projecting states of definite angular momentum from many-particle Nilsson functions. Both approaches will be tried by use of computer codes being developed in another project.

I - 7.2. Seniority Mixing in $1f_{7/2}$ Nuclei (Project V-12)

R. D. Lawson and B. Zeidman

The reduced widths for the neutron pickup from $1f_{7/2}$ nuclei were calculated for wave functions of mixed seniority. The results agreed satisfactorily with the experimental values. The calculated values for wave functions having pure seniority were not in agreement with experiment. No additional work is planned at this time.

I - 7.3. Dynamics of Nuclear Collective Motion (Project V-3)

D. R. Inglis

Heavy-particle stripping and the structure of Li^6. There is an interesting contrast between the angular distribution of the alpha group leading to the ground state and that leading to the second excited state in the reaction $C^{12}(Li^6, \alpha)N^{14}$. The proposed explanation is that the ground-state group has a peak only in the backward direction because only the mechanism of "heavy-particle stripping" can satisfy the requirements on the orbital angular momentum for the ground state of N^{14} (primarily a ^3D state). The "deuteron" of the incident Li^6 initially has insufficient angular momentum about the final core but acquires more because the force attracting it toward the target nucleus is not directed toward the center of mass of the twelve nucleons (eight from the target C^{12} and four from Li^6) which form the core of the final N^{14}. The other four nucleons from the target form the product alpha. The second excited state of N^{14} is approximately a ^3S and there is no such angular momentum limitation so both light- and heavy-particle stripping occur and give rise to both forward and backward peaks.

Phase relation in nuclear scattering. The striking observation that the maxima of elastic scattering of such particles as alphas on fairly heavy nuclei coincide with the minima of inelastic scattering (with no parity change) may be explained in an elementary way. Elastic scattering corresponds to diffraction of a wave passing through a circular aperture; inelastic scattering, in which a particle is acted on by a short-range force and loses energy in passing close to the edge of the nucleus, corresponds to diffraction of a wave passing through a ring. In other words, the alternating intensities of elastic and inelastic scattering are 180° out of phase with each other primarily because the former arises from integrating over the area of the nucleus while the latter arises from integrating over a ring around the edge. The contribution of a ring can be obtained from that of a circular opening by differentiation.

This graphic type of treatment is useful also in understanding simple reactions whose angular distributions display alternating maxima and minima somewhat similar to those observed in scattering.

I - 7.4. <u>Deformation Energy of a Charged Liquid Drop</u> (Project V-1)

S. Cohen and W. J. Swiatecki (Lawrence Radiation Laboratory)

The uniformly-charged liquid drop has been used as a model for the calculation of many of the properties of nuclei. The application of this model to the process of nuclear fission led to some understanding of qualitative features of the process but quantitative calculations had not been carried out for parameters corresponding to those of real nuclei. In the present study, numerical techniques with an IBM-7090 computer gave results bearing directly on the experimentally observed fission of nuclei.

The model is a liquid drop with an electric charge distributed uniformly throughout its volume. A given drop is characterized by a fissionability parameter x which is related to the ratio of the electrostatic energy to the surface energy due to the surface tension of the nuclear fluid. Nuclei which fission have $0.6 \leq x \leq 0.8$.

The shape of the drop at the instant of scission was approximated rather crudely. Then in the configuration space describing the shapes of drops, possible paths leading from the spherical shape to the unknown scission shape were considered and the potential energy along each path was calculated. The shape sought was the one which gave the minimum threshold energy for fission.

For $x < 0.67$, the shapes at the threshold energy are dumb-bell-like; for $x > 0.67$, they are cylinder-like. For $x > 0.39$, it is a true threshold for fission, but for values less than 0.39 the shape is unstable with respect to asymmetric distortions and therefore no true threshold exists. The particular values cited apply only to the approximate model assumed, but the general behavior should approximate that of actual nuclei.

I - 7.5. Resonance Theory of Nuclear Reactions Without Boundary Conditions (Project V-11)

A. M. Saperstein

Nuclear reactions were discussed by use of a dispersion-theory type of formalism, and resonances were defined by the poles of an analytic continuation of the imaginary part of the reaction amplitude. The result was an ordinary resonance of the Breit-Wigner type, but it was obtained without the need for an "internal" Schrödinger equation with artificial boundary conditions at a "nuclear radius."

I - 7.6. Statistical Properties of Nuclear Energy States (Project V-15)

N. Rosenzweig

The past year has seen important consolidations in the theory of fluctuations for the energy states of complex systems. (This theory, which has been the subject of this project for several years, has been very successful in explaining such statistical phenomena as the distribution of spacings and the dependence of this distribution on the symmetry properties of the system — such as invariance of the Hamiltonian under time reversal, rotation, and inversion of the coordinate system.

This is also the theory that leads to a derivation of the distribution of miscellaneous "widths" and magnetic moments.) A principle of uniformity was introduced (following the recent papers by Dyson) in the space of Hermitian matrices and implemented with a "micro-canonical ensemble"

$$\delta\ [\mathrm{spur}\ H^{\dagger} H - R^2]$$

which gives equal weight to all possible forms of the residual interaction of a fixed "strength." This ensemble leads to satisfactory agreement with experiment for the statistical phenomena mentioned above; and a graduate student, Harvey Leff, has worked out further consequences (including a calculation of the correlation coefficients between neighboring spacings).

The following remarks are intended to describe the lines along which the statistical model might develop in the near future. The Hamiltonian of the system may be written as

$$\mathcal{H} = H_0 + V ,$$

in which H_0 represents the zero-order part (shell-model or optical-model potential) which is largely responsible for the average behavior of the states (level density, gross structure of cross sections, etc.), whereas V determines the laws of fluctuation (fine structure). In the past, the quantitative interplay between these two parts — which must be important in appropriate regions of excitation — has been largely ignored from the theoretical point of view. It is proposed that these matters should be looked at with the help of the Brownian-motion model of residual interactions which was introduced last year by F. J. Dyson and was developed somewhat further by this writer.

I - 7.7. Nuclear-Structure Calculations

F. Coester, S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga

Computer study of the nuclear shell model. This investigation of the shell model, its foundations in many-body theory, its predictions concerning the properties of specific nuclei, and the nature of its single-particle potential and residual two-body forces falls naturally into two parts. On the one hand, there is an extensive program of conventional shell-model calculations whose chief aim is to examine the nature of the shell-model effective interaction. This is done by suitable parameterization of the effective force, after which the parameters are determined (in principle) by comparison with experiment. It should be stressed that the main emphasis here is not on the production of ever more precise fits to selectively limited patches of experimental data but rather on the nature of the effective interaction itself. What properties of the interaction are most important in producing agreement with experiment? To what extent are conclusions concerning these most essential aspects of the effective force influenced by more highly excited configurations excluded from the lowest order calculations? In considering these and other such questions, due attention must be paid not only to the idiosyncrasies of particular nuclei but also to systematic occurrences of the sort that are associated with collective properties of nuclear states. Accordingly it is useful to examine approximate procedures which accentuate the various kinds of systematic behavior. From a more fundamental viewpoint, the single-particle field and effective interaction must be related to the interaction between free nucleons in a self-consistent fashion. Such calculations are now in progress.

The arithmetic involved in the study just outlined far outstrips human capabilities; the entire calculation is being automated and will be carried out on the IBM-7090 at the University of Chicago and, when it becomes available, on the CDC-3600 at ANL.

Programs for shell-model calculations. During the past year and a half, about thirty computer programs have been developed for performing various parts of shell-model calculations. Most of these programs are operational on both the IBM-704 and the IBM-7090; all can and will be used on the CDC-3600 when it arrives.

Although each program of the existing set is complete in itself, available programs should be regarded as early versions of members of a group which will be developed and used (concurrently) during the next several years. The past year has been devoted mainly to development of programs; in addition to a complete chain of programs for a restricted class of shell-model calculations (orbits of the same parity), a monitor system has been developed whose function is to marshal and combine sequences of individual programs. This feature immensely increases the power and flexibility of the system. Many of the programs perform functions that are an essential part of any many-body calculation on a single-particle basis; the monitor system allows such basic programs to be embedded immediately in each new framework as need arises. Energy spectra and transition rates have already been calculated in the early ds shell (mass number 18 to 20). In addition, the range and degree of validity of the quasi-particle random-phase approximation in nuclei is under study. The approximate as well as the "exact" calculation is completely automated; this small phase of the study should be completed during the summer.

Calculations on the more fundamental problem of relating the shell model to the forces between free nucleons are also in progress. General theoretical arguments make it plain that good approximations to ground-state wave functions of closed-shell nuclei can be found by determining single-particle functions and two-body correlations in a mutually self-consistent fashion. The first step, currently in progress, will test the approximation scheme with a relatively crude nucleon-nucleon potential. Realistic computations for doubly-magic nuclei will be the next stage. The significant results will be in two areas. (1) It should be possible to compute binding energies of nuclei in such a manner that disagreement with experiment can be blamed quite definitely on the assumed force. (2) Shell-model calculations can be based self-consistently on a realistic nucleon-nucleon force.

Many of the programs developed as part of the general shell-model scheme are of immediate value to other users of the CDC-3600.

II. THEORETICAL HIGH-ENERGY PHYSICS

The theoretical group consists of permanent staff members, temporary visitors, and consultants. The consultants, who are drawn from among the leading high-energy theoretical physicists at the Midwestern universities, participate in all the activities of the Argonne group. Many of them could properly be regarded as part-time members of our group. Their presence will be especially valuable to Argonne during the next few years, before the Argonne group reaches its full strength. The Midwestern universities benefit equally by this contact with the Argonne physicists.

Both formal and informal seminars are held regularly by the theoretical group, some for the purpose of interpreting recent theoretical ideas to the experimentalists, some primarily of interest to theorists. Day-to-day contact with a strong group of theoreticians has obvious value for the experimental program.

II - 1. Analysis of Pion-Nucleon Scattering

A. W. Martin and J. L. Uretsky

Partial-wave scattering amplitudes for pion-nucleon scattering are obtained by solving integral equations. The integral equations are solved numerically on the IBM-704 computer. This allows great flexibility in the choice of the basic interactions that are assumed to govern the scattering process.

The results of this analysis will be of interest in a number of branches of high-energy physics: several implications of the Regge approach to high-energy behavior will be tested, a model for pion-pion interactions will be examined, and the positions of resonances in pion-nucleon scattering will be determined on the basis of several models.

II - 2. Dynamical Aspects of Unitary Symmetry in Strong Interactions

A. W. Martin and K. C. Wali

It has been suggested recently that along with the eight stable baryons, low-lying meson-baryon resonances should be identified as belonging to irreducible representations of SU_3. Our work has been mainly concerned with comparing the predictions based on strict SU_3 symmetry with the results obtained from more realistic calculations. So far we have completed the analysis of $J = \frac{3}{2}^+$ amplitudes. The dynamical model used is based on the fact that one single-nucleon-exchange contribution successfully explains the important features of pion-nucleon scattering in the $J = \frac{3}{2}^+$ state. This assumption is generalized to include all coupled two-particle states with a given isotopic spin and strangeness. A coupled-channel matrix formulation of the N/D method was used to determine the resonance conditions. We were able to obtain a set of Yukawa-type meson-baryon coupling constants by requiring that there exist the N^* (T = 3/2), the Y_1^* (T = 1), the recently discovered Ξ^* ($T = \frac{1}{2}$), and yet-to-be-discovered Z^- (T = 0) as a 10-fold representation of SU_3.

These considerations are being extended to other angular-momentum states. The computer facilities at Argonne will continue to be required for the necessary numerical integrations.

II - 3. <u>Meson-Nucleon Interaction</u> (Project V-45)

K. Tanaka, K. Hiida, L. S. Liu, and M. Soga

A hypothesis of generalized isospin independence is proposed to explain relations between total cross sections at high energies. In this hypothesis, the contribution of common channels to various two-particle states (whose total cross sections are considered) is assumed to be equal at sufficiently high energy. At high energies, the cross sections are expected to become insensitive to the intrinsic properties of the particles so long as the conservation laws are respected. Then it is meaningful to discuss the inequalities between total cross sections in terms of the available noncommon channels that are possible under the conservation laws. Various differences of total cross sections were written down on this basis. The present approach has been compared with another possible interpretation based on Regge poles.

The behavior of Regge poles (which are generalized bound states and resonances in the complex angular-momentum plane) were obtained as a function of the square of the momentum transfer by use of field theory on the basis of the ladder approximation in the crossed channel. This is of interest because many field-theoretic attempts have been made to correlate high-energy experimental data in terms of the known behavior of Regge poles in potential theory.

In the coming year, attempts will be made to obtain various consequences and properties of Regge poles and also of unitary symmetry SU(3) as an aid in understanding the physics of elementary particles.

II - 4. Charge Structure of the Nucleon (Project V-47)

K. Hiida

It is proposed that, except for the core region, the electromagnetic structure of the nucleon is determined by two- and three-pion intermediate states which contribute to isovector and isoscalar parts, respectively. It was shown that the total charge contributed from three-pion intermediate states is zero. Therefore there is an isoscalar charge $\frac{1}{2}e$ in the core region of the nucleon and the three-pion intermediate states play the role of polarizing the vacuum. In other words, it appears that the positive charge $\frac{1}{2}e$ in the core region attracts the negative charge $-\delta e$ toward the center of the nucleon and repels the positive charge δe toward the outer region.

The role of the three-pion resonance ω is to enhance the vacuum polarization very strongly. This fact of vacuum polarization, with the aid of experimental information and theorems obtained by meson theory, suggests that F_{1n} (the charge form factor of the neutron) is negative at low transferred momentum, and that the charge distribution of the proton is such that the bare proton is surrounded not only by a positively charged layer but also by a negatively charged layer because of the strong vacuum polarization due to the three-pion resonance ω.

II - 5. Interaction of Elementary Particles

K. Hiida

As indicated by the fact that the muon is sometimes called a massive electron, the electron and the muon have very similar natures in their interactions. The idea of this work is to assume that particles with similar natures should belong to the same group of elementary particles; that is, there is only one particle-number conservation law among them.

For leptonic weak interactions, the usual assumptions are (i) the existence of two neutrinos, (ii) no neutrino flip, and (iii) no neutral current. Since these cannot all be true if the conservation law is to hold, a third neutrino was introduced as the simplest modification of (i). This neutrino is the one from K-μ decay. Under the three-neutrino hypothesis, the discrepancy between the ratio $G_V/G\mu$ and unity (where G_V is the vector coupling constant for beta decay and $G\mu$ is the μ-decay coupling constant) was explained in a manner consistent with the small branching ratio in the leptonic decay of hyperons. It was shown that the hypothesis is relatively easy to prove or disprove by experiments on high-energy neutrino reactions if about 50% or more of the neutrinos are obtained from K-μ decay.

On the assumption that the Σ hyperon is a weakly bound state of the pion-lambda system, a class of experiments was proposed to determine the relative parity of $\Sigma^{\pm}$ and Λ hyperons and the magnitude of the $\Sigma\Lambda\pi$ coupling constant. The assumption of the weakly bound state also can be checked by the experiments.

II - 6. Low-Energy π-π Scattering Calculated by Use of Perturbation Theory and Unitarity (Project V-49)

A. M. Saperstein and J. L. Uretsky

The work of K. Smith and J. L. Uretsky is being extended to third order. The completed second-order calculations give practically the same results as those obtained via "bootstrap methods" by Chew, Mandelstam, and Noyes for the S- and P-wave scattering lengths. Neither of these two methods is expected to be valid at energies comparable to the observed P-wave resonance and neither gives any indication of such a resonance. It is hoped that the extension to third-order perturbation theory will be valid at higher energies and will give some insight into the ρ particle (P-wave resonance).

II - 7. Particles with Zero Mass and Particles with "Small" Mass (Project V-38)

F. Coester

The irreducible representations of the inhomogeneous Lorentz group which describe respectively particles with and without mass are qualitatively different. Nevertheless, the zero-mass representations can be obtained from the representation with mass by letting the mass go to zero. Particles of sufficiently small mass or sufficiently high energy behave like particles of zero mass.

II - 8. Time Reversal and Superselection (Project V-42)

H. Ekstein

It has been known for some time that one of the basic assumptions of conventional quantum mechanics, the superposition principle, cannot be generally true. In the Hilbert space of physical states, there must be vectors that do not correspond to states. The conjecture that coherent superpositions between states of different charge or baryon number are among these vectors without physical counterpart is consistent with observations. A plausible physical requirement on the nature of the time-reversal operators led to a geometrical theory of charge and its superselection, as reported a year ago. This physical principle has now been reformulated in terms of expectation values of operators with respect to proper states and the specific assumptions made earlier are replaced by the single postulate that the algebra of observables is closed.

II - 9. Foundations of Quantum Mechanics (Project V-44)

H. Ekstein

The basic postulate of quantum mechanics is the superposition principle. It has been felt by many, including the author, that a more directly verifiable, operational postulate would be more satisfactory. The suggested new approach is to concentrate on pure states (as contrasted with statistical mixtures) instead of trying to formulate axioms with respect to general ensembles. With a reasonably small number of postulates, it seems possible to build a scheme that is mathematically equivalent to quantum mechanics.

A study of the commutativity of superselecting operators leads to the conclusion that, according to the convention adopted, the "physical Hilbert space" is not a linear space; it is the union (not the direct sum) of linear subspaces. Further work along these lines is planned.

II - 10. Spin and Statistics with an Indefinite Metric (Project V-39)

R. Spitzer

A theory of spin-$\frac{1}{2}$ bosons and spin-0 fermions was formulated with an indefinite metric for physical states. The requirement that squares of S-matrix elements be interpretable as probabilities in the usual sense was formulated in terms of a symmetry principle as a consequence of which states with positive norms become separated from those with negative norms by a superselection law. The symmetry transformation, called metric conjugation, is induced by the metric operator and is non-local. An example of an interaction invariant under metric conjugation was shown to lead to a unitary S matrix and to a theory that admits a causal interpretation in the sense of Stueckelberg. Some consequences of the assumption that the muon is a spin-$\frac{1}{2}$ boson were derived. The theory then provides a physical basis for the absence of the decays $\mu \rightarrow e + \gamma$,

$\mu \rightarrow 3e$ in the sense that the conservation law that leads to these selection rules is the one required for the theory to admit a physical interpretation. The same conservation law forbids muon pair production.

II - 11. Geometric Properties of Angular Distributions of Decay Products (Project V-5)

Murray Peshkin

When an unstable particle is created in a reaction involving few quantum states, the angular distribution of its decay products depends upon the number of states involved in the production process. It was learned, for instance, that when the spin s of the unstable particle is larger than the number of states in the production process, the decay cannot be isotropic.

These methods were extended to the parity-mixing decay $\Xi^- \rightarrow \Lambda^0 + \pi^-$ following the production reaction $K^- + p \rightarrow \Xi^- + K^+$. If the angular distribution of π^- in the first of these decays is written in the form $I(\theta, \phi) = \sum_{L,M} a(L, M)\, Y_{LM}(\theta, \phi)$, then it is found that the asymmetry coefficients $a(L, M)$ must obey certain relations which depend upon the spin s of the Ξ^-. These new relations are considerably more restrictive than the relations of Lee and Yang, which are conventionally used to test the Ξ^- spin. The most important new result is that the angular distribution $I(\theta, \phi) = 1 + A \cos\theta$ with $|A| > 0$ implies unambiguously that $s = \frac{1}{2}$. The most promising previous analysis could exclude a given value of s only if $|A| > 1/(6s)$.

II - 12. The Supercurrent State (Project V-33)

Murray Peshkin

The method of Byers and Yang was extended for application to the current-carrying BCS state by inclusion of the magnetic interaction between electrons in the zero-order Hamiltonian. In the case of a thin superconducting ring, the problem was reduced to the zero-current problem by separating out the collective motion. In the general case, this process was not carried out completely, but the symmetry of the BCS state provided enough information to obtain the desired results. When the fluxoid is equal to an integral multiple of ($\pi \hbar c/e$), the single-particle states occur in pairs which go into each other under reflection about the average electron velocity at each point. A qualitative argument was given to show why this symmetry is necessary for the BCS reduced interaction to have its full effectiveness. The crux of the matter is that in the absence of such symmetry, the Fermi surface is irregular and a substantial fraction of the important states near that surface are unable to participate in a coherent BCS wave function. The Meissner effect is not necessary in obtaining the energy gap.

II - 13. Studies in Electron Theory (Project V-26)

Melvin Hack

Work during the past year centered on problems of electron theory (Lorentz-Dirac theory and its modifications).

One of the most striking aspects of the Lorentz-Dirac theory is its phenomenon of preacceleration: the "precognitive" response of the electron to an applied force before onset of the force, in apparent violation of customary ideas of microscopic causality. It is of interest that the preacceleration effect is a direct consequence of Van Kampen's solution for a classical analogue of the quantum emission field of a harmonic oscillator in the dipole approximation. The result is obtained from a consideration of the contributions of the anomalous (runaway) "oscillator" and the anomalous (acausal) poles. Adopting the Dirac prescription, which amounts to deleting the contribution from the anomalous "oscillator" to avoid its runaway radiation, one is left with the contributions from the ordinary and anomalous poles. The anomalous-pole term leads to the acausal field corresponding to the preacceleration of the electron.

Interest in this subject has been increasing, in spite of the fact that the problems involved data back to the early work of Lorentz and others, over half a century ago.

These problems have been passed on to modern field theory. A study of the heredity may lead to insights about the offspring.

III. EXTRANUCLEAR PROPERTIES OF MATTER

The largest program in Extranuclear Properties of Matter is the mass spectrometric studies. In addition, a modest effort in plasma physics concerns itself mainly with the properties of rf plasmas and the containment of plasmas in rf cavity fields.

During the past year, the investigation of scintillation phenomena was discontinued and the personnel were transferred to other divisions. The work on x-ray crystallography was also discontinued in the Physics Division.

III - 1. MASS SPECTROMETRIC INVESTIGATIONS

The mass-spectrometric investigations involve seven instruments, each designed for a specified task; and another (MA-24) is nearing completion. They include MA-15B, used primarily for the study of the molecular composition of high-temperature vapors and the kinetics of gas-phase reactions; two spectrometers designed for isotopic analysis applied to geochronometry (MA-16B employing surface ionization of solid samples, and MA-18 using electron-bombardment ionization for gaseous samples); MA-17, which incorporates an energy analyzer and is used for determining the kinetic energy of fragment ions; MA-23, having a high-speed pumping system necessary for the study of higher pressure phenomena, such as consecutive ion-molecule reactions and ionic fragments produced by nuclear decay; and a portable mass spectrometer (MA-27) which can be used in conjunction with particle accelerators for the study of ionization in gases and sputtering of solids by high-energy particles. In addition, an Atlas Werke mass spectrometer has been adapted so that interactions between ions or atoms and a metal surface can be studied by pulsed-beam techniques, and is also used for studying the diffusion of salts through metals.

In addition to the basic information that these studies provide about the fundamental atomic and molecular properties of matter (i.e., molecular structure, and the thermodynamics and kinetics of reactions), the results of these investigations can be directly applied to the solution of problems involving rocket propulsion, nuclear reactor technology, radiation chemistry, radiation damage to space vehicles, and re-entry behavior.

III - 1.1. Gaseous Species in Equilibrium at High Temperatures (Project II-29)

J. Berkowitz, W. A. Chupka, and J. R. Marquart

Heat of formation of the CN radical (J. Berkowitz). By mass spectrometric analysis of the gaseous products from the reaction of nitrogen with graphite at ca. 2000°—2500°K, it was possible to deduce a dissociation energy for the free radical CN. This helped to resolve a long-standing conflict regarding this value, toward which a variety of experimental techniques had been directed for at least three decades.

Mass spectrometric study of magnesium halides (J. Berkowitz and J. R. Marquart). Thorough mass spectrometric analysis of alkaline earth halides showed that the degree of dimerization in magnesium halide vapors is not greatly different from that in beryllium halide vapors, contrary to conjectures of another worker. The experimental energies of formation were in fair agreement with a theoretical model based on polarizable ions.

Equilibrium composition of sulfur vapor (J. Berkowitz and J. R. Marquart). By analyzing a variety of metallic sulfides having varying dissociation pressures of sulfur, it was possible to identify the

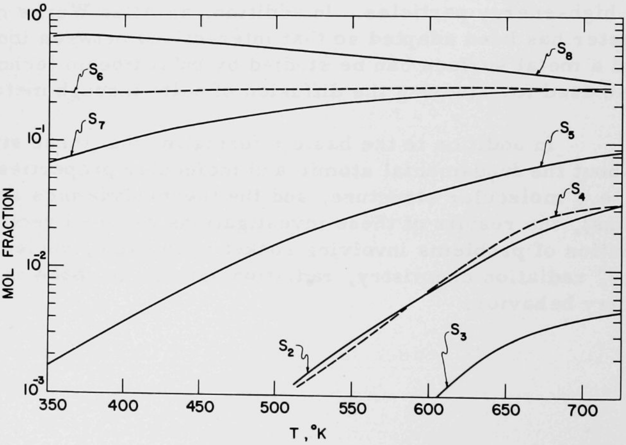


Fig. 20. Contributions of the various molecular species of sulfur to the composition of the saturated equilibrium vapor from room temperature to the boiling point of sulfur.

molecular species S, S_2, S_3, S_4, S_5, S_6, S_7, and S_8 in sulfur vapor under different equilibrium conditions. The analysis of the data permitted the determination of equilibrium constants relating these various species, as well as their energies of transformation into one another. In the vapor above pure sulfur, the species S_9 and S_{10} were also identified. The results were compared with a great mass of earlier experimental attempts, dating back more than 50 years.

Dissociation energies of some metal sulfides (J. R. Marquart and J. Berkowitz). In the course of the above experiments on sulfur, some metal sulfide molecules were identified and low limits were set for others. A statistical thermodynamic approach yielded useful values of D_0 for CaS and SrS, and limits for FeS, HgS, CdS, and ZnS.

Reaction of BaO with H_2O (J. Berkowitz, F. Stafford, and W. A. Chupka). It is shown that the accessible range of experimental conditions is also the transition range for the reactions

(1) $$2BaO\ (s) + H_2O\ (g) \rightarrow 2BaOH\ (g) + \tfrac{1}{2}\ O_2\ (g)$$

and

(2) $$BaO\ (s) + H_2O\ (g) \rightarrow Ba(OH)_2\ (g).$$

Reaction (1) takes place predominantly at the lower pressures of H_2O (< 0.05 mm Hg) and reaction (2) at $P(H_2O) > 0.1$ mm Hg.

The main apparatus used in the above studies was MA-15B.

Plans for future work include (a) remodeling MA-15B to incorporate faster pumping, more favorable geometric arrangement, and more efficient ion focusing and (b) studying the vibrational spectra of high-temperature molecules ("frozen" in an inert matrix) by use of an infrared spectrophotometer being requested for the coming year.

III - 1.2. Kinetics of Chemical Reactions in the Gas Phase (Project II-28)

J. Berkowitz, W. A. Chupka, and S. Wexler

Ionization potential of the CH_2 radical (J. Berkowitz and S. Wexler). From experimental mass-spectrometric results on thermal decomposition of $Hg(CH_3)_2$ and CH_2N_2, it was concluded that the lifetime toward reaction of CH_3 is much longer than that of CH_2. The current results cast serious doubt on the value earlier workers had reported for the ionization potential of CH_2 radical.

Vaporization process involving sulfur (J. Berkowitz and W. A. Chupka). Vapor species evaporating from various allotropic forms of sulfur differ drastically in molecular composition. The experimental results are explained in terms of the molecular architecture of the solid, and lead to a better understanding of the kinetics of vaporization processes.

Unimolecular decomposition of S_8^+ and S_6^+ ions (J. Berkowitz and W. A. Chupka). The decomposition of S_8^+ and S_6^+ ions has been interpreted in terms of the statistical theory of mass spectra. The simplicity of these ions, in comparison with the hydrocarbons in all previous studies, eliminates some complexities. The occurrence of metastables and the general characteristics of the decomposition are in agreement with the theory. A similar study of S_7^+ has begun.

Dissociation of butane molecule ions formed in charge-exchange collisions with positive ions (W. A. Chupka and E. Lindholm [Royal Institute of Technology, Stockholm]). This study, carried out at the Royal Institute of Technology, Stockholm, Sweden, while one author (W.A.C.) was on a Guggenheim fellowship, yielded a breakdown pattern for n-butane ions, i.e., the mode of decomposition as a function of the internal energy of the n-butane ion. This pattern, together with data on metastable ions produced, is adequately explained by the strictly quantum form of the statistical theory of unimolecular decomposition of isolated systems. The result for several of the modes of decomposition show clearly what structure must be assumed for the activated complex. In all such cases, the structures are the ones expected theoretically. The results lead to increased understanding of some fundamental processes of chemical kinetics and radiation chemistry.

Kinetic energy released in decomposition of excited molecular ions (W. A. Chupka). In this work, which was done in Mainz, Germany, while the author was on a Guggenheim fellowship, the quantum statistical theory of decomposition of isolated systems was used to calculate the kinetic energy of the resulting fragments. The calculated quantities are in good agreement with experimental measurements of other workers. The agreement supports the validity of the statistical theory and strongly suggests some interesting details of the process. These details, involving the intermediate formation of loose complexes in some unexpected cases, have important consequences for certain ion-molecule reactions whose initial steps can be regarded as the reverse of the dissociation reactions studied here. This information leads to increased understanding of chemical kinetics and radiation chemistry.

Plans for future work. During the coming year, it is expected that mass spectrometer MA-24 will continue to be the primary tool for chemical kinetic studies of (a) unimolecular decay of molecular ions, (b) recombination reactions and intermolecular energy-transfer reactions occurring in the gas phase, and (c) possibly some studies of afterglow. A vacuum monochromator for the ultraviolet and another for the visible region of the system will be used in all three of these. In addition, (d) MA-24 may be used for some studies of ion-molecule reactions and (e) MA-15B will probably be used to study the vapors produced by laser bombardment of surfaces. It is hoped that the laser will allow pulse studies of the composition of saturated vapors at extremely high temperatures (in the neighborhood of 10 000°K).

III - 1.3. Fragmentation of Polyatomic Molecules (Project II-40)

H. E. Stanton and J. E. Monahan

The relative yields of fragment ions resulting from the ionization of several polyatomic molecules by electron impact have been measured as functions of electron energy. These results indicate that the initial ionization event involves the excitation of two or more groups of electronic states in the parent ion and that these groups do not interact appreciably in the time interval before dissociation. Since the complete coupling of such states is a basic postulate in the statistical theory of ionization-dissociation processes, the results provide a measure of the validity of this theory.

Measurements of the energy distributions of the fragment ions should provide an additional test of this and other conclusions. For example, the width of the observed energy distribution of a given ionic species depends on the relative energies of the electronic states which contribute to the production of this species. A moment analysis of these measured distributions (which includes a correction for resolution effects) has been formulated and seems to give consistent results. If this technique can be developed, it will provide a sensitive method for the study of the mechanism of molecular excitation and dissociation.

Both lines of investigation will be extended to other molecules.

III - 1.4. Consecutive Ion-Molecule Reactions (Project II-41)

S. Wexler

The techniques of "high-pressure" mass spectrometry have been used to study consecutive ion-molecule reactions in methane and ethylene. Increasingly heavy ions are formed in chains of consecutive reactions between ions and methane and ethylene molecules. Evidence for specific chain mechanisms was obtained. Cross sections for reactions of primary and secondary ions with molecules were determined by a new procedure. Those for the primary ions agree reasonably well with results obtained elsewhere by different methods. These measurements are of importance in establishing mechanisms of chemical and biological effects initiated by ionizing radiations.

A further illustration is the study of the ionic mechanism of "Wilzbach labeling" of methane with tritium. It was established that the principal long-lived ionic transient is the species $C_2H_4T^+$, which takes part in both the decay-induced and the radiation-induced mechanisms of the labeling of CH_4.

It is proposed to build an electron-collimating magnet for the source system as well as a new source chamber which will make possible studies at lower source pressures than heretofore. Alterations in the source chamber of the portable mass spectrometer MA-27 will make it available for investigation of consecutive ion-molecule reactions initiated by ionization and excitation by massive, swiftly moving ions. These will be the first such studies ever made, and should give some insight into the chemical reactions in and near the tracks of ionizing particles.

This work will be continued in the Chemistry Division after July 1, 1963.

III - 1.5. Ionization by Ions in the MeV Range (Project II-26)

S. Wexler and D. C. Hess

The partial cross sections for ionization of the rare gases into various charge states were determined as a function of proton energy from 0.800 to 3.75 MeV. Also, the fragmentation patterns of several of the lower hydrocarbons under impact of 2.25-MeV protons were measured with the newly constructed portable mass spectrometer MA-27. The patterns observed for the polyatomic molecules were very similar to those found by others on electron impact of the respective molecules. The indication is that a consequence of the Born approximation is valid, namely, that the nature of the ionization and excitation of isolated molecules is independent of the ionizing particle, provided that the velocity is sufficiently high. But to test this conclusion more effectively, future work will include electron-impact experiments using the arrangement employed in the studies with protons of high energy.

Plans are being made to investigate the ionization and excitation of isolated molecules by impact of slower moving protons in the energy range from 10 keV to 200 keV as well as by bombardment with heavy ions with energies in the region from 200 keV to 1 MeV from the Van de Graaff generator recently acquired from Notre Dame. Such studies should increase our knowledge of the slowing down of recoils from nuclear reactions as well as other penetration phenomena.

A greatly improved mass spectrometer for study of ionic-impact processes on molecules is being designed. The horizontal machine will provide for both mass and energy analysis of the collision products and for measurement of their angular distributions. The spectrometer

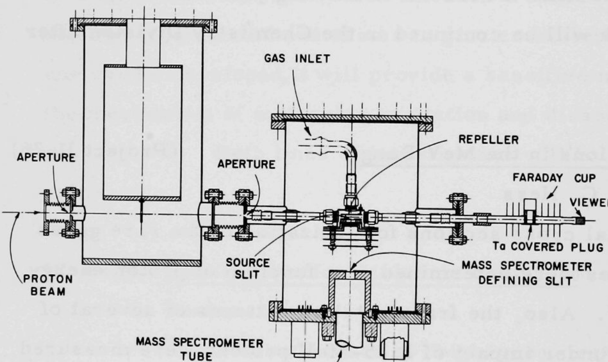


Fig. 21. Source assembly of the mass spectrometer for study of impact phenomena of protons and molecules with energies in the MeV range.

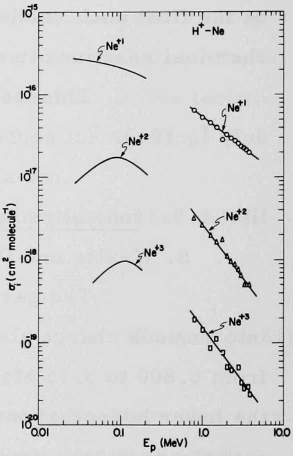


Fig. 22. Ionization cross sections for formation of Ne^{+1}, Ne^{+2}, and Ne^{+3}.

will be adaptable to the several ion accelerators at the laboratory. In addition to studies of ionic-impact phenomena on isolated molecules, plans are being made for investigation of transient species from chemical reactions of the ionization products and of penetration of massive ions through thin films.

III - 1.6. Atomic and Ionic Impact Phenomena on Metal Surfaces (Projects II-22, 23)

M. Kaminsky

Pulsed-molecular-beam mass spectrometer (MA-25). Construction of this machine is complete and the major components have been assembled and tested. Fig. 23 shows the machine in a recent stage of assembly. Its design offers a new approach in the investigation of atomic and ionic impact phenomena on metal surfaces; the pulsed beams of either ions or neutral atoms allow various time and time-of-flight measurements, the ultra-high vacuum maintains the requisite surface cleanness for a time long enough to be useful, and monocrystalline surfaces allow better defined experimental conditions for the impact phenomena considered. With incident neutral atoms, it permits measurements of the probability of desorption (inverse mean residence time) from a hot surface as ions and as neutrals, and also of the charge-transfer probability (which has not yet been directly measured experimentally), and of the unknown relaxation time for energy exchange between adatom and gas-free monocrystalline surfaces. Such experiments are now being set up for potassium atoms on tungsten monocrystalline surfaces. With incident ions it permits studies of desorption probabilities, reflection coefficients, and Auger and resonance neutralization of ions.

Portable mass spectrometer (MA-27) to study the species of particles leaving the target under high-energy ion bombardment. This recently completed machine is used in conjunction with the 4.5-MeV Van de Graaff accelerator and the Cockroft-Walton generator at the cyclotron

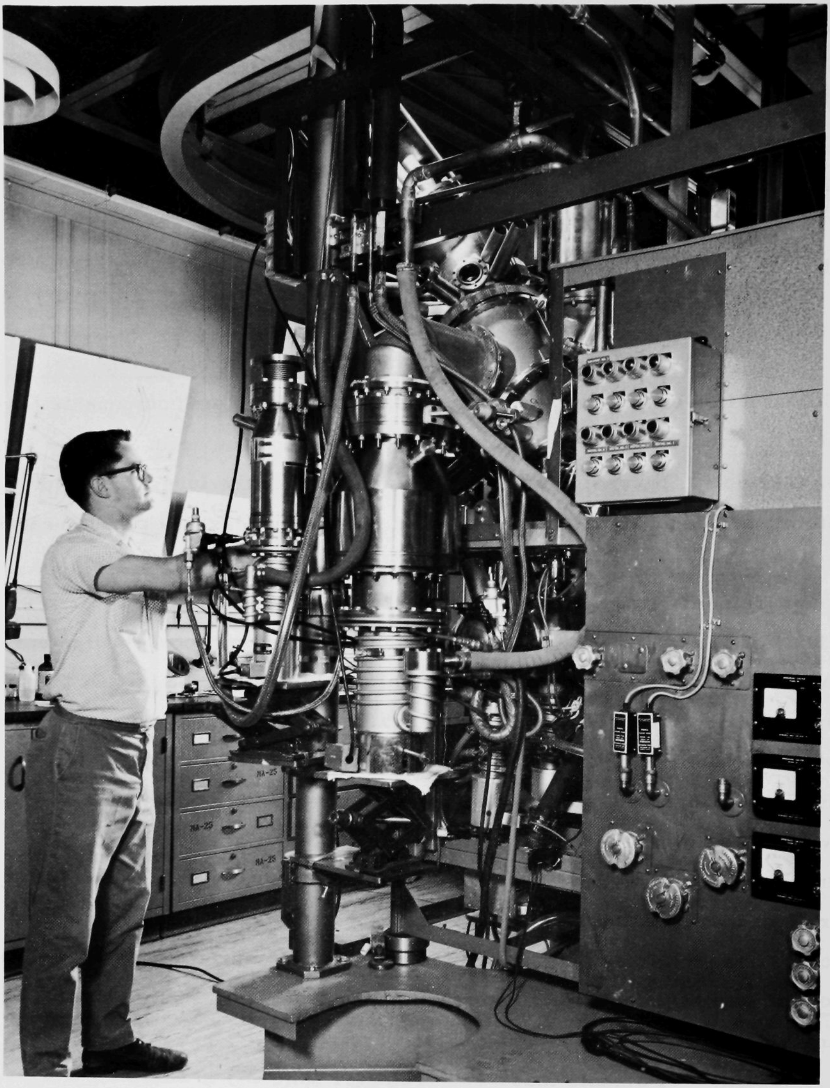


Fig. 23. Pulsed-molecular-beam mass spectrometer. The pulsed-beam apparatus with the ion source can be seen at the upper left. The analyzing magnet is in the central region. The detector (secondary-electron multiplier) is partly hidden at the bottom of the diffusion pumps.

building. The measurements are conducted to study the species of particles leaving a monocrystalline target in a charged or uncharged state under ion bombardment in the Rutherford collision region and thereby gain information about the sputtering mechanism operative in this energy region. So far the (100) planes of copper and silver have been bombarded with protons, deuterons, and He^+ ions in the energy range from 0.70 to 1.9 MeV. Table I contains some preliminary results for 750-keV D^+ on a Cu (100) plane and 800-keV protons on an Ag (100) plane. These continuing experiments will vary important collision parameters (masses of incident ion and target atom, incident-ion energy, crystal structure of target, etc.).

TABLE I. Species of particles sputtered in an uncharged or charged state. (The intensities relative to one of the atomic species are given in parentheses.)

	Neutral particles:	Cu (100%); Cu_2 (20%); CuO (1-2%); Na; K; Ca
750-keV D^+ on Cu (100)	Singly charged ions:	Cu^+ (100%)
	Multiply charged ions:	In no detectable amounts
	Neutral particles:	Ag (100%); Ag_2 (25%); AgO (2-3%); Na, K
800-keV p^+ on Ag (100)	Singly charged ions:	Ag^+ (100%)
	Multiply charged ions:	In no detectable amounts

<u>Sputtering in the Rutherford collision region</u>. A target chamber with a movable monocrystal mount and a high-vacuum system is being used to study the dependence of the sputtering ratio (sputtered

particles per incident ion) on the incident ion energy, the angular distribution of sputtered particles, and ionic etching effects on surfaces. While several theoretical approaches (based on different models for the emission mechanism) had been developed recently, no experimental data on "back sputtering" in the Rutherford collision region existed to check those theories. Optical transmission measurements of the sputtered deposits on a quartz wall [e.g., the deposits for D^+ normally incident on a (100) surface of Ag] revealed that the sputtering ratio S decreased with increasing energy ($S = 5.1 \times 10^{-3}$ atom/ion at 100 keV to $S = 1.2 \times 10^{-3}$ atom/ion at 975 keV) and was lower for Cu than for Ag, in qualitative agreement with theoretical predictions. A more detailed study will include the dependence of the sputtering rate on the mass and charge of the incident ion, the atomic mass and crystal structure of the target, the angle of incidence, and the target temperature. For normal incidence, electron micrographs reveal three types of surface etch pits; for oblique incidence, elongated grooves oriented along the direction of the beam are observed.

Atomic collision sequences. It has been possible to establish the existence of preferred ejection directions in the back sputtering of target particles from the (100) planes of Cu and Ag monocrystals under deuteron bombardment in the Rutherford collision region, despite the fact that most of the primary and secondary knock-ons are produced several thousand angstroms below the surface. Optical transmission measurements as well as autoradiography of the sputtered deposits collected on a quartz tube revealed four main spots corresponding to the [110] directions. Additional spots corresponding to the [112] and [100] crystal directions were less intense. These results confirm recent predictions of cascades of focused atomic collision sequences along close-packed directions in the crystal. Another significant observation was the increasing asymmetry in the densities of the four [110] spots, as the angle of incidence α increased, indicating an anisotropy in the momentum distribution of the primary recoil atoms. The density distribution of the deposit within one spot of the pattern is Gaussian and not cosine. This indicates that the recently suggested mechanism of sputtering by heated spikes is of no major importance in these experiments.

2-MeV Van de Graaff (with J. R. Wallace). An electron machine shipped from Notre Dame University is being converted into a positive-ion machine in order to fill the energy gap between the Cockroft-Walton generators and the Van de Graaff accelerators already in operation at ANL. An rf ion source will be used to produce light ions (protons, deuterons, and helium ions) and a surface-ionization source will produce ions of the alkali and alkaline earth metals. The latter will allow studies in which the incident ions are more massive than the target atoms. Adapting the machine to the present problem will take both machine work and auxiliary equipment.

III - 1.7. Diffusion of Alkali Salts Through Metals (Project II-22)

M. Kaminsky, D. Spears, and E. Bliss

The diffusion of alkali salts through platinum and tungsten was studied with the mass spectrometer from the pulsed-molecular-beam apparatus (MA-25). Such diffusion processes will be important in the thin-walled sections near the exit slit of the effusion cell in MA-25. The completed studies of the diffusion of LiCl through polycrystalline platinum indicate a decrease of the isotopic ratio Li^7/Li^6 with increasing temperature, and the activation energy for grain-boundary diffusion has been measured. Measurements of the diffusion of LiCl through monocrystalline tungsten are nearly complete. Future experiments will include different salts and monocrystalline material.

incidence is decreased, indicating an anisotropy in the [illegible] distribution of the [illegible]. The [illegible] [illegible] within [illegible] is Gaussian and not [illegible] indicates that [illegible] percent [illegible] of [illegible] spikes [illegible] major [illegible] in the [illegible] elements.

III - [illegible]. 2-MeV Van de Graaff (with J. R. Walton). An electrostatic machine obtained from Notre Dame University is being converted into a positive-ion machine in order to fill the energy gap between the Cockcroft-Walton generator and the Van de Graaff accelerators already in operation at ANL. A [illegible] ion source will be used to produce light ions (protons, deuterons, and helium ions), and a [illegible] ionization source will produce ions of the alkali and alkaline earth metals. The latter will allow studies in which the incident ions are more massive than the target atoms. Adapting the machine to the present problem will take both machine work and auxiliary equipment.

III - [illegible]. Diffusion of Alkali Salts Through Metals (Project [illegible])
M. Kaminsky, [illegible], and [illegible]

The diffusion of alkali salts through platinum and tungsten was studied with the [illegible] [illegible] spectrometer [illegible] apparatus [illegible]. [illegible] diffusion processes will be [illegible] in thin-walled sections [illegible] of the [illegible] cell [illegible]. Temperature studies of the diffusion of LiCl through [illegible] indicate a [illegible] of the [illegible] ratio Li^7/Li^6 with increasing temperature, and the activation energy for grain-boundary diffusion was [illegible]. Measurements on the diffusion of LiCl through [illegible] tungsten are nearly complete. Future experiments will [illegible] different salts and [illegible] crystalline material.

III - 2. HIGH-FREQUENCY PLASMAS (Project IV-10)

The dynamic properties of plasmas include several types of oscillations, resonances, and cutoffs — all associated with rf frequencies of the order of megacycles/sec up to hundreds of gigacycles/sec. These properties are usually studied in dc-excited plasmas by probing with weak rf fields. However, when rf fields are used to excite plasmas, these dynamic properties are enhanced by cooperative effects and plasma-field interactions to produce several new and unusual types of plasma phenomena not encountered in dc-excited plasmas. Although some of these phenomena indicate intriguing areas of application, such as improved rf ion sources and stable containment of high-density plasmas, the present fragmentary state of knowledge of properties of high-frequency plasmas indicates a more urgent need for basic research in this latter area.

The Argonne studies of basic properties of high-frequency plasmas are developing along two lines, the major distinguishing criterion being the degree of uniformity of the exciting rf field. The experiment on plasmas in uniform electric fields has been in progress for about five years and represents in part an extension of work done at other places. The experiment on plasmas in nonuniform cavity fields is only now coming into being and represents an almost completely new area of investigation. Both experiments are to be installed in an rf shielded room 16 ft × 24 ft × 8 ft high in order to avoid possible interference with other experiments in the Physics Building.

III - 2.1. Plasmas in Uniform Electric Fields

Albert J. Hatch

This is a study of fundamental properties and constitutive parameters of rf (15 Mc/sec) plasmas at low pressures ($\leq 20\,\mu$Hg) at which the electron mean free path exceeds the characteristic diffusion length (3.5 cm) of the plane parallel electrodes and at which the rf wavelength (2000 cm) greatly exceeds both the electrode separation (15 cm) and the oscillation amplitude of the electrons ($\leq$ 15 cm). The phenomena in this domain involve cooperative electron motion as manifested strikingly in the high-frequency plasmoids, and are of significance in understanding electron plasma oscillations as related to the complex conductivity of high-frequency plasmas.

Photographic studies of plasma structure, and circuit and probe measurements of plasma conductivity, dielectric constant, and internal dc and rf fields have led to a partial understanding of forced electron oscillations in rf plasmas. The most significant result is the measurement in the plasmoids of an effective dielectric constant greater than unity, typically 2 to 5, and the development of an explanation in terms of simple dispersion theory on the basis of bulk polarization of the plasmoid (arising mainly from sheath effects). A related significant feature of the spheroidal-shaped plasmoid is the existence of a boundary width of the order of 0.001 of an electron mean-free-path as shown in the photograph in Fig. 24.

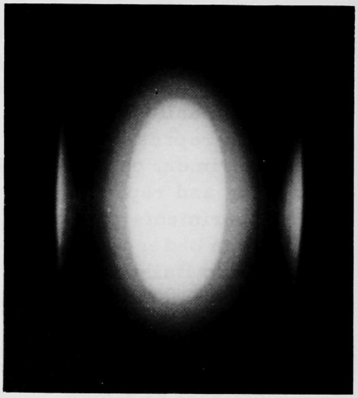


Fig. 24. Photograph of high-frequency plasmoid. The electrodes are identifiable on the left- and right-hand sides of the photograph by reflected light from the plasmoid. Electrode separation = 15 cm, frequency = 15 Mc/sec, rf potential = 52 V peak, pressure = 0.2 micron Hg in dry air.

A new ultra-high vacuum system is being assembled for improved quantitative measurements in pure gases. Dependence of phenomena on the type of gas will be studied by present methods supplemented by optical spectrography.

III - 2.2. Plasmas in Nonuniform (Cavity) Electromagnetic Fields

Albert J. Hatch

This is an exploratory study of fundamental phenomena and properties of plasmas in resonant-cavity fields at ultra-high frequencies (600 to 1000 Mc/sec) and micron pressures at which both the electron mean free path and the rf wavelength (30 — 50 cm) are comparable to the dimensions of the cylindrical rf cavity (30 to 50 cm diameter, 50 cm length) and large compared with the oscillation amplitude (< 1 cm) of the electrons. Special interest is in the plasma effects resulting from radiation pressure due to gradients in standing-wave electromagnetic fields in the cavity.

Theoretical studies and an analog experiment simulating radiation pressures on plasmas in resonant cavities have provided the basis for the design of the new experimental apparatus. The major components are a 2-kW continuous-wave tunable klystron amplifier (being built by Continental Electronics, Dallas, Texas), two cavities to accommodate the four fundamental modes of excitation (dipole and quadrupole, E and H), a vacuum system, and ancillary equipment for impedance measurement and matching, rf isolation, and diagnostics. The attainable radiation pressures will be in the range of a few microns, which is about 5 orders of magnitude greater than the radiation pressure due to solar radiation at the earth's surface and which can be competitive with the pressure in the background gas in the cavity. Use of the four fundamental modes of excitationwill permit meaningful correlation of theory with experimental observations.

In addition to the basic aspects of radiation-pressure effects on plasmas, a possible result of this experiment is a demonstration of stable and continuous dynamic containment of a sharply-bounded dense plasma in the vicinity of the nodal point in the quadrupole magnetic mode of the cavity. Such a result has potential applicability to plasma chemistry and thermonuclear processes and would encourage extending the experiments to higher levels of radiation pressure (stored energy density) in the cavity, either by increasing the power input to the cavity or by use of a cryogenically cooled cavity. An over-all diagram of the new experimental facility for these studies is shown in Fig. 25.

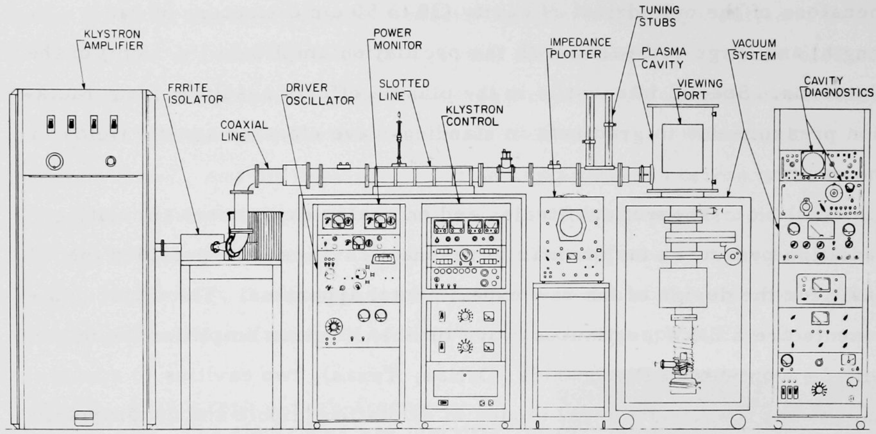


Fig. 25. Over-all layout of UHF plasma experiment. The klystron amplifier receives low-level UHF power (< 5 watts) from the driver oscillator and delivers high power (10 — 2000 watts) to the plasma cavity via the $3\frac{1}{8}$-in. coaxial line. This line includes power-monitoring, impedance-measuring, and impedance-matching units. Several details such as connecting cables and vacuum system fore-line have been omitted for clarity. The plasma cavity will consist of copper-clad stainless steel baseplates, a cylindrical bell jar, and a surrounding copper cylinder with an array of small perforations at eye level that will serve as a viewing port.

IV. PUBLICATIONS FROM 1 APRIL 1962 THROUGH 31 MARCH 1963

The papers listed here are those whose publication was noted by the reporting unit of the Laboratory in the 1-year period stated. The dates on the journals therefore are often earlier. The list of papers and books includes letters and notes; the list of abstracts includes all papers presented at meetings — even in cases in which the complete text was published in a volume of proceedings.

IV - 1. PUBLISHED PAPERS AND BOOKS

1. NEUTRON DETECTION WITH GLASS SCINTILLATORS
   L. M. Bollinger, G. E. Thomas, and R. J. Ginther
   Nuclear Instr. and Methods 17, 97-116 (1962).

2. A BORON-LOADED LIQUID SCINTILLATION NEUTRON DETECTOR USING A SINGLE PHOTOMULTIPLIER
   G. E. Thomas
   Nuclear Instr. and Methods 17, 137-139 (1962).

3. DIRECT OBSERVATION OF RESONANT p-WAVE NEUTRON CAPTURE
   H. E. Jackson
   Phys. Rev. 127, 1687-1690 (September 1, 1962).

4. RESONANT ABSORPTION OF NEUTRONS BY CRYSTALS
   H. E. Jackson and J. E. Lynn
   Phys. Rev. 127, 461-468 (July 15, 1962).

5. RATIO OF SYMMETRIC TO ASYMMETRIC FISSION FOR RESONANCE-NEUTRON FISSION OF U^{235}
   L. E. Glendenin (CHM), K. F. Flynn (CHM), and L. M. Bollinger
   Trans. Am. Nuclear Soc. 5 (1), 20-21 (June 1962).

6. GAMMA-RAY SPECTRUM FROM THERMAL-NEUTRON CAPTURE IN Hf^{177} AND ASSOCIATED ENERGY LEVELS IN Hf^{178}
   R. K. Smither
   Phys. Rev. 129, 1691-1708 (February 15, 1963).

7. HIGH-ENERGY GAMMA RAYS FROM Na^{24}
   J. E. Monahan, S. Raboy, and C. C. Trail
   Nuclear Phys. 33, 633-638 (1962).

8. MEASUREMENTS OF LIFETIMES OF RADIOACTIVE SOURCES
   J. E. Monahan, S. Raboy, and C. C. Trail
   Nuclear Instr. and Methods 17(3), 225-230 (December 1962).

9. GEOMETRICAL CONSIDERATIONS IN THE MEASUREMENT OF THE RATIO L/R IN THE SCATTERING OF POLARIZED NUCLEONS
   J. E. Monahan and A. J. Elwyn
   Nuclear Instr. and Methods 14, 348-350 (January 1962).

10. POLARIZATION OF NEUTRONS IN SCATTERING FROM LIGHT NUCLEI AND IN THE $Li^7(p,n)Be^7$ REACTION
    A. J. Elwyn and R. O. Lane
    Nuclear Phys. 31, 78-117 (January 1962).

11. POLARIZATION AND DIFFERENTIAL CROSS SECTION FOR NEUTRON SCATTERING FROM SILICON
    R. O. Lane, A. J. Elwyn, and A. Langsdorf, Jr.
    Phys. Rev. 126, 1105-1111 (May 1, 1962).

12. POLARIZATION AND DIFFERENTIAL CROSS SECTIONS IN n-d SCATTERING
    A. J. Elwyn, R. O. Lane, and A. Langsdorf, Jr.
    Phys. Rev. 128, 779-789 (October 15, 1962).

13. ENERGY-DEPENDENT MULTIPLE SCATTERING OF NEUTRONS IN THIN PLATES
    R. O. Lane and W. F. Miller (AMD)
    Nuclear Instr. and Methods 16, 1-16 (1962).

14. NEUTRON BACKGROUND DUE TO Ta BACKINGS FOR LITHIUM TARGETS
    C. T. Hibdon
    Nuclear Instr. and Methods 17, 177-180 (1962).

15. THIN dE/dx COUNTER WITH LARGE APERTURE
    J. A. Weinman and R. K. Smither
    Rev. Sci. Instr. 33, 653-654 (June 1962).

16. STATES IN B^{10} FROM ELASTIC SCATTERING OF ALPHAS BY Li^6
    G. Dearnaley, D. S. Gemmell, and S. S. Hanna
    Nuclear Phys. 36, 71-81 (July 1962).

17. THE ARGONNE 60-IN. SCATTERING CHAMBER
    J. L. Yntema and H. W. Ostrander (CS)
    Nuclear Instr. and Methods 16, 69-88 (1962).

18. (d, t) REACTION STUDIES ON IRON AND NICKEL
    M. H. Macfarlane, B. J. Raz, J. L. Yntema, and B. Zeidman
    Phys. Rev. 127, 204-212 (July 1, 1962).

19. (d, t) REACTION ON THE TITANIUM ISOTOPES
J. L. Yntema
Phys. Rev. 127, 1659-1663 (September 1, 1962).

20. POSSIBLE THREE-PHONON GROUP FROM Ni^{62}
H. W. Broek
Phys. Letters 3 (3), 132-134 (December 15, 1962).

21. ELASTIC AND INELASTIC SCATTERING OF 43-MEV ALPHA PARTICLES BY Ni^{58} AND Ni^{60}
H. W. Broek, T. H. Braid, J. L. Yntema, and B. Zeidman
Phys. Rev. 126, 1514-1520 (May 15, 1962).

22. SCATTERING OF ALPHA PARTICLES BY Zn^{64} and Zn^{68}
H. W. Broek, T. H. Braid, J. L. Yntema, and B. Zeidman
Nuclear Phys. 38, 305-315 (1962).

23. DAS VORZEICHEN DER HYPERFEINSTRUKTUR-AUFSPALTUNG DES $3d^5 4s^2\ {}^6S_{5/2}$ -GRUNDZUSTANDES DES Mn^{55}
L. Goodman, G. Nöldeke, and H. Walther
Z. Physik 167, 26-28 (1962).

24. ELECTRIC QUADRUPOLE MOMENT OF THE 14.4-KEV STATE OF Fe^{57}
C. E. Johnson, W. Marshall, and G. J. Perlow
Phys. Rev. 126, 1503-1506 (May 15, 1962).

25. THE MÖSSBAUER EFFECT IN METALLIC IRON
R. S. Preston, S. S. Hanna, and J. Heberle
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27. BERYLLIUM WINDOW FOR GAMMA RAYS IN A LIQUID-HELIUM CRYOSTAT
J. Heberle
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28. SENIORITY MIXING IN $1f_{7/2}$ NUCLEI
R. D. Lawson and B. Zeidman
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29. NUCLEAR MODELS AND SURFACES
D. R. Inglis
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30. NUCLEAR MODELS, THRESHOLD STATES AND REARRANGEMENT ENERGY
D. R. Inglis
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31. HEAVY-PARTICLE STRIPPING AND THE STRUCTURE OF N^{14}
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32. THE DEFORMATION ENERGY OF A CHARGED DROP. IV. EVIDENCE FOR A DISCONTINUITY IN THE CONVENTIONAL FAMILY OF SADDLE POINT SHAPES
S. Cohen and W. J. Swiatecki
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33. SCATTERING OF ALPHA PARTICLES BY A VIBRATIONAL NUCLEUS
L. J. Tassie
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34. THE PION-PION EFFECT ON LOW-ENERGY PION-NUCLEON SCATTERING
M. Marinaro and K. Tanaka
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35. POSSIBLE INTERPRETATIONS OF HIGH-ENERGY CROSS SECTIONS
K. Tanaka
Nuovo cimento 26, 537-540 (November 1, 1962).

36. REGGE TRAJECTORY IN FIELD THEORY
L. S. Liu and K. Tanaka
Phys. Rev. 129, 1876-1879 (February 15, 1963).

37. NEUTRAL SCALAR σ MESON AND THE MASS DIFFERENCE BETWEEN MUON AND ELECTRON
K. Tanaka
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38. CHARGE STRUCTURE OF THE NUCLEON
K. Hiida
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39. PARTICLES WITH ZERO MASS AND PARTICLES WITH "SMALL" MASS
F. Coester
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H. Ekstein
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42. SPIN AND STATISTICS WITH AN INDEFINITE METRIC
R. Spitzer
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43. POSSIBLE DETERMINATION OF THE SPIN OF THE Ξ^- FROM THE ANGULAR ASYMMETRY OF ITS DECAY
M. Peshkin
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44. FLUX QUANTIZATION AND THE CURRENT-CARRYING STATE IN A SUPERCONDUCTING CYLINDER
H. J. Lipkin, M. Peshkin, and L. J. Tassie
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M. Peshkin and W. Tobocman (Case Inst. of Techn.)
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47. DOUBLE-OVEN EXPERIMENTS WITH LITHIUM HALIDE VAPORS
J. Berkowitz, H. A. Tasman, and W. A. Chupka
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48. HEAT OF FORMATION OF THE CN RADICAL
J. Berkowitz
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49. ON THE IONIZATION POTENTIAL OF THE CH_2 RADICAL
J. Berkowitz and S. Wexler
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50. MASS SPECTRA RESULTING FROM HIGH-ENERGY ELECTRON IMPACT ON SOME HYDROCARBON MOLECULES
J. E. Monahan and H. E. Stanton
J. Chem. Phys. 37, 2654-2661 (December 1, 1962).

51. CONSECUTIVE ION-MOLECULE REACTIONS IN METHANE
S. Wexler and N. Jesse
J. Am. Chem. Soc. 84, 3425-3431 (September 20, 1962).

52. ON THE MECHANISM OF THE ISOTOPIC EXCHANGE OF TRITIUM WITH METHANE
S. Wexler
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53. CHARGE STATES OF MOLECULAR FRAGMENTS FROM CCl_3Br FOLLOWING NUCLEAR DECAY OF Br^{80} and Br^{82}
S. Wexler
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M. S. Kaminsky
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55. ÜBER EIN MASSENSPEKTROMETER ZUM NACHWEIS GEPULSTER MOLEKULARSTRAHLEN UND SEINE VERWENDUNG ZUR UNTERSUCHUNG VON ADSORPTIONS- UND DESORPTIONSVORGÄNGEN AN METALLOBERFLÄCHEN
M. K. Kaminsky
Phys. Verh. VDPG 1, 66 (1961).

56. SPUTTERING EXPERIMENTS IN THE RUTHERFORD COLLISION REGION
M. S. Kaminsky
Phys. Rev. 126, 1267-1270 (May 15, 1962).

57. EXPERIMENTAL ANALOG STUDY OF CONTAINMENT OF DENSE PLASMAS IN RESONANT-CAVITY FIELDS
A. J. Hatch and J. W. Butler
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58. EFFECT OF STYRENE MONOMER ON THE FLUORESCENCE PROPERTIES OF POLYSTYRENE
L. J. Basile
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59. ON THE FLUORESCENCE SPECTRUM AND DECAY TIME OF NAPHTHALENE
I. B. Berlman (RPY) and A. Weinreb
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60. FLUORESCENCE ENERGY TRANSFER AND OXYGEN QUENCHING IN SOLUTIONS OF DIPHENYLOXAZOLE IN CYCLOHEXANE
A. Weinreb
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IV - 2. PUBLISHED ABSTRACTS

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2. TWO RECENT ADVANCES IN SLOW-NEUTRON DETECTORS
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3. FISSION CROSS SECTION OF Th^{229} FOR SLOW NEUTRONS
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Bull. Am. Phys. Soc. 8, 370 (April 22-25, 1963).

4. TOTAL CROSS SECTION OF Th^{232} FOR SLOW NEUTRONS
G. E. Thomas and L. M. Bollinger
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5. NEUTRON RESONANCES IN SELENIUM
R. E. Coté, L. M. Bollinger, and G. E. Thomas
Bull. Am. Phys. Soc. 8, 334 (April 22-25, 1963).

6. GAMMA-RAY ANGULAR CORRELATIONS IN Ni^{59} and Ni^{61}
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7. RESONANCE AVERAGE VALUES OF PARTIAL RADIATION WIDTHS
R. T. Carpenter and L. M. Bollinger
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8. DIRECT OBSERVATION OF RESONANT p-WAVE NEUTRON CAPTURE
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9. p-WAVE NEUTRON CAPTURE IN Zr, Mo, AND Nb
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10. $Sm^{149}(n, \gamma)Sm^{150}$ AND THE ASSOCIATED ENERGY LEVELS IN Sm^{150}
R. K. Smither
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11. AN APPARATUS FOR THE STUDY OF GAMMA-RAY SPECTRA FROM THE CAPTURE OF MONOCHROMATIC NEUTRONS
J. E. Monahan, S. Raboy, G. R. Ringo, and C. C. Trail
Proceedings of the IAEA Symposium on Pile Neutron Research in Physics, Vienna, October 17-21, 1960 (International Atomic Energy Agency, Vienna, 1962), pp. 615-631.

12. CAPTURE GAMMA RAYS FROM Ca^{44}
S. Raboy and C. C. Trail
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13. POLARIZATION AND DIFFERENTIAL CROSS SECTION FOR NEUTRONS SCATTERED FROM DEUTERIUM
R. O. Lane, A. J. Elwyn, and A. Langsdorf, Jr.
Bull. Am. Phys. Soc. 7, 333 (April 23, 1962).

14. POLARIZATION OF NEUTRONS SCATTERED FROM Zr, Nb, Mo, AND Cd
A. Langsdorf, Jr., A. J. Elwyn, and R. O. Lane
Bull. Am. Phys. Soc. 7, 532 (November 23, 1962).

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F. J. Lynch and E. N. Shipley
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18. ON THE STATISTICAL NATURE OF FLUCTUATIONS IN NUCLEAR CROSS SECTIONS
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19. ELASTIC AND INELASTIC SCATTERING FROM Ni ISOTOPES
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20. $N^{14}(d, \alpha)C^{12}$ REACTION
R. G. Allas, T. H. Braid, L. L. Lee, Jr., and J. P. Schiffer
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21. A STUDY OF THE $Ca^{40}(d, d)Ca^{40}$ AND $Ca^{40}(d, p)Ca^{41}$ REACTIONS
L. L. Lee, Jr., J. P. Schiffer, and B. Zeidman
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22. ELASTIC SCATTERING OF PROTONS BY Mg^{26}
M. C. Mertz
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23. ELASTIC PROTON SCATTERING FROM Ni AND Cu
L. L. Lee, Jr., J. P. Schiffer, and J. R. Erskine
Bull. Am. Phys. Soc. 7, 532 (November 23, 1962).

24. PROTON REDUCED WIDTHS CALCULATED FOR A DIFFUSE-SURFACE POTENTIAL
J. P. Schiffer
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25. LIFETIME OF THE FIRST EXCITED STATE IN Ca^{41} AT 1.95 MEV
C. M. Class, P. P. Singh, and S. S. Hanna
Bull. Am. Phys. Soc. 8, 358 (April 22-25, 1963).

26. REACTION $B^{11}(p, \gamma)C^{12}$ IN THE RANGE $4 < E_p < 10$ MEV
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27. STATES IN C^{12} BETWEEN 17.5 AND 19.5 MEV
R. G. Allas, S. S. Hanna, and R. E. Segel
Bull. Am. Phys. Soc. 7, 550 (November 23, 1962).

28. STATE IN C^{12} AT 18.85 MEV
R. G. Allas, S. S. Hanna, and R. E. Segel
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29. GAMMA RAYS FROM PROTON BOMBARDMENT OF B^{10}
M. A. Grace, P. P. Singh, and R. E. Segel
Bull. Am. Phys. Soc. 7, 549 (November 23, 1962).

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R. E. Segel
Bull. Am. Phys. Soc. 7, 542 (November 23, 1962).

31. COLLECTIVE LEVELS IN ZIRCONIUM ISOTOPES
H. W. Broek
Bull. Am. Phys. Soc. 8, 376 (April 22-25, 1963).

32. (d, He^3) REACTIONS ON F^{19} AND Al^{27}
T. H. Braid and B. Zeidman
Bull. Am. Phys. Soc. 7, 300 (April 23, 1962).

33. (d, t) REACTIONS ON NUCLEI NEAR N = 28
B. Zeidman and T. H. Braid
Bull. Am. Phys. Soc. 7, 315 (April 23, 1962).

34. SOLID STATE DETECTORS FOR MEASUREMENTS OF dE/dx AND TOTAL ENERGY IN NUCLEAR REACTIONS AT CYCLOTRON ENERGIES
T. H. Braid and J. T. Heinrich
International Atomic Energy Agency Conference on Nuclear Electronics, Belgrade, May 15-20, 1961. Abstracts of Papers NE/134.

35. X RAYS FROM MU-MESONIC ATOMS
C. S. Johnson, H. L. Anderson, E. P. Hincks, S. Raboy, and C. C. Trail
Bull. Am. Phys. Soc. 8, 324 (April 22-25, 1963).

36. RESONANT ABSORPTION AND SCATTERING OF NUCLEAR GAMMA RADIATION
S. S. Hanna and G. J. Perlow
IAEA Conference on the Use of Radioisotopes in the Physical Sciences and Industry, Copenhagen, September 6-17, 1960. Abstracts of Papers, RICC/192.

37. SMALL SUPERCONDUCTING SOLENOID
J. Heberle and R. W. Reno
Bull. Am. Phys. Soc. 7, 431 (August 27, 1962).

38. EXPERIMENTAL DETERMINATION OF NUCLEAR PROPERTIES BY USE OF THE MÖSSBAUER EFFECT
S. S. Hanna
Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, Tennessee, October 5-7, 1961, Nuclear Science Series Report No. 37 (National Academy of Sciences, National Research Council, Washington, D. C., 1962), pp. 140-153.

39. MÖSSBAUER EFFECT OF Fe^{57} AS AN IMPURITY IN VARIOUS ALLOYS
J. Heberle, P. Parks, and J. P. Schiffer
Bull. Am. Phys. Soc. 7, 350 (April 23, 1962).

40. MÖSSBAUER EFFECT OF Fe^{57} IN HEXAGONAL COBALT
C. E. Johnson, G. J. Perlow, and W. Marshall
Bull. Am. Phys. Soc. 8, 351 (April 22-25, 1963).

41. ENHANCEMENT OF ELECTROMAGNETIC TRANSITION PROBABILITIES
D. Kurath
Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, Tennessee, October 5-7, 1961, Nuclear Science Series Report No. 37 (National Academy of Sciences, National Research Council, Washington, D.C., 1962), pp. 10-14.

42. BROWNIAN MOTION OF HAMILTONIAN MATRICES
N. Rosenzweig
Bull. Am. Phys. Soc. 8, 263 (25-28 March 1963).

43. REGGE TRAJECTORY IN FIELD THEORY
L. S. Liu and K. Tanaka
Bull. Am. Phys. Soc. 8, 44 (23 January 1963).

44. PION-PION SCATTERING FROM A LAGRANGIAN VIEWPOINT
K. Smith (AMD) and J. L. Uretsky
Bull. Am. Phys. Soc. 8, 300 (April 22-25, 1963).

45. GEOMETRIC THEORY OF CHARGE AND BARYON NUMBER
H. Ekstein
Proceedings of the Midwest Conference on Theoretical Physics, Argonne National Laboratory, June 1-2, 1962, pp. 115-119.

46. ON THE "REALITY" OF THE ELECTROMAGNETIC VECTOR POTENTIAL
M. Peshkin
Proceedings of the Midwest Conference on Theoretical Physics, Argonne National Laboratory, June 1-2, 1962, pp. 1-13.

47. BCS DESCRIPTION OF THE SUPERCURRENT STATE
M. Peshkin
Bull. Am. Phys. Soc. 8, 191 (25-28 March 1963).

48. PREACCELERATION IN ELECTRON THEORY
M. N. Hack
Bull. Am. Phys. Soc. 7, 493 (August 27, 1962).

49. THE REACTION OF GRAPHITE WITH NITROGEN AT ELEVATED TEMPERATURES
J. Berkowitz
Proceedings of the IAEA Symposium on Thermodynamics of Nuclear Materials, Vienna, May 21-25, 1962 (International Atomic Energy Agency, Vienna, 1962), pp. 505-516 (Abstracts of Papers, SM-26/40).

50. ON THE FRAGMENTATION OF HYDROCARBONS UNDER HIGH-ENERGY ELECTRON IMPACT
J. E. Monahan and H. E. Stanton
Bull. Am. Phys. Soc. 7, 399 (June 19, 1962).

51. SPUTTERING EXPERIMENTS IN THE RUTHERFORD COLLISION REGION
M. S. Kaminsky
Bull. Am. Phys. Soc. 7, 346 (April 23, 1962).

52. INTERACTION BETWEEN ION BEAMS AND METAL SINGLE-CRYSTAL SURFACES IN THE RUTHERFORD COLLISION REGION
M. Kaminsky
Bull. Am. Phys. Soc. 8, 338-339 (April 22-25, 1963).

IV - 3. ANL TOPICAL REPORTS

1. THE MEASUREMENT OF ENERGY AND INTENSITY OF GAMMA RAYS BY USE OF A SCINTILLATION SPECTROMETER
R. T. Julke, J. E. Monahan, S. Raboy, and C. C. Trail
Argonne National Laboratory Topical Report ANL-6499 (April 1962).

2. THE ELECTRIC-DIPOLE GAMMA-RAY STRENGTH FUNCTION FOR HEAVY EVEN-EVEN NUCLEI
   R. T. Carpenter
   Topical Report ANL-6589; thesis, Northwestern University.

3. BENDING-MAGNET AND QUADRUPOLE ABERRATIONS FOR PARAXIAL RAYS
   M. L. Good
   Argonne National Laboratory Topical Report ANL-6611 (November 1962).

4. HANDBOOK FOR THE NANOSECOND ELECTRON ACCELERATOR (NSEA)
   E. A. Mroz, W. L. Buck, R. K. Swank, and H. B. Phillips
   Argonne National Laboratory Topical Report ANL-6700 (March 1963).

V. STAFF MEMBERS OF THE PHYSICS DIVISION

The Physics Division staff as of May 1963 is listed below. Although the members are classified by programs, it must be understood that many of them work in two or more of the areas. In such cases, the classification indicates only the current primary interest.

In the period from 1 April 1962 through 31 March 1963, there were 24 temporary staff members (19 staff members from universities and other laboratories, 4 post-doctoral fellows, and 1 affiliate of the International Institute of Nuclear Science and Engineering—those with appointments of 1 month or more being listed below as resident research associates), 9 graduate students (including 4 doing thesis research), and 20 undergraduates (8 in the Argonne Semester program of the Associated Colleges of the Midwest, 3 in cooperative programs, and 9 on summer appointments).

RESEARCH AT THE REACTOR CP-5

Permanent Staff

Lowell M. Bollinger,* Ph.D., Cornell University, 1951

Herbert H. Bolotin, Ph.D., Indiana University, 1955

Merle T. Burgy, B.S., University of Chicago, 1939

Robert E. Coté, Ph.D., Columbia University, 1953

Harold E. Jackson, Jr., Ph.D., Cornell University, 1959

Victor E. Krohn, Ph.D., Case Institute of Technology, 1952

Allen P. Magruder, B.S., University of Chicago, 1959

J. P. Marion, M.S., DePaul University, 1959

Richard S. Preston, Ph.D., Yale University, 1954

Sol Raboy, D. Sci., Carnegie Institute of Technology, 1950

G. R. Ringo, Ph.D., University of Chicago, 1940

Robert K. Smither, Ph.D., Yale University, 1958

George E. Thomas, Jr., B.A., Illinois Wesleyan University, 1943

Carroll C. Trail, Ph.D., Texas A & M College, 1956

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*Director of Physics Division

RESEARCH AT THE 4.5-MEV VAN DE GRAAFF ACCELERATOR

Permanent Staff

Alexander J. Elwyn, Ph.D., Washington University, 1956

Carl T. Hibdon, Ph.D., Ohio State University, 1944

Robert E. Holland, Ph.D., University of Iowa, 1950

Raymond O. Lane, Ph.D., Iowa State College, 1953

Alexander Langsdorf, Jr., Ph.D., M.I.T., 1937

Frank J. Lynch, B.S., University of Chicago, 1944

RESEARCH AT THE 12-MEV TANDEM VAN DE GRAAFF

Permanent Staff

Thomas H. Braid, Ph.D., Edinburgh University, Scotland, 1950

Donald S. Gemmell, Ph.D., Australian National University, 1960

Stanley S. Hanna, Ph.D., Johns Hopkins University, 1947

Linwood L. Lee, Jr., Ph.D., Yale University, 1955

Luise Meyer, Ph.D., Technical University of Berlin, 1943

F. P. Mooring, Ph.D., University of Wisconsin, 1951

John P. Schiffer, Ph.D., Yale University, 1954

Ralph E. Segel, Ph.D., Johns Hopkins University, 1955

Jack R. Wallace, B.A., College of Wooster, Ohio, 1942

Resident Research Associates

Richard G. Allas, Ph.D., Washington University, 1961

John R. Erskine, Ph.D., University of Notre Dame, 1960

Marvin C. Mertz, M.S., Yale University, 1953

P. Paul Singh, Ph.D., University of British Columbia, 1959

RESEARCH AT THE 60-IN. CYCLOTRON

Permanent Staff

Howard W. Broek, Ph.D., Yale University, 1960

John J. Livingood, Ph.D., Princeton University, 1929

Jan L. Yntema, Ph.D., Free University of Amsterdam, Netherlands, 1952

Ben Zeidman, Ph.D., Washington University, 1957

OTHER NUCLEAR EXPERIMENTS

Permanent Staff

S. B. Burson, Ph.D., University of Illinois, 1946

William J. Childs, Ph.D., University of Michigan, 1956

John Dalman

Leonard S. Goodman, Ph.D., University of Chicago, 1952

Juergen Heberle, Ph.D., Columbia University, 1955

Gilbert J. Perlow, Ph.D., University of Chicago, 1940

Resident Research Associates

Dieter von Ehrenstein, Dr. rer. nat. degree, U. of Heidelberg, 1960

E. Brooks Shera, Ph.D., Western Reserve University, 1962

THEORETICAL NUCLEAR PHYSICS

Permanent Staff

Fritz Coester, Ph.D., University of Zurich, 1944

Stanley Cohen, Ph.D., Cornell University, 1955

David R. Inglis, D. Sci., University of Michigan, 1931

Dieter Kurath, Ph.D., University of Chicago, 1951

Robert D. Lawson, Ph.D., Stanford University, 1953

Malcolm H. Macfarlane, Ph.D., University of Rochester, 1959

James E. Monahan, Ph.D., St. Louis University, 1953

Norbert Rosenzweig, Ph.D., Cornell University, 1951

Resident Research Associates

Alvin Saperstein, Ph.D., Yale University, 1956

Michitoshi Soga, D. Sci., Tokyo University of Education, 1958

THEORETICAL HIGH-ENERGY PHYSICS

Permanent Staff

Hans Ekstein, Ph.D., University of Berlin, 1934

Melvin Hack, Ph.D., Princeton University, 1956

Murray Peshkin,* Ph.D., Cornell University, 1951

Katsumi Tanaka, Ph.D., University of California, 1952

Jack L. Uretsky, Ph.D., M.I.T., 1956

K. C. Wali, Ph.D., University of Wisconsin, 1959

Resident Research Associates

Kichiro Hiida, Ph.D., Hiroshima University, 1959

Arthur W. Martin, Ph.D., Stanford University, 1962

B. M. Udgaonkar, M.S., Bombay University, 1949

MASS-SPECTROMETRIC INVESTIGATIONS

Permanent Staff

Joseph Berkowitz, Ph.D., Harvard University, 1955

William A. Chupka, Ph.D., University of Chicago, 1951

David C. Hess, Ph.D., University of Chicago, 1949

Manfred Kaminsky, Ph.D., University of Marburg, Germany, 1952

Henry E. Stanton, Ph.D., University of Chicago, 1944

Sol Wexler, Ph.D., University of Chicago, 1948

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*Associate Director of Physics Division

HIGH-FREQUENCY PLASMAS

Permanent Staff

Albert J. Hatch, M.S., University of Illinois, 1947

ADMINISTRATIVE

Permanent Staff

Charles Eggler, B.S., Virginia Polytechnic Institute, 1944

Francis E. Throw, Ph.D., University of Michigan, 1940