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PHYSICS DIVISION SUMMARY REPORT

Annual Review

1 April 1968—31 March 1969

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Physics

PHYSICS DIVISION SUMMARY REPORT

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

Annual Review

1 April 1968—31 March 1969

Lowell M. Bollinger, Division Director

Preceding Summary Reports:

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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 1969. 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 1968 through 31 March 1969 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. EXPERIMENTAL NUCLEAR PHYSICS

INTRODUCTION

The over-all purpose of the program continues to be to obtain a much more complete understanding of the atomic nucleus. Consequently, most of the program consists of experimental and theoretical studies of the energies, quantum numbers, and lifetimes of nuclear energy levels and investigations of the mechanisms by which simple nuclear projectiles interact with nuclear targets. Experimenters and theorists work closely together so that new results in one area may suggest new approaches in another. An effort is made to stress work that can be done more advantageously at Argonne than elsewhere because of the special facilities available here. In view of the history and tradition of the Laboratory, it is natural that considerable emphasis is placed on studies of interactions between nuclei and neutrons; but this is balanced by a well diversified program of other nuclear investigations.

With a few exceptions, the program in experimental nuclear physics 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 current categories are:

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

(2) Neutron and charged-particle reactions at the 4-MeV Dynamitron.

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

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

(5) Various other nuclear experiments, including the γ- and β-ray spectroscopy of radioactive sources.

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

A. 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, studies of neutron cross sections and resonances, and a variety of measurements with neutron-capture γ rays.

The experimental phase of all of this work was suspended at the beginning of 1969 because the reactor was shut down for extensive rehabilitation. Unfortunately, this long interruption of the experimental program will not result in a facility with greatly improved characteristics from the users point of view, but the work was necessary to extend the life of the reactor. The reactor is expected to be operational again in late 1969.

In spite of the shutdown, the past year has been an exceptionally productive one for research at CP-5. The highlights of the program have been three experiments of fundamental interest to physics—a study of the weak interaction by means of a refined measurement of the asymmetries in the decay of polarized neutrons, the first measurement of Delbrück scattering of γ rays, and a novel and sensitive study of parity violation in the strong interaction. These experiments are likely to be of general and lasting interest.

The various experiments on neutron-capture γ rays were also very productive, and the refined state of development of four different experimental systems at CP-5 guarantees an effective program in the future. These systems are the bent-crystal spectrometer, a Ge(Li)-detector coincidence system, an internal-target facility, and an internal-conversion spectrometer. Each of these systems is probably the best of its kind.

Only the neutron resonance experiments with the fast chopper have failed to prosper—partly because of a shortage of manpower, but also because a chopper at a relatively low-flux reactor is not competitive with pulsed accelerators for many experiments on neutron cross sections. Consequently, the chopper will not be reinstalled at CP-5 in the near future.

1. FUNDAMENTAL EXPERIMENTS

a. Measurement of A and B Coefficients in the Decay of Polarized Neutrons

C. Christensen, V. E. Krohn, and G. R. Ringo

A paper entitled "Measurements of A and B Coefficients in the Decay of Polarized Neutrons" has been published.[1] The coefficients found were A = -0.115 ± 0.008 and B = 1.01 ± 0.04. The value of A leads to $|G_A/G_V| = 1.26 \pm 0.02$ for the ratio of coupling constants in beta decay, and B is consistent with $G_S = G_T = 0$. These results favor the new Danish measurement of the neutron lifetime. The value of $|G_A/G_V|$ is in excellent agreement with the theoretical calculation of Adler, who obtained 1.24 ± 0.03. This experiment was described in greater detail in a recent Physics Division Summary Report.[2] Additional measurements of higher precision are still very desirable because of the importance of these measurements to the theory of the weak interaction. Hence, the apparatus is being improved so that better data can be obtained when the reactor CP-5 resumes operation.

---

[1] C. J. Christensen, V. E. Krohn, and G. R. Ringo, Phys. Letters 28B, 411 (1969).

[2] C. J. Christensen, V. E. Krohn, and G. R. Ringo, in Argonne National Laboratory Report ANL-7512, pp. 1-3.

b. Parity Violation in Nuclear Reactions

R. E. Segel, E. L. Segel, and R. H. Siemssen

The parity-violating α decay of the 2^- 8.87-MeV state in ^{16}O has been sought. Previous measurements placed an upper limit of $\Gamma_\alpha < 2 \times 10^{-8}$ eV. The state is fed by a 1% branch in the β decay of ^{16}N. In the present experiment ^{16}N was made by the $^{19}F(n,\alpha)$ reaction induced by fast neutrons from the CP-5 reactor. A gas-flow

system picked up the radioactive nitrogen atoms and carried them along to a cold surface where the activity was frozen out. A silicon detector viewed the cold surface. The intense β background, which would be sufficient to ruin the resolution of the silicon detector, was eliminated by having the cold surface and detector in the 50-kG magnetic field generated by a superconducting magnet. A peak two standard deviations above the background was observed at the expected place of the parity-violating transition. This corresponds to an α width of $\Gamma_\alpha = 2.5 \times 10^{-9}$ eV which places the intensity of the parity-violating component in the wave function as $F^2 \approx 5 \times 10^{-13}$. This value is of the order of magnitude predicted by the conserved-vector-current theory.

c. The Scattering of Photons by the Nuclear Coulomb Field

H. E. Jackson and K. J. Wetzel

One of the earliest predictions of quantum electrodynamics, made by Delbrück in 1933, was that photons should be elastically scattered by an electric field. However, the effect is so small that only the electric fields of atomic nuclei are strong enough to make the process observable. Because of its fundamental nature, interest in the experimental verification of Delbrück scattering has remained very high and in the succeeding thirty years many experiments have been attempted—but none had been completely successful. The prediction has now been confirmed by the Argonne experiment described below.[1]

This high-resolution measurement of the scattering of 10.8-MeV photons was the first in which the elastic scattering of photons was resolved experimentally from inelastic contributions. The results showed that for scattering angles less than 45° the process

[1] H. E. Jackson and K. J. Wetzel, Phys. Rev. Letters 22, 1008 (1969).

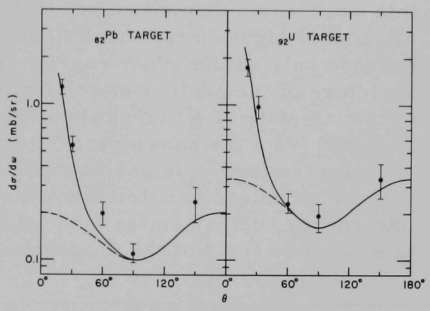

Fig. 1. Differential elastic-scattering cross sections measured for 10.83-MeV photons. The dashed curve represents the values calculated if Delbrück scattering is neglected; the solid curve follows the values obtained by including the most recent theoretical estimates of the Delbrück amplitudes. At forward angles the cross sections are enhanced by as much as a factor of three due to the presence of the Delbrück effect.

is indeed dominated by Delbrück scattering. The high-intensity internal-target facility at the CP-5 reactor was used to generate a beam of 10.8-MeV photons by means of the $^{14}N(n,\gamma)^{15}N$ reaction in a 250-g melamine target. Radiation scattered by external Pb and U targets was detected in a large-volume Ge(Li) detector with an energy resolution width of 15 keV at 10 MeV. In analyzing the data, recent results from related experiments were used in a careful determination of the contributions from the coherent scattering processes (namely nuclear resonance, Thomson, and Rayleigh scattering). The data (Fig. 1) indicate that the measured cross section is much larger at forward angles than that calculated with no Delbrück amplitude. This is interpreted as an unambiguous observation of the Delbrück effect.

2. RESONANCE NEUTRON CAPTURE

a. Average-Resonance-Capture Measurements

The program of measurements on the average γ-ray spectra formed by capture of neutrons in many resonances has reached full maturity during the past year. The initial emphasis in these experiments (carried out at the internal-target facility at CP-5) was an investigation[1] of the mechanisms responsible for the high-energy

[1] L. M. Bollinger and G. E. Thomas, Phys. Rev. Letters 18, 1143 (1967).

γ rays formed by neutron resonance capture. The principal result of this work was a demonstration that in many nuclides the γ-ray strength function of high-energy transitions of a given kind (E1, M1, etc.) depends only on the γ-ray energy—i.e., it is very insensitive to the structure of the nuclear states involved. Also, the energy dependence of the intensity of E1 transitions is usually consistent with what is expected from the known properties of the E1 giant resonance. More recently the emphasis has shifted to the use of the average-resonance-capture technique to determine[2] the energies, spins, and parities of low-energy nuclear states; and we have gradually come to believe that this second aspect of the program is the one that is likely to be of most lasting value.

---

[2] L. M. Bollinger and G. E. Thomas, Phys. Rev. Letters 21, 233 (1968).

(i) E2 Transitions

L. M. Bollinger and G. E. Thomas

The single-particle model of high-energy radiative transitions predicts that a typical high-energy E1 transition is about 150 times stronger than E2 transitions of the same energy. This prediction and the fact that very few E2 transitions have been observed until recently has led most workers in the field to believe that the E2 transitions are almost undetectably weak. However, our average-resonance-capture measurements are now sensitive enough to reveal at least some E2 transitions in more than half of the nuclides that have been studied. These transitions are considerably stronger than had been expected from the simple theory.

(ii) Nuclear Spectroscopy

Since an average-resonance-capture spectrum of good quality can be obtained in several days of running time, it has been possible to study a very large number of nuclei during the past year. The sample materials used in these measurements were Ge, ^{91}Zr, Nb, Mo, Ru, Pd, Cd, ^{111}Cd, ^{117}Sn, Te, ^{125}Te, Cs, Ba, ^{135}Ba, Sm,

Gd, Dy, ^{164}Er, Er, Ho, Tm, Yb, Hf, ^{177,179}Hf, W, Os, Pt, Hg, and ^{238}U. These data give extensive information about states in ^{76}Ge, ^{92}Zr, ^{94}Nb, ^{94,96}Mo, ^{100,102}Ru, ^{106}Pd, ^{112,114}Cd, ^{118}Sn, ^{124,126}Te, ^{134}Cs, ^{136,138}Ba, ^{148,150}Sm, ^{156,158}Gd, ^{162,164}Dy, ^{166}Ho, ^{168}Er, ^{170}Tm, ^{172,174}Yb, ^{178,180}Hf, ^{184}W, ^{188,190}Os, ^{196}Pt, ^{200,202}Hg, and ^{239}U. Less complete information was obtained for many other nuclides.

Typically our measurements reveal the presence of a much larger number of states than had been reported previously, establish the parity of almost all of these states, and set limits on the spins of many of them. Thus, we usually obtain spectroscopic data for a larger number of nuclear states than is provided by any competing technique, but our measurements give little information about the structure of the states. It is clear then, that the average-resonance-capture measurement is a powerful spectroscopic technique, but the data become much more interesting when combined with related data obtained in other experiments.

During the present period in which the reactor is out of operation, the mass of data collected during the past year is being analyzed. The results reported below are representative of the kinds of information that are being obtained for the large number of nuclides that have been studied.

^{166}Ho (L. M. Bollinger and G. E. Thomas). The high-energy transitions observed in the average-resonance-capture spectrum of ^{165}Ho(n, γ)^{166}Ho give directly the energies E of 52 low-energy states in ^{166}Ho, and the intensities give the parities π and set limits on the spins J of the states. This information is listed below in the form EJ^{π}, where the energies are in keV and the possible values of J are given by the notation i ≡ 3 or 4, j ≡ 2 or 5, k ≡ 1 or 6, and n ≡ 2, 3, 4, or 5. The states observed are: 54 j^-, 82 k^-, 171 i^-, 180 i^-, 191 i^+, 261 i^+, 264 j^+, 277 k^-, 295 k^-, 330 j^-, 348 j^+, 372 i^+,

417 j^-, 430 j^+, 454 k^-, 464 j^+, 471 j^+, 475 n^-, 482 i^+, 522 i^+, 543 n^-, 548 i^+, 559 i^+, 562 n^-, 592 i^+, 598 i^+, 605 j^+, 628 n^-, 634 n^+, 638 n^-, 655 n^+, 662 n^+, 667 n^-, 672 n^+, 683 n^-, 694 n^+, 704 n^-, 719 i^+, 726 n^-, 736 i^+, 741 n^-, 757 n^-, 760 n^-, 769 j^+, 771 n^-, 789 n^-, 792 n^-, 806 j^+, 814 i^+, 824 n^-, 831 n^+, and 836 n^+. These states have been analyzed in terms of a rotational-band structure. Our data are consistent with the five bands that have been reported previously and in addition reveal the presence of at least three additional bands.

^{106}Pd (L. M. Bollinger and G. E. Thomas). High-energy transitions observed in the average-resonance-capture spectra of ^{105}Pd(n, γ)^{106}Pd give directly the energies of 40 low-energy states in ^{106}Pd. In this case the γ-ray intensities for E1 and M1 transitions do not differ greatly, so that (unlike ^{166}Ho and most other heavy nuclides) the γ-ray intensities alone do not establish the parity unambiguously. However, because of the importance of p-wave capture in ^{105}Pd, the shape of the γ-ray line depends markedly on the parity of the final state. This phenomenon, combined with the information on intensities, makes it possible to determine the parities of all of the observed states.

^{112,114}Cd (R. K. Smither, D. J. Buss, L. M. Bollinger, and G. E. Thomas). A sample of Cd was surrounded with boron and placed in the high-flux region of the Argonne research reactor. The resultant neutron-capture gamma-ray spectrum was investigated with a Ge(Li) detector. The primary transitions to 30 levels in ^{114}Cd below 3 MeV excitation were identified on the basis of their energy. The normalized intensities I_γ/E_γ^3 were compared with the spin and parity of the levels, assigned on the basis of previous (n, γ) and (d, p) experiments, and were found to fall in groups corresponding to J^π assignments of 0^+, 1^+, 2^+, 3^+, 1^-, and 2^-, as shown in Fig. 2. The reliability of this method for spin and parity assignments as well as the one exception to this simple grouping, the 2^+ level at 1365 keV, are being investigated. Similar average-resonance-capture work with the reaction ^{111}Cd(n, γ)^{112}Cd is in progress. An

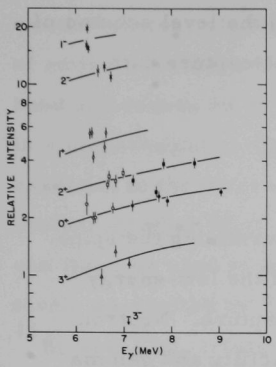

Fig. 2. Plot of the normalized gamma intensities (const. $\times I_\gamma/E_\gamma^3$) of the primary transitions following average resonance capture in ^{113}Cd.

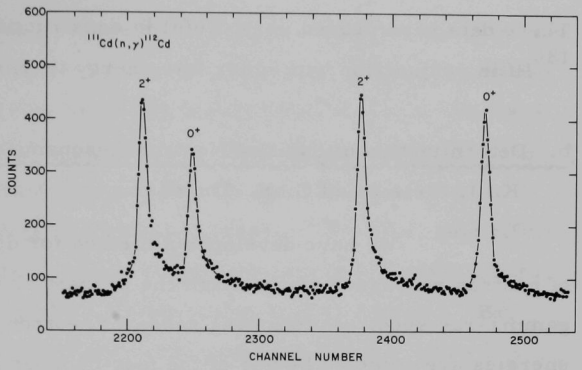

Fig. 3. A section of the average-resonance-capture data taken with a highly-enriched ^{111}Cd sample.

example of the data, taken with a sample enriched in ^{111}Cd, is shown in Fig. 3.

<u>^{148,150}Sm</u> (D. J. Buss and R. K. Smither). The spectrum of high-energy gamma rays from ^{150}Sm produced by average neutron resonance capture was obtained by placing a boron-shielded sample of natural samarium in the research reactor CP-5. The normalized relative intensities of the primary gamma-ray transitions separate these transitions into rather distinct groups characterized by final states with the spins and parities (3^+, 4^+), (2^+, 5^+), and (3^-, 4^-). These data will aid in the further development of the level schemes of ^{148,150}Sm.

<u>^{180}Hf</u> (D. J. Buss and R. K. Smither). Analysis of the high-energy gamma-ray spectrum following average neutron resonance capture in ^{179}Hf has been completed. On the basis of their normalized relative intensities, primary transitions divide into groups which can be characterized by the spins and parities of the final states.

These data have proved very useful in constructing the level scheme of ^{180}Hf in conjunction with other low-energy thermal-capture data.

b. Determination of Spins of Neutron Resonances

K. J. Wetzel and G. E. Thomas

We have developed a method for determining the spins of neutron resonance states from the properties of the low-energy gamma-ray spectrum following resonant neutron capture. Neutron energies are selected by use of the fast-chopper facility and gamma rays are observed in a high-resolution Ge(Li) spectrometer. Each gamma ray can be ascribed to the level it depopulates and thus its intensity characterizes the population probability of the nuclear level. The probability that a three- or four-step dipole cascade will populate a low-lying 2^+, 4^+, or 6^+ level (appropriate to even-even final nuclei) should depend on the spin ($J_{res} = I_{target} \pm \frac{1}{2}$) of the initial resonant state. In a study of neutron capture in several even-Z odd-N nuclei (^{105}Pd, ^{135}Ba, ^{177,179}Hf, ^{183}W) having resonances with known spins, the relative population of pairs of low-lying 2^+, 4^+, 6^+ states in the product nuclei showed a direct correlation with the resonance spins and was in reasonable quantitative agreement with predictions of the simple dipole-cascade model. This method was also successfully applied to a number of resonances in ^{187}Os and ^{189}Os for which no prior spin assignments to capture resonances exist.

3. THERMAL-NEUTRON-CAPTURE GAMMA RAYS

a. Doppler Broadening of γ-Ray Transitions in Light Nuclei

K. J. Wetzel

The recoil velocity imparted to a light nucleus ($A \lesssim 30$) by the emission of an energetic gamma ray ($E_\gamma \gtrsim 3$ MeV) is often sufficient to produce a measurable Doppler shift in a subsequently

emitted photon, also having several MeV energy. The random direction of emission of the secondary γ rays produces energy shifts in a limited band and causes an effective lineshape broadening, typically $\sim$0.7 keV, in a high-resolution Ge(Li) spectrometer. Knowledge of this effect is essential to the determination of an accurate detector lineshape for evaluating other high-energy gamma-ray spectra. Further, this effect can itself be used in some cases to obtain information about the nuclear levels de-excited by the γ rays. In the nuclei studied to date (^{10}Be, ^{11}B, and ^{15}N), improved lifetime information for several levels has been extracted from the attenuation of this Doppler broadening. Also, a detailed computation of the expected broadening depends on the angular correlation $W(\Theta)$ between the first and second γ rays so that, in principle, the spectroscopic parameters that determine $W(\Theta)$ can be studied. Such an analysis applied to the ^{15}N results suggests that neutron capture in ^{14}N occurs through a spin-$\frac{3}{2}$ state in ^{15}N.

b. Investigations of the Level Structure of Low-Lying Excited States of Selected Nuclides

H. H. Bolotin and D. A. McClure

This experimental program seeks to provide detailed information concerning the energies, radiative decay characteristics, and other pertinent parameters of the low-lying excited states of selected nuclides populated in thermal-neutron-capture gamma-ray reactions. Two types of experimental systems are used to unravel these complex spectra. The high-energy primary gamma-ray transitions that populate the low-lying states of the product nucleus from direct decay of the capture state are observed in an efficient pair-spectrometer arrangement at the high-sensitivity internal-target facility at the CP-5 reactor. These transitions establish the excitation energies of states up to $\sim$1—2 MeV above the ground state. The low-energy secondary gamma-ray transitions among the low-lying excited states are studied by means of singles and coincidence gamma-ray spectroscopic techniques at the external-neutron-beam facility at CP-5. Here targets are placed in the external neutron beam (thermal flux $\approx 10^7$ neutrons cm^{-2} sec^{-1}). Singles and coincidence spectra are obtained entirely with the use of high-resolution Ge(Li) detectors in conjunction with a two-parameter magnetic-tape recording system in a 1024$\times$1024-channel pulse-height array.

Two types of two-parameter Ge(Li)-Ge(Li) coincidence studies are performed: (a) "high-low" coincidences between high-energy primary transitions (~6—8 MeV) and low-energy secondary gamma rays (~30—2000 keV) and (b) "low-low" coincidences with both detectors set to view the low-energy transitions. These two sets of coincidence experiments provide the independent and complementary information necessary to delineate the level scheme and radiative decay properties of excited states up to ~1—2 MeV above the ground state.

Two additions to the external-beam coincidence facility have significantly enhanced its usefulness. (a) Employment of large-volume Ge(Li) detectors results in materially higher detection efficiency for gamma rays of all energies. (b) Improved shielding and collimation have increased the signal-to-background ratio. In combination, these improvements allow a substantial reduction of the required quantities of isotopically separated targets and consequently enlarge the number of nuclides that can be studied with presently available quantities of separated isotopes. We now obtain data of enhanced quality and detail in experimental runs of substantially shorter duration.

A further major improvement in apparatus, expected to be in operation soon after the rehabilitation of the CP-5 reactor is completed, will modify the present computer-incompatible 2-parameter coincidence magnetic-tape storage array from 1024×1024 pulse-height channels to a 3-parameter 2048×2048×256-channel array stored in a computer-compatible format on magnetic tape. The two larger dimensions will register γ-ray pulse heights for the two detectors of the coincidence combination. For each coincidence, the time between events (represented as the pulse-height from the time-to-pulse-height converter) is stored in the small dimension. This improvement will broaden the scope and character of these experiments—not only by doubling the γ-ray energy range recorded, but also by allowing (a) variable (and thus more judicious) hind-sight selection of the coincidence resolving time to be employed for each specific pulse-height coincidence gate set on the γ-ray spectrum after the data have been recorded and (b) determinations of the lifetimes of various excited nuclear levels that fall within the time range measurable with these detectors.

We have developed a new analytical technique by which the energies of low-energy and high-energy γ-ray transitions can be determined from high-resolution Ge(Li) singles data. The materially improved accuracy (e.g., ~0.1 keV at 1 MeV) leads to correspondingly improved confidence in the uniqueness of the level schemes constructed.

(i) Levels in ^{70}Ga and ^{72}Ga

H. H. Bolotin, J. Vervier,* and J. L. Yntema)

The excited states of the odd-odd ^{70}Ga and ^{72}Ga nuclides have been investigated by the ^{69,71}Ga(n, γ)^{70,72}Ga and ^{69,71}Ga(d, p)^{70,72}Ga reactions. Recently completed thermal-capture γ-ray studies of the ^{71}Ga(n, γ)^{72}Ga reaction have provided additional detailed information. The combined results of these studies of these two complementary reactions have yielded a comprehensive description of the level structures of these nuclides with which to compare shell-model calculations. This work is now complete and has been submitted for publication.

(ii) Level Structure of ^{187}W

H. H. Bolotin and D. A. McClure

A study of the low-lying excited states of ^{187}W populated in the ^{186}W(n, γ)^{187}W reaction has been completed at the external-neutron-beam facility. Singles and coincidence spectra were obtained exclusively with Ge(Li) detectors and were stored in a two-parameter 1024×1024-channel pulse-height array. Both "high-low" and "low-low" coincidence data of high quality were obtained. These data have provided a great deal of new information about the level structure and radiative-decay characteristics of the low-lying excited states of ^{187}W. These findings are summarized in the proposed level scheme (Fig. 4) for states up to an excitation energy of ~1220 keV.

Of most significance is the identification of two main rotational-band structures at low excitation: the ground-state band, assigned to the $\frac{3}{2}^-$[512] Nilsson orbital, and an excited-state band built upon the $\frac{1}{2}^-$[510] Nilsson orbital starting at an excitation energy of 145.7 keV. To each of these bands the present work has added

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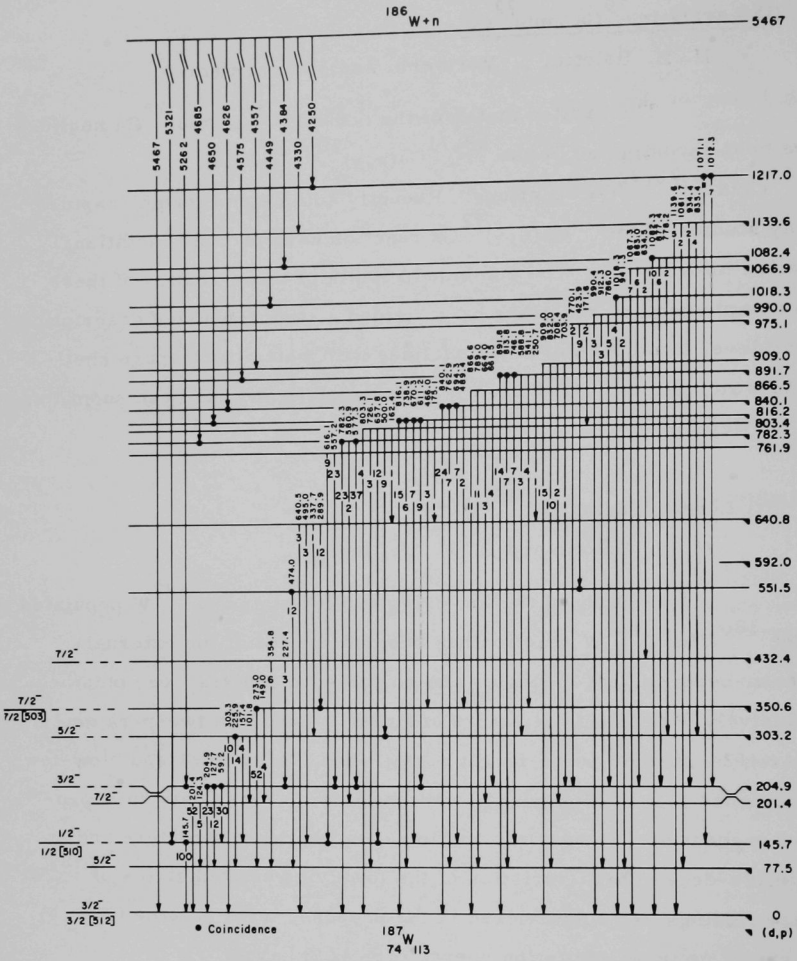

Fig. 4. Level scheme of ^{187}W. Levels observed in the present coincidence and singles γ-ray studies appear as long lines. Excitation energies are expressed in keV. A dot at the beginning or end of an arrow indicates coincidence with one or more other γ rays to or from the marked level. Levels established by these coincidences or through primary high-energy γ-ray transitions (arrows at left) are proposed more confidently than are those based solely upon the energy and intensity balance of low-energy transitions. The spins, parities, and rotational-band configurations indicated at the left are assigned mainly from the (d, p) study (Ref. 1).

one member not observed in the previous (d,p) studies.[1] The branching ratios in the radiative decay of all observed members of these bands have also been determined.

The excitation energies of the members of these bands do not fit the prescription of the simple rotational model, and Coriolis band mixing calculations (corrected for pairing) were performed in an effort to achieve better agreement with the experimental energy spectrum, radiative branching ratios, and the previously reported[1] (d,p) strengths. The values of the parameters used in the band-mixing calculations were varied to obtain the best fit. However, no fit obtained could be considered good. Even the most "satisfactory" agreement between calculation and experimental data prescribed a disturbingly large "stretching" term originating in the rather large spacing between the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ members of the ground-state band. A similar situation is also found in the same band in ^{189}Os (an isotone of ^{187}W) in which the $\frac{7}{2}^-$ member lies at an unexpectedly high excitation energy. We have considered several possible effects that individually or in combination may give rise to the observed discrepancies in this model description of this transitional nuclide. However, proper evaluation of these possibilities will require additional experimental data. A complete description of the present work and a thorough discussion of the applicability of the rotator-plus-odd-nucleon model is presently being prepared for publication.

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[1] J. R. Erskine, Phys. Rev. 138, B66 (1965).

(iii) Level Structure of ^{175}Yb

H. H. Bolotin and D. A. McClure

The levels of ^{175}Yb populated in the thermal-neutron capture reaction ^{174}Yb(n,γ)^{175}Yb have been investigated by means of singles and coincidence spectroscopic techniques at the external neutron beam and internal-target facility at the CP-5 reactor. A complete

series of "high-low" and "low-low" coincidence studies were performed. Although a NaI(Tl)-Ge(Li) coincidence study of this reaction has already been reported,[1] the results appeared to contain ambiguities and/or inconsistencies. We therefore felt that the present comprehensive Ge(Li)-Ge(Li) coincidence investigation of this interesting rotational nuclide could help to clear up these discrepancies and allow a more meaningful and detailed understanding of the level structure of ^{175}Yb.

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[1] W. Bondarenko, N. Kramer, P. Prokofjew, P. Manfrass, A. Andreef, and R. Kastner, Nucl. Phys. A102, 577 (1967).

(iv) Level Structure of ^{179}Hf

H. H. Bolotin and D. A. McClure

Singles and coincidence gamma-ray spectroscopic studies of the ^{179}Hf levels populated in the thermal-neutron-capture reaction ^{178}Hf(n, γ)^{179}Hf have been completed. These include "high-low" and "low-low" coincidence data of excellent quality. These data, when fully analyzed, will be combined with earlier results of one of the present workers to establish the detailed level scheme and radiative decay characteristics of the low-lying excited states. It is anticipated that these data, when combined with previously reported (d,p) studies of this nuclide, will serve to establish the rotational band characteristics and their assignments within the framework of the Nilsson deformed-potential model of rotational nuclei.

(v) Level Structure of ^{147}Nd

H. H. Bolotin and D. A. McClure

The level structure of the low-lying excited states of ^{147}Nd populated in the reaction ^{146}Nd(n, γ)^{147}Nd have been investigated by means of all the spectroscopic techniques available at the external-neutron-beam facility. This transitional nucleus, about which little is known, is of considerable interest in that a detailed description

of the level structure of this nuclide would help to elucidate the characteristics of nuclides in this mass region. Analysis of these data is not complete, but preliminary analysis has already yielded important new information concerning the low-lying excited states of ^{147}Nd.

c. (n, γ) Studies with the Bent-Crystal Spectrometer and Ge-Diode Detector

(i) Modification of the Bent-Crystal Spectrometer

R. K. Smither, D. J. Buss, and D. L. Bushnell

The energy-resolution and sensitivity of the bent-crystal spectrometer have been considerably improved by a number of recent modifications. Installation of the new 2-mm bent quartz crystal (which measures 30 cm × 30 cm × 2 mm thick) has yielded twice the energy resolution obtained with the previous crystal (4 mm thick) without any appreciable loss in efficiency (reflectivity of the crystal). At the same time, the sensitivity has been increased as a result of a general reduction in background. The line width of the spectrometer has now been reduced to about 5 keV (FWHM) at 1 MeV and 50 eV at 100 keV. Plans to obtain a 1-mm-thick crystal and further improvement in energy resolution are under consideration.

A new multislit precollimator has been installed and is now in use. The addition of this precollimator is equivalent to tripling the length of the post-collimator; and it has the advantage of moving the region in which the unwanted radiations are stopped to a position well ahead of the bent crystal and post-collimator. This greatly simplifies the problem of shielding the NaI detectors from the fast neutrons and gamma rays arising from sources other than the neutron-capturing sample. The precollimator has reduced the spectrometer background by a factor of 10 at 50 and 100 keV, by a factor of 30 at 1 MeV, and by a factor of 2000 at 3 MeV. As a consequence of the

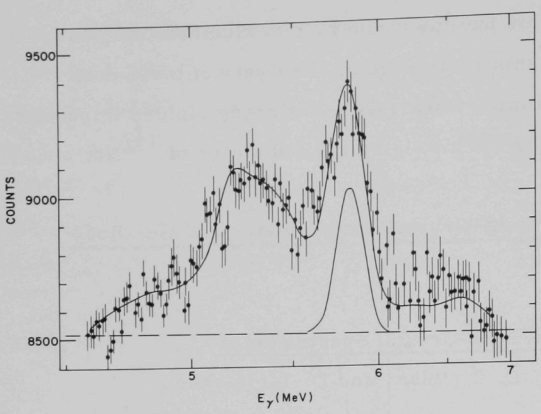


Fig. 5. A bent-crystal spectrometer run over the strong 5.8-MeV line in the $^{113}Cd(n,\gamma)^{114}Cd$ spectrum. It was obtained with the 1st-order diffraction of the (310) planes in quartz. The solid line is the envelope of the known spectral components in this energy region; it is based on Ge(Li) data normalized to the experimental counting rate. A single line shape of appropriate height for the 5.8-MeV line is also shown. The dashed line is the undiffracted background.

greatly improved sensitivity made possible by this background reduction, the strong 5.83-MeV line in ^{114}Cd (Fig. 5) was successfully diffracted for the first time in a recent experiment. Better detector shielding is expected to reduce background over most of the energy regions by another factor of two.

Other modifications to improve the general reliability and flexibility of the system are in the planning or construction stages.

(ii) High-Energy K Conversion Coefficients

R. K. Smither, D. J. Buss, and E. Bieber

The K conversion coefficients for the 1—9-MeV region of the $^{113}Cd(n,\gamma)^{114}Cd$ γ-ray spectrum are obtained by combining the Ge-diode analysis of the (n,γ) spectrum with the conversion-electron intensities from the published work of von Egidy and Kaiser. The coefficient was found to depend on the γ-ray energy as $E_\gamma^{-1.96}$ for the E1 radiation and as $E_\gamma^{-2.18}$ for the M1. Contrary to the suggestion from extrapolating the theoretical calculation, the values of the E1 and M1 coefficients do not cross at high energies; at 9 MeV they still differ

in the ratio of 1.7:1.0. A similar analysis of the $^{149}Sm(n,\gamma)^{150}Sm$ spectrum, combined with the conversion-electron intensities of Elze, showed that the α_K had a more nearly $E_\gamma^{-1.4}$ dependence at high energies, as seen in Fig. 6. The ratio of $\alpha_K(M1)/\alpha_K(E1)$ was 2:1 at 7 MeV. Thus it is possible to distinguish between E1 and M1 transitions in the high-energy spectra of both ^{114}Cd and ^{150}Sm and to assign parities to many of the states in these nuclei. Analysis of the average-resonance-capture data for both these nuclei is expected to aid in confirming the multipolarities of many of the observed transitions.

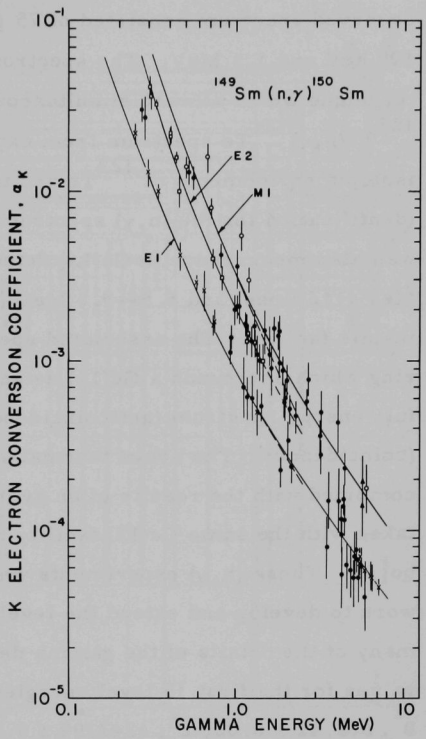


Fig. 6. K conversion coefficients for the $^{149}Sm(n,\gamma)^{150}Sm$ spectrum. The crosses, open circles, and open squares are known E1, M1, and E2 transitions, respectively. The dashed curves are the theoretical values of Sliv and Band up to 2.5 MeV. The solid lines are drawn by hand through the points of known multipolarity. Contrary to the early theoretical extrapolations, the E1 and M1 curves appear to remain well separated at 7 MeV.

(iii) Neutron-Capture Gamma-Ray Studies of the Level Structure of the ^{124}Te Nucleus[1]

R. K. Smither, D. L. Bushnell, and R. P. Chaturvedi

The gamma-ray spectrum resulting from thermal-neutron capture in ^{123}Te was investigated with the Argonne 7.7-m bent-crystal spectrometer. The

[1] D. L. Bushnell, R. P. Chaturvedi, and R. K. Smither, Phys. Rev. 179, 1113 (20 March 1969).

observed spectrum consisted of 75 gamma rays with energies between 100 keV and 1.1 MeV. The spectrometer used a new split-source technique which allowed simultaneous measurement of the $^{123}Te(n,\gamma)^{124}Te$ spectrum from capturing samples with two different isotopic enrichments of ^{123}Te and thus gave immediate isotopic identification for the (n,γ) spectrum. The $^{123}Te(n,\gamma)^{124}Te$ spectrum was also measured with Ge(Li) detectors in the energy regions 0.5—4.0 MeV (112 lines) and 5.5—9.5 MeV (63 lines) by use of the Argonne in-pile facility. The associated spectrometer has a long, split NaI ring which surrounds a Ge(Li) detector and was used to enhance the full-energy spectrum (anticoincidence) and the double-escape spectrum (coincidence). The above thermal-neutron-capture spectrum was combined with the results of an average-resonance-capture spectrum taken with the same Ge(Li) facility but with the target surrounded with boron. These (n,γ) experiments were then combined with all previous work to develop and extend the level scheme of ^{124}Te and to define many of the details of the gamma decay of these levels. The new values for the first 15 level energies (keV) and J^{π} are: ground state, 0^+; 602.42 ± 0.02, 2^+; 1247.99 ± 0.05, 4^+; 1324.82 ± 0.05, 2^+; (1655.9 ± 0.2, $\underline{0^+}$); (1736.5 ± 0.3); (1747.40 ± 0.16); 1956.18 ± 0.11, $\underline{3^{\pm}, 4^+}$; 2037.68 ± 0.07, 2^+; 2090.65 ± 0.35, $\underline{0^+, 2^+}$; 2152.04 ± 0.15, $\underline{0^+, 2^+}$; 2181.20 ± 0.40, $\underline{1, 2}$; 2293.10 ± 0.30, 3^-; 2322.57 ± 0.20, $\underline{0^+, 2^+}$; 2452.9 ± 2.6, $\underline{0^+, 2^+}$. The parentheses indicate uncertainty in the level assignments while the underlined spins and parities indicate new values. The level scheme (Fig. 7) now includes 37 levels extending to an energy of 3100.78 keV.

The relative intensities of γ rays from states at $\sim$2 MeV suggest that E2 transitions to the two-phonon states at 1248 and 1325 keV are enhanced relative to transitions to states at 0 and 602 keV; so these 2-MeV levels are very likely collective and possibly vibrational. The (n,γ) data imply a neutron binding energy E_n = 9425 ± 2 keV for ^{124}Te.

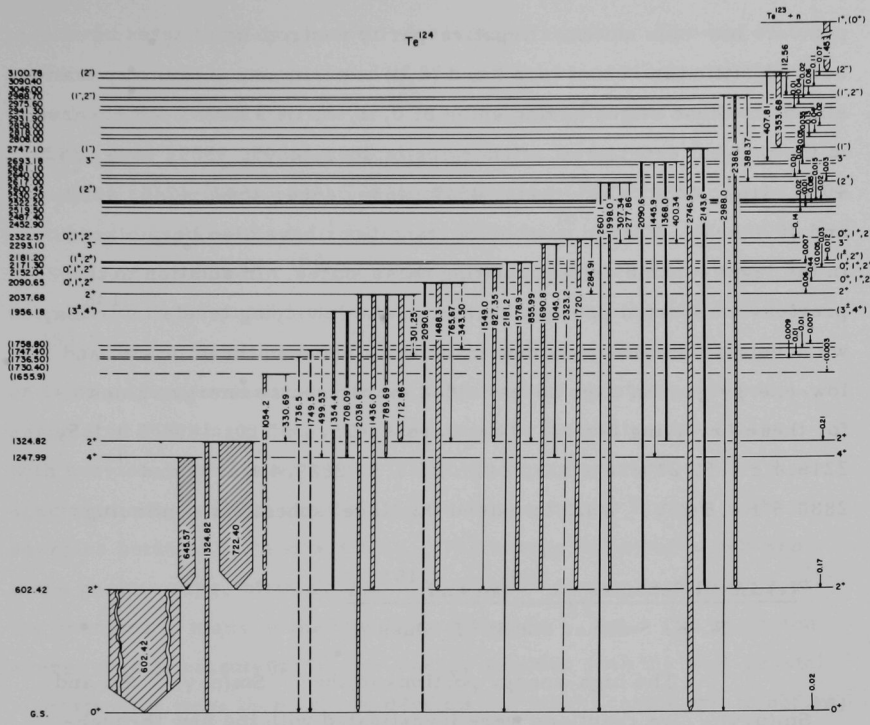


Fig. 7. Level scheme for Te^{124}. The widths of the lines representing transitions are proportional to the gamma-ray intensities. Each high-energy transition from the capture state is described at the right by a small arrow with an intensity number directly above. All intensities are given in photons per 100 neutron captures. The level assignments include conclusions based on the resonance as well as the thermal-neutron results. Wherever a parenthesis is used, it denotes uncertainty.

(iv) Level Scheme of ^{138}Ba

D. J. Buss and R. K. Smither

The $^{137}Ba(n,\gamma)^{138}Ba$ spectrum has been studied with the Ge(Li) spectrometer. Seventy-eight of the 207 transitions observed in this spectrum have been placed in a tentative level scheme of ^{138}Ba. Primary transitions from the capture state (1^+, 2^+) are expected to

populate low-spin states. Negative-parity neutron-hole states have been identified in recent (p,p') and (d,p) experiments. Primary transitions to those states having spins of 0, 1, 2, or 3 have been observed in the present experiment at energies of 2881, 2895, 3505, 3646, 3923, 4079, 4167, 4280, 4325, 4446, 4517, 4536, 4564, 4647, 4745, 4799, and 4876 keV. A large number of transitions have also been placed in the level scheme as depopulating these states. In addition to the previously reported primary transitions to low-lying levels in ^{138}Ba, we have also observed six new transitions between these levels; and low-energy gamma rays have yielded more precise energy values for these low-lying levels. These are: 1435.6 ± 1.0, 1898.5 ± 1.5, 2218.1 ± 1.5, 2306.6 ± 1.5, 2445.9 ± 1.5, 2639.4 ± 1.5, and 2880.5 ± 1.5 keV. Work to extend this level scheme is continuing.

(v) Level Schemes of ^{150}Sm and ^{151}Sm

R. K. Smither and D. J. Buss

The high-energy portions of the ^{149}Sm(n,γ)^{150}Sm and ^{150}Sm(n,γ)^{151}Sm reactions were investigated with the new through-hole Ge-diode facility at the reactor CP-5. The results are now being combined with the bent-crystal data on the low-energy portion of the (n,γ) spectrum to extend the level scheme of ^{150}Sm and ^{151}Sm. The average-resonance-capture spectra are expected to be a valuable supplement to other data used in developing these level schemes.

(vi) The Level Scheme of ^{153}Sm Based on (n,γ), (n,e$^-$), and (β,γ) Experiments[1]

R. K. Smither, E. Bieber, T. v. Egidy,* W. Kaiser,* and K. Wien†

The ^{152}Sm(n,γ)^{153}Sm spectrum was measured with the Argonne bent-crystal spectrometer and with a Ge(Li) detector at the

*Technischen Hochschule München, Germany.

†Technischen Hochschule Darmstadt, Germany.

[1] R. K. Smither, E. Bieber, T. v. Egidy, W. Kaiser, and K. Wien Phys. Rev. (20 November 1969).

in-pile facility at the Argonne CP-5 research reactor. The low-energy bent-crystal spectrum consisted of 251 gamma transitions associated with thermal-neutron capture in ^{152}Sm and with energies between 35 keV and 1041 keV. The identification with the ^{152}Sm(n, γ)^{153}Sm reaction was made by comparing relative gamma intensities from three neutron-capturing samples—the first being enriched in ^{149}Sm, the second in ^{150}Sm, and the third in ^{152}Sm. The gamma-ray intensities were normalized to the previously established intensity of the 103-keV line in ^{153}Eu from the β decay of ^{153}Sm. The energies and intensities of 24 other lines measured with the bent-crystal spectrometer and associated with this β decay are also given to facilitate comparison with previously published work. The high-energy portion of the (n, γ) spectrum obtained with the Ge(Li) detector contained 35 lines with energies between 5.2 and 6.3 MeV. The energy differences between these gamma rays, often good to 0.1—0.2 keV, were used to suggest the energies of many of the low-lying states in ^{153}Sm. The precision energy measurements of the low-energy gammas with the bent-crystal spectrometer were then used to develop this level scheme and to obtain the details of the γ-decay branching ratios and to define the level energies to ±0.005—0.030 keV. The conversion-electron spectrum resulting from ^{152}Sm(n, e^-)^{153}Sm was measured with the high-resolution magnetic spectrometer at the Munich research reactor. The measured spectrum, which consisted of 43 K and L conversion lines, was used to obtain K and L conversion coefficients and corresponding multipole assignments for 30 of the low-energy gamma transitions. This information was used in conjunction with the (n, γ) data to determine the parity of 20 of the 39 levels identified in the level scheme of ^{153}Sm and to make unique spin assignments for 13 of these levels and to restrict the spins of most of the other levels to two choices.

Of special interest is the very low-energy (7.53 keV) first excited state with spin and parity assignment $\frac{5}{2}^+$. Evidence for

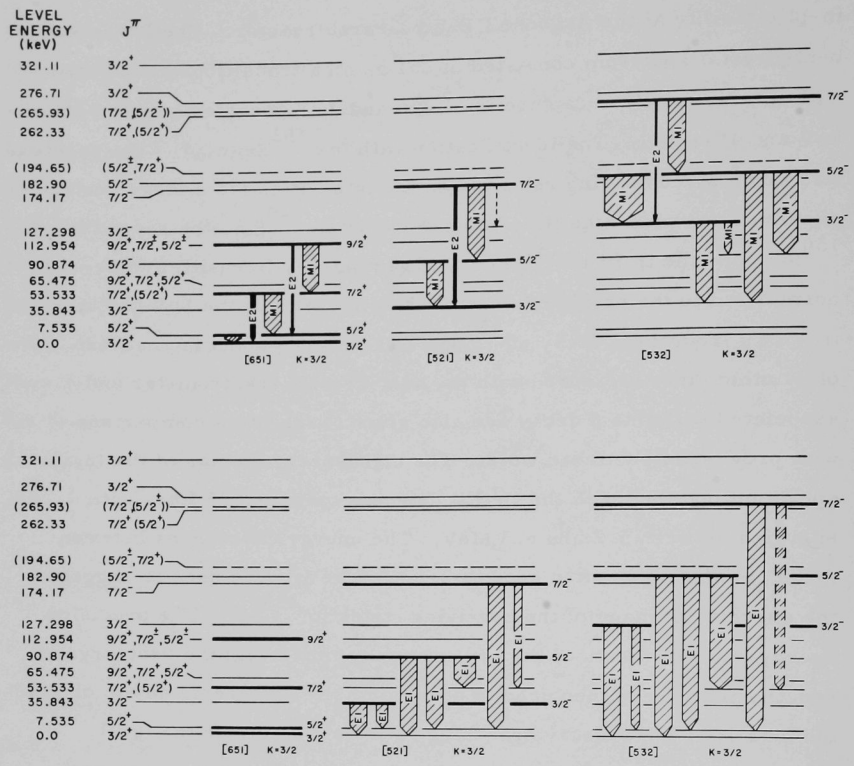


Fig. 8. The normalized gamma decay of the low-lying rotational band. The upper row shows the M1 and E2 transitions between levels with the same parity. The lower row shows E1 transitions between levels of different parity. The experimental values for the level energies (in keV) and for the spin and parity assignments are shown on the left. The proposed J^{π} assignments for the rotational bands are given to the right of each group. The width of each transition is proportional to its normalized γ intensity I_N = constant $\times I_{\gamma}/E_{\gamma}^{3}$. The labels on the transitions indicate the lowest possible multipole assignment that is consistent with the proposed spin and parity assignments. No transitions are left out. The dashed lines indicate missing transitions that may be hidden under lines of almost the same energy. The width of each dashed line represents the normalized upper limit of its intensity. The experimental upper limits on the normalized intensities of the other missing transitions are much smaller than these.

the 7.53-keV transition was obtained with a specially constructed proportional counter.

On the basis of a direct comparison with the well calibrated lines in nitrogen, the neutron binding energy of ^{153}Sm was found to be 5869.3 ± 2.0 keV.

The observed gamma-ray branching ratios of the decays of the low-lying levels were compared with the theoretical predictions of the Nilsson model for a single particle coupled to a deformed core. A good match between theoretical predictions and experimental results was obtained when ten of the eleven levels below 200 keV were assigned to one positive-parity and two negative-parity $K=\frac{3}{2}$ rotational bands. The gamma-decay branching ratios of the low-lying rotational bands are shown in Fig. 8. Above 200 keV the level scheme becomes quite complex and the gamma-decay branching ratios can no longer be interpreted by assuming pure Nilsson states.

(vii) Level Scheme of ^{180}Hf

D. J. Buss, D. L. Bushnell, and R. K. Smither

The gamma-ray spectrum following thermal neutron capture in ^{179}Hf has been obtained with the precision capture gamma-ray spectrometer equipped with a new, higher resolution Ge-diode detector. Analysis of the 1—2-MeV region of this spectrum has led to the identification of transitions between upper levels and the ground-state band. Twelve of these upper levels have thus been identified. Primary transitions to eleven of the twelve upper levels have been observed in the average neutron-resonance-capture spectrum, and have led to J^{π} values for these levels which are consistent with the 1—2-MeV data. Improved low-energy gamma-ray spectra obtained with the bent-crystal spectrometer with the new 2-mm quartz crystal and precollimator in place are being analyzed to identify transitions between the upper levels and to obtain more precise values for the level energies.

4. SUPERCONDUCTING INTERNAL-CONVERSION-ELECTRON SPECTROMETER

S. B. Burson and P. F. A. Goudsmit

The Argonne superconducting internal-conversion-electron spectrometer has been completed and placed in operation. Although the electronic system for coincidence measurements has not yet been constructed, data already obtained indicate that the equipment

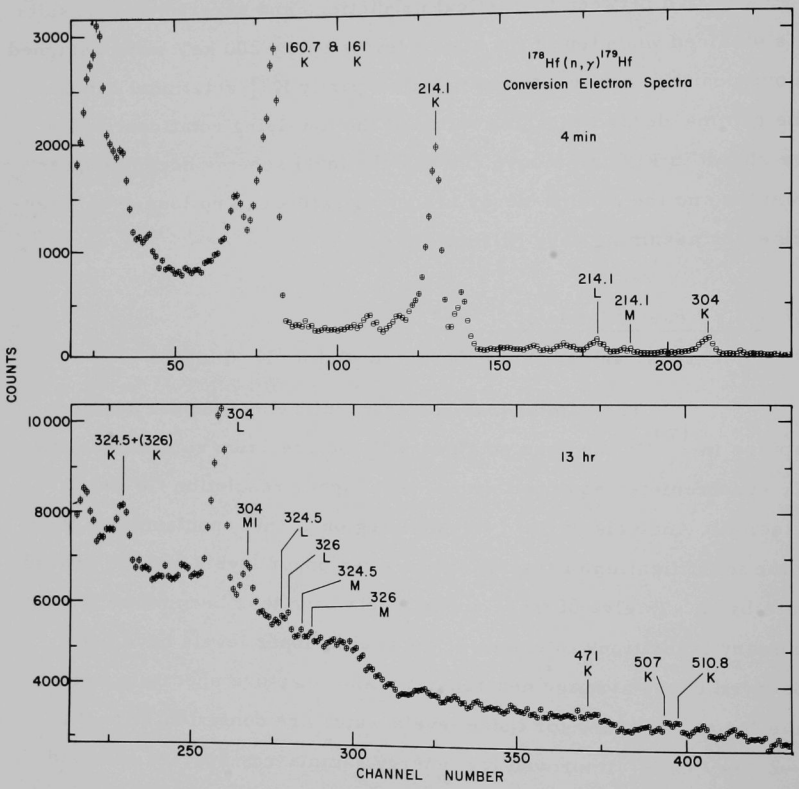
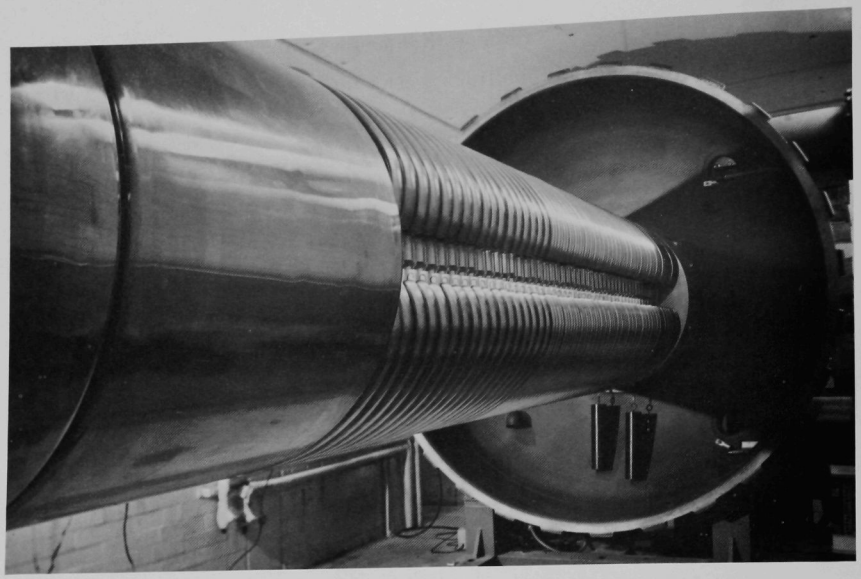
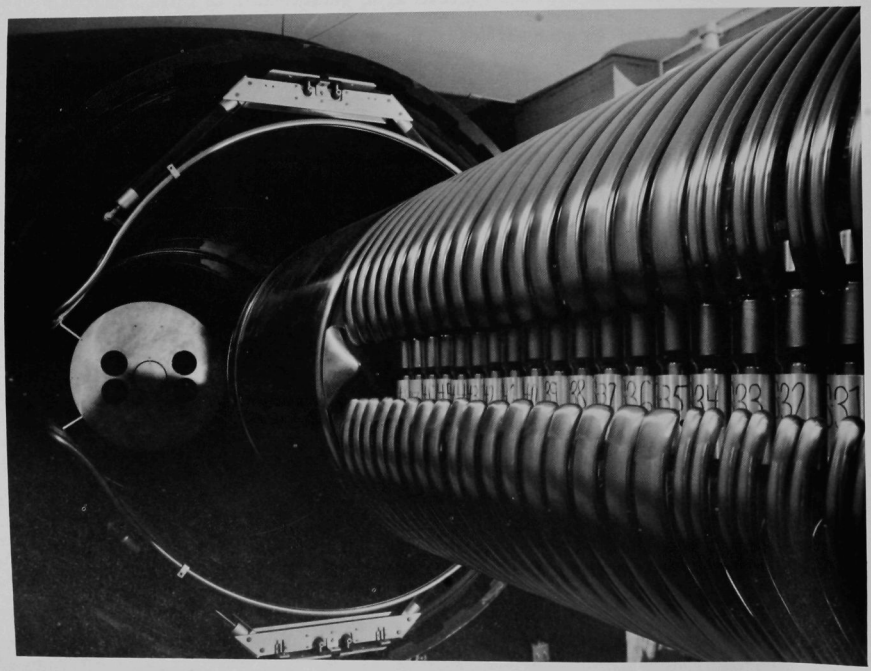


Fig. 9. The internal-conversion-electron spectrum of ^{179}Hf following thermal-neutron capture in ^{178}Hf. The upper spectrum was collected in 4 min, the lower in 13 h.

will be a valuable source of heretofore unavailable information about the excited states of many nuclides. The instrument was designed with two types of experiments in mind. The first type, the investigation of radionuclides, has so far been confined to taking preliminary data on ^{181}Os and ^{182}Os. In the second type, the measurement of internal-conversion coefficients of neutron-capture gamma rays, targets of ^{178}Hf, ^{180}Hf, ^{181}Ta, ^{174}Yb, ^{109}Ag, and ^{146}Nd have been studied at the CP-5 reactor. These data are currently being analyzed. For illustration, the internal-conversion spectra of ^{179}Hf are shown in Fig. 9.

The complexity of the spectra observed in both the radioactive work and the neutron-capture gamma-ray studies points up two conclusions: (1) the electron-gamma coincidence facility of the apparatus must be made available before definitive conclusions can be reached and (2) more sophisticated techniques of data analysis must be developed. In one effort in the direction of improved analysis, a Fortran program for the IBM-360-50-75 computer has been written to make a systematic search for meaningful relations among the gamma rays. All of the experimental transition energies are inserted into the computer which then searches for common differences that satisfy a programmable acceptance criterion. The program is in operation and is being tested on the data described above.





B. FAST-NEUTRON EXPERIMENTS AT THE 4-MeV VAN DE GRAAFF ACCELERATOR AND THE NEW DYNAMITRON

During the past year most of the effort of the group involved in fast-neutron physics has been devoted to the installation of a new accelerator, a 4-MeV Dynamitron (Fig. 10). The installation of the accelerator itself has been completed and the experimental area is being prepared for experiments that will start in late spring 1969.

Although the Dynamitron is now ready for routine use, the most effective use of the machine will require a continuing effort to develop methods for using the extremely large beam currents now available from the Dynamitron and to develop a pulsed-beam technology.

The general nature of the research program at the Dynamitron will be similar to that at the 4-MeV Van de Graaff, but the high current of the new accelerator will provide a major improvement in research capability. A continuing objective is to take advantage of the large beam currents available from the new machine to carry out triple-scattering experiments, which (if they can be made with good accuracy) will provide qualitatively new kinds of information about nuclear reactions. Other aspects of the planned research program are outlined below.

a. Operation of the 4-MeV Van de Graaff Accelerator and Installation of the 4-MeV Dynamitron

(i) Operation and Replacement of the Van de Graaff

Jack R. Wallace

The 4-MeV Van de Graaff accelerator was operated in this period from 1 April to 31 May 1968, at which time it was shut

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Fig. 10. The new Dynamitron with the tank removed. Above: High-voltage terminal and accelerating column. Below: The rf electrodes (dees) on insulating supports inside the pressure tank. When the tank is closed, these dees are connected to an rf inductance (out of sight to the right of the upper photograph) to form a 120-kHz tuned circuit. The Dynamitron is a 96-stage voltage multiplier in which rf power is supplied by way of the capacitance between the "dees" and the "semi-arcuate rings" along the accelerating column. The rectifier tubes are shown along the sides of the column.

down and dismantled to make way for the installation of the new 4-MeV Dynamitron Accelerator. No changes or improvements were made in the original accelerator system.

The 4-MeV Van de Graaff accelerator had been an important research tool in the Physics Division for 19 years. It has been given to Brigham Young University and will become a part of their training facilities for new physicists.

(ii) Installation of the 4-MV Dynamitron

A. S. Langsdorf, Jr., F. P. Mooring, W. G. Stoppenhagen, and J. R. Wallace

During the summer of 1968, the area to house the new Dynamitron was modified in preparation for its installation. The floor of the experimental area was lowered 4 ft, shield walls were stacked, tracks for the pressure tank were laid, and electrical and water distribution systems were installed. By the early fall of 1968, all those alterations that could be made prior to the actual installation of the new accelerator were complete.

The Dynamitron was delivered on 2 October 1968. Radiation Dynamics, Inc., the vendor, also contracted to install the accelerator. In addition, the company supplied a gas-handling system and a system for providing chilled water to cool the accelerator and its peripheral equipment. These systems and the accelerator were installed concurrently. Simultaneously a program to train Argonne personnel in the operation, maintenance, and basic principles of the Dynamitron was conducted.

By the middle of December the installation of the various systems was complete, and on 17 December 1968 the Dynamitron was first operated. By 20 December it reached a terminal voltage of 4 MV. The various tests continued and the minor problems that arose were corrected during the month of January. On 28 January 1969 the Argonne Dynamitron successfully produced a hydrogen-ion beam

in excess of 1 mA and a particle energy slightly above 4 MeV for more than 2 hours. However, the energy spread in the beam exceeded that permitted by specifications.

Investigation showed that the principal source of the spread in beam energy was that the charging system caused a 120-kHz ripple in the terminal voltage. At Argonne's suggestion, a variable trimmer capacitor was built and installed between the lower dee and ground. This capacitor allowed the terminal ripple to be reduced by a large factor, and present indications are that the energy spread in the beam has been reduced to a value less than ±2 keV. All the acceptance tests were successfully completed by 19 February 1969. To date the accelerator has produced hydrogen-ion currents as large as 1.6 mA and beam energies as great as 4.2 MeV.

Since we were not sure what radiation levels should be expected, all beam tests were performed in a shielded vault. Radiation levels, though high, were not as high as had been anticipated and our radiation shield was more than adequate for the levels produced during the test runs. Outside the shield, the levels of both neutron and x radiation were below accepted tolerances for inhabited areas. It is still to be seen how effective our shield is when deuteron beams are accelerated.

Of the five 4-MV Dynamitrons now in the field, the Argonne machine (the last to be delivered) was the first to successfully pass all acceptance tests. After a short conditioning period, the accelerator can be raised to full voltage and current very rapidly. This behavior is not characteristic of most other electrostatic accelerators, including all other 4-MV Dynamitrons. However, it is indicative of the reserve capacity built into the present accelerator.

As mentioned, the new machine has produced a well-focused beam of positive ions in excess of 1 mA from 1.5 to 4 MeV. A similar machine has already delivered 3 mA of positive ions. The power supply is adequate to generate an ion beam as large as 10 mA

at 4 MeV. Thus the machine has the potential for the production of much larger beam currents. However, at present a principal deterrent to the production of larger beam currents is the loading of the power supply by the so-called corona current. This current arises from ionization of the insulating gas by x rays which at maximum beam current and voltage reach a dose rate of 100 R/h at a point outside the pressure tank and near the high-voltage terminal. Thus before still larger beams of positive ions are generated, it is imperative that the production of x rays be reduced.

The x rays are generated by electrons that are produced in the accelerator tube and then accelerated back to the terminal. There are at least five known ways to reduce the effects of x-ray production. (1) Use heavy metal around the source spots to absorb the x rays before they enter the insulation gas. (2) Reduce the yield of x rays per electron by using a light metal such as beryllium wherever electrons impinge. (3) Improve the vacuum inside the accelerating tube to reduce the number of electrons generated. (4) Trap the electrons by electric or magnetic fields before they acquire enough energy to produce very hard x rays. (5) Use mass analysis in the terminal to prevent undesirable beams of particles from entering the accelerator tube. For example, an ion beam of molecular hydrogen is very unstable and upon breakup becomes a potent source of electrons. With the possible exception of (4), all of these methods are relatively simple and will be utilized in an attempt to increase the maximum current available.

In addition, the energy spread of the ion beam can be still further reduced. The present ±2-keV spread in energy is caused mainly by voltage ripples from various sources. Studies of the various sources of the ripple indicate that with a minimum of effort the energy spread can be reduced by another order of magnitude. When this is accomplished, Argonne will indeed have an accelerator that is unique in the world.

A beam-switching magnet and beam-line system have been installed. The permanent shield walls between the target area and the control room have been constructed. A radiation alarm and safety interlock system, based on knowledge obtained during the testing of the Dynamitron, is being devised. A new data-recording room has been constructed. The new experimental program was begun in August 1969.

(iii) Nanosecond Terminal Pulsing Equipment for the 4-MeV Dynamitron

W. G. Stoppenhagen, F. P. Mooring, A. Langsdorf, Jr., A. J. Elwyn, J. Wallace, and F. J. Lynch

A nanosecond beam-pulsing system to be placed in the high-voltage terminal of the 4-MeV Dynamitron has recently been ordered from ORTEC for installation in the fall of 1969. The system will consist of standard pulsing and klystron bunching equipment capable of producing proton pulses less than 1 nsec in width at a maximum repetition rate of 2 MHz and with a peak current in excess of 2.5 mA. In addition, a crossed-field analyzer will provide terminal beam analysis when the accelerator is operated in the dc mode.

One important use of the pulsed beam will be in the continuing program of measuring angular distributions and polarizations of elastically scattered neutrons. Employing time-of-flight techniques will more reliably eliminate effects due to neutrons from the low-lying excited states of the source nucleus. Another improvement accompanying the use of time-of-flight techniques is a considerable reduction in the backgrounds due to gamma rays or beam-correlated neutrons.

Among the other types of experiments that are expected to make use of the pulsed-beam capability are: studies of particle-neutron reactions such as (d,n) and (p,n) reactions, neutron inelastic angular distributions and angular correlations, triple-scattering experiments, nuclear lifetime measurements, and charged-particle time-of-flight measurements.

b. Planned Experimental Program with Neutron Beams at the Dynamitron

A. J. Elwyn, A. S. Langsdorf, Jr., J. E. Monahan, F. P. Mooring, and W. G. Stoppenhagen

With the proper choice of the neutron-producing target, the Dynamitron accelerator will provide a partially-polarized neutron beam with well-defined energy over an interval from ~20 keV to ~20 MeV. This beam is expected to be from 10 to 100 times more intense than that available at the 4-MeV Van de Graaff machine. This increase in intensity, together with the possibility of pulsing the beam, makes feasible a number of "low-yield" measurements that can provide detailed information about nuclear structure and nuclear reactions.

Part of the program of neutron experiments that will be carried out at this facility will be an extension of previous measurements of angular distributions and polarization distributions to include triple scattering. A brief description of this and other areas of research that are being considered follows.

(i) Triple (Elastic) Scattering of Neutrons

These measurements, which determine both the initial and final states of polarization of the neutrons, provide the basis for the design of a set of experiments to determine all of the S-matrix elements for reactions with spin-zero scatterers. Such complete information is of interest only in special cases. One example is scattering in the resonance region of light nuclei where it may be possible to compare the observations with calculations that employ "realistic" nucleon-nucleon forces.

In general, however, it seems more practical to select only that subset of experiments that bear most directly on a specific question of interest. For example, as described in Sec. I. Bc, one of the set of triple-scattering measurements at small scattering angles provides a measure of the compound elastic cross section. These measurements will permit an investigation of structure in the neutron strength function (as a function of excitation energy). In conventional measurements this structure is generally obscured by shape-elastic contributions. The observation and identification of any intermediate

structure in the strength function of a nuclear reaction is an important area of current research.[1] Obvious extensions of the single-particle optical model depend on the existence and identification of these simple (intermediate) excitations.

Triple-scattering measurements provide also the possibility of obtaining other information about the optical-model potential. For nonzero-spin scatterers that are not polarized, these measurements are no longer complete. Again, however, a select subset of such measurements is sufficient to provide information about the magnitude of the spin-spin term in the optical potential. Also, at neutron energies ~10 MeV, small-angle polarizations should yield some information about the radial dependence of the nuclear spin-orbit potential.

One experiment that will make use of a polarized target is being considered, namely the scattering of polarized neutrons from a polarized hydrogen target. One purpose of this measurement is to determine the isospin triplet phase shifts for low-energy n-p scattering.

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[1] J. E. Monahan and A. J. Elwyn, Phys. Rev. Letters 20, 1119 (1968); A. J. Elwyn and J. E. Monahan, Nucl. Phys. A123, 33 (1969).

(ii) Inelastic Scattering of Neutrons

Measurement of the polarization of n' and the n'-γ angular correlation in (n,n'γ) reactions initiated with polarized neutrons offers several interesting possibilities. The n'-γ correlation reveals whether a spin flip has occurred in the reaction and, in scattering from an isolated resonance, determines the spin of the resonance. This, together with a left-right asymmetry measurement of n', indicates whether a true compound nucleus was formed in the reaction. It remains to be determined whether such measurements permit a unique separation of direct and compound-nucleus processes, particularly at energies at which resonances overlap. To the extent that this

is possible, such data would yield information that is particularly relevant to statistical reaction theories.

(iii) Neutron Absorption

The accuracy of the self-indication method in the measurement of neutron absorption cross sections has been demonstrated in the measurement[1] of the $^{10}B(n,\alpha)$ cross section. A similar measurement of the $^{6}Li(n,\alpha)$ cross section is planned. These reactions are commonly used as secondary flux standards and are also of interest as examples of possible α clustering in light nuclei.

[1] F. P. Mooring, J. E. Monahan, and C. M. Huddleston, Nucl. Phys. 82, 16 (1966).

(iv) Neutron Reactions Leading to Three-Body Final States

Measurements that determine sufficient kinematic variables for a unique definition of a three-body final state have yielded useful information about final-state interactions. In particular, quite interesting resonance interference effects can be studied in this type of experiment. A survey of such measurements that seem practical at the Dynamitron will be made in the near future.

(v) Spontaneously-Fissioning Isomers in Neutron-Induced Reactions

In the last few years there has been considerable interest in the existence and properties of short-lived spontaneously-fissioning isomers of nuclei in the actinide region of the periodic table. Most of the information related to isomer production is at present based on experiments with charged-particle beams—although, recently, short-lived isomeric activity has been observed in neutron-induced fission experiments.[1] Studies have in general centered on the

[1] A. J. Elwyn and A. T. G. Ferguson, Proceedings of the Second Symposium on the Physics and Chemistry of Fission, Vienna, 28 July-1 August 1969 (International Atomic Energy Agency, Vienna, to be published). See also Sec. I. Bf.

measurement of both the half-life of the isomeric state and its production cross section. However, the accuracy of these measurements has been limited. More accurate half-life determinations as well as systematic measurements of the energy dependence of the isomer production cross sections in a number of different reactions are needed. The values of these experimental quantities are related to the excitation energy and spin of the isomeric states, as well as to the height of the potential barrier governing the fission process. Thus, such isomer studies can provide quantitative information about some of the properties of the recently-proposed double-humped structure in the deformation dependence of the nuclear potential energy. The pulsed-beam facility that will be available at the Dynamitron should prove useful in studies of isomer production in neutron reactions as well as in various other aspects of the neutron-induced fission process at neutron-beam energies of $\sim 0.1 - 20.0$ MeV.

c. Small-Angle Scattering of Neutrons

F. T. Kuchnir, A. J. Elwyn, J. E. Monahan, A. Langsdorf, Jr., and F. P. Mooring

Two potential energy terms that are generated by the interaction between a neutron and the Coulomb field of a target nucleus may contribute measurably to the elastic scattering of neutrons through small angles ($\lesssim 15^{\circ}$ for high-Z nuclei). These terms are: (i) the $\vec{\mu} \cdot \vec{H}$ interaction between the magnetic moment of the neutron and the magnetic field of the "moving" target, and (ii) the αE^2 interaction between the Coulomb field $\vec{E}$ and the dipole moment $\alpha \vec{E}$ induced in the neutron by the field.

In an effort to observe and make use of these interactions, the differential cross sections and polarizations of neutrons elastically scattered from several heavy nuclei have been measured[1] at the Argonne

[1] F. T. Kuchnir, A. J. Elwyn, J. E. Monahan, A. Langsdorf, Jr., and F. P. Mooring, Phys. Rev. 176, 1405 (1968).

4-MeV Van de Graaff accelerator. These measurements covered a range of scattering angle from 1.75° to 15° for incident neutron energies between 0.6 and 1.6 MeV. The energy spread of the primary neutron beam was such that the measured cross sections and polarizations were averaged over many resonances. Analysis of these data has led to the following conclusions: (a) A left/right asymmetry measurement of neutrons scattered through angles less than $\sim 10^{\circ}$ provides a polarization analyzer that is calibrated simply in terms of the transmission of the scatterer and the known scattering of the $\vec{\mu} \cdot \vec{H}$ interaction. (b) An upper limit $\alpha \lesssim 2 \times 10^{-40}$ cm^3 can be assigned to the polarizability of the neutron.

The increase in beam intensity available from the 4-MeV Dynamitron, which was installed recently at Argonne, makes practical the consideration of a number of modified small-angle measurements. Two such possibilities are described below.

The small-angle differential cross sections for neutron scattering in the neighborhood of a single resonance are considerably more sensitive to the αE^2 interaction than are the energy-averaged measurements described above. Calculations indicate that values of α of the order 10^{-42} cm^3 could be detected by decreasing the energy spread of the primary beam to a value not greater than the width of an isolated resonance in the compound system. A determination of the value of α accurate to 10^{-42} cm^3 would provide meaningful information about the internal structure of the neutron.

A measurement of the polarization perpendicular to the direction of motion of neutrons scattered through small angles can be shown to be equivalent to a measurement of the compound-elastic cross section of the scatterer. Such "triple-scattering" measurements thus provide a means of separating direct from compound-nucleus processes and provide information about the mechanism of a nuclear reaction. Any fine structure in the compound elastic cross section as a function of neutron energy would indicate the formation of

states of intermediate complexity as stages through which the system evolves to the final compound-nucleus state. The identification of such intermediate excitations could be of considerable interest. The existence of "few-particle" or collective excitations is necessary to — and could provide the basis for — a simple description of the scattering process. Finally, the separate measurement of shape-elastic and compound-elastic cross sections should be of value in the study of corrections to the statistical theory of nuclear reactions arising from particle emission that may occur before the compound nucleus is formed.

d. Properties of the 3.39-MeV State in ^{12}B

F. P. Mooring, J. E. Monahan, and R. E. Segel

The 3.39-MeV state in ^{12}B appears as a resonance in the $^{11}B + n$ system at a (laboratory) neutron energy of 20.8 ± 0.5 keV. Neutron scattering and transmission measurements (Fig. 11)

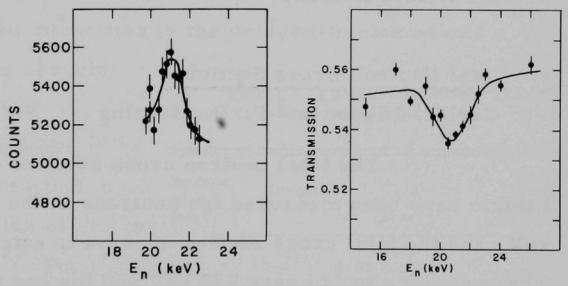

Fig. 11. The 21-keV resonance as observed in scattering (left) and in transmission (right).

have been made in the neighborhood of this resonance.[1] Comparison of these results with $^{11}B(d,p)$ data indicates that the resonance is d-wave and that its spin and parity is 3^-. For this assignment the neutron data indicate that $\Gamma_n = 3.1 \pm 0.6$ eV, which is about equal to the Wigner limit. Neutron capture measurements, in which the residual ^{12}B

[1] F. P. Mooring, J. E. Monahan, and R. E. Segel, Phys. Rev. 178, 1612 (1969).

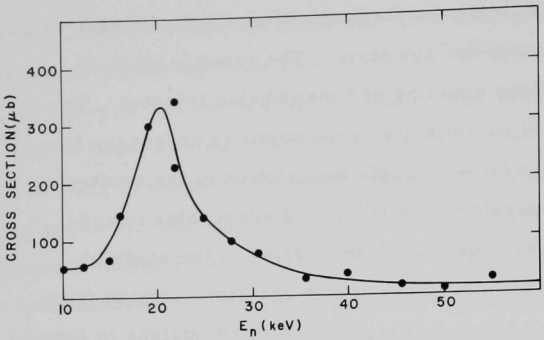

Fig. 12. Yield curve of ^{12}B activity from the neutron bombardment of ^{11}B. The neutron energy resolution was poorer than it was for the scattering and transmission measurements. The yield integrated over the resonance is independent of the energy resolution, although the apparent cross section at any one energy is, of course, very dependent on the energy resolution.

activity was observed (Fig. 12), were also carried out in the neighborhood of the resonance. These data yield a total radiation width $\Gamma_\gamma = 0.025 \pm 0.008$ eV. The 18.36-MeV state in ^{12}C appears to be the $T_z = 0$ analog of this state. A paper based on this work has appeared in the Physical Review.[1]

e. Total Neutron Cross Sections

Carl T. Hibdon and F. P. Mooring

The total neutron cross sections of ^6Li and natural lithium have been measured for neutrons in the energy range 10—1235 keV, and the total cross section of ^7Li was extracted from the results. The resonance in ^6Li near 250 keV and the one in ^7Li near 260 keV are being analyzed.

The absorption cross section of ^6Li has been measured from 10 to 100 keV. It is planned to extend these measurements to higher energies.

The total neutron cross sections of Al and Mg have been measured up to 640 keV. Measurements were made by the transmission method. Flat-detection measurements were made over the entire region and self-detection over the resonances. The data on Al

are being used to analyze the resonances. Only a small number of the many resonances in Al can be attributed to s-wave levels. The average level spacing of all levels is about 23 keV.

f. Spontaneously-Fissioning Isomers in Neutron-Induced Reactions*

A. J. Elwyn and A. T. G. Ferguson†

We have searched for short-lived spontaneously-fissioning isomers in neutron-induced reactions on various isotopes of U and Pu. The pulsed proton beam from the IBIS electrostatic accelerator at Harwell was utilized to produce 0.55- and 2.2-MeV neutrons in pulses of between 1 and 2 nsec duration. Fission fragments from the bombardment of thin foils of the fissile samples were detected in a Si surface-barrier counter and the time distribution of the pulses was measured relative to the proton beam pulse with a time-to-amplitude converter. The results based on numerical analyses of the observed time distributions are shown in Table I. The ratios listed in the last column are the integrated intensities in the delayed-fission events relative to the intensities associated with the prompt-fission process. As seen in the table, short-lived activities are found in the neutron-induced fission of ^{233}U, ^{234}U, ^{235}U, and ^{239}Pu. These activities are probably associated with the (n, γ) reactions on the targets listed, so that the data are consistent with the existence of fissioning isomers in ^{234}U,

TABLE I. Lifetimes associated with spontaneous fission induced by neutrons.

Neutron energy (MeV)	Target	$\tau_{1/2}$ (nsec)	$R = \frac{\text{Delayed}}{\text{Prompt}}$ ($\times 10^{-4}$)
2.2	Pu^{239}	29.0 ± 3.8	4.1
		4.1—5.2	39
	U^{233}	30.4 ± 4.9	4.7
	U^{234}	19.7 ± 4.9	1.2
	U^{235}	66.6 ± 8.7	3.1
	U^{238}	No lifetime observed	
0.55	U^{233}	34.9 ± 4.5	7.4

*See also Sec. I. Bb(v).

†Nuclear Physics Division, Atomic Energy Research Establishment, Harwell, Berks., England.

^{235}U, ^{236}U, and ^{240}Pu. Of particular interest is the apparent existence of two lifetimes associated with isomers in the nucleus ^{240}Pu.

C. RESEARCH AT THE TANDEM VAN DE GRAAFF ACCELERATOR

The FN tandem Van de Graaff accelerator provides the principal research tool for about 15 Argonne scientists in the Physics Division and several in the Chemistry Division. Also, running time is made available to qualified physicists from universities. Currently research groups from six universities are using the system.

The tandem is used to full capacity on an operating schedule of 24 hours per day. A terminal voltage of 8.5 million volts is attained with ease and 9.0 MV has been achieved on occasion.

The research carried out at the Tandem is very broad in scope, reflecting the diverse interests of the physicists involved. The general features of the work have not changed greatly during the past year, although there have been some significant changes in emphasis. Perhaps the most noteworthy of these is the start of a series of measurements on heavy-ion reactions. These measurements are very difficult because of low counting rates, and it is only because of the availability of a large fully-automated scattering chamber that the measurements are feasible. These are probably the first nuclear-physics experiments in which the positions of the detectors are automatically changed by a computer to satisfy kinematic requirements of the reaction, and it is doubtful if the measurements could be carried out in any other laboratory. In view of the rapidly growing interest in heavy-ion reactions, these pioneer experiments are likely to attract widespread attention.

Another major technical development in the past year has been the installation of a split-pole magnetic spectrograph. This instrument, which has unusual efficiency and accuracy, is expected to be used very heavily during the coming year; our increasingly more sophisticated automatic plate scanner will be a valuable asset in keeping pace with the output of this spectrograph.

The individual experiments, some of which are seen in Fig. 13, are described below. However, since the detail of these descriptions and the great diversity of the work tend to obscure the more general features of the research, we first outline some of the basic ideas and trends of the program.

Analog States. The remarkable relationship between the "isobaric analog states" in nuclei was discovered in 1962 and the basic characteristics of these states have been the subject of continuing intense interest. However, now these states are also becoming an important tool for obtaining spectroscopic information. Work at Argonne has pioneered in using analog states for the study of particle-hole states in complex nuclei.

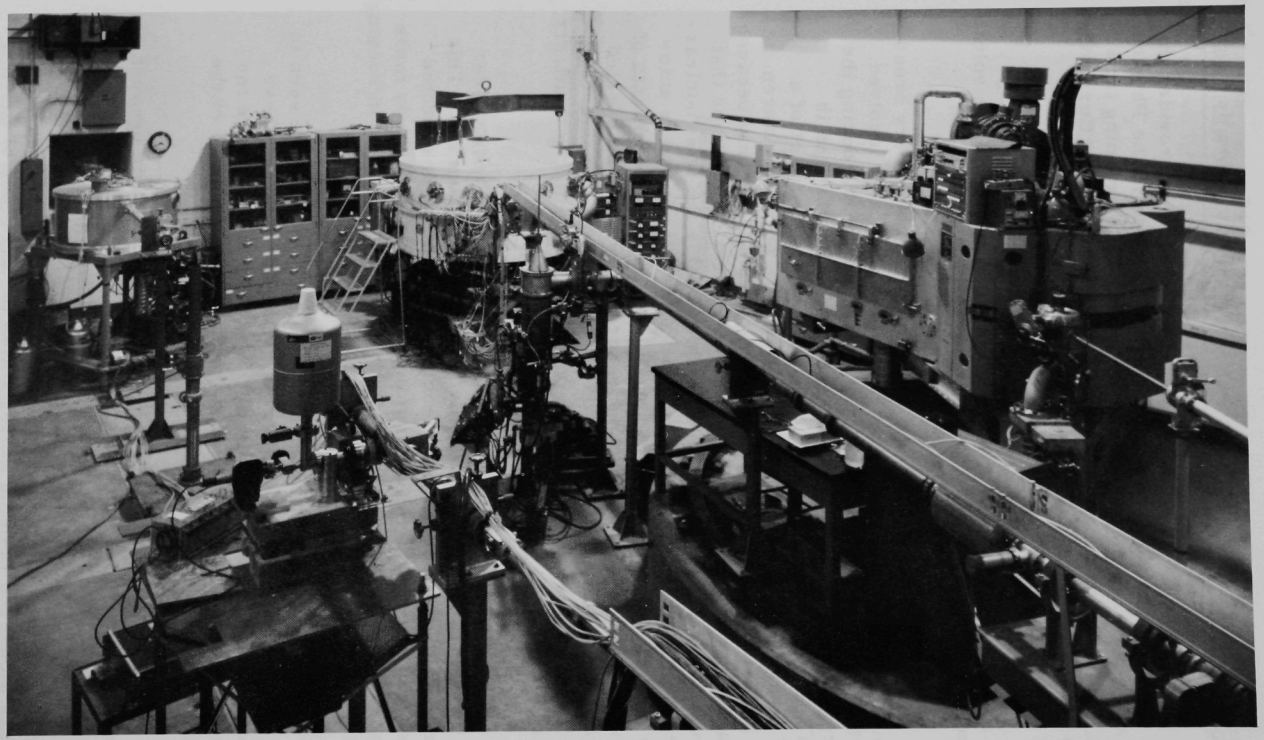

Fig. 13. Apparatus in the west target room at the tandem Van de Graaff in November 1969. The 6-gap orange β-ray spectrometer (Sec. I. Ee) is shown in the left background, the computer-controlled 70-in. scattering chamber (Sec. I. C1f, g) in the center background, and the new split-pole magnetic spectrograph (Sec. I. C1c) at the right.

Coulomb Energies and Matter Radii. The energies of analog states also contain important information on nuclear radii. Work at Argonne has recently focused attention on at least two new phenomena in the behavior of nuclear matter radii as derived from analog-state energies.

Neutron-Proton Correlations. Although identical-nucleon pairing correlations in complex nuclei have been known for some time and are understood reasonably well, virtually nothing is known about the correlations between neutrons and protons. Experiments are being carried out at Argonne to search for such effects.

Higher Isospin States. The gamma-ray decay of states of higher isospin than the ground state has been of considerable interest at Argonne both experimentally and theoretically. Studies of (p,γ) T-forbidden resonances and the decay systematics observed in $(^3He,p\gamma)$ angular-correlation measurements show interesting simple features that had been predicted in shell-model calculations at Argonne.

Transfer Reactions on Deformed Nuclei. Particle-transfer reactions on deformed nuclei were first studied with high resolution at Argonne and there is a continuing interest in the subject. So far most of the experimental information is limited to neutron stripping and to energies above the Coulomb barrier. With the new magnetic spectrograph we expect to be able to extend these investigations to particle-pickup and to proton-stripping reactions. These measurements will yield much useful information about collective states in nuclei.

Heavy-Ion Scattering. The observation of pronounced gross structure in the excitation function of $^{16}O + ^{16}O$ has created considerable interest in heavy-ion elastic scattering. The sophisticated computer-controlled scattering chamber mentioned earlier is being used to extend the measurements to a variety of heavy-ion systems such as $^{16}O + ^{24,26}Mg$. The observed structure is expected to provide a good understanding of the heavy-ion nuclear potential.

Reaction Mechanisms. In this area Argonne work has contributed heavily with the discovery of j dependence in angular distributions and with one of the first and most careful systematic experimental tests of the distorted-wave theory. Studies on j-dependent effects are still being carried out in order to obtain a more complete understanding of the phenomenon.

1. TANDEM OPERATION AND EQUIPMENT

a. Operation of the Tandem Van de Graaff Accelerator

Jack R. Wallace

The FN tandem operated 5058 hours in the period from 1 April 1968 to 14 March 1969. This accelerator has consistently exceeded its guaranteed operating specifications. Much valuable data has been obtained with accelerator terminal voltages of 8.5 MV. Many electronic improvements have been made at the control console. A new control circuit (designed and built by the Electronics Division) has been installed and has cut the energy fluctuation to less than half. It also has additional control features that allow greater ease of working with higher charge states of heavy ions. Several modifications in the electronics of the ion source facilitate work with heavier ions.

b. University Use of the 12-MeV Argonne Tandem

J. P. Schiffer and F. P. Mooring

Interest in the outside-users program has remained strong during the last year. Though several universities no longer participate in the program, other participants have increased their use of the Tandem facility and additional ones have expressed a desire to join the program.

The following experiments are currently active at the Tandem or have recently been completed.

(1) Multiple Coulomb Excitation and Reorientation Effect*

R. P. Scharenberg, J. A. Thomson, Jr., R. Beyer, and W. Lutz

Purdue University, W. Lafayette, Indiana

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*Completed.

(2) Studies of Energy Levels in Light Nuclei

C. P. Browne, G. Marolt, A. F. Hrejsa, E. Berkowitz, A. Rollefson, and J. Sobol

Notre Dame University, South Bend, Indiana

(3) Scattering of Alpha Particles

P. P. Singh, D. W. Devins, D. Plummer, J. Kroepfl, R. Li, R. Verma, T. Marvin, and T. Hall

Indiana University, Bloomington, Indiana

(4) J Dependence of Inelastic Scattering

J. C. Legg and D. R. Abraham

Kansas State University, Manhattan, Kansas

(5) Properties of Nuclear Energy Levels

Gerald Hardie

Western Michigan University, Kalamazoo, Michigan

(6) Nuclear Reactions Induced by Lithium Beams

Richard R. Carlson and H. W. Wyborny

The University of Iowa, Iowa City, Iowa

(7) Low-Lying Levels of ^{151}Eu[†]

E. Bernstein, R. E. Shamu, and G. Boss

Western Michigan University, Kalamazoo, Michigan

The following individuals who have received their doctorate during the past year have based their theses wholly or in part on research performed at the Argonne tandem Van de Graaff accelerator:

Notre Dame University, South Bend, Indiana

John R. Duray

William D. Callender

Purdue University, W. Lafayette, Indiana

Gerhardt Schilling

David W. Grissmer

Indiana University, Bloomington, Indiana

Alvin H. Sauter

Bruce Watson (AMU-ANL predoctoral fellow)

[†] Completed.

c. Split-Pole Magnetic Spectrograph

J. R. Erskine

Our new split-pole magnetic spectrograph is undergoing final focusing adjustments and energy calibration and will shortly be producing new data. This instrument will replace our older Browne-Buechner spectrograph which has led a long and productive life. The new instrument is superior to the old one in energy resolution, solid angle, lower background, larger maximum energy, and greater range of energies simultaneously recorded. We have built our own camera system which is designed to give superior mechanical reproducibility and greater ease of use.

Experience with our older spectrograph has shown that different experimenters will make many different uses of the new spectrograph. For example, in research with the older spectrograph, the present writer uncovered several problems in deformed nuclei, and plans to pursue these further. Prominent among these problems are (1) the reaction mechanism of charged-particle reactions on deformed nuclei and (2) the nature of vibrational levels in odd-A deformed nuclei. The better resolution and larger solid angle should make it possible to study individual vibrational levels.

Other experimenters as well as the author will use the instrument as a general-purpose tool for investigations of specific nuclei. The special properties of the new instrument will be exploited, for example, in studies of close multiplets or of reactions with very low cross sections.

d. Automatic Plate-Scanning Machine

J. R. Erskine and R. H. Vonderohe*

A new type of high-resolution scanning tube has been installed. Initial tests show that this tube gives at least twice as

*Applied Mathematics Division.

much detail on a single scan as did the older scanning tube. The computer program and operating procedure have not yet been changed to fully exploit this improved scanning tube. However, on the basis of previous experience, we expect a considerable improvement in our ability to scan poor-quality plates with weak tracks.

Routine use of the machine continues as before for plates with good-quality tracks. We expect much of the data from the new split-pole spectrograph (Sec. I. C1c) to be scanned by the machine.

e. Polarized-Ion Source

D. von Ehrenstein and D. C. Hess

The source for polarized ions (protons and deuterons) at the Argonne tandem is basically completed and the initial tests were successful. The last major event was the repeated observation of polarization (30% was achieved during the first attempt). To test this polarization the beam had to be accelerated by the Tandem and brought onto a target in the regular 18-in. scattering chamber. At the exit of our source and after mass analysis, negative-ion currents of up to 25 nA have been observed. Actual values of polarizations and currents are quoted with great reluctance because they are only first-performance results obtained without a good acquaintance with the machine and without the optimization of parameters that would be achieved during routine operation. Work with the facility has been discontinued, at least for the present.

f. 70-in. Scattering Chamber

J. L. Yntema

The scattering chamber has operated under computer control this year. It was necessary to develop a secondary system for indication of the angular position of the arms. The programs used

with the system were expanded considerably. Further development of the programs and modifications of the control circuits will be necessary to exploit the potential of the instrument. In addition, a change in the target mounting arrangement and better protection of the instrument against power failure and misuse are necessary improvements.

g. Computer-Controlled Multiple-Detector System for Heavy-Ion Scattering Experiments

R. H. Siemssen, J. Bicek, H. T. Fortune, J. W. Tippie,* and J. L. Yntema

The study of heavy-ion reactions is complicated by the low counting rates associated with the thin targets and small solid angles necessary to achieve adequate energy resolution. These deficiencies can be at least partly compensated for by the use of relatively inexpensive large-area detectors with appropriately-shaped apertures in conjunction with the associated-particle method for particle detection and identification. For systems of nonidentical particles, however, the associated-particle method is impractical if large arrays of detectors are to be used—the reason being that the kinematic conditions change with angle. In the present setup, these difficulties are overcome by use of the Argonne computer-controlled 70-in. scattering chamber (Fig. 14). Arrays of up to 12 large-area detectors (10 × 50 mm) similar to those in a previous experiment are used. The detectors are mounted on four independent arms that are remotely controlled by an on-line computer so that their positions satisfy the kinematic conditions for each pair of detectors operated in coincidence and for each angle setting of the master arm. Rectangular apertures in front of the detectors and in the beam collimation system maximize beam transmission and detection efficiency; and a rotating

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*Applied Mathematics Division.

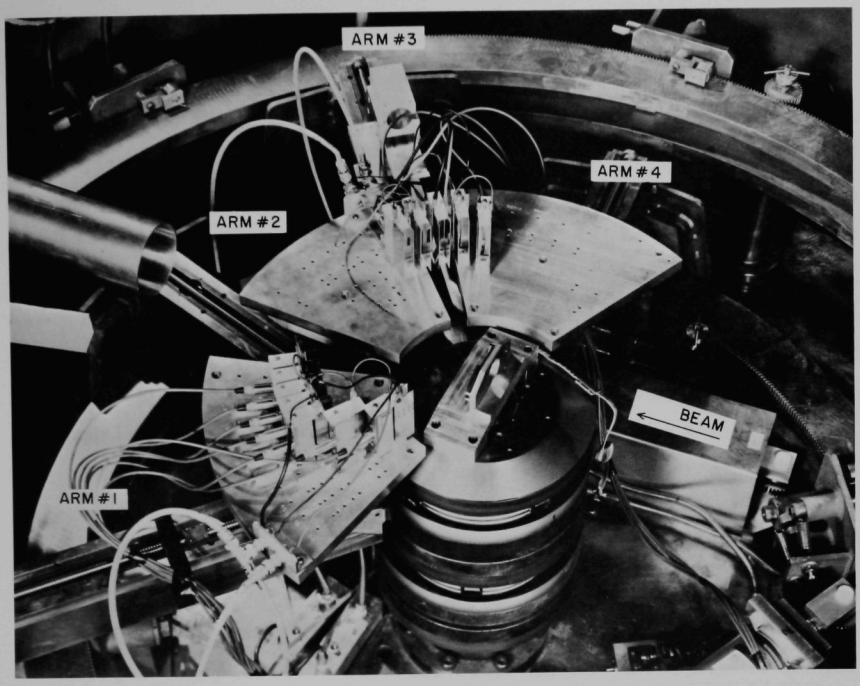

Fig. 14. Interior view of the computer-controlled 70-in. scattering chamber at the tandem, showing the arrays of detectors mounted on the four arms.

target is under construction. Four two-dimensional (64 × 128) coincidence spectra of 8192 channels each are multiplexed into the 96-k direct-access external memory and subsequently analyzed with the light-pen facility.

2. STUDIES WITH LIGHT TARGETS (A < 16)

a. Lifetime of the First Excited State in ^{8}Li

M. J. Throop,* G. C. Morrison, and D. H. Youngblood†

The attenuated-Doppler-shift technique has been utilized to measure the lifetime of the 981-keV state in ^{8}Li populated in the

*University of Iowa, Iowa City, Iowa.

†Texas A & M University, College Station, Texas.

reaction $D(^7Li,p)^8Li$ induced by the ^7Li beam from the University of Iowa Van de Graaff. The beam energy, after passage through a thin nickel window, was 7.4 MeV. With a 20-cc Ge(Li) detector at 0° to the beam, the typical energy difference between a fully shifted (D_2 gas target, 1.5—2.5 cm Hg) and an attenuated (ZrD target, 110 or 140 $\mu g/cm^2$) gamma ray was found to fall in the range 500 ± 200 eV, depending on experimental conditions. About 170 eV of this difference can be attributed to the difference in energy loss in the two targets. The ZrD targets were found to contain substantial amounts of oxygen with an O/Zr atomic ratio of 1.1. The calculations of energy loss and stopping power took such an oxygen content into account. The Doppler-shifted ^8Li peak located at 1016 keV was found to be significantly contaminated by the 2101—1080-keV transition in ^{18}F from the $^{12}C(^7Li,n)^{18}F$ reaction. An additional contaminant line (source unidentified) was located at 1015 ± 1 keV and was correlated in intensity with lines in the spectra induced by neutron reactions. Corrections for the effects of the contaminant lines were made for three separate groups of D_2 and ZrD measurements made under slightly different experimental conditions. The resulting net D_2—ZrD energy difference was 410 ± 190 eV, which leads to a deduced ^8Li lifetime of 9.6 ± 4.4 fsec. Because of the high initial recoil velocity ($v_0 \approx 1.2 \times 10^9$ cm/sec), it was only necessary to consider electronic stopping in the derivation of this result.

b. Direct Reactions on ^{10}Be

D. L. Auton

A ^{10}Be target has been prepared from beryllium enriched by the AREMIS isotope separator in the Chemistry Division. Angular distributions from the (d,p), (d,t), (p,p'), and (d,d) reactions on ^{10}Be were obtained with this target. Protons leading to the ground state and first excited state of ^{11}Be at 12.0 MeV incident energy indicate

spin and parity assignments of $\frac{1}{2}^+$ and $\frac{1}{2}^-$, respectively. At an incident deuteron energy of 15.0 MeV, tritons could be detected up to an excitation of 5.5 MeV in ^{9}Be. No evidence was seen for an $\ell=1$ transition to known states of less than 3.0 MeV excitation in ^{9}Be, other than that to the ground state. Spectroscopic factors for observed states in the (d,p) and (d,t) reactions were extracted with the code JULIE. Elastic and inelastic scattering of protons was observed on ^{10}Be at several energies from 12.0 to 16.0 MeV. The elastic scattering was compared with optical-model calculations, and values of B(E2) for the 3.37-MeV $(2^+) \rightarrow (0^+)$ transition were obtained with the code JULIE. Spectroscopic information concerning transitions within the 1p shell is in good agreement with the calculations of Cohen and Kurath.

c. The ^{11}B(d,p)^{12}B Reaction at 17.0 MeV

J. R. Comfort, H. T. Fortune, and J. Maher

As part of a continuing program to investigate the highly excited states of light nuclei, a study of the ^{11}B(d,p)^{12}B reaction has been initiated. A 17.0-MeV beam of deuterons, a self-supporting ^{11}B target, and the Brown-Buechner magnetic spectrograph are being used. Spectra covering the excitation region between 3.2 and 11.5 MeV have been obtained at forward angles. It is expected that the data will shed light on the analog nature and structure of the T=1 state in ^{12}C. The results will be correlated with those from other charged-particle reactions leading to final states in ^{12}B and ^{12}C.

d. Deuteron Elastic and Inelastic Scattering from ^{11}B

J. C. Legg, D. Abraham, H. T. Fortune, R. C. Bearse, and J. L. Yntema

Further attempts have been made to understand the mechanism responsible for the observed J dependence in (d,p) reactions on light nuclei. In attempts to assess the properties of the entrance

channel, deuteron elastic and inelastic scattering from these light nuclei should be studied. In the present experiment, data were obtained for the $^{11}B(d,d)$ and $^{11}B(d,d')$ scattering processes by using four ΔE-E counter telescopes simultaneously. Detailed angular distributions were measured in 1-MeV steps from 12.0 MeV to 17.0 MeV. In addition, excitation functions were measured at four angles in 50—100-keV steps over the same energy range. The analysis of the data is just beginning.

e. Energy Variation of J Dependence in the $^{11}B(d,p)^{12}B$ Reaction

H. T. Fortune, R. C. Bearse, J. Maher, J. C. Legg, J. Comfort, and J. L. Yntema

In a continuing study of the energy dependence of the $\ell=1$ J dependence in stripping reactions, the $^{11}B(d,p)^{12}B$ reaction has been studied over the bombarding energy range 12—17 MeV. For this reaction the $\ell=1$ ground-state transition proceeds roughly 85% via $\Delta J = \frac{1}{2}$, and 15% via $\Delta J = \frac{3}{2}$. At 12 MeV this ground-state angular distribution is very similar to that for the $^{12}C(d,p_0)^{13}C_{g.s.}$ reaction. Since the J dependence for $^{12}C(d,p)^{13}C$ gradually disappeared as the bombarding energy was increased, it was of interest to study the $^{11}B(d,p)^{12}B$ reaction also. The analysis of the data is continuing. Preliminary results indicate that the angular distributions at 16 MeV are similar for the $^{11}B(d,p)$ and $^{12}C(d,p)$ reactions.

f. Energy Variation of J Dependence in the $^{12}C(d,p)$ Reaction

H. T. Fortune, R. C. Bearse, J. L. Yntema, and H. Ohnuma

The $^{12}C(d,p)^{13}C$ reaction has been measured over the bombarding energy range 9.6—17 MeV. Neither the J dependence nor the magnitude of the forward-angle maximum appears to be correlated with the narrower structure ($\Gamma \lesssim 1$ MeV) in the $^{12}C + d$ system around 12 MeV. There does, however, seem to be a correlation

with the large resonance-like bump centered at 12 MeV and having a width of several MeV. Earlier analyses had shown that the experimentally-extracted spectroscopic factor for the $^{12}C(d,p_0)^{13}C(g.s.)$ reaction had a resonance-like structure centered at about 12 MeV. Those analyses yielded a value $S_{exp}/S_{th} \approx 2.0$ at 12 MeV, slowly decreasing to $S_{exp}/S_{th} \approx 1.0$ at 17 MeV. In the present measurements, the J-dependent dip at about $\theta_{c.m.} = 90^{\circ}$—which is characteristic of $\Delta J = \frac{1}{2}$ transitions—slowly disappears as the bombarding energy is increased from 12 to 17 MeV. The dip is almost completely absent at 17 MeV.

g. Deuteron-Induced Reactions on ^{12}C

H. T. Fortune, R. C. Bearse, J. L. Yntema, and H. Ohnuma

Recent measurements of deuteron-induced reactions in light nuclei for bombarding energies around 12 MeV have indicated contributions to the reaction mechanism other than simple direct processes. The ^{12}C + d system seemed to be of special interest. Thus, we have obtained data for the (d,d), (d,d'), (d,p), and (d,α) reactions on ^{12}C. Angular distributions of these d-induced reactions were obtained at 1-MeV intervals from 10 to 17 MeV. In addition, excitation functions at several angles were measured in 50-keV steps from 11 to 17 MeV. Preliminary analysis indicates a correlation of the gross structure in the various exit channels.

h. Excitation Functions for ^{3}He-Induced Reactions on ^{12}C

H. T. Fortune and N. Williams

The $^{3}He^{++}$ beam from the tandem and self-supporting C foils were used to measure excitation functions from 18 to 24 MeV. Data were taken at four forward and four backward angles. Yield curves were obtained for elastic and inelastic scattering and for the $^{12}C(^{3}He,\alpha)^{11}C$ reaction leading to states in ^{11}C below 8.1 MeV.

The back-angle yield curves show resonance-like structure having widths of a few MeV. This structure is present in all the exit channels. At forward angles the cross sections are generally smooth monotonic functions of the energy. Preliminary analyses indicate that the structure may be due to "optical-model" resonances in the $^{12}C + {}^{3}He$ system.

3. STUDIES WITH TARGETS IN THE RANGE $16 < A < 40$

a. Study of the Low-Lying $T=\frac{3}{2}$ States in ^{21}Na

R. C. Bearse, J. C. Legg, G. C. Morrison, and R. E. Segel

In a continuing study of the gamma-ray decay of $T=\frac{3}{2}$ states in $T_z = -\frac{1}{2}$ nuclei, the $^{20}Ne(p,\gamma)$ reaction has been investigated. Because analog states have simpler configurations than do the $T_<$ states nearby, their gamma decay can be quite strong and comparison with simple nuclear models becomes tractable. The resonances observed at 8.973 and 9.216 MeV correspond to the analogs of the ground state and first excited state of ^{21}F, respectively. A Ge(Li) detector was used in a detailed study of their γ-ray de-excitation to the low-lying $T=\frac{1}{2}$ excited states in ^{21}Na, with the result that the two resonances were assigned $J^{\pi} = \frac{5}{2}^{+}$ and $\frac{1}{2}^{+}$, respectively. Since the low-lying states of ^{21}Na are well described by the rotational model, the observed gamma-ray branching ratios (Fig. 15) were compared

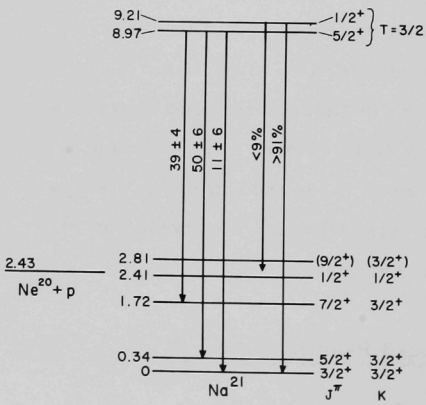

Fig. 15. Gamma-ray branching ratios for the two lower $T=\frac{3}{2}$ states in ^{21}Na.

with the predictions of the Nilsson model. The model indicates that only the $K = \frac{1}{2}^+$ parts of the analog-state wave function participate in the gamma-ray decay, so no measurement of the K mixing in the analog states themselves is provided. However, the fact that the branching ratios are consistent with the predictions of the model does indicate that the $K = \frac{3}{2}$ strength is approximately the same for each of the first three states of ^{21}Na. This supports a previous conclusion from a study of the lifetimes of the low-lying states of ^{21}Ne.

b. States in ^{21}Na from the ^{24}Mg(p,α) Reaction

G. C. Morrison, R. C. Bearse, R. Boudrie, W. Pickles,* and E. Kashy*

The reaction ^{24}Mg(p,α)^{21}Na has been studied at an incident proton energy of 35.0 MeV on the variable-energy cyclotron at Michigan State University. States have been observed in ^{21}Na to an excitation energy of 9 MeV, and the angular distributions of the emitted alphas have been determined. The motivation for the experiment arises both from an attempt to establish the reaction mechanism of the (p,α) reaction in the sd shell and from our interest in the low-lying states in ^{21}Na per se (Sec. I. C3a). Of particular interest is the location of the low-lying negative-parity levels which may also be compared with those recently established in the mirror nucleus ^{21}Ne. The ^{26}Mg(p,α)^{23}Na reaction is now being studied for comparison with the present results on ^{21}Na.

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*Michigan State University, East Lansing, Michigan.

c. Structure of Odd-Odd Nuclei in the 2s-1d Shell

R. C. Bearse, H. T. Fortune, and G. C. Morrison

Very few (d,p) reactions leading to odd-odd nuclei in the 2s-1d shell have been studied at bombarding energies above 8 MeV. At these lower energies, the analysis of the data is complicated

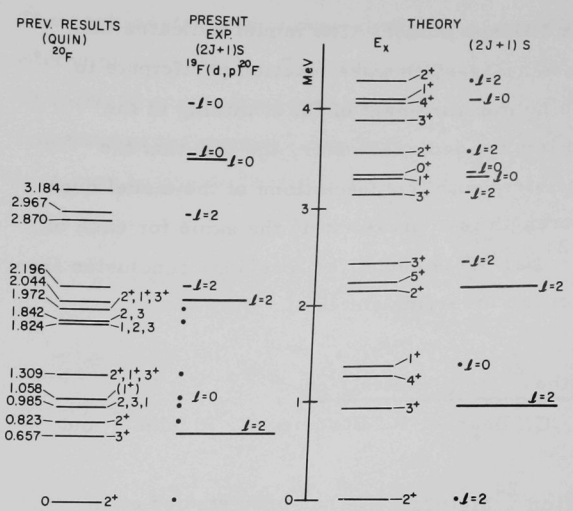

Fig. 16. Comparison between experimental and theoretical spectroscopic information on ^{20}F.

by the presence of reaction mechanisms other than direct stripping. We have measured several of these reactions at a bombarding energy of 16 MeV, where the direct-reaction mechanism is expected to dominate. Because of the large number of closely-spaced levels, it was necessary to use a magnetic spectrograph and photographic emulsions to obtain the data. For the $^{19}F(d,p)$ reaction the data have been analyzed and distorted-wave calculations have been carried out. Figure 16 shows the comparison between the spectroscopic information obtained and the results of recent shell-model calculations on ^{20}F. Measurements on the $^{23}Na(d,p)$ and $^{27}Al(d,p)$ reactions have been completed.

d. Study of the $^{27}Al(^3He,p)^{29}Si$ and $^{27}Al(^3He,p\gamma)^{29}Si$ Reactions

L. Meyer-Schützmeister, D. S. Gemmell, R. E. Holland, F. T. Kuchnir, H. Ohnuma, and N. G. Puttaswamy

The levels of ^{29}Si have been studied with angular distributions of the $^{27}Al(^3He,p)^{29}Si$ reaction. A few states, in particular the level at 8.310 MeV (the analog of the ^{29}Al ground state), have been

strongly excited with an orbital-angular-momentum transfer $L = 0$ leading to states with $J = \frac{3}{2}^+$, $\frac{5}{2}^+$, and possibly $\frac{7}{2}^+$. The γ decay of some of these levels has been studied by p-γ coincidences.

In continuation of our earlier work on $^{39}K(^3He, p\gamma)^{41}Ca$, the γ decay of the analog state was of special interest. For sd-shell nuclei, it had been shown that whenever an unpaired nucleon with its magnetic moment due to spin parallel to that due to orbital motion (e.g., a $d_{5/2}$ or $f_{7/2}$ nucleon) is coupled to a core with isospin T_c to form an analog state with $T = T_c + \frac{1}{2}$, a strong M1 transition to the antianalog is expected; but an analog state consisting of the core and an unpaired $d_{3/2}$ nucleon with its magnetic moments antiparallel is expected to show only a weak transition to its antianalog. The earlier work on the $^{39}K(^3He, p\gamma)^{41}Ca$ reaction has shown that indeed the gamma transition between the analog with $J = \frac{3}{2}^+$ and $T = \frac{3}{2}$ at 5.832 MeV and its antianalog at 2.017 MeV with $T = \frac{1}{2}$ and $J = \frac{3}{2}^+$ is weak. Here the analog state consists of an unpaired $d_{3/2}$ hole coupled to a core with $T_c = 1$, $J_c = 0$ to form a state with $T = \frac{3}{2}$, $J = \frac{3}{2}$. In the present experiment the studied analog state at an energy of 8.31 MeV in ^{29}Si has an unpaired $d_{5/2}$ hole and a strong transition to its antianalog is expected. Our experimental results on the γ decay of this state show that the transition strengths to two $\frac{5}{2}^+$ states are the largest. In particular, the $\frac{5}{2}^+$ state at 4.906 MeV seems to be the best candidate for the antianalog—especially since also the absolute gamma strength is comparable to that of other strong M1 transitions between analog and antianalog states.

Similar investigations for nuclei in the f-p shell have been initiated by L. Meyer-Schützmeister and J. Smith.

e. Study of the $(^3He, d)$ Reaction for $A \approx 31$

Richard A. Morrison

The $(^3He, d)$ reaction on targets of ^{30}Si, ^{31}P, and ^{32}S has been produced by 15-MeV ^3He particles—and on ^{34}S targets by

13-MeV ^{3}He. Angular distributions were measured at $\sim 3^\circ$ intervals from 7° to 45° and at $\sim 5^\circ$ intervals from 45° to $\sim 90^\circ$, and absolute cross sections were deduced. The data on ^{31}P and ^{30}Si at E(^{3}He) = 15 MeV were used to test ^{3}He optical models; deuteron optical models were tested against available data. Levels were analyzed to 7.15 MeV excitation in ^{31}P, 6.62 MeV in ^{32}S, 2.85 MeV in ^{33}Cl, and 5.76 MeV in ^{35}Cl by use of the DWBA code Julie, and ℓ-value assignments and spectroscopic factors were obtained. The spectroscopic factors are in reasonable agreement with those of previous (^{3}He,d) reactions on ^{30}Si and ^{31}P targets. On the basis of the Nilsson model, a comparison of the spectroscopic factors deduced from the ^{30}Si(d,p)^{31}Si reaction and those from the ^{32,34}S(^{3}He,d)^{33,35}Cl reactions suggests that the chlorine isotopes are less deformed than ^{31}Si.

f. The ^{30}Si(α,pγ)^{33}P Reaction

G. Hardie, R. E. Holland, L. Meyer-Schützmeister, F. T. Kuchnir, N. G. Puttaswamy, and H. Ohnuma

The proton-gamma coincidences in this reaction have been measured as a function of the angle between the proton detector and the gamma detector. The proton detector, an annular surface-barrier detector, is located at 180° to the incident beam. As Ferguson and Litherland have pointed out, in many cases this particular geometric arrangement simplifies the spin assignment of states in the final nucleus. We have been able to determine the spin as well as the gamma branching ratios of a few levels in ^{33}P. These results allow not only a comparison with calculated level schemes but also with measured gamma-decay schemes of similar nuclei such as ^{31}P and ^{29}P. We feel that more measurements on ^{33}P are needed for such a comparison and we intend to continue the studies on ^{33}P by using the reaction ^{34}S(d,^{3}He)^{33}P. This reaction had been applied earlier but only for the very lowest states in ^{33}P. It seems to us that we should be able to extract spectroscopic factors and transferred ℓ values for

the higher excited states as well if we have the cyclotron available in connection with the magnetic spectrograph which is now being installed.

4. STUDIES ON NUCLEI WITH $40 \leq A < 70$

a. Lifetimes of the First Three Excited States in ^{40}K

R. E. Segel, N. G. Puttaswamy, and N. Williams

The attenuated-Doppler-shift technique was used to measure the lifetime of the second and third excited states in ^{40}K. These two states plus the ground state and first excited state have been described as a $d_{3/2}^{-1} f_{7/2}$ quartet, in which case all of the magnetic dipole transitions between these states are governed by the same reduced matrix element. The lifetime of the first excited state has been measured by Holland and Lynch [Sec. I. Eb(ii)]. For the second excited state we find 0.8×10^{-13} sec and for the third excited state 2×10^{-12} sec. The lifetime for the second excited state is somewhat longer than that predicted theoretically but, when all the errors are considered, can perhaps be brought into agreement. However, the lifetime of the transition from the third excited state to the ground state is at least twice as long as can be explained by the model.

b. Multipole Decomposition of Two-Body Multiplets

J. P. Schiffer, M. Moinester,* and W. P. Alford*

A Legendre multipole analysis has been carried out for all known particle-particle, particle-hole, or hole-hole spectra near closed shells. This procedure was suggested long ago by J. B. French, but only recently did sufficient data become available, namely measurements on ^{208}Bi, ^{210}Bi, ^{92}Nb, ^{48}Sc, ^{50}Sc, and ^{42}Sc. The

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*University of Rochester, Rochester, New York.

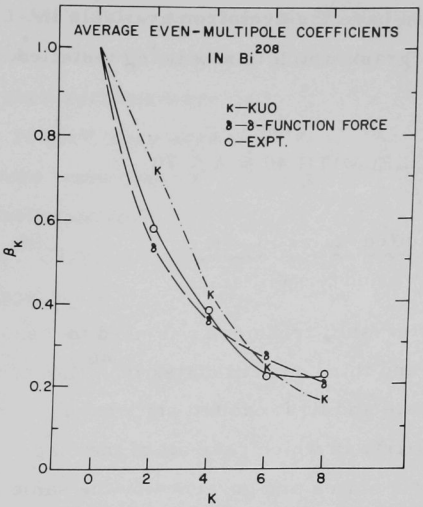

Fig. 17. A comparison of even-multipole coefficients. The coefficients, extracted from four particle-hole multiplets in Bi^{208} and averaged, are compared with those expected for a delta-function force and for an effective interaction used in a shell-model calculation by Kuo.

multipole coefficients (Fig. 17) derived from experimental spectra reflect the range of the effective two-body force. The results indicate a short-range effective interaction; in fact, a delta-function force reproduces the extracted coefficients very well.[1]

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[1] M. Moinester, J. P. Schiffer, and W. P. Alford, Phys. Rev. 179, 984 (1969).

c. Gamma-Ray Decay in ^{43}Ca

R. E. Segel, N. Williams, and N. G. Puttaswamy

A 500-μg/cm^2 ^{42}Ca target backed by gold was bombarded with 3-MeV deuterons to form the states of ^{43}Ca through the $^{42}Ca(d,p)$ reaction. Gamma-ray spectra taken with a Ge(Li) detector in coincidence with protons feeding the second and third excited states support the previously reported decay of these states. However, in contrast to the previous report that the chief decay of the 1.389-MeV fourth excited state is an 80% branch to the 0.993-MeV third excited state, this state was found to decay mainly by a 1.015-MeV transition to the

first excited state. The present work puts an upper limit of about 20% on this 396-keV transition and requires an increase in the accepted log ft value for the β branch from ^{43}K to the fourth excited state of ^{43}Ca. Doppler-shift measurements on gamma rays originating from the first four excited states indicate that in each case the lifetime is long compared to the slowing-down time in calcium, with the observed shift nowhere more than about 10% of the full shift.

d. Study of the $^{48}Ca(^{3}He,t)^{48}Sc$ Reaction

H. Ohnuma, J. R. Erskine, J. P. Schiffer, J. A. Nolen, Jr., and N. Williams

Further information about the energy levels of ^{48}Sc has been obtained from the spectra and angular distributions observed with the $^{48}Ca(^{3}He,t)^{48}Sc$ reaction. The angular-distribution information, together with other outside information, has enabled us to make the spin assignments $J^{\pi} = 7^{+}$, 2^{+}, and 1^{+} for the 1095 ± 5, 1145 ± 5, and 2526 ± 5 keV excited states, respectively. The ground state and the states at 133 ± 2, 253 ± 2, and 624 ± 4 keV had previously been assigned $J^{\pi} = 6^{+}$, 5^{+}, 4^{+}, and 3^{+}, respectively, by other workers. Interpretation of these data is being assisted by new data from the $^{50}Ti(d,\alpha)^{48}Sc$ reaction (taken at the University of Minnesota). The $(^{3}He,t)$ reaction is also being used to study other medium-weight nuclei.

e. The $^{50}Ti(d,p)^{51}Ti$ Reaction

J. L. Yntema, H. Ohnuma, and H. T. Fortune

In a continuing study of the energy variation of the J dependence for $\ell=1$ transitions, the $^{50}Ti(d,p)^{51}Ti$ reaction was studied at energies between 12 and 17 MeV. Elastic scattering in the incident channel was also measured. Analysis of the data is still in progress. Preliminary results indicate that the conventional distorted-wave Born approximation can at least qualitatively explain the $\ell=1$ J dependence in the 2p shell.

f. Correlated States in Medium-Mass Nuclei

H. T. Fortune, G. C. Morrison, J. P. Schiffer, and B. Zeidman

Counters were used in an attempt to observe correlated states in medium-mass nuclei which result from the transfer of two and four particles into degenerate orbitals. These states are expected to show enhanced cross sections in reactions such as (^{7}Li,t), (^{6}Li,d), or perhaps (^{3}He,p) on targets of Ca, Ti, Ni, or Sn. While preliminary studies have not produced any positive results, it is clear that competing reactions and contaminants present a technical problem. Improvements in technique, as well as use of the split-pole spectrograph, should enable us to obtain definitive evidence concerning the existence of correlated states.

g. Interpretation of Coulomb Energies

J. A. Nolen, Jr., and J. P. Schiffer

A computer code has been developed to calculate single-particle wave functions in a Woods-Saxon well and then evaluate Coulomb energies with such wave functions. Exchange and electromagnetic spin-orbit effects are also calculated. Experimental values of Coulomb energies for isobaric analog states in the Ca and Ni isotopes had been measured in this laboratory previously. They have been analyzed with the aid of this program, as have Coulomb energies in mirror nuclei and those for Sn and Pb isotopes. This analysis leads to the conclusion that the distribution of nucleons contributing to the isobaric analog state has a radius very similar to that of the core,

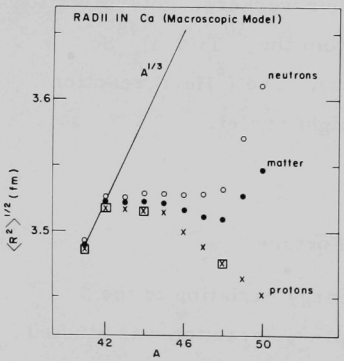

Fig. 18. Rms neutron and matter radii derived from charge radii and Coulomb energies in the Ca isotopes.

for which both proton and neutron orbits are occupied. This result cannot be explained by any simple single-particle potential model of the nucleus nor is it explained by published Hartree-Fock calculations.[1] Another result seems to be that throughout the Ca isotopes the neutron and proton radii remain approximately constant (Fig. 18) while in the Ni isotopes they increase as neutrons are added (Fig. 19). This may be the result of the difference in polarizabilities of the ^{40}Ca core by $1f_{7/2}$ neutrons and the ^{56}Ni core by $2p\text{-}1f_{5/2}$ neutrons.[2]

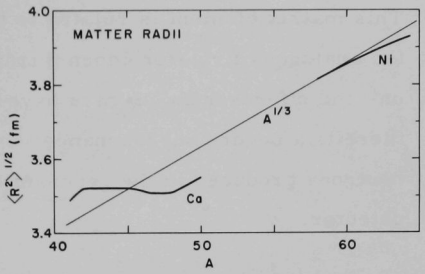

Fig. 19. The trend in rms matter radii for Ca and Ni isotopes (heavy line) plotted along with an $A^{1/3}$ line (light).

[1] J. A. Nolen and J. P. Schiffer, Phys. Letters 29B, 396 (1969).

[2] J. P. Schiffer, J. A. Nolen, and N. Williams, Phys. Letters 29B, 399 (1969).

5. STUDIES ON NUCLEI WITH $70 < A < 140$

a. Electric-Dipole Transition from the $2d_{5/2}$ Isobaric Analog Resonance to the $2p_{3/2}$ Ground State in ^{87}Rb

R. C. Bearse, J. V. Maher, G. C. Morrison, and A. Richter

We are attempting an experiment to detect the electric-dipole γ rays in the reaction ^{86}Kr(p, γ_0) from the $2d_{5/2}$ isobaric analog state $(2T_0)^{-1/2}T_-|i\rangle$ to the $2p_{3/2}$ ground state $|f\rangle$ in ^{87}Rb by use of a gas chamber and a Ge(Li) detector. The purpose of the experiment is to extract the matrix element of the E1 gamma transition, namely

$$|\langle f|m_\gamma T_-(2T_0)^{-1/2}|i\rangle|.$$

This matrix element is related to the matrix element $|\langle f|m_\beta|i\rangle|$ of the analogous first-forbidden β transition. In a preliminary experiment, on- and off-resonance γ rays have been observed. It is obvious that there is a severe on-resonance γ-ray background which arises because neutrons produced in the resonant (p, n) reaction interact in the Ge(Li) detector.

b. Low-Lying States of ^{103}Ru and ^{105}Ru from the ^{102,104}Ru(d, p) Reaction

H. T. Fortune, J. A. Nolen, Jr., P. Kienle, and G. C. Morrison

The ^{102,104}Ru(d, p) reactions on isotopically enriched targets were studied at a bombarding energy of 14 MeV. Angular

TABLE II. Energies and spectroscopic factors for states observed in ^{102}Ru(d, p)^{103}Ru and ^{104}Ru(d, p)^{105}Ru.

^{102}Ru(d, p)^{103}Ru			^{104}Ru(d, p)^{105}Ru		
E_x	ℓ	$(2J_f + 1)S$	E_x	ℓ	$(2J_f + 1)S$
0.000	2	1.40	0.000	2	1.34
0.170	0	0.85	0.094	(2)	(0.05)
0.213	(0)	(0.04)	0.140	0	0.79
	(4)	(2.4)	0.186	4	5.0
0.237	4	4.4	0.208	(0)	(0.02)
0.306	?	. . .		(4)	(1.7)
0.401	2	0.85	0.302	(0)	(0.02)
0.429	0	0.055		(2)	(0.05)
0.541	2	0.15	0.423	2	0.28
0.551	0	0.08	0.445	2	1.09
0.589	2	0.33	0.558	2	0.19
0.658	2	0.24	0.607	0	0.088
0.735	0	0.064	0.738	2	0.19
0.906	2	0.67	0.786	0	0.20
1.005	2	0.091	0.804	2	0.46
1.105	0	0.076	0.855	0	0.14
1.245	2	0.26	0.869	2	0.11
1.320	(2)	(0.05)	0.893	(2)	(0.11)
	(4)	(1.1)	0.973	2	0.15

distributions were obtained for the levels below E_x = 1.0 MeV (12 levels in ^{103}Ru and 17 levels in ^{105}Ru). The angular distributions were fitted with DWBA calculations in order to obtain ℓ values and spectroscopic factors. The ground-state transitions in both nuclides have ℓ = 2. Both ^{103}Ru and ^{105}Ru have low-lying $\frac{1}{2}^+$ states (E_x = 0.170 MeV in ^{103}Ru and 0.140 in ^{105}Ru).

The target thicknesses were obtained by measuring the elastic scattering at extreme forward angles at low energies and comparing with Rutherford scattering. The absolute spectroscopic factors obtained for states in both ^{103}Ru and ^{105}Ru are shown in Table II. The emptiness of the $g_{7/2}$ shell agrees with other measurements in the region A ≈ 110.

c. Coulomb-Excitation Studies of the Low-Lying Excited States of ^{105}Pd

H. H. Bolotin and D. A. McClure

Coulomb-excitation studies of the odd-mass nuclide ^{105}Pd were undertaken to test suggestive evidence that collective effects may be present in nuclides in this mass region. A determination of the reduced E2 excitation probabilities to the low-lying excited states of ^{105}Pd is clearly significant for an understanding of any collective behavior associated with these states. In this study, a thick target enriched in ^{105}Pd was bombarded with alpha particles from the Argonne tandem Van de Graaff at seven energies from 4.4 to 8.0 MeV. A large-volume, high-resolution Ge(Li) detector was employed in conjunction with a 4096-channel pulse-height analyzer to view the de-excitation γ-ray transitions. A total of ten excited states up to an energy of ~800 keV were observed to be populated in this reaction; only two of these states had been reported in earlier Coulomb-excitation studies with a NaI(Tl) detector. The excitation of each of the ten excited states has been found to be consistent with excitation of the E2 type. The thick-target yields of 13 de-excitation transitions are presented

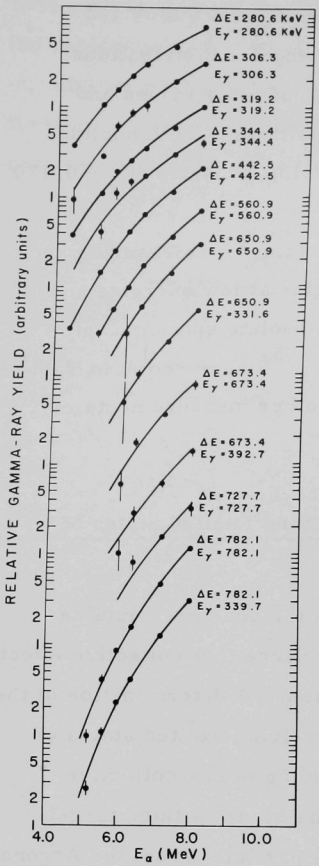

Fig. 20. Relative γ-ray thick-target yields obtained in this study. The points represent the data and the lines represent the normalized theoretical thick-target yields for E2 excitation of each state. The yields of all observed de-excitation γ rays are consistent with E2 Coulomb excitation.

in Fig. 20. The value of B(E2↑) has been determined for each state. Only two of these ten states show B(E2↑) values that are significantly enhanced over single-particle estimates and thus qualify as possible candidates for collective states. A level scheme summarizing the present findings on ^{105}Pd is shown in Fig. 21. These results were compared with the core-excitation model of Lawson and Uretsky[1] in an attempt to understand these enhanced transitions as collective excitations of the ^{104}Pd core. Although the B(E2) values obtained for these two levels are consistent with core-excitation expectations, other predictions of this model are not borne out experimentally. Thus the observed characteristics of the low-lying excited states of ^{105}Pd appear to be more complex than might have been anticipated. A strong similarity was found between the present results for ^{105}Pd and the work of others[2] in similar studies of the odd-mass ruthenium isotopes.

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[1] R. D. Lawson and J. L. Uretsky, Phys. Rev. 108, 1300 (1957); A. de-Shalit, Phys. Rev. 122, 1530 (1961).

[2] O. C. Kistner and A. Schwarzschild, Phys. Rev. 154, 1182 (1967).

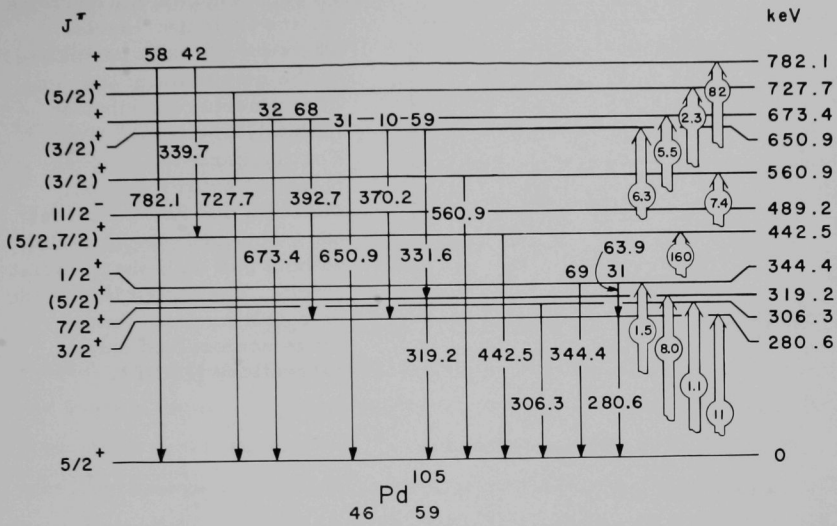

Fig. 21. Level scheme of ^{105}Pd up to an excitation energy of 782 keV. Only the transitions observed in this study are included. However, the $\frac{11}{2}^-$ state at 489.2 keV, observed in the β-decay studies but not in Coulomb excitation, is included so that all of the known excited states below 782 keV are displayed. The spins indicated on the left are those reported by other workers studying the β decay of ^{105}Ag. Doubtful spin assignments are enclosed in parentheses. The positive parities of states so marked are confirmed by their E2 Coulomb-excitation character. The branching ratios for the decay of each level are indicated above the appropriate transition and the energies (in keV) of the γ rays appear within the arrow representing the transition. The pot-bellied arrows represent observed E2 excitation, and the B(E2↑) values (in units of 10^{-51} e^2cm^4) appear in the bulges of the arrows.

d. Studies of the Barium Isotopes

G. C. Morrison, D. von Ehrenstein, N. Williams, and J. A. Nolen, Jr.

(i) The (d,p) Reaction

In the (d,p) studies on the barium isotopes, particular emphasis has been placed on the theoretical fitting of the measured

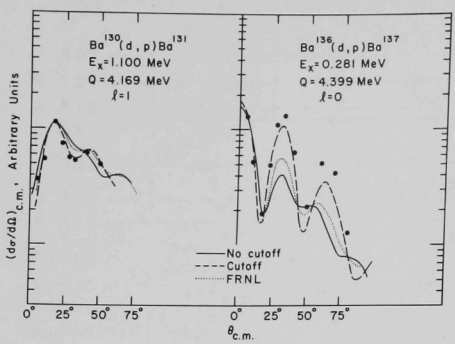

Fig. 22. Angular distributions for the indicated levels. The curves, each normalized to the maximum of the experimental distribution (points), are DWBA fits. For the zero-range local-potential approximation, the solid and dashed curves were obtained respectively without and with sharp radial cutoff. The dotted line is the fit resulting from finite-range nonlocal-potential corrections (FRNL).

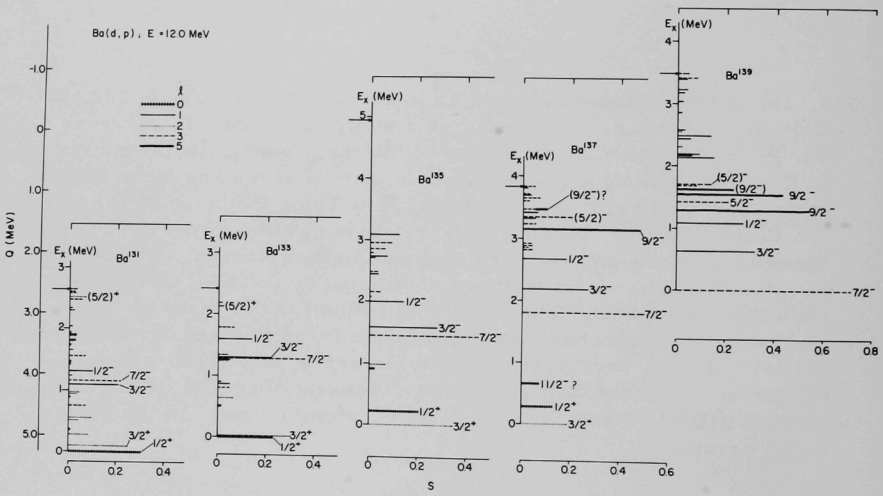

Fig. 23. Absolute spectroscopic factors S for states populated in (d, p) reactions on the even-mass barium target isotopes. These spectroscopic factors have been calculated with sharp radial cutoff (the same for all ℓ values) at about the nuclear surface; and with a radius r_n = 1.20 F and a diffuseness a_n = 0.70 F of the bound-state (neutron) potential well.

angular distributions and on the extraction of absolute spectroscopic factors. The DWBA calculations which were previously performed with zero-range and local potentials have been supplemented by calculations using finite-range approximations and nonlocal potentials. It is found that the shapes of the measured angular distributions cannot be fitted by these later calculations, but only by zero-range, local-potential DWBA calculations that include a radial cutoff—as seen in Fig. 22.

To extract reliable absolute spectroscopic factors, the absolute cross section has been carefully redetermined. This confirmed our earlier results although the values obtained are significantly different from those in the literature. To establish a confidence limit on the spectroscopic factors, additional calculations [discussed in Sec. I. C5d(ii)] have been performed to find their dependence on the rms radius of the bound-state (neutron) potential well. Slight variations of this rms radius produced sizeable changes in the spectroscopic factors; this effect often has not been recognized in the literature. Calculations were also made to determine how the spectroscopic factors are affected when the deuteron and proton wave functions are described by other sets of parameters. The overall results for the even-A target isotopes are displayed in Fig. 23.

(ii) Comparison of Spectroscopic Factors from (p, p_0) and (d, p) Reactions

In the studies of proton elastic scattering on the five stable even-even barium isotopes (masses 130—138), strong s-, p-, d-, and f-wave analog resonances have been observed. These can be related to the $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$ neutron single-particle levels above and the $3s_{1/2}$, $2d_{3/2}$ levels below the N=82 closed shell which are observed in the (d, p) reactions on the same targets. Spectroscopic factors from the two reactions have been compared by using the same

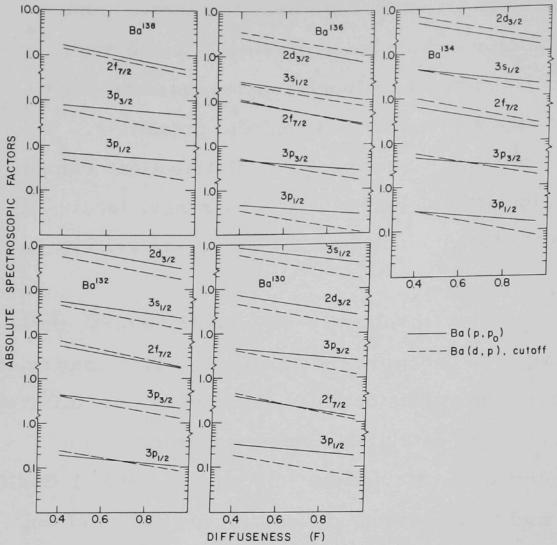

Fig. 24. Absolute spectroscopic factors from the Ba(p, p_0) and the Ba(d, p) reactions on the indicated targets. These were calculated for identical, fixed radii of the bound-state neutron potential well and the isospin-dependent nuclear well ($r_n = r_0 = 1.20$ F).

set of smoothly-varying optical-model parameters in the analysis of both processes. Their dependence on the mean-square radius of the optical potential is found to be slightly different for the (p, p) and (d, p) analyses. In principle then, the intersection of the (p, p) and (d, p) curves could provide a unique spectroscopic factor for each level and, in addition, values of the mean-square radius for each target. In the present analysis, however, no consistent crossover was found—as is seen in Fig. 24. [Actually, the differences between the (p, p_0) and the (d, p) curves become insignificant when the spread due to experimental errors and procedural uncertainties is taken into account.] The dependence of the proton-scattering analysis on the symmetry potential is being further examined.

6. STUDIES ON NUCLEI WITH 140 < A

a. ^{3}He-Induced Reactions in Rare Earth Nuclei

A. M. Friedman* and B. Zeidman

Preliminary runs at the cyclotron indicated the need for better resolution than is now available for (^{3}He,d) reactions. Subsequently, ^{3}He-induced reactions on a number of rare earth nuclei were briefly investigated at the tandem. These data showed that the (^{3}He,d) reaction will require long runs on many targets to provide an understanding of proton levels as complete as that already obtained for neutron levels. This survey also indicated, however, that the (^{3}He,α) reaction complements existing neutron-transfer data by preferentially exciting high ℓ values (ℓ = 4 or 5), in contrast to the (d,t) reaction which accentuates low ℓ values. A series of relatively short runs at several angles provided data on the location and strength of high-spin states in rare earth nuclei. Of particular interest was the location of the [505 $\frac{1}{2}$] state which had previously escaped detection in several nuclei. This work will be expanded so as to provide a clearer picture of the low-lying proton and neutron states in rare earth nuclei. Those studies will be facilitated by the use of the split-pole spectrograph which will allow the use of higher energy ^{3}He ions and a broader range of acceptable momenta.

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*Chemistry Division.

b. Coulomb Excitation of ^{185}Re and ^{187}Re

H. H. Bolotin and D. A. McClure

Coulomb-excitation studies of the odd-mass rotational nuclides ^{185}Re and ^{187}Re have been conducted at the tandem Van de Graaff in order to obtain a more detailed description of the low-lying excited states of these nuclei. The data are being analyzed to determine B(E2↑) for the states observed in this reaction.

c. Gross Structure Observed in Analog-State Studies on Heavy Nuclei

J. P. Schiffer, P. Kienle, and G. C. Morrison

The elastic and inelastic scattering of protons was studied with targets of ^{197}Au, ^{196}Pt, and ^{184}W. Excitation functions were obtained from 12.0 to 18.0 MeV. The structure observed in the elastic excitation functions (Fig. 25) is rather similar to that seen in scattering from ^{208}Pb, particularly in the vicinity of the $2g_{9/2}$ single-particle analog resonance. However, the fact that these effects are weaker indicates that the $2g_{9/2}$ configuration might be spread out among a number of states. For inelastic scattering (Fig. 26), the excitation function to the 2^+ state of ^{196}Pt bears some resemblance to the inelastic scattering from ^{208}Pb at corresponding energies; inelastic scattering to a state at ~2.6 MeV resembles the inelastic

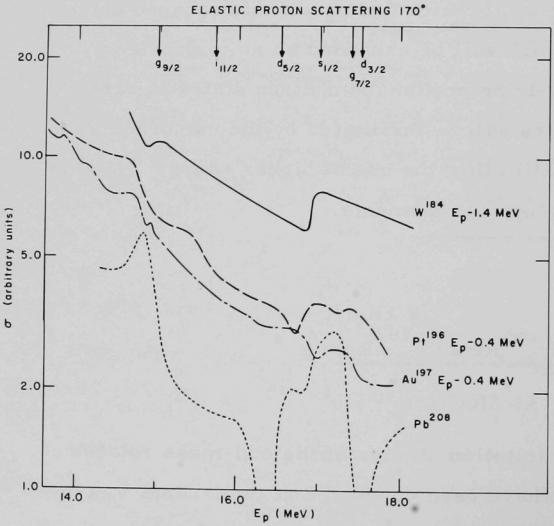

Fig. 25. Excitation functions for the elastic scattering of protons from ^{206}Pb, ^{197}Au, ^{196}Pt, and ^{184}W. The lines represent smooth curves drawn through the data points. The energy scales for the curves had been shifted by the amounts indicated in the figure to match ^{208}Pb data at what is believed to be the $g_{9/2}$ resonance. The single neutron states in ^{209}Pb are indicated by arrows at the top of the figure.

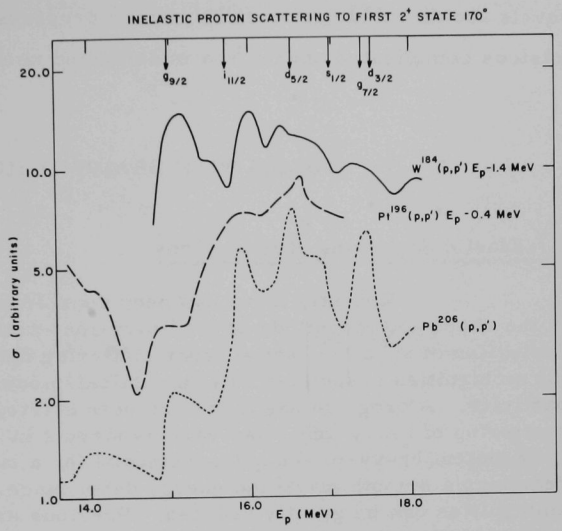

Fig. 26. Excitation functions for the inelastic scattering of protons to the first excited 2^+ states of ^{206}Pb, ^{196}Pt, and ^{184}W. The lines represent smooth curves drawn through the data points. The energy scales are adjusted exactly as in Fig. 25.

scattering to the 3^- state in Pb; and the observation that some higher states seem to resonate at the "$2g_{9/2}$" energy indicates a simple particle-hole structure. Some similar effects were also seen in the excitation function for inelastic scattering to the 2^+ state of ^{184}W.

d. Study of Actinide Nuclei with Charged-Particle Reactions

T. H. Braid, J. R. Erskine, and A. M. Friedman*

Our investigations of odd-A deformed nuclei in the actinide region has continued this past year with major emphasis on analysis and interpretation of the many spectra previously acquired. Our studies will be greatly aided by the new split-pole spectrograph (Sec. I. C1c). Its larger solid angle and better resolution will make it possible to obtain, for example, angular distributions of individual vibrational energy levels. Little is known experimentally about the wave functions of these levels. Our new instrument together with the experience we have gained in studying the deformed single-particle

*Chemistry Division.

levels should enable us to make further progress in understanding various complicated phenomena in deformed nuclei.

7. STUDIES WITH BEAMS OF HEAVY IONS

a. Elastic Scattering of Heavy Ions

Recently there has been considerable theoretical interest in the shape and magnitude of the heavy-ion—nucleus potential. The derivation of such a potential from scattering data is complicated by the ambiguities associated with the optical-model analysis of complex particles. A program has therefore been started to study the elastic scattering of heavy ions from various targets in an attempt to obtain a consistent heavy-ion—nucleus potential for a large set of data. By requiring a smooth mass and energy dependence, it is hoped that the ambiguities can be greatly reduced. Previous experience with excitation functions has shown that these are less subject to ambiguities in the potentials than are angular distributions. Also, in the presence of compound elastic scattering, fits to the gross structure in excitation functions were found to be better suited for deriving average potentials than were fits to individual angular distributions.

(i) $^{18}O + ^{16}O$ Elastic Scattering

R. H. Siemssen, H. T. Fortune, A. Richter, and J. W. Tippie*

In view of the striking gross structure found in the $^{16}O + ^{16}O$ excitation functions, a study of the $^{18}O + ^{16}O$ system is of considerable interest. Excitation functions measured at five angles from 70° to 100° in the center-of-mass system (Fig. 27) exhibit a marked and very regular diffraction pattern similar to that observed in the $^{16}O + ^{16}O$ scattering, although the peak-to-valley ratios are not as pronounced as in the latter. More significantly, the structure in the $^{16}O + ^{18}O$ excitation function is reproduced with optical-model parameters almost identical to those derived from the $^{16}O + ^{16}O$ scattering.

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*Applied Mathematics Division.

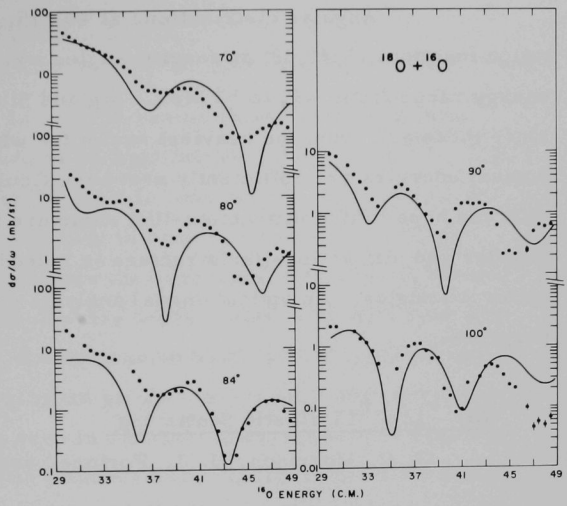

Fig. 27. $^{18}O + ^{16}O$ excitation functions at c.m. angles 70, 80, 84, 90, and 100°. The solid curve is the result of an optical-model calculation with parameters almost identical to those found for the $^{16}O + ^{16}O$ scattering.

(ii) ^{16}O Elastic Scattering from ^{24}Mg, ^{26}Mg, ^{28}Si, and ^{30}Si

R. H. Siemssen, H. T. Fortune, A. Richter, and J. Yntema

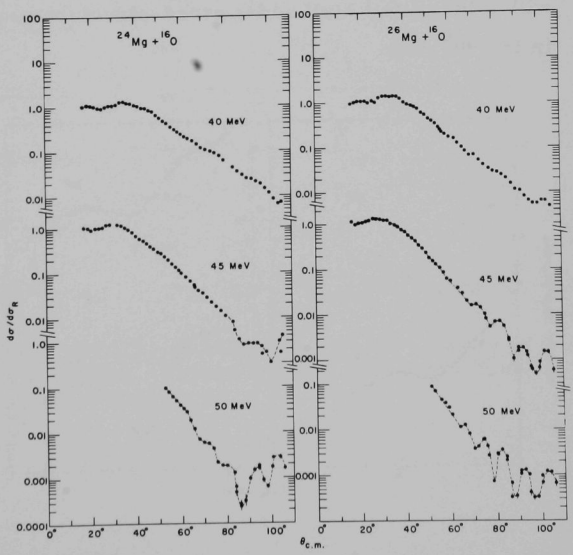

Fig. 28. Angular distributions from the elastic scattering of ^{16}O off ^{24}Mg and ^{26}Mg.

Angular distributions at 40, 45, and 50 MeV and excitation functions (Fig. 28) at several angles were measured in the energy range from ~35 to 52 MeV. Mg and Si were chosen as targets since these are about the heaviest nuclei for which the maximum FN tandem energies are sufficiently above the Coulomb barrier that one still can hope to find diffraction-like structure in the excitation functions. Regular and diffraction-like structure is indeed observed at the most backward angles. An optical-model analysis of these data is in progress.

(iii) ^{6}Li + ^{6}Li Elastic Scattering

G. C. Morrison, H. T. Fortune, and R. H. Siemssen

After ^{4}He + α, the lightest identical-particle system accessible to scattering studies is ^{6}Li + ^{6}Li. Elastic-scattering excitation functions were measured at four angles at c.m. energies from 5 to 17 MeV, and angular distributions were obtained at 6, 10, and 14 MeV. The excitation functions (Fig. 29) are relatively smooth, with a broad (~4 MeV wide) gross-structure peak centered at 13 MeV in the 90° data.

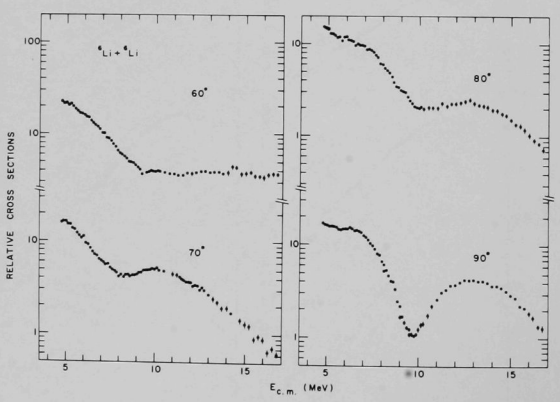

Fig. 29. Excitation functions from the ^{6}Li + ^{6}Li elastic scattering in the energy range from 4 to 16 MeV.

b. Li-Induced Reactions on Light Nuclei

J. R. Comfort, H. T. Fortune, G. C. Morrison, and B. Zeidman

Energetic ^{6}Li and ^{7}Li beams from the tandem have been used to study the structure of light nuclei. Targets of ^{10}B, ^{11}B, and ^{12}C were bombarded by 30-MeV Li ions and the emergent α, d, and t were detected simultaneously in counter telescopes. These studies are intended to investigate the correlated structure (clusters) of states in light nuclei and compare these results with data involving single-nucleon transfers. Excitations up to 25 MeV were observed in some nuclei, including a broad group at about 20.5 MeV excitation in ^{16}O. This state can be seen in the spectra reproduced in Fig. 30. This study is continuing with counters and will utilize the split-pole spectrograph when it becomes operational.

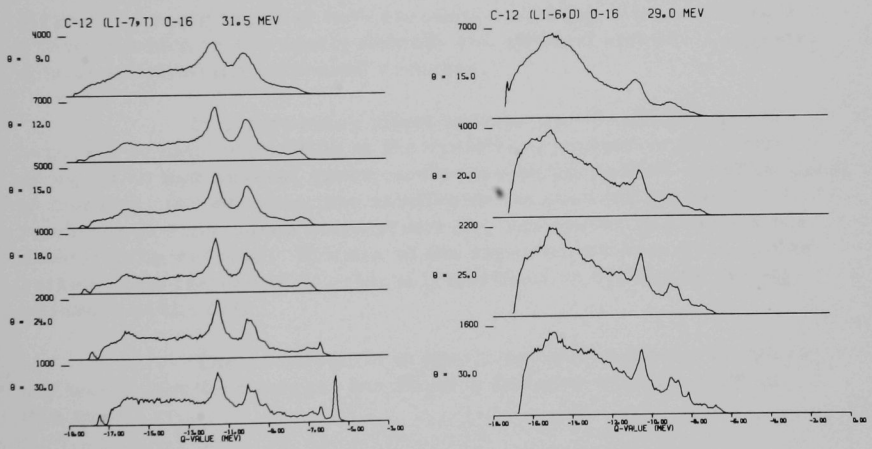

Fig. 30. Spectra for (^{7}Li,t) and (^{6}Li,d) reactions on ^{12}C. Angles and vertical scales are indicated. Ground-state Q values are 4.69 and 5.69 MeV, respectively.

c. ^{16}O-Induced Transfer Reactions

A. Friedman,* H. T. Fortune, G. C. Morrison, and R. H. Siemssen

The (^{16}O, ^{12}C) reaction has been utilized to study α transfer to nuclei in the calcium region. The reaction tends to populate several low-lying states with comparable cross sections. Typical cross sections are ~100 μb/sr in the region near $\theta_{c.m.} = 25^{\circ}$. The angular distributions are relatively smooth for an ^{16}O energy of 50 MeV. From the ^{40}Ca(^{16}O, ^{12}C)^{44}Ti reaction, five states in ^{44}Ti (previously unreported) were observed below an excitation energy of 5 MeV. Future plans include extending these studies to a wider range of nuclei.

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*Chemistry Division.

D. RESEARCH AT THE 60-in. CYCLOTRON

The 60-in. cyclotron is one of the low-energy accelerators operated by the Chemistry Division. The beam energies are fixed at 46.5 MeV for α particles, 36 MeV for ^{3}He, 23 MeV for deuterons, and 11.5 MeV for protons. These values are the maximum possible with the existing components. Two experimental areas, Tunnels I and II, are available for use. The beam-handling facilities allow use of three stations in Tunnel I for experiments with the unanalyzed beam and of two beam lines in Tunnel II for analyzed-beam experiments. In addition, the split-pole magnetic spectrograph is located in Tunnel I where the continuation of an unanalyzed beam line intersects a new analyzed beam line which passes through Tunnel II. An 18-in. scattering chamber and a 60-in. scattering chamber, located in Tunnel II, are used for counter experiments.

The beam-analyzing magnet system provides a resolution width $\leq 0.1\%$. To utilize the analyzed beam to the maximum extent, a split-pole magnetic spectrograph of the Enge type is being installed at the cyclotron. This design, with its broad momentum range and large solid angle together with excellent resolving power, provides a facility which is extremely flexible and efficient and which supplies data of substantially improved accuracy.

In a continuing effort to improve the efficiency and accuracy of data acquisition at the cyclotron, equipment has been designed so that several experiments may be performed simultaneously. In this way, for example, the relative cross sections for several reactions are measured more precisely, and systematic errors are substantially reduced. In many of the experiments described in this section, this feature is of critical importance in evaluating the significance of the data.

The cyclotron is in operation approximately 80 hours per week. On the average, the Physics Division uses 25—30% of this time.

1. REACTION MECHANISMS AND STRUCTURE OF LIGHT NUCLEI

a. ^{3}He-Induced Reactions on ^{12}C

H. T. Fortune and B. Zeidman

(i) Elastic and Inelastic ^{3}He Scattering

In this study, the angular distribution of scattered ^{3}He particles was measured at an incident energy of 35.6 MeV over the c.m. angular range 8—170°. These detailed measurements are at a higher energy than in previous studies. Striking features of these results are the very deep minimum in the elastic cross section at about 130° c.m. and the strong excitation of the 0^+ state at 7.6 MeV. The optical-model parameters obtained provide a reasonable fit to both elastic and inelastic scattering. To clarify some questions, the (^{3}He, ^{3}He'γ) reaction is to be investigated.

(ii) ^{12}C(^{3}He,α)^{11}C

The angular distributions of the ^{12}C(^{3}He,α)^{11}C reaction were studied at E(^{3}He) = 35.6 MeV. Since data were obtained in 1° steps over much of the range, a detailed theoretical fit to the data was attempted. While a satisfactory fit was obtained over the limited range up to about 70°, it was not possible to fit the entire angular distribution.

(iii) Assignment of $J^\pi = \frac{3}{2}^-$ for the 8.1-MeV State in ^{11}C

with J. R. Comfort and J. V. Maher

To determine the spin of the 8.10-MeV state in ^{11}C, we have measured the angular distributions for single-nucleon pickup and stripping reactions leading to it (Fig. 31). Previous single-nucleon-transfer reactions to this state have not yielded unambiguous ℓ-value

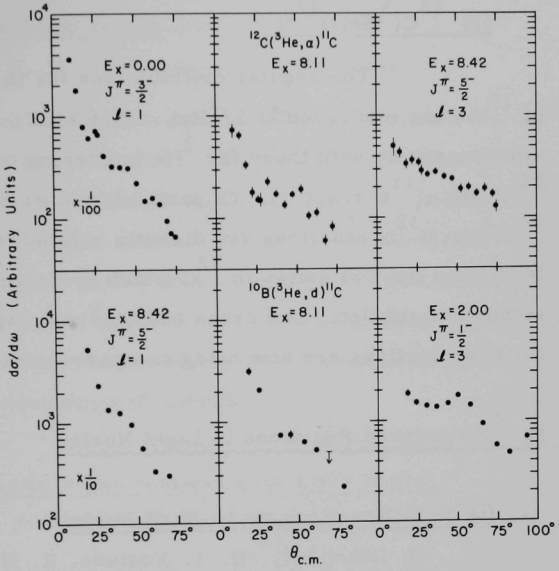

Fig. 31. Angular distributions of selected states excited in the $^{12}C(^3He,\alpha)^{11}C$ reaction at $E(^3He) = 35.6$ MeV (top) and in the $^{10}B(^3He,d)^{11}C$ reaction at $E(^3He) = 21.0$ MeV (bottom).

assignments, mainly because of the low bombarding energies. In the present work, the ^3He beam energies were 21 and 36 MeV for the $^{10}B(^3He,d)$ and $^{12}C(^3He,\alpha)^{11}C$ reactions, respectively. The assignment $\ell = 1$ in the $(^3He,\alpha)$ angular distribution to the 8.10-MeV level yields $J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$. The $^{10}B(^3He,d)$ angular distribution is dominated by $\ell = 1$. This leads to the unambiguous assignment $J^\pi = \frac{3}{2}^-$ since a $\frac{1}{2}^-$ state could not be reached from $^{10}B(J^\pi = 3^+)$ via $\ell = 1$.

(iv) $^{12}C(^3He,d)^{13}N$

This reaction was studied at $E(^3He) = 35.6$ MeV in an attempt to fit the angular distribution of the excited states in ^{13}N. These states are unbound and the usual formalism is not applicable to such states. The high energy of both emergent and incident beam allows the use of approximations not valid at lower energies. It is hoped that a consistent technique for the extraction of spectroscopic factors for unbound states may result.

(v) $^{12}C(^{3}He,t)^{12}N$

The angular distributions for the three lowest states of ^{12}N were measured at $E(^{3}He) = 35.6$ MeV. The data were obtained simultaneously with those for ^{3}He scattering on ^{12}C and for the $^{12}C(^{3}He,\alpha)^{11}C$ reaction. Of particular interest is the fact that the $^{12}C(^{3}He,t)^{12}N$ reactions are directly related to the inelastic scattering leading to the T=1 states in ^{12}C which are members of the same isobaric multiplet. The cross sections and angular distributions for the two reactions are now being compared with theoretical predictions.

b. ^{4}He-Induced Reactions in Light Nuclei

(i) (α,t) Reactions on 1p-Shell Nuclei

D. Dehnhard,* H. T. Fortune, R. H. Siemssen, and B. Zeidman

The (α,t) reaction on targets of ^{6}Li, ^{7}Li, ^{10}B, ^{11}B, ^{12}C, and ^{13}C have been studied at an incident alpha energy of 46 MeV. Angular distributions have been obtained over the approximate angular range $\theta_{c.m.} = 9-75^{\circ}$ for the transitions to the ground state and to excited states at 0.431 and 4.53 MeV in ^{7}Be; to states up to 8.10 MeV in ^{11}C; to states at 4.433, 7.66, 9.63, and 12.70 MeV in ^{12}C; to the doublet at 3.55 MeV in ^{13}N; and to states up to 6 MeV in ^{14}N. The data are consistent with the assumption of a direct interaction in which a proton is transferred from the incident alpha particle. These results are being compared with other proton-transfer reactions—e.g., $(^{3}He,d)$ and (d,n)—as well as with (α,t) data at two other energies. To date, DWBA calculations have reproduced the experimental angular distributions over only a limited angular range.

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*University of Minnesota, Minneapolis, Minnesota.

(ii) (α, d) Reactions on Light Nuclei

H. T. Fortune, R. H. Siemssen, and B. Zeidman

The (α, d) reaction on several 1p-shell nuclei has been investigated with 46-MeV alpha particles. The resolution is substantially better than in previously published data and allows for comparison with (^{3}He, p) reactions on the same nuclei. Of particular interest is the possible existence of a state at 1.7 MeV excitation in ^{9}Be which might be reached via the ^{7}Li(α, d)^{9}Be reaction. Our data show a peak in this vicinity, but it is not yet clear whether this corresponds to a state or to the very close continuum threshold.

(iii) Elastic and Inelastic Alpha Scattering on Light Nuclei

H. T. Fortune, J. Maher, R. H. Siemssen, and B. Zeidman

We have obtained preliminary data on the elastic and inelastic scattering of 46-MeV ^{4}He particles on light nuclei. This study is intended to provide suitable optical-model parameters for light nuclei and to test various descriptions for inelastic scattering. The bulk of the data is yet to be taken.

c. Reactions Resulting in Ions Heavier Than He

(i) ^{12}C + ^{3}He

H. T. Fortune and B. Zeidman

Angular distributions have been measured for emergent ^{7}Be, ^{9}Be, and ^{6}Li resulting from ^{3}He bombardment of ^{12}C at E(^{3}He) = 35.6 MeV. Data were obtained for all reaction products simultaneously. A typical energy spectrum is shown in Fig. 32. The angular distributions for ^{7}Be, ^{7}Be*, and ^{6}Li show a pronounced diffraction structure indicative of a direct reaction mechanism. In addition, the difference between the angular distributions for the ^{7}Be and ^{7}Be* (Fig. 33), both leading to the ^{8}Be ground state, suggest a

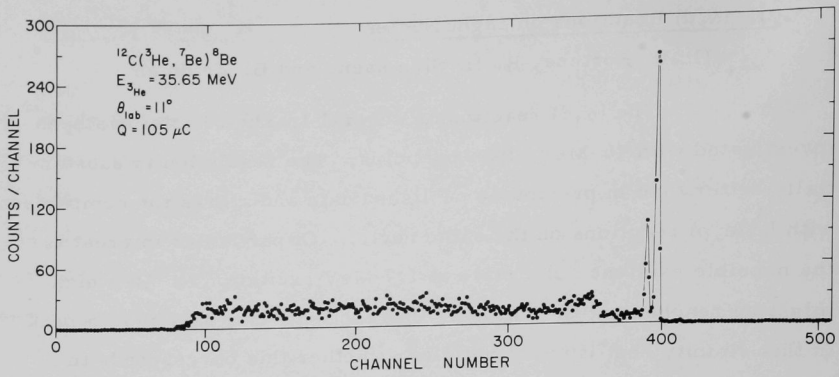

Fig. 32. Energy spectrum of ^{7}Be from the ^{3}He bombardment of ^{12}C.

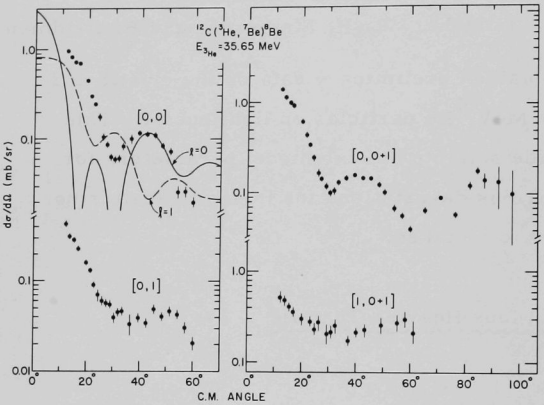

Fig. 33. Angular distributions for the $^{12}C(^3He, ^7Be)^8Be$ reaction. The notation [i,j] signifies that ^{8}Be is left in its ith excited state and ^{7}Be in its jth excited state. The curves are the result of preliminary zero-range DWBA calculations for the indicated values of ℓ.

J-dependent effect which may reflect the internal structure of ^{7}Be and $^7Be^*$. A study of the effect of the internal structure upon the angular distribution is being attempted.

(ii) Heavy Ions from ^{3}He-Induced Reactions on 1p- and 2s1d-Shell Nuclei

H. T. Fortune and B. Zeidman

We have obtained preliminary data for reactions yielding heavy ions ($A \geqslant 6$) produced by 35.6-MeV ^{3}He bombardment of ^{10}B, ^{11}B, ^{12}C, ^{16}O, ^{24}Mg, and ^{28}Si. A more detailed investigation is planned. The objective of the study is to determine to what extent the cross section is influenced by the internal correlations both in the target nuclei and the reaction products. Such correlations (i.e., clustering) result in differences between the cross sections for different reactions leading to the same final product.

(iii) Heavy Ions from ^{4}He-Induced Reactions on 1p- and 2s1d-Shell Nuclei

H. T. Fortune and B. Zeidman

Targets of ^{10}B, ^{11}B, ^{12}C, ^{13}C, and ^{16}O were bombarded with 46-MeV alpha particles, and preliminary data were obtained for reactions yielding heavy ions. Extension to heavier nuclei and collection of more detailed data are planned. Together with the ^{3}He-induced reactions, the ^{4}He-induced reactions provide a means for varying initial conditions as well as final conditions in determining clustering effects upon cross sections and angular distributions. The simultaneous measurement of a number of reactions substantially reduces systematic uncertainty—particularly in the comparison of different reactions.

(iv) Experimental Test of the Barshay-Temmer Theorem

H. T. Fortune, A. Richter, and B. Zeidman

The reactions ^{10}B(α, ^{7}Be)^{7}Li and ^{11}B(^{3}He, ^{7}Be)^{7}Li were used in an experimental test of the Barshay-Temmer theorem.[1]

[1] S. Barshay and G. M. Temmer, Phys. Rev. Letters 12, 728 (1964).

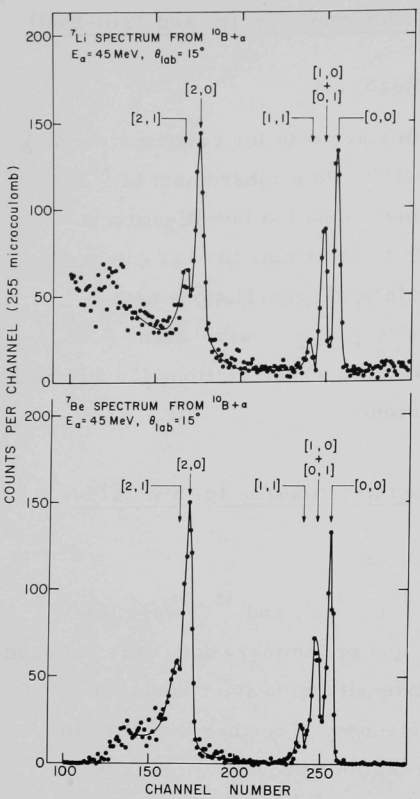

Fig. 34. Pulse-height spectra of the reactions $^{10}B(\alpha,{}^7Li)^7Be$ and $^{10}B(\alpha,{}^7Be)^7Li$. The notation used in labeling the peaks in the spectra from the nuclear reaction A(B, C)C' is that the double index [i, j] linked with the peaks in the C spectrum indicates that C' is left in its ith excited state and C in its jth.

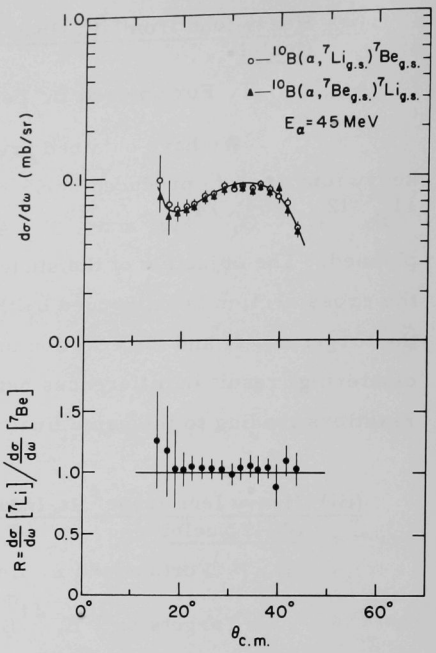

Fig. 35. Angular distributions (above) and the ratio R of the cross sections (below) for the ground-state transitions [0, 0] of the reactions $^{10}B(\alpha,{}^7Li)^7Be$ and $^{10}B(\alpha,{}^7Be)^7Li$. The line in the upper panel is drawn only to guide the eye. The indicated errors are due to background and statistics. The average of the ratios in the lower panel is $\overline{R}$ = 1.021 ± 0.030, the individual ratios being weighted with their reciprocal squared errors due to background and statistics.

In brief, the theorem implies that if the initial system is prepared in a pure isospin state (i.e., if either target or projectile has T = 0) the angular distributions and cross sections are identical for all

reactions in which both products are members of the same isospin multiplet, provided isospin is strictly conserved. The system $^{10}B + \alpha$ satisfies the initial conditions; in fact, both ^{10}B and ^{4}He have T = 0. Hence the reaction provides a means of testing isospin conservation. Data were obtained simultaneously for the various reactions from the $^{10}B + \alpha$ system; the angular range was 8—25° lab. in 1° steps. Typical particle spectra and angular distributions are shown in Figs. 34 and 35, respectively. The cross sections for the reactions to the $^{7}Li_{g.s.}$ and $^{7}Be_{g.s.}$ were found to be equal within statistical errors. In the absence of special circumstances, the implication[2] is that the isospin nonconservation is $\leq 3\%$, a substantial reduction from the limit set by earlier experiments. The cross section for reactions from the $^{10}B + \alpha$ system to reaction products that are not both members of the same multiplet (i.e., $^{7}Be^{**}$ and $^{7}Li_{g.s.}$) are not equal. The $^{11}B(^{3}He, ^{7}Be)^{7}Li$ reaction was studied in order to check the validity of the $^{10}B + \alpha$ result.

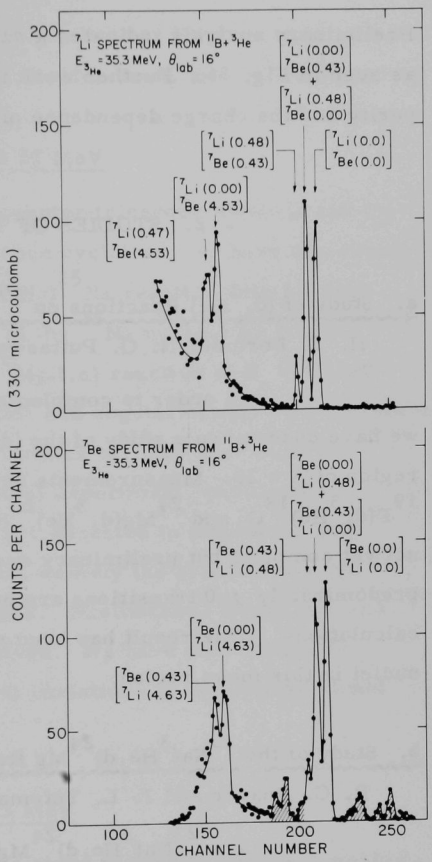

Fig. 36. Pulse-height spectra of the reactions $^{11}B(^{3}He, ^{7}Li)^{7}Be$ and $^{11}B(^{3}He, ^{7}Be)^{7}Li$. The ground-state transitions [0,0] have markedly different yields, as can be seen from the different areas under the corresponding [0,0] peaks.

[2] H. T. Fortune, A. Richter, and B. Zeidman, Phys. Letters (in press).

Preliminary analysis indicates a substantial deviation from equality, as seen in Fig. 36. Further work is planned to check the isospin purity and the charge dependence of nuclear interactions.

2. STUDIES OF 1d2s-SHELL NUCLEI

a. Study of (d, ^{3}He) Reactions on ^{19}F and ^{24}Mg

H. T. Fortune, N. G. Puttaswamy, and J. L. Yntema

In order to complement experiments at other laboratories, we have undertaken a study of the (d, ^{3}He) reaction on nuclei in the region of A ≈ 20. Measurements have been completed for the ^{19}F(d, ^{3}He)^{18}O and ^{24}Mg(d, ^{3}He)^{23}Na reactions. The analysis is not yet complete but preliminary results indicate that the data for predominantly $\ell=0$ transitions are not fitted well by distorted-wave calculations. This result has been pointed out previously for other nuclei in this mass region.

b. Study of the ^{23}Na(^{3}He, d)^{24}Mg Reaction[1]

R. C. Bearse and J. L. Yntema

The ^{23}Na(^{3}He, d)^{24}Mg reaction induced by 35-MeV ^{3}He ions has been studied for the first seven states in ^{24}Mg. Spectroscopic factors have been extracted and compared with theoretical predictions. The simple picture of the K=2$^+$ band being built on the one-phonon γ-vibrational level appears to be contradicted by this evidence. A simple Nilsson argument predicts spectroscopic factors in fair agreement with the data.

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[1] R. C. Bearse and J. L. Yntema, Phys. Rev. 175, 1442 (1968).

c. Single-Nucleon Transfers at N = 14

H. T. Fortune, J. V. Maher, G. C. Morrison, and B. Zeidman

(i) $^{26}Mg(d, {}^{3}He)^{25}Na$ Reaction at 23 MeV

Using standard ΔE-E counter-telescope methods and the 23-MeV deuteron beam from the Argonne cyclotron, we have measured angular distributions for the $^{26}Mg(d, {}^{3}He)^{25}Na$ reaction with 60-keV resolution. The only previous study of the ^{25}Na nucleus by single-nucleon transfer was a study of the $^{26}Mg(t, \alpha)$ reaction at $E_t \leq 6$ MeV. In that experiment angular distributions and angular-momentum transfers were not obtained, but seven residual states of ^{25}Na were seen at excitations below 3 MeV. In the present experiment, performed at an energy at which direct processes are expected to dominate, only three levels are appreciably populated, namely the ground state and the excited states at 1.07 and 2.20 MeV. Preliminary DWBA fits and spectroscopic factors have been obtained. We have also studied the sensitivity of the DWBA predictions to variations in the optical-model parameters.

(ii) $^{27}Al(d,p)^{28}Al$ Reaction at 23 MeV

As part of a systematic study of single-nucleon-transfer reactions on N = 14 nuclei, angular distributions for the $^{27}Al(d,p)^{28}Al$ reaction have been measured for states below 4.4 MeV excitation in ^{28}Al. The Argonne cyclotron was used to provide 23-MeV incident deuterons and standard ΔE-E silicon-detector-telescope methods were used to measure the reaction with an overall resolution of $\sim$60 keV. States at 1.372, 1.633, 2.49, 2.59, 2.66, 3.46, and 4.03 MeV, and the triplet (partially resolved) at 2.14, 2.21, and 2.28 MeV were strongly excited. The doublets at 0.00 and 0.03 MeV, 0.933 and 1.017 MeV, 2.99 and 3.01 MeV, 3.29 and 3.35 MeV, 3.54 and 3.49 MeV, and at 3.67 and 3.70 MeV also appeared strong but unresolved.

Previous measurements of this reaction have been performed at energies below 8 MeV and were analyzed with the plane-wave Born approximation. The present results have been analyzed with the DWBA. Spectroscopic factors and ℓ-transfer assignments are determined and compared with those of the earlier work.

(iii) Comparison of Spectroscopic Factors for Mirror States Populated in the (d,t) and (d,^{3}He) Reactions on ^{28}Si

Angular distributions have been measured simultaneously for the ^{28}Si(d,t) and ^{28}Si(d,^{3}He) reactions leading to states in the mirror nuclei ^{27}Si and ^{27}Al. The experiment was performed with the 23-MeV deuteron beam of the Argonne cyclotron. Conventional ΔE-E counter-telescope techniques yielded an overall energy resolution of $\sim$60 keV. Previous proton and neutron pickup experiments have yielded spectroscopic factors which differ by as much as a factor of three for the four low-lying positive-parity states at $E_x = 0.0$ ($\frac{5}{2}^+$), 0.842 ($\frac{1}{2}^+$), 1.013 ($\frac{3}{2}^+$), and 2.731 MeV ($\frac{5}{2}^+$) in ^{27}Al and their mirror states in ^{27}Si. Even the relative spectroscopic factors have differed by as much as a factor of two. In the present experiment, the simultaneous measurement of both reactions serves to eliminate systematic errors. Thus a consistent test of the DWBA analyses for these two reactions may be achieved.

d. (d,^{3}He) Reaction on the Chlorine Isotopes at 23.35 MeV[1]

N. G. Puttaswamy and J. L. Yntema

Levels in ^{36}S and ^{34}S up to about 8 MeV excitation energy (Fig. 37) have been studied with the (d,^{3}He) reactions on ^{37}Cl and ^{35}Cl, respectively. Spectroscopic factors have been extracted for four states in ^{36}S and ten states in ^{34}S. The levels at 4.58 MeV

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[1] N. G. Puttaswamy and J. L. Yntema, Phys. Rev. 177, 1624 (1969).

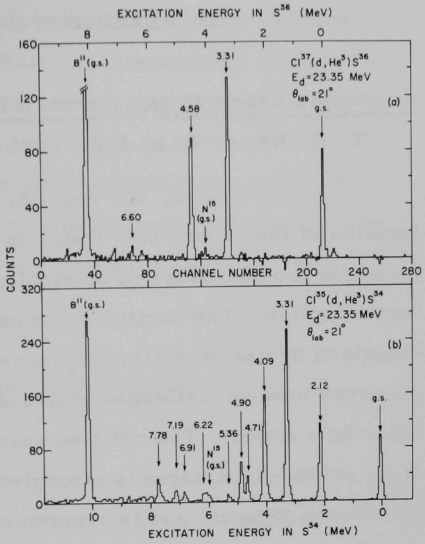

Fig. 37. Spectra of the $^{37}Cl(d,{}^3He)^{36}S$ and $^{35}Cl(d,{}^3He)^{34}S$ reactions.

in ^{36}S and 4.09 MeV in ^{34}S may be the 1^+ states that shell-model calculations predict at 5.75 and 4.97 MeV, respectively. Considerable $d_{5/2}$ strength is seen to the states above 4.71 MeV in ^{34}S.

e. Study of the $^{39}K(d,t)^{38}K$ Reaction

H. T. Fortune, N. G. Puttaswamy, and J. L. Yntema

A 22.8-MeV deuteron beam from the Argonne cyclotron was used to obtain angular distributions for the $^{39}K(d,t)^{38}K$ reaction leading to nine strongly-populated states below an excitation energy of 5 MeV. Two weak negative-parity transitions were observed—one having $\ell=1$ and another with $\ell=3$ angular distributions. For positive-parity transitions in which both $\ell = 0$ and $\ell = 2$ could contribute, attempts were made to extract the relative intensities of the two types. Comparison with results of $^{39}K(p,d)^{38}K$ and $^{39}K(^3He,\alpha)^{38}K$ experiments show that at these energies and in this mass region, the (d,t) reaction is a better tool with which to extract admixtures of $\ell = 0$ and $\ell = 2$ transition strengths.

3. REACTIONS IN 1f2p-SHELL NUCLEI

a. Proton Levels in $1f_{7/2}$-Shell Nuclei

T. H. Braid, J. A. Nolen, Jr., and B. Zeidman

The (d, ^{3}He) reaction has been used to investigate the location of the proton-hole states in $1f_{7/2}$-shell nuclei. Evidence is found for the admixture of nominally unfilled orbitals in the target wave function. The particle-hole nature of collective states was examined by use of odd-proton targets and a correspondence was observed between collective states seen in inelastic scattering and some hole states. The relative spacing between $2s_{1/2}$, $1d_{3/2}$, and $1f_{7/2}$ proton-hole states is strongly correlated with neutron number for even-A targets, and is consistent with a monopole interaction model.

b. Proton Levels in fp-Shell Nuclei

T. H. Braid, J. A. Nolen, Jr., and B. Zeidman

The effects of neutrons in the 2p-shell upon the proton levels for $1f_{7/2}$, $1d_{3/2}$, and $2s_{1/2}$ was investigated via the (d, ^{3}He) reaction on ^{56,58}Fe and ^{58,60}Ni. Because of additional degrees of freedom, greater fragmentation of hole states results, although the correspondence between levels in adjacent nuclei persists. Evidence is found for a strong interaction between 2p- and 2s1d-shell particles. This effect is yet to be explained.

c. Levels in the Odd-A Cu Isotopes

J. A. Nolen, Jr., and B. Zeidman

Together with data from (^{3}He, d) reactions, the (d, ^{3}He) reaction on zinc isotopes provides a means for studying the levels of the odd-A Cu isotopes from A = 59 to 69. The number of levels, interactions, and spacings between levels are strongly correlated with

the number of neutrons in each isotope. The nearly empty neutron shell in the lightest isotopes of this chain (or alternatively the nearly full shell in the heaviest) results in few levels, mostly single-particle in character, and a wide spacing. In the middle of the shell, the interactions produce fragmentation, multiplicity of levels with the same J and parity, and levels with both single-particle and collective behavior. A quantitative description of these phenomena is being attempted.

d. Study of the J Dependence in the (d, ^{3}He) Reaction

H. Ohnuma and J. L. Yntema

The J dependence of the angular distributions in the (d, ^{3}He) reactions was experimentally observed at small angles in the 2p proton pickup. This J dependence is qualitatively reproduced by distorted-wave calculations (such as those in Fig. 38 in Sec. I. D4b) which indicate that the effect arises mainly from the deuteron spin-orbit potenital. The calculated angular distributions are strongly dependent on the Q value of the reactions and the incident deuteron energy. The calculations also show that the J dependence is localized at the surface of the nucleus, and is very sensitive to the volume of the real part of the deuteron optical potential. This sensitivity may be understood by considering the role of the spin-orbit term in the optical potential. The sensitivity of the calculated angular distributions to the other parameters was investigated.

e. Study of the ^{40,48}Ca(d,α) Reactions

H. T. Fortune, N. G. Puttaswamy, and J. L. Yntema

Measurements for the ^{40}Ca(d,α) reaction (reported previously) have been extended to larger angles. Angular distributions for the ^{48}Ca(d,α) reaction were also measured. The analysis of the data is continuing. Attempts to fit the angular distributions with

distorted-wave calculations have not been very successful. The predicted angular distributions are quite sensitive to the various parameters in the distorted-wave calculations.

f. Scattering of Helium Ions

T. H. Braid,* T. W. Conlon,† and B. W. Ridley‡

The optical-model analysis of the elastic scattering of ^{3}He on ^{40}Ca and ^{58}Ni, which was initiated by the measurements made at the Harwell Variable-Energy Cyclotron in the fall of 1967, has been extended to cover additional data from other laboratories. The potential previously reported continues to predict the measured angular distributions excellently over a 70-MeV range of incident energy, the agreement being particularly good for the ^{40}Ca target. So far it has not proved possible to obtain a potential that describes the α-particle elastic scattering well over a wide energy range, although excellent fits to the data can be obtained at individual energies.

With the aid of the ^{3}He potential, the predictions of the DWBA theory have been used to fit the inelastic scattering to the first excited state of ^{58}Ni and extract a value for the deformation parameter β_2. We are attempting a coupled-channels calculation for these quantities, and a computer program that will search for optimum parameters in such a calculation is almost operational.

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*Work done while on assignment at AERE Harwell, 1966-67.

†AERE Harwell, England.

‡AERE Harwell; now at University of Colorado, Boulder, Colorado.

4. STRUCTURE OF NUCLEI NEAR A = 95

a. Experimental Study of the (d,t) Reaction on Even-Mass Mo Isotopes

H. Ohnuma and J. L. Yntema

The (d,t) reaction on ^{92,94,96,98}Mo was studied with the 23-MeV deuteron beam from the Argonne cyclotron. The

experimental angular distributions of triton groups were compared with the DWBA theory, and the ℓ values and the spectroscopic factors were determined. The level structure of the ^{91}Mo nucleus is very similar to that of ^{89}Zr. Evidence for core excitation in ^{92}Mo was found. The results for the other isotopes show that neutron orbits higher than the $2d_{5/2}$ shell are admixed in the ground-state configuration of these nuclei. These results are compared with previous data and with shell-model calculations.

b. Experimental Study of the (d, ^{3}He) Reaction on Even-A Isotopes of Mo[1]

H. Ohnuma and J. L. Yntema

The (d, ^{3}He) reactions on ^{92,94,96,98}Mo and the ^{92}Mo(^{3}He, d) reaction were studied with 23-MeV deuterons and 34-MeV ^{3}He particles from the Argonne cyclotron. Experimental angular distributions were analyzed on the basis of the DWBA theory to determine the ℓ values and spectroscopic factors (Fig. 38). Results were compared with previous data and the shell-model predictions. Experimental strengths of the $g_{9/2}$ and $p_{1/2}$ components in the ground state of ^{92}Mo are consistent with the calculations. Very-low-lying states with large $p_{3/2}$ and $f_{5/2}$ strength were observed.

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[1] H. Ohnuma and J. L. Yntema, Phys. Rev. 176, 1416 (1968).

c. Study of the ^{94}Zr(^{3}He, d)^{95}Nb Reaction

H. Ohnuma and J. L. Yntema

The ^{94}Zr(^{3}He, d)^{95}Nb reaction was studied with 34-MeV ^{3}He particles from the Argonne cyclotron. Experimental angular distributions were analyzed on the basis of the DWBA theory to determine the ℓ values and spectroscopic factors (Fig. 39). The results were compared with the previous data on the (d, ^{3}He) reactions on

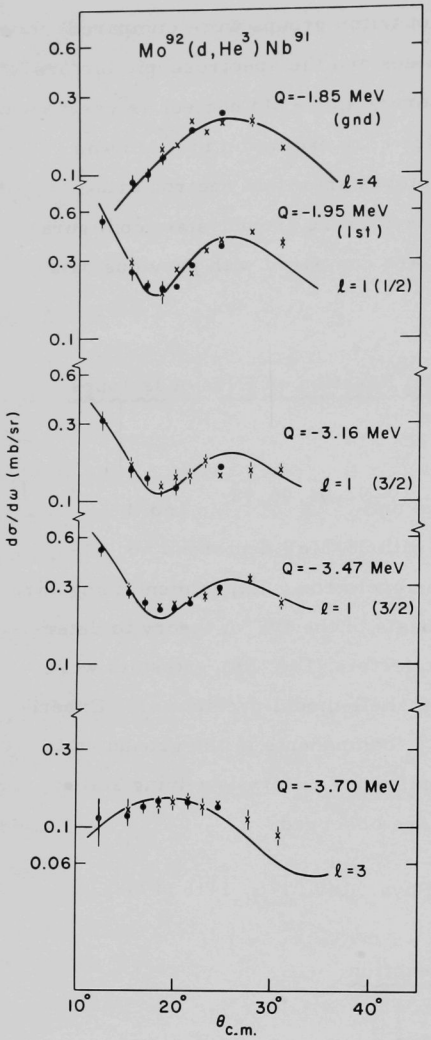

Fig. 38. Angular distribution for the $^{92}Mo(d,{}^{3}He)^{91}Nb$ reaction. The significant difference between the angular distributions for the level labeled ($\frac{1}{2}$) and for those labeled ($\frac{3}{2}$) is well reproduced by the theoretical calculations.

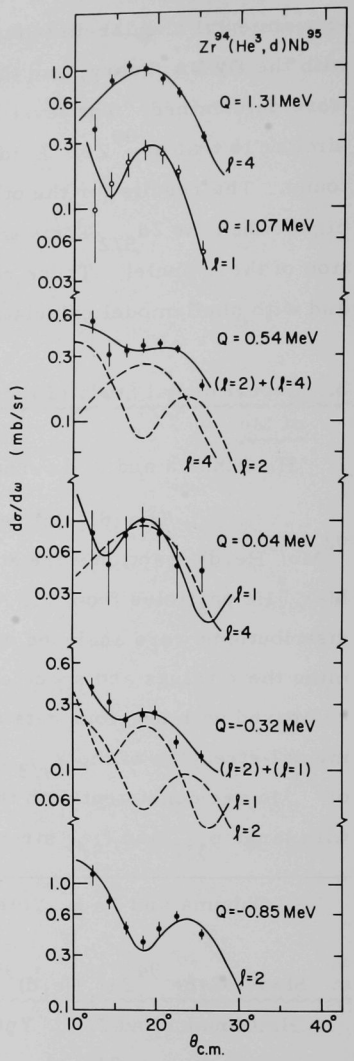

Fig. 39. Angular distributions and calculated DWBA curves for the $^{94}Zr(^{3}He,d)^{95}Nb$ reaction.

Mo and Zr isotopes, and the proton configurations of the nuclei in this region are discussed.

5. ISOMERIC STATES PRODUCED IN (^{12}C, Xn) REACTIONS IN THE REGION Z > 50, N < 82

T. W. Conlon* and A. J. Elwyn

We have studied the gamma-ray spectra associated with new short-lived activities produced in the ^{12}C-ion bombardment of separated isotopes of Sn, Cd, and Sb nuclei at the Harwell Variable Energy Cyclotron. Both the energy of the gamma ray and its time of arrival after bombardment by the pulsed 88-MeV ^{12}C beam were measured simultaneously by use of a 4096-channel two-dimensional analyzer. Several isomers with half-lives between 60 nsec and 0.5 sec have been observed. These activities have been assigned to the odd-mass nuclei ^{121}Xe, ^{123}Xe, ^{125}Ba, ^{129}La, and ^{131}La. The basis upon which the observed isomeric activity was assigned exclusively to odd-mass nuclei was the lack of any observed gamma-ray transitions associated with the known low-lying energy levels of some of the even-even nuclei that could be produced in ^{12}C-induced reactions [mainly (^{12}C,4n) and (^{12}C,5n) reactions] at a beam energy of 88 MeV. Further experimental studies are necessary to determine the level structure in the final nuclei as well as the properties of the isomeric transitions.

*Nuclear Physics Division, Atomic Energy Research Establishment, Harwell, Berks., England.

6. REACTIONS ON HEAVY NUCLEI

a. Spectroscopy in Heavy Nuclei

A. M. Friedman* and B. Zeidman

Preliminary investigations of the proton-transfer reactions (^{3}He,d) and (α,t), as well as inelastic scattering of ^{3}He and

*Chemistry Division.

^{4}He, on rare earth and actinide nuclei indicate the need for better resolution than is available from counters. These experiments have been delayed until the new magnetic spectrograph becomes operational.

b. (^{3}He,α) Reactions on Heavy Nuclei

T. H. Braid and A. M. Friedman*

To supplement our earlier (d,p) and (d,t) studies of neutron levels in the actinide elements, we have begun measurements on the neutron hole states, using the (^{3}He,α) reaction initiated by 35-MeV ^{3}He ions from the 60-in. cyclotron. We have observed α-particle spectra from ^{238}U, ^{236}U, and ^{234}U targets. In addition to a large number of weakly-excited levels, there are a few strong peaks which are to be associated with high-ℓ-value transitions, since enhancement of such transitions is characteristic of this reaction. These levels presumably belong mainly to the n=7 shell.

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*Chemistry Division.

7. INSTRUMENTATION AT THE CYCLOTRON

a. Split-Pole Magnetic Spectrograph at the Cyclotron

B. Zeidman

During the past year the split-pole spectrograph at the 60-in. cyclotron has been delivered, mounted, and aligned. Fabrication of the target chamber and camera box have proceeded, and assembly and calibration of the system is rapidly nearing completion. Installation and modification of utilities (power and water) is virtually completed. Subsequent development of techniques for operating with a collimator-free beam-transport system and acquisition and installation of a focal-plane counter assembly will be needed to improve the operation of the spectrograph.

Measurements of the magnetic field contours up to 17.6 kG show no significant deterioration over this range. At 17.6 kG, the spectrograph will allow the analysis of particles with momenta corresponding to mass-energy products Me/Z^2 up to 116—i.e., 38.5-MeV tritons or 116-MeV alpha particles. The dynamic range p_{max}/p_{min}, determined by the length of the focal-plane detectors, is 2.25 and hence $E_{max}/E_{min} = 5$ for any given particle. For the sharpest energy resolution (1 part in 2500), the solid angle is restricted to about 0.002 sr, but data may be taken with solid angles up to 0.010 sr provided that deterioration of the resolution by about a factor of 2 is acceptable. Because of the large solid angles to be used, the focal plane may be moved so as to compensate for the kinematic angular variation in energy for a given reaction.

b. Multi-wire Proportional Counters

T. H. Braid, J. Himes, and R. Lieb

Multi-wire proportional-counter systems are being studied for possible use in position-sensitive detection of charged particles, determination of trajectory, etc. The preliminary work shows that such devices can be useful in a number of places in our work, e.g., in the focal plane of a magnetic spectrograph. An inexpensive amplifier and discriminator (supplied by C. Rush of the Argonne Electronics Division) have been evaluated and found suitable as the basis of an economical system for amplifying and standardizing the signal from each wire. A convenient and flexible structure for multi-wire arrays is based on standard printed-circuit boards which are inserted into slots in a basic support. An arrangement in which all the wires in a plane are connected as anodes at the same voltage results in a wide spread of pulse heights due to the variation in the strength of the collecting field (e.g., half way between the wires there is a neutral point). If alternate wires are connected to the cathode voltage,

the spread in pulse heights at the anode wires is rendered much more closely uniform. For use with low-energy charged particles in "thin" counters, such a characteristic has great advantages. Hence we are continuing our development of this configuration.

c. Improvement of the 60-in. Scattering Chamber at the Cyclotron

J. L. Yntema

Preliminary sketches for redesign of the scattering chamber to permit automated control have been made. Modifications on the design of the target-foil-changing system have been designed.

E. 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.

a. Detectors and Circuits for Fast Electronic Timing

(i) Improvements in the Time Resolution of Scintillation Detectors

F. J. Lynch

The time resolution calculated on the basis of the measured time constants and efficiency of the scintillator and the conversion efficiency and transit-time spread in the photomultiplier agrees with the measured value. Such calculations indicate that the transit-time spread in fast photomultipliers currently constitutes the most important limitation on time resolution.

The fixed-fraction discriminator has been further improved so that it more conveniently provides the sharpest possible time resolution from the detector.

(ii) Fast Timing Circuits for Ge(Li) Detectors

F. J. Lynch

New electronic circuits developed for use with Ge(Li) detectors provide improved timing of gamma rays without impairment of the excellent energy resolution of these detectors. These circuits include a low-noise fast amplifier, a pulse-shaping amplifier, and a zero-crossing discriminator. With these new circuits one can obtain resolution widths as small as 1.6 nsec FWHM for 500-keV gamma rays and 5 nsec for 100-keV gammas.

b. Lifetimes of Nuclear Excited States

(i) The 11.23-keV State of ^{134}Cs

F. J. Lynch

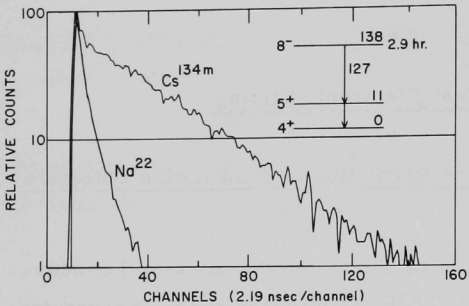

Fig. 40. The probability distribution of the delay times of the 11-keV gamma rays and L x rays relative to the 127-keV gamma ray from Cs^{134m}.

The lifetime of the first excited state (E_x = 11.23 keV) in ^{134}Cs was measured by use of a delayed-coincidence technique and found to be $\tau = 69 \pm 1$ nsec. A typical decay curve is shown in Fig. 40. This is 1.8 times the lifetime calculated by D. Kurath on the basis of the odd-group model from the magnetic moments of neighboring nuclei.

(ii) The 29.4-keV State of ^{40}K

F. J. Lynch and R. E. Holland

We have remeasured the lifetime of the first excited state (E_x = 29.4 keV) of ^{40}K by using the pulsed-beam facility at the tandem accelerator. The interest in this comes from Segel's recent measurements of the lifetimes of the second and third excited states of this nuclide.

The positions of the four levels involved in these three transitions are well explained by the jj-coupling model; in fact, this case has long been thought to provide one of the best examples of the

application of this model. The model also predicts a relationship between the lifetimes. The only measurement on the first excited state was our 10-year-old mean lifetime $\tau = 5.6 \pm 0.6$ nsec. In view of the much better techniques available now, we redid this with the result $\tau = 6.1 \pm 0.4$ nsec. This result is only about half that implied by Segel's results and the theory.

(iii) The 280-keV State of ^{75}As

F. J. Lynch and R. E. Holland

The mean lifetime of the third excited state of ^{75}As at 280 keV was remeasured because of a disagreement between our previous measurement (0.4 ± 0.2 nsec), which was made by a pulsed-beam technique, and a measurement of Varma and Eswaran who reported 0.78 ± 0.08 nsec. The remeasurement gave a mean lifetime $\tau = 0.44 \pm 0.10$ nsec.

We plan to use the pulsed beam of the tandem to continue the measurement of lifetimes of states in the $f_{7/2}$ shell and, in addition, to investigate the level structure of some nuclei in this region through the (α,n) reaction.

(iv) Gamma Isomers in Fission Fragments

P. Kienle, F. J. Lynch, and R. E. Holland

Johansson reported that about 6% of the gamma rays from fission fragments had meanlives of 10—100 nsec and that the relative yield of these isomers varied greatly with fragment mass. We have looked for possible delayed neutrons or alpha particles that are precursors of the delayed gamma rays, and have found no evidence of neutrons with energies above 200 keV nor of alpha particles above 2 MeV that are delayed 10—100 nsec relative to the fission. Since the fission fragments cover regions of the isotopic chart that are not readily accessible in other reactions, a detailed study of these isomeric

transitions should be valuable. We are planning an experiment in which Ge(Li) detectors will be used to obtain good energy resolution for gamma rays. Three parameters will be recorded: the gamma-ray energy, the fission-fragment energy, and the time delay of the gamma ray (the time elapsed from detection of the fission fragment to detection of the gamma ray).

c. Coriolis Mixing of Negative-Parity States in ^{161}Dy

Walter Henning

From radioactive decay studies and (d,p) experiments, a number of energy levels below 1 MeV have recently become known for the deformed odd-neutron nucleus ^{161}Dy. The negative-parity states can be assigned as members of four rotational bands built upon the following Nilsson states: $\frac{1}{2}^-$ [521] at 368 keV, $\frac{3}{2}^-$ [521] at 75 keV, $\frac{5}{2}^-$ [523] at 26 keV, and $\frac{5}{2}^-$ [512] at 799 keV. The deviation of the experimental energy levels from the rotational formula and the enhanced interband transition probabilities indicate Coriolis mixing between the bands.

Three- and four-band Coriolis-mixing calculations have been performed, fitting the theoretical energy expressions to the experimental values. The parameters determined were: the Coriolis interaction matrix elements $A(\frac{1}{2}\,521 - \frac{3}{2}\,521) = 10.5$ keV, $A(\frac{3}{2}\,521 - \frac{5}{2}\,523) = 6.5$ keV, and $A(\frac{3}{2}\,521 - \frac{5}{2}\,512) = 5.9$ keV; the moment of inertia $\hbar^2/2J = 11.435$ keV; and the energetic decoupling parameter $a = 0.455$ of the $K=\frac{1}{2}$ band. With these results the wave functions of the 14 known negative-parity states were calculated. The degrees of mixing found between the bands explain the experimental interband transition probabilities.

The computer calculations were very conveniently made by the use of the SPEAKEASY language.

d. Level Structure of Low-Lying Excited States of ^{66}Ga Populated by the Decay of 2.2-h ^{66}Ge

H. H. Bolotin and D. A. McClure

The decay of 2.2-h ^{66}Ge to levels in ^{66}Ga has been investigated by use of both singles and coincidence gamma-ray spectroscopic techniques that made exclusive use of high-resolution Ge(Li) detectors. The internal-conversion-electron spectrum was also studied. A total of 23 transitions were observed in this decay and were incorporated in a complete and unambiguous level scheme (Fig. 41) that differs markedly from those previously proposed. The excitation energies of the ^{66}Ga states found to be populated in this decay are 43.8, 108.9, 234.0, 290.9, 381.8, 514.6, 536.6, and 706.0 keV. The half-life of the ^{66}Ge activity was redetermined to be 2.23 ± 0.10 h. The half-life of the first excited state was measured by delayed-coincidence techniques to be 21 ± 2 nsec. The multipolarities of many of the transitions were determined. Spin and parity assignments of many of the excited states were inferred and severe limitations could be imposed on the spin assignments of the remainder of the levels. The log ft values of all β branches were established and limits on the amount of isobaric-spin impurity present in the ground state of ^{66}Ge were set. The level characteristics were found to be consistent with expectations derived from theoretical considerations. A report on this work has been published.[1]

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[1] H. H. Bolotin and D. A. McClure, Phys. Rev. 180, 987 (1969).

e. Argonne Six-Gap Beta-Ray Spectrometer

G. T. Wood

Preparation to place the six-gap beta-ray spectrometer on one of the beam lines of the Tandem accelerator are nearing completion. Initially, it is planned to study conversion electrons from rare earth targets with (p,xn) and (α,xn) reactions and Coulomb

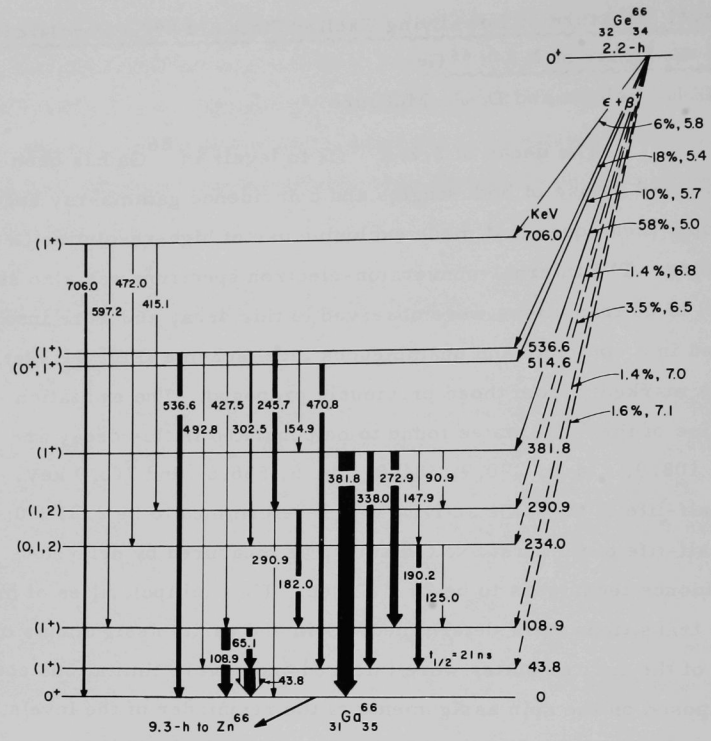

Fig. 41. Proposed β-decay and level scheme of 2.2-h ^{66}Ge. All level excitation energies in ^{66}Ga are in keV, as are the energies of the γ-ray transitions. The β branches indicated by dotted lines correspond to upper limits on the relative intensities of these groups (in %) and consequently to lower limits on stated values of log ft. The spins and parities shown in parentheses are inferred from the results of the present experimental study. However, in no case should these be considered as experimentally measured parameters. The relative intensities of the γ-ray transitions are indicated by the breadths of the arrows. The open areas shown in the arrow representing the 43.8-keV transition indicate the fraction of the transition intensity that proceeds by internal conversion.

excitation with heavy ions. The object is to obtain nuclear-structure information on these nuclei—in particular, to study the collective and particle characteristics of the excited levels.

Magnetic spectrometers have already been used in several other laboratories to study conversion-electron spectra from nuclear reactions. We are attempting to improve on these earlier systems by developing a spectrometer that simultaneously has high transmission, freedom from background, and good energy resolution. High transmission (10%) and freedom from background are characteristics provided by the six-gap magnetic spectrometer; and good energy resolution (about 0.2% at 1 MeV) is obtained by using a silicon surface-barrier detector at the focus of the magnetic spectrometer.

The combination spectrometer system incorporates several advanced features that will make it exceptionally useful for research at the Tandem. The silicon detector will view all six gaps of the magnetic spectrometer and, since a momentum range of about 4% is detected for each setting of the magnetic field, the counting efficiency will approach four times that for the conventional application as a magnetic spectrometer with 1% momentum resolution width. The existing sweep system of the spectrometer will sweep the magnetic field over the range of interest at a constant dB/dt. The spectrum will be obtained from the pulse-height spectrum of the silicon detector and will be collected in an existing computer-based data-acquisition system. To take full advantage of the magnetic resolution, the computer digitally selects the pulses whose height matches the electron energy being magnetically selected at each instant as the field sweeps across the region of interest.

The improved resolution obtainable with the new system should justify new measurements on many previously published cases since most of the earlier measurements were done at a 1% momentum resolution width and show considerable unresolved structure. In addition, targets not previously feasible for study may now yield

information of interest. This improvement in the quality of spectra will be especially valuable for determining the positions of high-lying energy levels, for studying band mixing from measurements of branching ratios, for identifying the residual nucleus of each transition on the basis of the K-L splitting, and assigning the multipole order of the transition from the K/L ratio. From the B(E2) strengths of the transitions, useful information on the collective and quasi-particle nature of the states can be obtained. Conversion-electron spectroscopy is a particularly useful tool for the determination of monopole matrix elements. Initially, it is planned to investigate only singles spectra. Other possible uses of the instrument include (ion, e) or (e, γ) coincidences, electron angular distributions, and lifetime measurements by the delayed-coincidence method.

f. Pattern Recognition for Nuclear Events

C. Harrison,* D. Jacobsohn,* and G. R. Ringo

The mechanization of the procedure for identification of interesting events is a problem of increasing importance in nuclear and particle physics. It is particularly critical in the case of emulsions where it is desirable to scan large volumes of material with microscopes showing volumes of 10^{-8} cc or less in a view. Our approach to this problem uses a four-layer random-connection network similar in its general character to the Perceptron of F. Rosenblatt. It is intended to separate patterns presented in the form of 80-bit words into wanted and unwanted classes after a learning phase using a few hundred cases of each. The approach differs from the original Perceptron in that in the original the random connections were reinforced or weakened on the basis of the learning performance. In the Argonne version, many completely different sets of connections are tried and the most useful (in the learning phase) kept.

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*Applied Mathematics Division.

Recent work has tested programs that weight the learning patterns to produce a more uniform response over the learning set. The results would be called encouraging rather than remarkable, but numerous improvements in the strategy can readily be imagined and are fairly easy to test with the present program.

g. Microscopic Location of ^{17}O, ^{18}O, and ^{15}N

G. R. Ringo and V. E. Krohn

A technique by which the tracer isotopes ^{17}O, ^{18}O, and ^{15}N could be located (possibly simultaneously) within a resolution diameter of 1 micron or better would have obvious value in biological research. We believe this could best be done by scanning a specimen with a focused beam of ions (e.g., Ne^{+}) to convert the tracer isotopes to ions which will be identified in a mass spectrometer with high resolution (a resolution of, say, 5000). The high-resolution mass spectrometer is available, but an ion beam with less than 1 μ diameter and more than 1 pA current remains to be produced.

A duoplasmatron ion source and an ion-lens system have been obtained and the remainder of the ion-beam system is being designed. The particle optics which have been designed should achieve efficient collection of the secondary ions. Other parts of the system are under construction.

II. MEDIUM-ENERGY PHYSICS

Although the program in medium-energy physics is small, it is divided into two distinct parts. One part is a study of accelerators for the production of particles in the medium-energy range; the other is concerned with preparations for the use of the Meson Factory at Los Alamos.

The main aspect of the latter effort is a fairly intensive involvement by one of our staff members in various design and planning activities connected with the Meson Factory. A much smaller effort (described in Sec. I. D7b) is devoted to the development of new detector systems.

The study of accelerators is carried out by means of financial support to a design group within the Chemistry Division. This cooperative arrangement is proving to be quite satisfactory—not only because of the limited funds available, but also because there is a strong overlap between the accelerator requirements of nuclear chemistry and nuclear physics.

During the past year, most of the effort of the accelerator design group has been devoted to the study of an advanced accelerator system consisting of a TU tandem Van de Graaff and an open-sector cyclotron. The immediate enthusiasm of prospective users of this powerful combination stimulated an intensive study of the design concept. On the basis of this study, the Laboratory has submitted to the AEC a proposal for the construction (at Argonne) of a mjaor regional accelerator facility for nuclear-physics and nuclear-chemistry research. An outline of the proposal, published as ANL-7582, is given below.

Summary of the Proposal for the Midwest Tandem Cyclotron (MTC)

The Midwest Tandem-Cyclotron accelerator system is proposed as a facility to be built at Argonne National Laboratory and operated by the Laboratory as a regional facility for advanced research in nuclear chemistry and nuclear physics. The research to be carried out at the proposed accelerator will encompass much of basic nuclear science, with special emphasis on (a) the search for the predicted "islands" of stable superheavy elements, (b) the investigation of the nuclear structure revealed by energetic collisions between complex

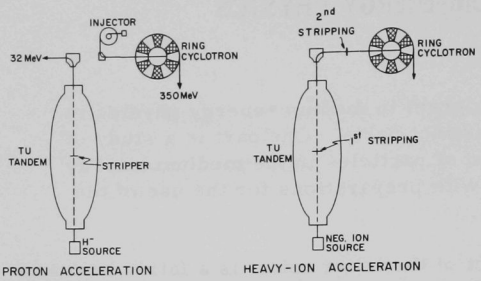

Fig. 42. The two alternative modes of operation of the MTC system.

nuclei, and (c) the elucidation of momentum distributions of nucleons and the correlation between nucleons in nuclear matter. The proposed accelerator system is believed to be the next logical step in the development of the experimental apparatus needed to attack these frontier problems of nuclear science.

As its name suggests, the proposed Midwest Tandem Cyclotron (MTC) complex consists of two major components—a TU tandem Van de Graaff and a variable-energy open-sector ring cyclotron. These two accelerators would be operated in two alternative modes, as is illustrated in Fig. 42. For the acceleration of heavy ions to high energy, the tandem must serve as an injector for the cyclotron. Alternatively, the tandem and the cyclotron can be used independently and simultaneously.

Consider first the independent mode of operation. Here the TU tandem will accelerate hydrogen ions to 32 MeV (or perhaps 40 MeV) and almost all heavier ions to higher energies. At the same time, the cyclotron will provide protons over a wide energy range up to a maximum energy of 350 MeV, deuterons to 200 MeV, ^{3}He to 516 MeV, and ^{4}He to 400 MeV. In the alternative injection mode of operation, intended primarily for heavy-ion acceleration, energetic ions issuing from the tandem are stripped to a high charge state before they enter the cyclotron, where they are accelerated on up to energies well above the Coulomb barrier for interactions on any target nucleus. For both light- and heavy-ion acceleration, the MTC will provide beams

with high intensity, high resolution, high maximum energy, and an energy that is continuously variable over a wide range. The maximum energies and currents of the system for representative projectiles are given in Tables III and IV.

The MTC accelerator system is designed to have unexcelled research capability in a very wide range of nuclear investigations. The heavy-ion beams will have energies and intensities far greater than any that have yet been achieved; these properties are essential for an effective investigation of the predicted new superheavy elements and will also provide a probe with which to investigate the nucleus in entirely new ways. Similarly, the light-ion beams will have much better intensity and energy resolution than any now available in the range covered by the MTC; these features and the variable energy will permit many qualitatively new investigations in a broad energy range which (for protons) extends well above the pion-production threshold.

TABLE III. Characteristics of beams from the TU tandem and from the cyclotron.

	Hydrogen beams			Helium beams		
	Energy range		Beam current (10^{12} particles/sec)	Energy range		Beam current (10^{12} particles/sec)
	p (MeV)	d (MeV)		^{3}He (MeV)	^{4}He (MeV)	
TU tandem	6—32 (40)[a]	6—32 (40)[a]	180	6—48 (60)[a]	6—48 (60)[a]	36
Cyclotron	50—350	30—200	50	48—510	48—400	10

[a]Maximum energy calculated for a 20-MV terminal voltage.

TABLE IV. Maximum beam currents of heavy ions (10^{12} particles/sec).

Ion species	^{16}O	^{19}F	^{35}Cl	^{79}Br	^{127}I	^{238}U
TU tandem	50	40	40	40	40	30
Cyclotron	10	10	7	1.5[a]	1[a]	0.7[a]

[a]These currents are not limited by the current-carrying capacity of the TU.

The availability of two machines that can be used simultaneously for independent experiments will allow the system to support a large volume of research, an important consideration for a regional facility that is intended for the use of some 200 experienced scientists from 25 or more institutions.

Scientific Considerations. Although the proposed facility will have characteristics that make it very well suited to a wide variety of investigations, the requirements of two areas of investigation have had a determining influence on the parameters of the accelerator system. The primary requirement is that the system should provide intense, energetic beams of heavy ions over the full range of the periodic table. These heavy ions are intended largely for the study of very heavy elements and especially for the search for the widely discussed "islands" of stability that are predicted to occur at masses considerably heavier than any that have yet been identified experimentally. An island of this kind is expected to result from the influence of closed nuclear shells, and currently it is thought that closed shells of 114 and perhaps 126 protons and of 184 neutrons will have a dominating influence on stability. The discovery and understanding of superheavy nuclides of this kind, if they can be produced, would have a profound influence on our understanding of the nucleus; and it could also have major consequences for applied science.

Finding effective ways to produce enough of the predicted superheavy nuclei for study is a considerable technical and scientific challenge. It seems clear that efficient production will require nuclear reactions between two heavy nuclei. However, one of the intriguing aspects of the problem is that we have little solid information on what kinds of reactions are most effective, what energies are required, or indeed on what product nucleus to strive for. Consequently, an accelerator intended for the production of superheavy nuclei should have rather general capabilities that will allow all reasonable approaches to

be explored. It should provide intense, high-energy beams of ions throughout the periodic table, and in particular it should be able to accelerate the heaviest ions (^{238}U) well above the Coulomb barrier for an interaction with a uranium target. Exactly what the desirable upper energy limit is for the uranium ion is not clear. The energy needed to overcome the Coulomb barrier in an interaction between two spherical nuclei of mass 238 is only about 6 MeV per nucleon, but the deformation of actual heavy nuclei is likely to increase this to about 8 MeV per nucleon. Also, the recent indication that heavy-ion-induced fission is an effective way to produce superheavy nuclei and that the production cross section increases with increasing projectile energy up to well above the Coulomb barrier suggests that it may be important to be able to accelerate ^{238}U up to energies of 10 or 15 MeV per nucleon. These considerations suggest that most of the accelerators now being actively considered for heavy-ion acceleration have too low an upper energy limit for the heaviest projectiles. It is to achieve the desired high energy that we use a TU tandem (rather than the smaller MP model) as the injector and that our cyclotron is larger than the 200-MeV four-sector Indiana cyclotron.

The prospect of using heavy ions for other nuclear investigations is also exciting, since we now have very little knowledge of what can happen in energetic collisions between complex nuclei. Undoubtedly this field will prove to be a rich source of qualitatively new information for our understanding of the nucleus. There are also interesting new possibilities for the use of energetic heavy-ion beams for investigations in atomic and solid-state physics and in biology and medicine.

The second area of research that has had a major influence on the design of the new accelerator system is the kind of nuclear-physics research done with light ions in the medium-energy range. Here the determining considerations are that it is important to be able to explore the region of energy up to and through the meson threshold

much more thoroughly than will be practical with accelerators in existence or under construction. The physics of this region is interesting because of the presence of the meson threshold (at about 290 MeV for nucleon-nucleon interactions) and because the region links two fundamentally different sorts of nuclear physics. At the low-energy end of the region one studies the energy levels one by one and attempts to describe the level structure in terms of nuclear models; the models themselves have to be related to the nucleon-nucleon forces, a connection that must necessarily be indirect. At high energies (> 100 MeV for protons) interest shifts to pair-correlation functions, momentum distributions, etc.; these are related more directly to the nucleon-nucleon forces, although virtually nothing is now known about them. Our accelerator complex may well turn out to be the ideal system for the study of nuclear structure in that it is equally well suited for both kinds of physics—its energy is low enough to permit the good energy resolution required to study individual states and at the same time its maximum energy is high enough to permit a thoroughgoing investigation of the more general features of nuclear matter. Thus, the MTC may allow the gulf between the two areas of nuclear physics to be bridged.

Accelerator Considerations. The MTC accelerator complex combines two modern accelerators, each of which would be a valuable research tool by itself; when used as a system, they will provide a unique and powerful probe for nuclear research.

The TU tandem is the largest of the tandem Van de Graaff accelerators; a prototype is nearing completion. The choice of this tandem is dictated by the need to inject highly-stripped heavy ions into the cyclotron so as to minimize the radius of curvature (and thus the size and cost) of the cyclotron. The use of the smaller MP model would require the construction of a substantially larger cyclotron; and the even smaller FN tandem probably would not be suitable at all, because it could not provide the required intensity of heavy-ion beam.

Moreover, the TU by itself will be much more valuable than the smaller tandems in many areas of research.

The TU will be used in its tandem mode of operation at all times. That is to say, negative ions will be injected into the machine from an ion source near ground potential, and these ions will be accelerated to the terminal, where they will pass through an electron-stripping medium. An alternative, and superficially attractive, possibility is to produce highly-stripped heavy ions in a source mounted in the terminal of the TU. This possibility was rejected partly because of questions regarding its feasibility and partly because of our judgement that a terminal source would severely prejudice the reliability of the system for heavy-ion acceleration, in view of the short lifetimes of all known sources producing usable intensities of ions in the required high charge states. In contrast to these problems with the terminal source, the planned external source at ground potential is much more reliable and its accessibility makes all technical problems much easier to solve. The reliability of the external source is essential for our system, which (because of its regional character) must support the work of a very large number of users.

The open-sector cyclotron with free-standing magnet sections has characteristics that make it especially suitable for the proposed application. In particular, the space between magnets allows the problems of beam injection and extraction, vacuum pumping, and the design of the accelerating structure to be solved much more easily than in a conventional cyclotron. The technology of open-sector cyclotrons is relatively well understood now, and the experience gained at the machine now under construction at Indiana University should provide answers to many of the remaining questions.

The size of the proposed cyclotron was set by the dual requirements that the upper energy limit for protons should be well above the meson threshold and that the cost of the cyclotron should not be substantially higher than would be required for heavy-ion acceleration

alone. Both four-sector and six-sector designs were carefully considered. A six-sector design was chosen because orbit calculations showed that resonance instabilities in a four-sector machine could cause unsatisfactory operation for both protons and heavy ions. Such resonances are unimportant for the proposed six-sector machine, which will reliably accelerate protons up to at least 350 MeV.

Construction and Operation. The way in which the proposed facility will be constructed can only be specified in general terms at this time. Consider first the TU tandem. The major responsibility for the construction of this accelerator will, of course, rest with the manufacturer (High Voltage Engineering Corporation). However, in order to minimize the cost, we propose to take on a limited responsibility for the design and development of some parts of the tandem system that do not interact in a fundamental way with the basic characteristics of the accelerator. Also, this experience will prove valuable later, since an effective use of a machine of this magnitude will require an operating staff that is fully competent in all aspects of electrostatic-accelerator technology, especially in view of the potential of the system for future improvements. Because of the experience gained from constructing and operating a Van de Graaff accelerator (starting in 1948) and from operating a tandem since 1962, Argonne already has on its staff men with many of the technical skills that will be needed for the development and operation of the TU-tandem system.

The conceptual design of the proposed cyclotron has been worked out by the accelerator design group in the Argonne Chemistry Division, who have had the previous experience of designing several other cyclotrons and who for many years have had the broadening experience of being responsible for the operation and development of several different kinds of accelerators—a cyclotron, a Van de Graaff, a high-current electron linac, and a Cockcroft-Walton. In view of this existing competence, the Laboratory plans to take on the prime responsibility for the design and assembly of the proposed cyclotron,

although major mechanical construction will be done outside and major components will be purchased from commercial sources, when possible. An important aspect of this approach is the backup provided by the pool of skilled manpower concerned with the operation and improvement of the ZGS. Also, the universities in the area have staff members with demonstrated competence in cyclotron technology.

Building. The great range of experiments for which the accelerator system may be used places severe demands on the beam-handling system and on the building that houses the facility. It would not be justifiable to make full provision initially for all of the many experiments for which the system is well suited. Nevertheless, it is important that the design of the supporting facilities and especially the building should not preclude the possibility of exploiting the accelerator fully in any area of science that might become especially interesting in the future. Thus, we have attempted to lay out the facility in such a way as to permit the future development of many features of the system that do not appear to be of primary importance now. In general terms, this has been done by considering what would be required to emphasize various characteristics of the accelerated projectiles (energy resolution, time resolution, etc.) and the building has been designed to make it feasible to satisfy these requirements later, if it becomes desirable. Similarly, the building (Fig. 43) was planned to permit the simultaneous use of several ion beams from the tandem in several independent experiments.

Since the proposed accelerator complex is to be a regional facility, some office and laboratory space for outside users is provided in the accelerator building. Additional space will be made available in existing buildings such as those that house the Chemistry and Physics Divisions.

Supporting Facilities. Existing equipment and auxiliary facilities at Argonne will contribute greatly to the effective use of the proposed accelerator complex. For experiments tied directly to the

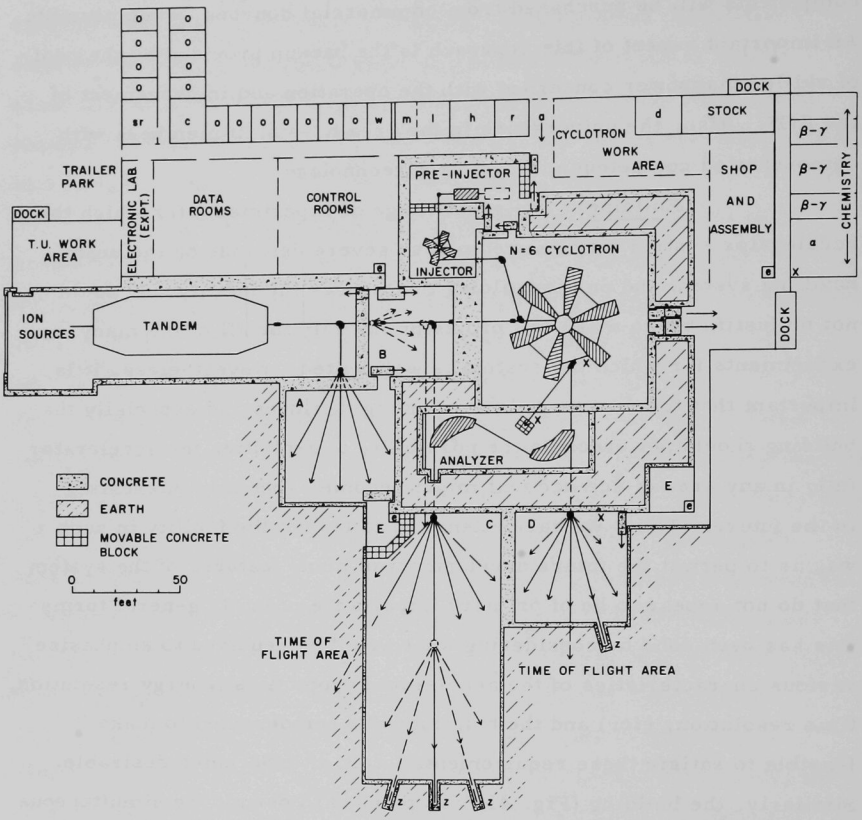

Fig. 43. The plan of the building. The directions of particle beams are indicated; some alternative beams, or beam directions, available to particles of less than the maximum rigidity are shown by dashed lines. The important beam-bending and switching magnets are shown (not necessarily to exact scale) but many minor components (e.g., quadrupoles) are omitted. Alternative positions of components are shown dashed. The experimental areas are labeled A, B, C, D, and E. Non-fixed shield walls in C are not shown. Other areas are: a—access route for heavy components to injector area, c—conference room, d—drafting room, e—elevator positions, h—target and radioactive-components laboratory, ℓ—locker room, m—men, o—office space, r—radiation safety, sr—secretary-reception, w—women, x—rabbit stations, and z—shielded beam dumps.

accelerator, the existing items consist of major pieces of equipment (magnetic spectrograph, etc.) now being used in nuclear-physics experiments at the present cyclotron and tandem; also, the Sigma-7 multiple-task computing system now being developed by the Chemistry Division will serve initially as an on-line data-handling facility. The existing auxiliary facilities available for off-line experiments are even more valuable. The most notable of these is the M-wing "hot laboratories" of the Argonne Chemistry Division, probably the world's most sophisticated research facilities for carrying out laboratory operations on high-activity materials, particularly heavy elements. Other major facilities that will play an important role in off-line experiments are a mass separator, a high-resolution alpha spectrometer, and a double high-resolution high-transmission beta-ray spectrometer. The existence of these major facilities will greatly extend the research capability of the MTC.

Research Personnel. One of the most important justifications for the construction of the MTC is the large and outstanding group of nuclear chemists and physicists eager to use it—perhaps the largest group of experienced scientists who have ever banded together to support the construction of an accelerator to be used in nuclear science. This pool of manpower skilled in research consists of nuclear chemists and nuclear physicists both at Argonne and at universities in the area.

The nuclear chemists from the Argonne Chemistry Division constitute one of the largest and most productive groups of its kind and, of central importance for this proposal, it has had years of experience in heavy-element and nuclear chemistry. An approximately equal number of nuclear chemists are distributed over seven Midwestern universities. They provide a wide range of competence in nuclear chemistry. The large group of nuclear physicists in the Argonne Physics Division are an essential ingredient for an effective use of the MTC for physics since, as members of the operating

institution, they will establish the core of the physics research program. The largest group of all consists of the nuclear physicists from the AUA universities (and a few others)—about 135 physicists with long-term appointments. Associated with these groups of experienced scientists are a total of about 500 postdoctoral fellows and graduate students.

Allocation of Experimental Time. In view of the large number of scientists who have already indicated a desire to use the proposed facility, it is clear that running time on the new facility will be in great demand and that no single institution should control its use. Thus, although the facility will be built and operated by Argonne, it is assumed that its use will be governed by a representative group of users from the Midwest in somewhat the way the ZGS is.

A necessary implication of the concept that the MTC will be a regional facility used by a very large number of investigators is that, in spite of its capacity to support a large volume of research, the new system cannot be expected to support the entire research programs of many users. Thus, much of the research that is now carried out at other accelerators in the area will need to continue. Indeed, an important aspect of this proposal is that the new accelerator system will be effectively used because most of the users have smaller accelerators at their home institutions and their research can be effectively extended and complemented by experiments at the MTC.

Cost. The estimated cost for the construction of the proposed facility is $24.4 million. This total allows $6.8 million for the TU tandem, $8.6 million for the cyclotron and its light-ion injector, $7.3 million for the building, and $1.7 million for beam-handling and other equipment. The accelerator system will be operational in 1975 if the project is authorized and funded in fiscal year 1971.

III. THEORETICAL PHYSICS

The theoretical group consists of permanent staff members, postdoctoral research associates, and long- and short-term visiting scientists. Four of the permanent staff members hold joint appointments at neighboring universities. Others teach occasional courses at various universities. Members of the group also participate in research collaborations with university faculty members, some of whom serve as consultants to ANL. The group has also undertaken a responsibility for postgraduate and postdoctoral training in nuclear theory.

Although the largest concentration of theoretical effort is in nuclear physics, theoretical research is also being carried out in superconductivity, statistical mechanics, hypernuclear structure, elementary-particle physics, and the mathematical structure of quantum mechanics. There is also a systematic development of software facilities for the numerical computations needed in nuclear-structure calculations. This facility has by now become an important theoretical resource. Parts of it have successfully been transferred to other laboratories for the use of other groups, and that process is continuing.

The theoretical group maintains an active partnership in the experimental program of the Physics Division—through research collaborations, informal cooperative effort and mutual criticism, and also through joint seminars whose principal purpose is to facilitate the flow of ideas between theorists and experimentalists.

The major programs of theoretical research are computer-based studies of nuclear structure via the spherical or deformed nuclear shell models, of nuclear-reaction theory via the shell model, and of the nuclear many-body problem. Common features of these problems, such as the nucleon-nucleon interaction and some of the computational techniques, are developed in active discussion sessions. The aims and achievements of these and other research efforts are described briefly below.

a. General Computational Programs

(i) The SPEAKEASY Programming Language

S. Cohen and C. M. Vincent

SPEAKEASY is now available in a card-input version and in a version for the IBM-2250 display console. A new manual describing the basic language now enables users to learn the language quickly.

Means of solving second-order linear differential equations have been added to the language. These are certain to be very useful in getting quick solutions to one-dimensional Schrödinger equations. The compiler now being developed will greatly increase the execution speed of SPEAKEASY programs. Means of temporarily incorporating user-written FORTRAN programs in SPEAKEASY are being explored. These developments, together with ready access to a library of manipulative routines within the Delphi system, are expected to expand greatly the application of SPEAKEASY.

(ii) The Shell-Model System (3600 Version)

S. Cohen and D. Kurath

The CDC-3600 version of the nuclear shell-model programs is in active use. Major revisions in these programs were made last year to increase their capabilities and efficiency. The most important of these was the addition of a program to calculate two-particle coefficients of fractional parentage. This program has enabled us to improve the older program for calculating energy matrices, and to expand the size of problems that can be handled by the system. It will also be possible to calculate cross sections for two-nucleon transfer experiments.

(iii) The Delphi System for Theoretical Nuclear Calculations

S. Cohen and C. M. Vincent

Delphi is an advanced system for the development of algorithms and their synthesis into programs for carrying out large-scale physics computations. A basic version of Delphi has been implemented for computers of the IBM-360 series.

It is in the nature of every theoretical investigation that new or modified techniques must constantly be developed to augment existing methods. Built into the structure of this system are many features that greatly ease the task of constructing new computational programs. Of particular interest is the expandable set of independent yet easily interlinkable algorithmic routines. This provides the means for rapid programming of new studies. As each new routine becomes available, it goes into the toolbox of the system. It is then usable with other routines or as parts of new computational programs. To aid in the development of new routines, ways of storing, cataloging, and updating FORTRAN programs and their machine-language counterparts are being developed.

Results of calculations can be stored in data libraries of the system. Such results are then available for use by computational programs for later examination or manipulation. Both a growing algorithmic library and a growing data reservoir are thus available. Each addition increases the capabilities of the system for further growth.

(iv) The Shell-Model System (360 Version)

S. Cohen, D. Kurath, J. Soper,* and A. Stamp†

An IBM-360 version of the nuclear shell-model programs is being developed. During the past year most of the development work

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*A. E. R. E., Harwell, England.

†Department of Nuclear Physics, Oxford University, England.

has involved setting up the features that relate to the system functions and the adaptation to the Delphi system. This phase of the adaptation is now complete and the computational programs will now be transferred.

b. Theoretical Nuclear Spectroscopy

(i) Shell-Model Calculations in a Deformed Basis, and Shape Mixing

M. H. Macfarlane and A. P. Shukla

Nuclei far from closed shells show a strong tendency to assume nonspherical shapes. Much of the complexity of the description of such nuclei in terms of the spherical shell model arises from the attempt to represent deformations in a spherical basis. Simplified computations and greater physical insight can be expected if the single-particle states underlying the shell-model description are themselves adapted to the deformation. Computer programs have therefore been written to carry out shell-model calculations in a deformed basis. The aim is to characterize the shell-model description of deformed nuclei in terms of as few deformed intrinsic states as possible.

We have carried out many such calculations for nuclei between ^{18}F and ^{22}Na; here we report briefly some of our results for ^{20}Ne. The shell-model vector space is that spanned by the configurations $(1d_{5/2}, 2s_{1/2}, 1d_{3/2})^4$. The intrinsic states are obtained from restricted Hartree-Fock calculations[1] within those configurations. States with definite angular momentum J and isobaric spin T are projected from the intrinsic states. These J components are orthogonalized and used to span a subspace of the complete model space $(d, s)^4$; the shell-model Hamiltonian is diagonalized within the subspace so spanned. Calculations were performed with a variety of different model Hamiltonians; the qualitative results are the same for any Hamiltonian that

[1] G. Ripka, in Advances in Nuclear Physics, Vol. 1, edited by M. Baranger and E. W. Vogt (Plenum Press, New York, 1968).

reproduces the observed spectra with reasonable accuracy. The results given here correspond to the phenomenological Hamiltonian used in most ds-shell Hartree-Fock studies[1] —a Rosenfeld two-body interaction with single-particle energies ($\epsilon d_{5/2}$, $\epsilon s_{1/2}$, $\epsilon d_{3/2}$) = (-7, -4.2, 0) (in MeV).

There are five known[1,2] solutions of the restricted Hartree-Fock equations for ^{20}Ne and, correspondingly, there are five deformed intrinsic states. There are two prolate axial solutions, two oblate axial solutions, and one axially asymmetric solution; of these, one of the prolate solutions is lowest in energy, followed by the nonaxial solution. We find that inclusion of the nonaxial solution is essential to a description of the first excited states of spin 0^+ and 2^+ in ^{20}Ne.

Three different shell-model spectra for ^{20}Ne are shown in Fig. 44. All use the interaction Hamiltonian described above; they

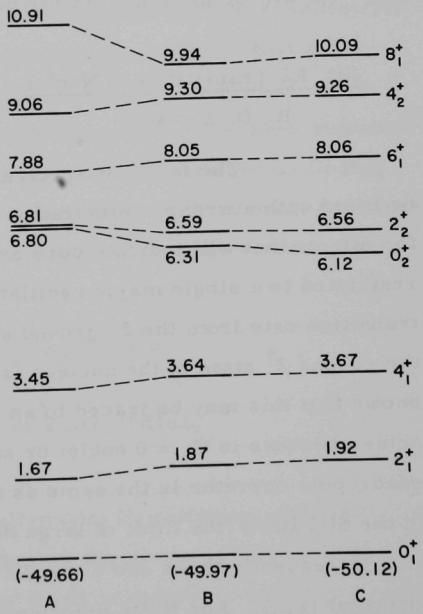

Fig. 44. Calculated deformed shell-model spectra for ^{20}Ne. The bracketed quantity at the foot of each level diagram is the ground-state binding energy. All energies are given in MeV. Calculations labeled A, B, and C are described in the text.

[2] J. C. Parikh, Phys. Letters 25B, 181 (1967).

differ in the number of deformed intrinsic states included in the basis. Calculation A includes the lowest prolate HF intrinsic state (K = 0) and the nonaxial HF intrinsic state (a mixture of K = 0, 4 and 8). Calculation B adds to the intrinsic states of calculation A all 1-particle–1-hole excitations with K = 0 and K = 2 based on the lowest prolate HF solution. Calculation C includes all states of the configurations $(1d_{5/2}, 2s_{1/2}, 1d_{3/2})^4$. This 'exact' calculation is in qualitative agreement with experiment.

It is clear that the truncated shape-mixing calculation B yields an excellent approximation to the exact shell-model spectrum of calculation C. The ^{20}Ne states in question therefore arise, to a high degree of approximation, from the lowest prolate HF intrinsic state, from its 1p-1h excitations, and from the lowest axially asymmetric HF intrinsic state. Further results for ^{19}F, ^{20}F, ^{20}Ne, ^{21}Ne, ^{22}Ne, and ^{22}Na will be presented in forthcoming publications.

(ii) E2 Transitions in Nuclei

R. D. Lawson

The fact that spectra and transition rates in nuclei can be fitted with a wrong configuration assignment has led to a search for effects that will indicate core excitation. Shell-model calculations restricted to a single major oscillator shell have shown that the E2 transition rate from the 0^+ ground state of an even-even nucleus to the second 2^+ state of the nucleus is quite small. The present work shows that this may be traced to an asymptotic selection rule which arises because in $T_z = 0$ nuclei or single-closed-shell nuclei the mass quadrupole operator is the same as the E2 transition-rate operator. In the SU3 limit (the limit of large deformation) this operator is diagonal and consequently there can be no E2 transitions between states with different (λ,μ). For finite deformation, the present calculation showed that although the selection rule is not rigorously satisfied, the phasing

of the various constituents of the wave functions tends to produce a cancellation. In fact it was shown that the size of the relevant matrix element remains small even when the nucleus approaches spherical shape. Therefore, for $\Delta T = 0$ transitions in $T_z = 0$ nuclei or in single-closed-shell nuclei, finding that the transition to the second 2^+ state has a B(E2) $\gtrsim$ 25% of the B(E2) to the first 2^+ gives strong evidence for excitation out of the given major oscillator shell. Similarly if the E2 lifetime of the first excited 0^+ state exhibits a nuclear matrix element which is $\gtrsim$25% of the first $2^+ \rightarrow 0^+$ matrix element, excitation out of the shell is indicated.

(iii) Shell-Model Matrix Elements from a Realistic Potential[1]

R. D. Lawson

In recent years there has been a great deal of interest in using a realistic two-body potential to deduce the effective-interaction matrix elements to be used in a shell-model calculation. Most of the attempts to obtain these matrix elements have relied on the use of the reaction-matrix formalism. In this work the problem has been reformulated so that the needed interaction energies can be obtained by finding the eigenvalues and eigenvectors of coupled integral differential equations. If one considers two particles outside an inert core, the relevant eigenvalue problem that must be solved is

$$\{H_0(1) + H_0(2) + V(r_1 - r_2, \sigma_1, \sigma_2) - E\}\,\psi$$

$$= \sum_j \phi_j(1,2) \int \phi_j^*(1,2)\, V\psi(1,2)\, d1d2,$$

where $H_0(i)$ is the single-particle shell-model Hamiltonian, V is the residual two-body force, and ϕ_j represents the jth two-particle state which must be excluded because of the Pauli principle.

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[1] R. D. Lawson and J. M. Soper, Nucl. Phys. A133(2), 473 (1969).

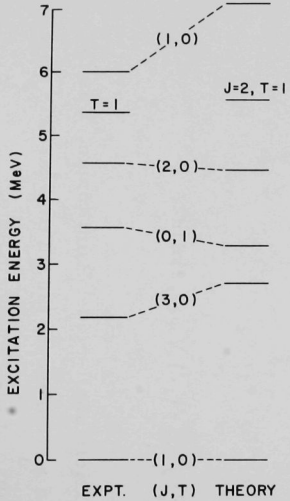

Fig. 45. Comparison of the experimental and theoretical level schemes of ^{6}Li. The residual two-body force is represented by the Hamada-Johnston potential V in the equation and the shell-model potential is taken to be an harmonic oscillator with $\hbar\omega$ = 13 MeV.

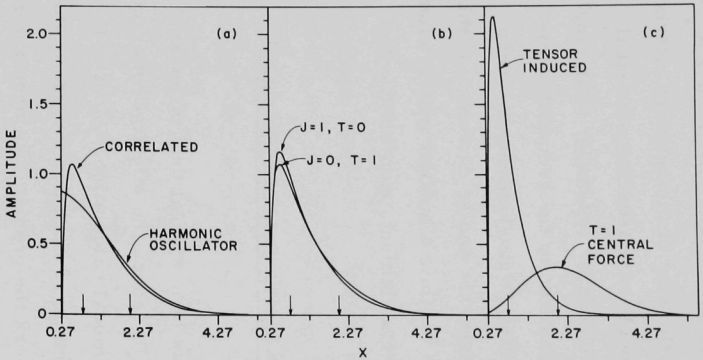

Fig. 46. Correlated wave functions that arise when the residual two-body interaction is considered. (a) Comparison between the correlated J=0 T=1 wave function (obtained when the exclusion principle is ignored, i.e., when the right-hand side of the equation is set equal to zero) and the harmonic-oscillator wave function.
(b) The ℓ=0 parts of the J=0 T=1 and J=1 T=0 wave functions when the exclusion principle is ignored.
(c) d-state wave function induced in the J=1 T=0 eigenfunction by the tensor force. The unperturbed harmonic-oscillator d-state wave function is almost indistinguishable from the T=1 central-force eigenfunction shown in the graph. The exclusion principle changes the wave functions only slightly. Each eigenfunction is individually normalized.

Programs have now been set up on the IBM-360 computer for the solution of these coupled integral differential equations, an harmonic-oscillator form being assumed for the one-particle shell-model potential. The resulting interaction energies will be used in the Argonne shell-model programs to compute nuclear level schemes. The level diagram resulting for ^{6}Li is shown in Fig. 45. The resultant two-particle wave functions ψ contain correlations due to all possible single-particle and two-particle excitations of the valence nucleons. These wave functions (Fig. 46) can be used in conjunction with the shell-model programs to compute transition rates etc. in nuclei.

This work was begun at the Weizmann Institute of Science in Israel, where Dr. J. M. Soper of UKAEA, Harwell collaborated in the early phases.

(iv) 1p-Shell Nuclei

S. Cohen and D. Kurath

Spectroscopic factors for two-nucleon transfer have been extracted for comparison with particular experiments at various laboratories. The agreement with results of ^{15}N(p,t)^{13}N and ^{14}N(^{3}He,p)^{12}C experiments is very encouraging. We have employed the results of an earlier calculation[1] to extract coefficients for two-nucleon transfer involving all possible 1p-shell targets between mass numbers A = 9 and A = 16. These calculated values show some interesting predictions of relative strengths and dominant values of the orbital angular momentum transfer, thereby suggesting further experiments to test the accuracy of this nuclear model.

[1] S. Cohen and D. Kurath, Nucl. Phys. 73, 1 (1965).

(v) Gamma Decay of Isobaric Analog States

D. Kurath

Isobaric analog states are often particularly simple states, lying at rather high excitation in the nucleus. These states

usually decay preferentially by strong M1 gamma transitions. The study of the decay modes provides important clues about the nature of the nuclear structure.

In the region A = 20—25, the rotational model can explain the general observations, but the analog decays provide additional information. For example in order to explain the branching ratios in A = 25 nuclei, one must include a small amount of a higher configuration which has especially large matrix elements for M1 transition to certain lower states.

In many other regions the analog state is well represented by coupling an odd nucleon to a core. The decays to more complicated lower states are determined by the relative magnitude and phase of the core transition and the odd-nucleon transition. Studies of such transitions help unravel the nuclear structure of the intermediate states.

Analyses of these decay patterns have provided much structure information not accessible in other ways, and such studies will continue to be of vital interest.

c. Nuclear Reactions

(i) The Shell Model in the Continuum

William J. Romo

The success of shell-model calculations for bound nuclear systems has led to the application of shell-model techniques to the calculation of scattering problems. The treatment of the continuum-continuum interaction due to the residual nucleon-nucleon potential causes a serious numerical problem. The difficulty can be traced to the presence of narrow single-particle resonances in the model system. We have developed a method that provides a separation of the kernel of the Lippman-Schwinger equation into resonant and nonresonant components. The separation permits us to treat the

nonresonant background by perturbation theory, thus providing a rather efficient calculational scheme. The connection between the effective interaction that appears in this formulation and the effective interaction of conventional shell-model theory was discussed in a paper coauthored with Prof. K. W. McVoy. The original calculational scheme has been improved and a paper is in preparation. The techniques will be applied to the calculation of cross sections for elastic and inelastic scattering of nucleons from nuclei.

(ii) Distorted-Wave Theory of Stripping to Unbound States

C. M. Vincent and H. T. Fortune

In many stripping experiments the residual nucleus is left in a resonant state rather than a bound level. In the past, a realistic analysis of such experiments has usually been prevented by the very slow convergence of the radial integrals appearing in the distorted-wave Born amplitudes. A contour integration method to circumvent this difficulty has been devised, and implemented in a CDC-3600 program. The total cross section for a reaction leading to a resonant state is obtained by integrating over the resonance. The shape of the angular distribution is found to vary only slightly as the energy traverses a resonance, although its over-all magnitude peaks sharply.

The program has been translated for the IBM-360 computer, and will be incorporated in the DELPHI system, so that the various form factors and cross sections can be calculated and stored conveniently and flexibly. This is expected to facilitate further use of the program to analyze experiments, and hence to obtain spectroscopic factors for unbound nuclear states.

(iii) Stripping to Unbound States

H. T. Fortune and C. M. Vincent

Distorted-wave calculations have been performed for a number of stripping reactions leading to unbound final states. For

the $^{16}O(d,p)^{17}O$ reaction leading to the $\frac{3}{2}^+$ state at 5.08 MeV, the present calculations agree reasonably well with earlier calculations of Huby and Mines in shape but not in magnitude. Calculations were also performed for the $^{11}B(d,p)^{12}B$ reaction leading to the 3.39-MeV state, which is neutron-unbound by 20 keV. These calculations,[1] together with $^{11}B(d,p)^{12}B$ and $^{11}B + n$ data, establish the parity of this state as negative, in contradiction to earlier assignments. The earlier assignments lead to a value 10^3 for the ratio of the spectroscopic factor S from $^{11}B(d,p)$ to the reduced width θ_n^2 from $^{11}B + n$. For negative parity, $S \approx \theta_n^2$ to within a factor of 2.

For the $^{40}Ca(^3He,d)^{41}Sc$ reaction, the calculations produce angular distributions whose shapes agree with the data and whose magnitudes yield spectroscopic factors for the unbound states of ^{41}Sc which are in reasonable agreement with those of the mirror states in ^{41}Ca.

At present, calculations for the $^{12}C(^3He,d)$ reaction to unbound states in ^{13}N have not successfully reproduced the data. Since the fits to the ground state (which is bound) are also poor, it is probable that the difficulties are due to poor choices of distorting potentials or to basic deficiencies in the DWBA, rather than to uncertainties involving the unbound states themselves.

Future plans include doing calculations for stripping to states that are unbound by several MeV in both light and medium-weight nuclei.

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[1] H. T. Fortune and C. M. Vincent, Phys. Rev. (in press).

d. Average Properties of Nuclear and Atomic States, Transitions, and Cross Sections

At sufficiently high excitation energies the density of nuclear states is so great that it becomes impossible to furnish a detailed theoretical description of individual states, and interest becomes focused on average properties. One aim of the statistical theory is to derive the laws that govern the fluctuations of quantities (such as

a decay width) associated with individual quantum states. Another aim is to derive the gross structure (such as the dependence of the nuclear level density on the parameters of the shell model) by averaging over many states. Some of the statistical principles discovered in the course of analyzing nuclear data have been found to be useful also in the description of atomic spectra. Applications of the statistical theory to a variety of complex quantum systems are expected to develop.

(i) Phenomenological Theory of Nuclear Level Densities

N. Rosenzweig and P. B. Kahn*

Accurate and transparent spin-dependent level-density formulas have been derived for a system of neutrons and protons moving in arbitrary periodic independent-particle energy-level schemes.[1] It is expected that these results will lend themselves to a semi-empirical description of the nuclear level-density data derived from slow-neutron spectroscopy. In particular, a semiquantitative fit of the large effects associated with the filling of major nuclear shells now seems possible. The effects of "nonperiodic" perturbations in the single-particle energy-level sequences has also been investigated.[2]

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*State University of New York, Stony Brook, N.Y.

[1] N. Rosenzweig and P. B. Kahn, Phys. Rev. (in press).

[2] N. Rosenzweig and P. B. Kahn, J. Math. Phys. 10, 707 (1969).

(ii) Giant-Dipole Resonance Absorption and Radiative Strength Function of ^{196}Pt[1]

N. Rosenzweig

The value of the radiative strength function observed in (n, γ) reactions at the neutron binding energy is compatible with the value deduced from the inverse (γ, n) reaction with the help of the hydrodynamical model. An analysis of the observed energy dependence

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[1] N. Rosenzweig, Nucl. Phys. A118, 650 (1968).

of the radiative strength function suggests that the family of displaced resonance-absorption curves based on the various excited states of ^{196}Pt have roughly similar shapes in the excitation energy range from 6.3 to 7.9 MeV. More generally, it is made plausible that the value of a certain mean energy should be displaced by an amount precisely equal to the energy displacement of the initial state.

(iii) Dispersion of Atomic Gyromagnetic Ratios—Approach to Statistical Equilibrium[1]

N. Rosenzweig and B. G. Wybourne*

The dispersion of the gyromagnetic ratios about their mean value is calculated as a function of the magnitude of the spin-orbit coupling parameter for some energy matrices of the complete electrostatic and spin-orbit interactions in the f^6 and f^7 electron configurations. It follows from orthonormality alone that the dispersion assumes its greatest value in the LS-coupling limit. As the magnitude of the spin-orbit coupling is increased, the energy matrix becomes more complex, its pseudo-random character is intensified, and the value of the dispersion declines monotonically until it reaches a minimum value which corresponds approximately to a state of statistical equilibrium. Some aspects of the observed variation may be understood with the help of some schematic models for the transformation matrix connecting the LS and intermediate coupling schemes. The minimum values of the dispersion about the mean are roughly equal to the values predicted by a statistical model in which all of the LS components of the wave function are assumed to be statistically equivalent.

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*Chemistry Division.

[1] N. Rosenzweig and B. G. Wybourne, Phys. Rev. 180, 33 (1969).

(iv) Conservation Laws and Distribution of Energy Levels of Complex Quantum Systems[1]

N. Rosenzweig

The definition of random-matrix models by applying the principles of information theory has provided a unified approach to diverse statistical problems, namely (1) the fluctuation of nuclear level spacings as a function of the degree of violation of time-reversal symmetry, (2) the distribution of atomic energy-level spacings as a function of the relative magnitude of spin-orbit and Coulomb forces, and (3) the temperature dependence of the specific heat of a collection of small metallic particles as a function of the magnitude of the external magnetic field. It is expected that similar applications will be found, in due course, in molecular and elementary-particle spectroscopy.

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[1] N. Rosenzweig, in Proceedings of the International Symposium on Contemporary Physics, Trieste, June 1968, Vol. II, pp. 381-390.

e. Studies of Nuclear Forces and Nuclear Matter

(i) Meson Theory of Nuclear Forces

F. Coester

Elimination of the meson degrees of freedom from the nuclear Hamiltonian requires a knowledge of the meson structure of the physical one-nucleon states. Conventional relativistic one-meson exchange potentials obtain if the one-nucleon states are calculated in first-order perturbation theory. If the meson-nucleon system is treated as a relativistic particle system without fields, then the physical one-nucleon state can be obtained exactly. Some of the features of local field theories can be recaptured in such models. The static limit of the nucleon-nucleon potential is local but otherwise largely arbitrary. The velocity-dependent terms are then unambiguously determined.

(ii) The Ground State of Homogeneous Nuclear Matter and the Foundation of the Nuclear Shell Model

F. Coester

A series of lectures on this topic was given at the 1968 Summer School on Quantum Liquids and Nuclear Structure, University of Colorado, 8—19 July 1968. The Proceedings will be published by Gordon & Breach.

The ground-state problem of homogeneous nuclear matter of infinite volume is formulated as a fixed-point problem in a suitable Banach space. Approximation procedures appropriate to different potentials are discussed.

This framework is then extended to finite closed-shell nuclei and the shell-model problem, i.e., to the problem of finding the stationary states of a nucleus that differs from a closed-shell nucleus by a few nucleons or holes.

(iii) Variation in Nuclear-Matter Binding Energies with Phase-Shift-Equivalent Two-Body Potentials

F. Coester, S. Cohen, B. D. Day, and C. M. Vincent

For any given two-body Hamiltonian there exists a large class of unitarily equivalent Hamiltonians that lead to the same scattering phase shifts at all energies. We have calculated typical saturation curves (shown in Figs. 47 and 48) for reasonable equivalent potentials. The binding energy per particle changes by several MeV in either direction and the saturation minimum shifts to higher or lower density as the binding increases or decreases. Softening the potential increases the binding. The separation approximation for the reaction matrix provides qualitative insight into these effects. Our exact calculations start with simple local s-wave potentials with either a hard core or a Yukawa core. The binding energy per particle is calculated in the Brueckner approximation with self-consistent single-particle energies below the Fermi level. For our examples

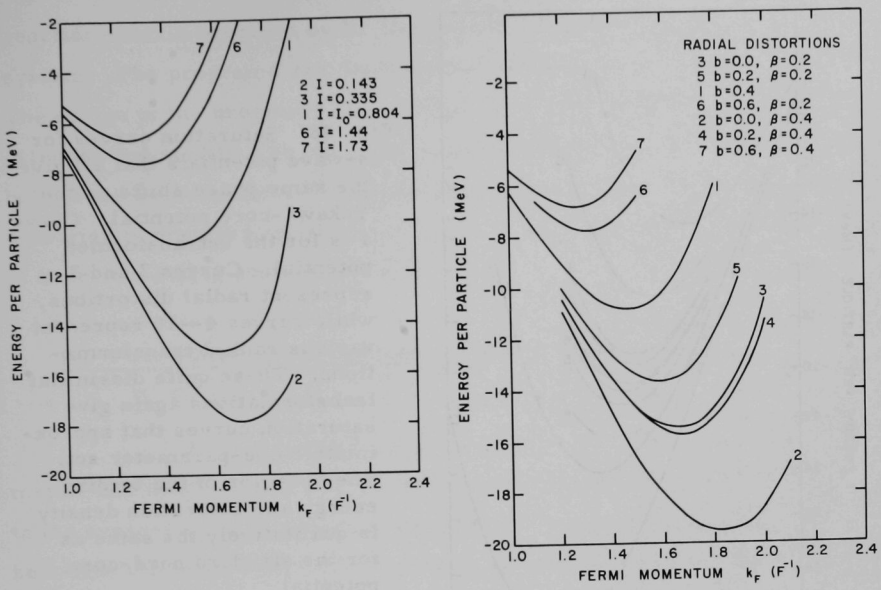

Fig. 47. Saturation curves for s-wave potentials that give the same phase shifts as the standard hard-core potential. The calculations illustrated on the left depend on the separation approximation. The contribution of the long-range part of the potential is assumed to be unaffected by the short-range transformation which preserves the phase shifts. In this approximation the family of saturation curves depends on a single parameter I that measures the distortion of the correlated wave function. Exact Brueckner calculations (shown on the right) strikingly reproduce the main results of the separation approximation.

we use unitary transformations that differ from the identity by a short-range operator of rank two and transformations induced by distortions of the radial scale. The latter class of transformations alters the core radius and produces potential terms that are linear in the square of the momentum.

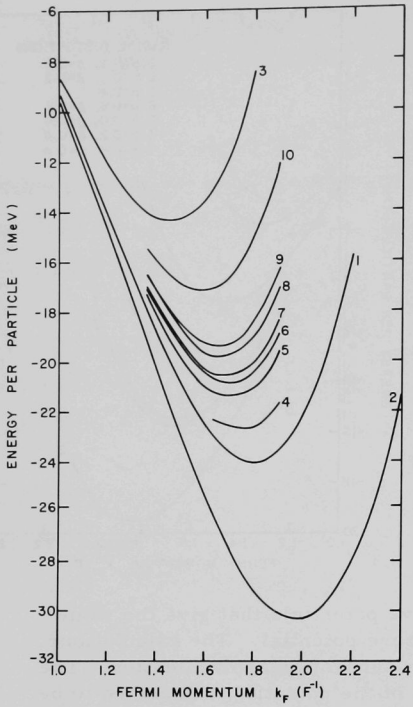

Fig. 48. Saturation curves for s-wave potentials that all give the same phase shifts as the Yukawa-core potential. Curve 1 is for the untransformed potential. Curves 2 and 3 represent radial distortions, while curves 4—10 represent various rank-2 transformations. These quite dissimilar transformations again give saturation curves that approximate a one-parameter set. The behavior of the binding energy and saturation density is qualitatively the same as for the standard hard-core potential.

(iv) Nuclear-Matter Programs

F. Coester, S. Cohen, and C. M. Vincent

A system of programs for the solution of nuclear-matter problems is being constructed. These programs can calculate the binding energy of nuclear matter as a function of the density, using the Brueckner approximation with a reaction matrix computed from a self-consistent single-particle spectrum. The calculation is made in momentum space. For hard (highly singular) potentials, the reference-spectrum reaction matrix is a more suitable input than the potential itself. Accordingly, a coordinate-space reference-spectrum

reaction-matrix program by B. Day is being incorporated into the system. The programs are designed for use with the Delphi system. The design of the programs is such that the computation can be radically extended and modified by changing a few subprograms, leaving the bulk of the system intact. Thus the system has a considerable advantage over rigidly designed programs in that it is able to adapt to methods of ever-increasing sophistication.

(v) Four-Hole-Line Diagrams in Nuclear Matter

B. D. Day

An investigation of the four-hole-line diagrams in nuclear matter has been completed. These diagrams constitute the third term in the expansion for the energy, the first two terms coming from two-hole-line and three-hole-line diagrams. Sixteen classes of diagrams have been found, and formal expressions have been given for their contributions to the energy. Each class has also been calculated numerically. The result is 0.5—1.5 MeV of additional binding for nuclear matter at normal density. This confirms the convergence of the hole-line expansion and reduces the discrepancy between the present theoretical 13 MeV and the value 16 MeV obtained from the semi-empirical mass formula. A paper describing this work has been accepted for publication.[1] The methods and results of this work can usefully be applied to the Brueckner-Goldstone theory of liquid ^{3}He and ^{4}He at zero temperature. In liquid He, three-hole-line and four-hole-line terms are considerably more important than in nuclear matter. Calculations have been started on liquid ^{4}He, but so far only the two-hole-line diagrams have been evaluated.

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[1] B. D. Day, Phys. Rev. (in press).

f. Studies of Hypernuclei and the Interactions of Λ Particles

(i) Λ in Nuclear Matter; Effective Interactions[1]

A. R. Bodmer and D. M. Rote*

A comprehensive study is being made of this interesting nuclear many-body problem in which an impurity (Λ particle) is present in nuclear matter. Relevant experimental data are available on the binding energy of a Λ particle in heavy nuclei; it is about 30 MeV. This is the only other nuclear infinite many-body problem in addition to the classical one of pure nuclear matter. Compared to the latter, it has distinctive features due to the Λ being distinct from the nucleons, due to the short range of the Λ-nucleon force, and also due to the strong coupling of the Λ-nucleon channel with the energetically close Σ-nucleon channel. The problem is not only basic and important for the physics of hypernuclei, but is also of interest as a test and a further application of nuclear many-body techniques. The work completed and in progress is conveniently divided up as follows.

(a) Perturbation theory with use of purely attractive forces. Both schematic forces and more "realistic" meson-theory potentials (with zero cutoffs) are being used. Second-order calculations, in particular including tensor forces, are in an advanced state. It is intended also to study the third-order contributions to obtain a more significant idea of the convergence of the perturbation series. The second-order results indicate that this will be considerably slower than for the purely nuclear case as a result of the Λ being distinct.

(b) Extensive and accurate reaction-matrix calculations have been made using central ΛN potentials with repulsive cores.

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*University of Illinois at Chicago Circle, Chicago, Illinois.

[1] A. R. Bodmer and D. M. Rote, in Proceedings of the International Conference on Hypernuclear Physics, Argonne National Laboratory, May 1969 (Argonne National Laboratory, Argonne, Illinois, 1969), p. 521.

This work is completed and is being written up. It is, we believe, a great improvement on previous studies and should be rather definitive. A wide range of potentials has been considered, including both soft and hard repulsive cores. The calculations are self-consistent and are based on the improved reference-spectrum method due to Day and Kallio. The importance of odd-state interactions, of various gap parameters and assumptions about the spectrum for the nucleons, of the angle-average approximation for the exclusion principle, and of the relation with the separation method have been studied. Comparison with the experimental binding energy indicates the presence of an appreciable repulsive core, a very weak (or even repulsive) odd-state ΛN force, and possibly also appreciable suppression of the ΛN-ΣN coupling in nuclear matter (or appreciable repulsive three-body ΛNN forces).

(c) Effective central interactions equivalent to a tensor force (or to a coupling to the ΣN channel). Much less is known about the ΛN force than about the nucleon-nucleon force; and it is important to know whether an effective central ΛN interaction, fitted to the scattering data, may also be used for the binding-energy calculations even though strong tensor forces and/or coupling to the ΣN channel may be present. The approach used has been to construct, and then compare, effective central nonlocal potentials for both the scattering case and the nuclear-matter case which are equivalent to a tensor force. This approach is in fact an approximation to the solution of the coupled equations which are being used to obtain the final results. Results so far obtained indicate that for the very-short-range tensor forces expected theoretically for the ΛN interaction, there is almost complete equivalence for scattering and for nuclear matter, as illustrated in Fig. 49 which shows the results of reaction-matrix calculations for "realistic" one-boson-exchange potentials [Sec. III.f(ii)]. A range of mixtures of σ-meson ($T = 0$, $J = 0^+$) and K-meson exchange potentials was considered such that all mixtures give the same scattering length.

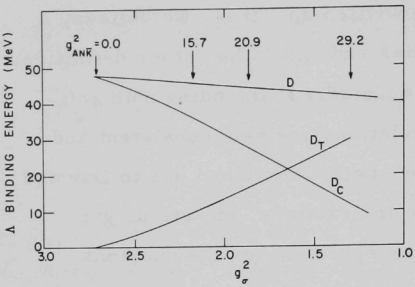

Fig. 49. Some reaction-matrix results for the binding energy of a Λ particle in nuclear matter. The binding energy is plotted as a function of g_σ^2 — the square of the coupling constant for the coupling of the σ meson to the nucleons — for mixtures of σ-meson and K-meson exchange potentials that all give the same Λ-nucleon scattering length of -2 F. The appropriate values of the square of the $\Lambda N\bar{K}$ coupling constant $g_{\Lambda N\bar{K}}^2$ are also indicated; $g_{\Lambda N\bar{K}}^2 = 0$ corresponds to a purely central potential. D_C is the contribution due exclusively to the central part of the potential, and $D_T = D - D_C$ is the contribution from the tensor part.

Since the σ-meson exchange potential is purely central whereas the K-meson exchange potential has a tensor-force component, one has a range of mixtures with varying amounts of central and tensor forces such that they compensate each other for the low-energy scattering. The figure then shows that there is almost complete compensation also for the binding energy for the short-range tensor forces involved. This strongly suggests that a very considerable and valid simplification is to use effective central forces (which are fitted to the scattering) also for binding-energy calculations. Similar studies are being made for the coupling of the ΛN with the ΣN channel.

(d) Study of the terms in the square of the density. These terms correspond to the next significant approximation in the Brueckner-Bethe expansion. Their evaluation is essential for a meaningful study of the problem, and will indicate the rate of convergence of the density expansion. These terms involve the analog for a Λ particle in nuclear matter of the Bethe-Fadéev three-body (Λ plus two nucleons) equations, and are also part of a continuing interest in three-body problems [Sec. III. f(iii)].

(ii) Theoretical Models of the ΛN and ΛΛ Interactions

A. R. Bodmer and D. Rote*

Our nuclear-structure investigations are being complemented by studies of the Λ-nucleon (and Λ-Λ) interactions by use of a one-boson-exchange (OBE) model which also includes coupling to the ΣN channel. Such models can provide (in spite of all the uncertainties) a valuable guide to the form of interactions to use in studies of hypernuclear structure. Thus, they can provide indications of the ranges and the importance of the possible components of the interaction, such as tensor and spin-orbit forces. In fact, even rather qualitative information about the components of the interaction may have very valuable implications for studies of hypernuclear structure as in our study of the effect of ΛN tensor forces [Sec. III.f(i)]. Conversely, the results of phenomenological hypernuclear analyses of binding energies and scattering data may give some information about coupling constants, hard-core radii, etc. Hence, theoretical models of the interactions are also of more fundamental interest, in the sense of leading to information about meson-baryon coupling constants.

To date, the emphasis has been on the low-energy, in particular on the s-state, ΛN and ΛΛ interactions for which the work is now in an advanced state. These interactions have also been used for our nuclear-matter calculations [Sec. III.f(i)(a)]. We intend to extend these studies to higher partial waves (in particular, to the p-wave interaction which is important for nuclear-structure studies) and to higher energies. Eventually, we also intend to study momentum-dependent terms in the OBE potentials.

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(iii) Variational Studies of Bound Three-Body Systems

A. R. Bodmer and A. Mazza*

Variational studies of bound three-body systems are being made. In particular we are considering the problem of improving variational wave functions such that these have a more adequate asymptotic behavior consistent with possible separations of the three-body system into two parts. This problem may also be considered as a calculable model for the more general problem of a core plus an extra particle, where the core has dynamical properties. Progress has been made in setting up the variational calculations, but no definite results have yet been obtained.

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g. Presymmetry

H. Ekstein

The general aim of this study is to obtain new insights into fundamental physical laws by making the relationship between laboratory procedures and theoretical objects (such as operators) more explicit. A paper entitled "Presymmetry II," which is now ready for publication, shows for example that the quantum mechanical form of Newton's second law can be derived from no more than invariance considerations and the basic postulates of quantum mechanics. The paper gives an operationalist foundation to nonrelativistic quantum mechanics. During the coming year, these methods will be applied to relativistic quantum mechanics. The main effort will go toward an operational interpretation of operators "at finite times," in connection with an operational definition of "Einstein causality" (i. e., locality). It has become clear during the last few years of theoretical development that the operators most likely to have a direct physical interpretation are the current densities rather than the fields, and this approach will be used.

h. Decay Theory

H. Ekstein and A. J. F. Siegert*

The weakness of existing theories of decay is that they do not use an operator that corresponds to the actual laboratory procedure in which the instant of the decay (the click of a counter or the appearance of a fork in a bubble chamber) is recorded. We have constructed such an operator θ in accordance with the accepted interpretative (Bohr) rules of quantum mechanics, and we are investigating its properties. Our emphasis is not on approximation methods but on conceptual clarification.

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*Northwestern University, Evanston, Illinois.

i. Gravity-Induced Electric Field Near a Conductor

Murray Peshkin

Dessler, Michel, Rorschach, and Trammell have suggested on theoretical grounds that an electric field should be present in and near a metallic conductor which is stressed to nonuniform density. For a typical metal compressed by its own weight, this electric field should be of the order of 10^{-6} V/m. A qualitative theoretical model has been developed on the basis of this theory. The main point is that, in a plausible model of the surface region, it is energetically advantageous for the conduction electrons to produce a surface charge distribution which leaves the large field predicted by Dessler *et al.* in the interior of the metal, but which provides a smaller field in a region shielded by the metal. This latter field, which precisely compensates the weight of a test electron in the shielded region, agrees with the experimental result of Witteborn and Fairbank. A detailed account of this work has been published.[1]

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[1] M. Peshkin, Phys. Letters 29A, 181 (1969).

j. Angular Distribution of Photoelectrons

Murray Peshkin

Angular distributions of photoelectrons have often been calculated on the basis of particular dynamical models. It turns out that electric-dipole absorption by randomly-oriented atoms or molecules always leads to the same one-parameter angular distribution, and that changing the polarization state of the incident light varies that angular distribution in a predictable way, independently of the dynamics of the photoejection process. This result has been recognized as a manifestation of symmetry under rotation and space inversion, but the consequences of those symmetries for photoelectron angular distributions have not previously been pursued in a systematic way. Such a systematic treatment has now been carried out. The angular distributions of the electrons, for general multipole mixtures of the absorbed photons, have been determined for various polarization states of the absorbed light. The parameters that depend upon the specific dynamical properties of the target atoms or molecules have been identified. It has been found, for instance, that polarization never introduces new dynamical information in one-electron measurements, but that polarization can introduce new information when two-electron angular correlations are considered. A complete report is in press.[1]

[1] M. Peshkin, Advances in Chemical Physics (Interscience Publishers, New York, to be published).

k. Magnetic Charge in Quantum Mechanics

H. J. Lipkin,* W. I. Weisberger,* and Murray Peshkin†

Dirac found in 1931 that, under some assumptions, electric and magnetic charges must be quantized in units (e and g, respectively) that obey

*Weizmann Institute of Science, Rehovot, Israel.

†Work done while on assignment to the Weizmann Institute.

$$eg/c = n\hbar/2, \tag{1}$$

where n is an integer. Dirac's quantization law (1) has usually been accepted in spite of questions which may be raised about his assumptions, principally because of qualitative arguments indicating that the quantity eg/c represents the angular momentum of an electromagnetic field. An accurate derivation has now been given to find reasonable assumptions under which the quantization law (1) is directly related to the quantization law for angular momentum. A detailed account of this work has been published.[1]

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[1] H. J. Lipkin, W. I. Weisberger, and M. Peshkin, Ann. Phys. (N.Y.) 53, 203 (1969).

IV. EXPERIMENTAL ATOMIC PHYSICS

Four entirely different kinds of physics are included in the atomic physics program. These are studies of the Mössbauer effect, atomic-beam experiments, plasma physics, and the use of mass spectroscopy to investigate various problems in chemical, surface, and solid-state physics.

Major new technical developments are continuing to strengthen the program. Preparations to use the MURA electron storage ring as a source of synchrotron radiation for photoionization measurements are proceeding well and measurements are expected to start during 1970. In the meantime, a more conventional experimental system at Argonne is being intensively used for a series of photoionization experiments.

The work on channeling of charged particles in monocrystals was badly interrupted during the past year by the need to move the 2-MeV Van de Graaff at which the work is carried out. This machine has now been reinstalled and the experimental system improved, however, and what are probably the first experiments on charge exchange in monocrystals are in progress. These experiments are of considerable fundamental interest, but there is also some possibility that the results obtained will have technological implications of great interest for nuclear physics (as pointed out in Secs. IV. 4i(i—iii).

The scope of measurements that can be carried out by means of the Mössbauer effect has recently been expanded greatly by the development at Argonne of techniques that make it feasible to work with very-short-lived radioactive absorbers and with source states that are formed by α decay.

The rf confinement part of the program in plasma physics has now developed to the point where it should be expanded considerably in order to reap the benefits of many years of preparation and thought.

1. MÖSSBAUER MEASUREMENTS

In the last few years, the Mössbauer effect has become a powerful tool for the study of many phenomena in solid-state, chemical, and low-energy nuclear physics. The experiments are aimed in two directions: (a) to yield accurate measurements of previously

unobtainable nuclear properties (e.g., the quadrupole moments and magnetic moments of excited nuclear states) and (b) to make accurate determinations of the environment in which a nucleus is immersed (e.g., to determine the charge transfer from an iodine atom as it forms a chemical bond with chlorine). Recent Argonne experiments have been concerned with such diverse nuclear species as ^{40}K, ^{57}Fe, ^{83}Kr, ^{119}Sn, ^{121}Sb, ^{127}I, $^{129,131}Xe$, ^{133}Cs, ^{133}Ba, ^{152}Sm, ^{237}Np, ^{238}U, and ^{243}Am, and others are being considered.

The past year has been an especially fruitful one for the development of experimental techniques that will have an important impact on future research by means of the Mössbauer effect. One of these is based on the idea that the influence of unwanted radiation from a radioactive absorber itself can be minimized by making the area of the absorber as small as possible. The experimental techniques needed to implement this idea have been developed and applied successfully to measurements on a tiny absorber of ^{133}Ba, whose half-life is only 7.2 years. The small-area technique, using as it does only a few micrograms of absorber material, opens the way to numerous applications in which only very small amounts of material are available. Another technological advance is the development of techniques for using alpha decay to populate low-lying states whose γ decay is then used in Mössbauer experiments. Several isotopes of uranium have been studied in this way. These two major technical developments may be expected to add significantly to the utility of the Mössbauer effect as a research tool.

a. Properties of Nuclear Excited States

(i) Systematic Interpretation of Isomer Shifts in Elements with $50 \leqslant A \leqslant 54$

S. L. Ruby and G. K. Shenoy*

The inability of nuclear experimenters to determine $\delta\langle r^2\rangle/\langle r^2\rangle$, the fractional change in the mean-square radius during a transition from an excited state to the ground state, has left this an adjustable parameter to be determined from chemical evidence. For several elements (e.g., ^{119}Sn), however, the chemists also have disagreed as to how to proceed. Until now, determinations via the

*Solid State Science Division.

isomer shift have been confined to separate studies of individual NGR nuclei; but during the past year we have used Hartree-Fock atomic calculations to calibrate the chemical parameters in a systematic intercomparison of the members of the sequence Sn, Sb, Te, I, and Xe (Z = 50, 51, 52, 53, 54, respectively).

A major result is that the well-understood situation in iodine reinforces the most popular interpretation for tin; and this in turn establishes the otherwise weakly based interpretations in Sb, Te, and Xe. The result is a technique for using NGR results to determine the chemical state in any solid environment. In addition, we obtain fairly accurate values of the nuclear parameter $\delta\langle r^2\rangle$ for these five elements.

(ii) Magnetic Moment of the First Excited State in ^{83}Kr by the Mössbauer Effect

L. E. Campbell, G. J. Perlow, and M. A. Grace*

The magnetic moment of the 9.3-keV first excited state in ^{83}Kr has been measured by use of the Mössbauer effect. Source and absorber were solid krypton at 4.2°K with the absorber in a longitudinal magnetic field of 77.8 kOe from a superconducting solenoid. The ratio R of the g factor of the $\frac{7}{2}^+$ excited state to that of the $\frac{9}{2}^+$ ground state is found to be +1.249 ± 0.002, from which $\mu(\frac{7}{2}^+)$ = -0.939 ± 0.002 nm without diamagnetic correction. If the ground state could be considered a pure configuration of three $g_{9/2}$ neutron holes coupling to J = $\frac{9}{2}$ and the excited state a recoupling within the same configuration, then R = 1. Furthermore the M1 transition matrix element would vanish. The transition is indeed retarded. It appears from the work of Noya, Arima, and Horie that a modest admixture into each state of the configuration obtained by promoting one $g_{9/2}$ neutron to $g_{7/2}$ can in the main account for both the observed transition rate and the excess in R. A publication is in press.

*Nuclear Physics Laboratory, Oxford, England.

(iii) Uranium

S. L. Ruby, G. M. Kalvius,* B. D. Dunlap,* G. K. Shenoy,* D. Cohen,† M. B. Brodsky,‡ and D. J. Lam‡

During the past year, the nuclear gamma resonance (NGR) technique has been extended to make it applicable to the even-A isotopes of U. In these experiments, the sources ^{242}Pu, ^{240}Pu, and ^{238}Pu have been used with the absorbers ^{238}U, ^{236}U, and ^{234}U, respectively. Since it is much easier to prepare absorbers from natural uranium (mainly ^{238}U) than from enriched samples of the other isotopes, most of the experiments have been performed with ^{238}U, despite the low counting rates associated with the ^{242}Pu source. The other isotopes are used when special accuracy is needed.

Owing to the short lifetimes, this is poor-resolution NGR spectroscopy and consequently we can measure only relatively large hyperfine fields. However, both magnetic and quadrupole interactions large enough to be readily measured have been found in the first experiments. For example, the first measurement of the magnetic field at the uranium nucleus in UO_2 has given 2700 kOe. Light has been shed on several traditional uranium puzzles; for example, we do not see magnetic behavior below the transition in α-uranium at 43°K.

Within the next year or so, we expect to extend these studies to include a wide variety of solid-state problems involving uranium.

(iv) ^{243}Am

S. L. Ruby, G. M. Kalvius,* B. D. Dunlap,* G. K. Shenoy,* and M. B. Brodsky‡

The NGR technique has been extended to the element americium, and the technical problems associated with a highly

*Solid State Science Division.

†Chemistry Division.

‡Metallurgy Division.

radioactive absorber have been solved. The experiments turn out to be technically feasible; the only remaining problem is to find a source that gives a sharper line at liquid helium temperatures than does the present irradiated PuO_2.

The preliminary measurements indicate a large change in nuclear radius during the transition; and this in turn implies an unusually high sensitivity to the chemical environment. The NGR technique will be useful in solving many problems regarding americium, especially with reference to magnetism.

b. Studies of Chemical Environment and Electronic Configurations

(i) Ions in Ice

S. L. Ruby and I. Pelah*

Starting from NGR measurements on tin atoms in frozen aqueous solutions, we have gone on to electrical conductivity, NMR,

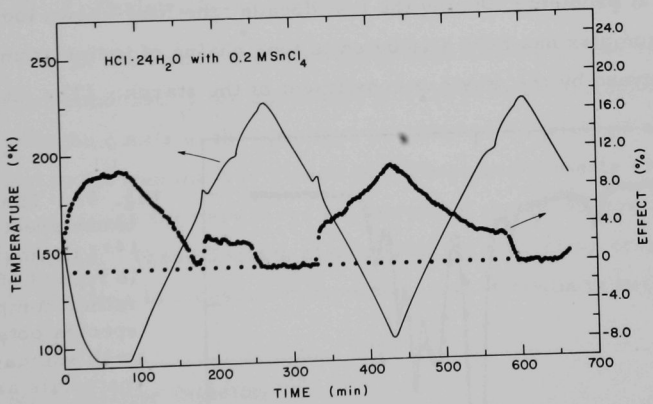

Fig. 50. Record of thermal analysis and Mössbauer effect done simultaneously. This graph proves that the appearance and disappearance of the Mössbauer effect upon heating and cooling represent the melting and crystallization of eutectic pockets in frozen acid solutions.

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*Solid State Science Division.

and differential thermal analysis techniques. By using all these in combination, we have solved the problem of the anomalous disappearance (Fig. 50) of the Mössbauer resonance in ice and have achieved a clear picture of the rather complicated sequence of eutectic formation, supercooling, glass transitions, and meltings involved in those experiments.

In addition to the satisfaction of clearing up a puzzle, this work has led to the discovery of two new ways of studying eutectic formation and freezing, namely NGR and conductivity. Further work on this in collaboration with physical chemists will be most productive.

(ii) Iodine in Starch

S. L. Ruby

The use of NGR techniques for iodine in organic compounds is barely beginning; this work is the first attack on a somewhat biological problem. During the last decade, the long-known iodine-starch complex has been attributed to long chains of iodine atoms inside tubes formed by the amylose constituent of the starch. (The glucose

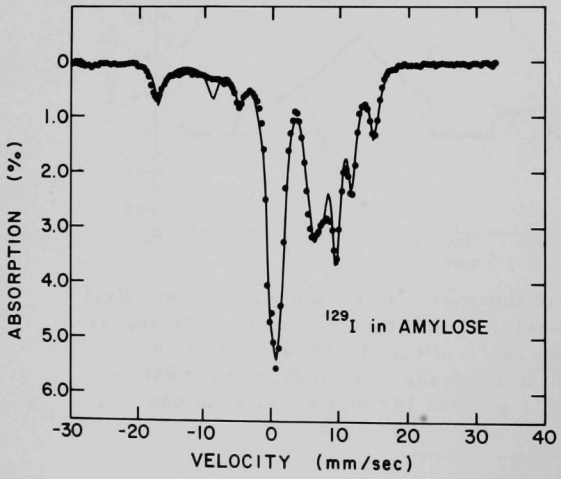

Fig. 51. The Mössbauer spectrum of ^{129}I in amylose. It is typical of the rather complicated spectra obtained in such starch-like materials as amylose, cyclodextrin, and benzamid. The solid line demonstrates that calculations do not always exactly fit the data.

units combine to form a rather linear α-helix whose interior is adequate for the iodine atoms.) Several authors have considered the result to be a "linear metal," with all the iodines playing an equivalent role.

Other authors, using x-ray techniques, have suggested that the I_3^- ion plays a central role and that the chain may be made up of such links. Preliminary measurements, not yet fully analyzed with the computer (Fig. 51), indicate the merit of this suggestion.

The measurements are technically not very difficult, and the interpretation of iodine NGR results is well understood. The only barrier to exploitation of this technique is our lack of knowledge of suitable chemical and biological problems. During the next few years we expect the study of biological compounds such as thyroxin to become important.

(iii) Studies of Cesium-Graphite Compounds

G. J. Perlow, G. L. Montet,* and L. E. Campbell

In the continuing Mössbauer experiments on the cesium-graphite compound CsC_8, the absorbers are made from pyrolytic graphite with the c axis of the absorber oriented at a variety of angles with respect to the gamma-ray direction. These experiments are designed to measure the very large anisotropy of the recoilless fraction in this compound. These spectra also exhibit the only clear case of quadrupole splitting in a cesium compound. A publication is being prepared.

*Solid State Science Division.

(iv) Mössbauer Studies with ^{191}Ir and ^{193}Ir[1]

G. J. Perlow, D. N. Olson, and W. Henning

The isotopes of iridium with mass numbers 191 and 193 have very similar nuclear properties, exhibiting rotational spectra

[1] G. J. Perlow, W. Henning, D. Olson, and G. L. Goodman, Phys. Rev. Letters 23, 680 (1969).

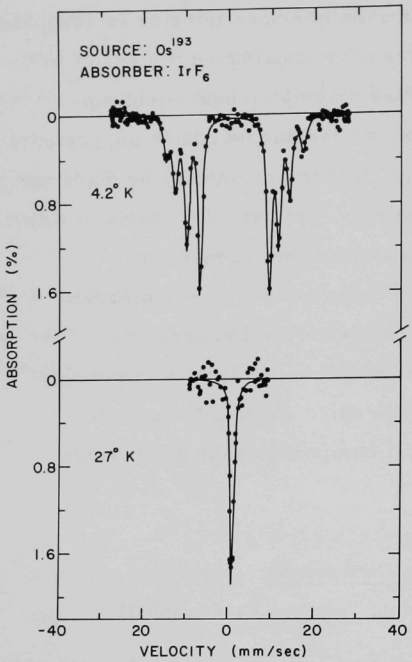

Fig. 52. Velocity spectrum of IrF_6 below and above the transition temperature. (The compound IrF_6 is an antiferromagnet with a magnetic transition at about $8^{o}K$.)

characteristic of deformed nuclei. One level in each of these isotopes is most suitable for Mössbauer studies, namely the 83-keV level in ^{191}Ir and the 73-keV level in ^{193}Ir. A velocity spectrum of the latter is shown in Fig. 52. Magnetic and chemical investigations are under way.

(v) Mössbauer Investigation of the Unequilibrated Ordinary Chondrites

E. L. Sprenkel-Segel

The recoilless resonant interaction of 14.4-keV gamma rays in ^{57}Fe was used for the investigation of iron minerals in the ordinary chondrites. The absorption spectra are composites of the 2-line patterns of olivine $(Mg.Fe)_2SiO_4$ and pyroxene $(Mg,Fe)SiO_3$ and the 6-line patterns of troilite (FeS) and kamacite (nickel-iron alloy

with body-centered cubic structure). All the spectra of the ordinary chondrites investigated were similar in general appearance. For the equilibrated bronzite chondrites the mean ratio of olivine to pyroxene iron was 1.6; for the equilibrated hypersthene chondrites the values clustered about 2.2. The spectra of the unequilibrated ordinary chondrites give the appearance of having a very large ratio of olivine to pyroxene iron. In certain meteorites, however, some of the pyroxene iron resides in a nonequivalent lattice site such that the corresponding absorption is in the same region of the spectrum as the absorption by ^{57}Fe in olivine. When a correction for this effect is taken into account, the olivine/pyroxene iron ratios are found to be more similar to the ratios for the equilibrated ordinary chondrites (except for Tieschitz, unless it is reclassified as an unequilibrated hypersthene chondrite).

Some of the meteorites studied have undergone various degrees of terrestrial weathering. The absorption patterns of oxidation products were investigated by studying the completely oxidized Wolf Creek meteorite. The patterns observed correspond to maghemite, α-FeOOH, β-FeOOH, and γ-FeOOH (in order of decreasing intensity).

Published electron-microprobe studies indicate that the <u>most unequilibrated</u> chondrites of the bronzite, hypersthene, and amphoterite groups have similar compositions for the olivine and the pyroxene as well as similar relative proportions of the two minerals. On the other hand, the olivine and pyroxene of the <u>equilibrated</u> hypersthene and amphoterite groups have higher iron contents. If it is correct to assume that the equilibrated groups result from thermal metamorphosis of their unequilibrated counterparts, then the source of the iron introduced during equilibration must be identified. A search for such sources of iron was made in the Mössbauer absorption spectra of the unequilibrated ordinary chondrites. The unequilibrated meteorites investigated were: Tieschitz, Bremervorde, Clovis No. 1, Hallingeberg, Barratta, Chainpur; the equilibrated meteorites Bruderheim and Soko Banja were included for comparison. The Mössbauer

absorption spectra of the unequilibrated chondrites show that the FeO contents reported in the chemical analyses occur almost entirely in the form of ferrous minerals with absorption patterns corresponding to olivine and pyroxene. Dodd, Van Schmus, and Koffman suggested magnetite as the source of iron to be introduced into the olivine and pyroxene during equilibration. The Mössbauer spectra, however, show virtually no magnetite and the required amounts of iron are not present. Large amounts of FeO reported in the chemical analyses are not accounted for in the olivine-pyroxene systems described by the electron-microprobe work on the most unequilibrated ordinary chondrites. The Mössbauer spectra require that this FeO be present as high-iron olivine and/or pyroxene (presumably in a microcrystalline phase) or another ferrous mineral whose absorption pattern overlaps the olivine-pyroxene absorption.

(vi) Mössbauer Spectra Near Second-Order Phase Transitions

Richard S. Preston

The Mössbauer spectrum of iron metal near the magnetic Curie temperature has been studied further. The Mössbauer fraction varies smoothly, showing that there is no sudden change in the lattice vibrations; but the centroid of the spectrum shifts abruptly. Thus, since there is no change in the lattice vibrations to account for this shift, it must be attributed to a change in the isomer shift produced by a slight modification of the electronic wave functions in the metal. A certain spikiness of the density-of-states curve for s-like electrons is usually ignored in band-structure theory but could have accounted for this shift if the shift had occurred in the ferromagnetic region where the spikes ought to move about as the spontaneous magnetization changes with temperature. However, the observed anomaly occurs just above the critical temperature T_c where the average magnetization is zero. I. Goroff (MET) and F. Mueller (SSS) are attempting some

refined band-structure calculations to see if they can account for the shift. A valuable kind of information that could come out of their fit to the experimental data would be the temperature dependence of the correlations of the atomic spins. The large and rapid changes in these correlations are typical of the critical behavior of systems undergoing second-order phase transitions.

In other second-order phase transitions, there may well be sudden changes in the Mössbauer fraction and quadrupole splitting as well as in the isomer shift because the ordering of atoms—not just their spins—is involved. Additional measurements of this sort will be carried out in the future in an effort to gain more insight into the critical phenomena associated with second-order phase transitions.

(vii) Computer Simulation of a Second-Order Phase Transition

Richard S. Preston

The critical phenomena associated with second-order phase transitions are difficult to deal with either experimentally or theoretically because they require measurement or calculation of the detailed shapes of various thermodynamic functions as close as possible to the critical point, which is the point at which many of these functions exhibit infinite singularities. Some elegant mathematical procedures have been used to find exact solutions for one special model, the infinite two-dimensional Ising lattice. But these bare results do not help one to form any mental image of what is happening on the microscopic level to produce these singularities, although it is clear that these are cooperative effects and that little change occurs in the behavior of single atoms. There have been some interesting computer studies of finite Ising and Heisenberg lattices but they, too, have not provided any insight into the microscopic behavior near the critical temperature.

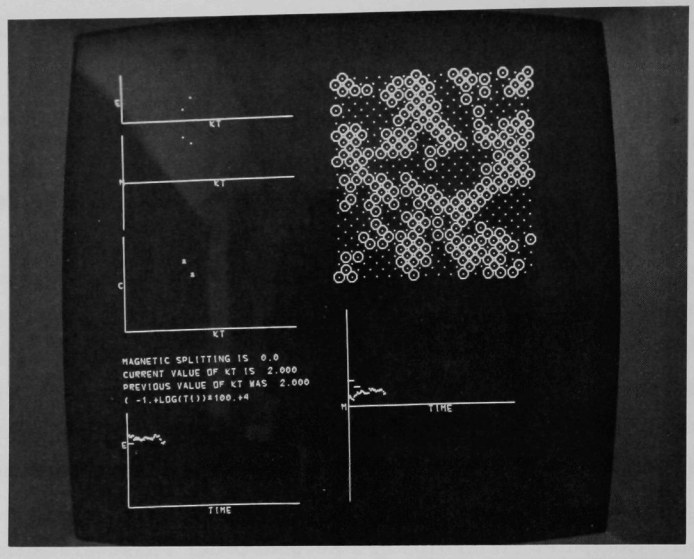

Fig. 53. Photograph of the screen of the cathode-ray tube during a run of the simulation program. The grid at the upper right represents a two-dimensional lattice. Each dot represents a spin which is either up (if circled) or down (if not circled). The plots of E and M vs time show how the energy and magnetization of the lattice have varied during the time that kT has been set at its current value. The plots of E, M, and C show the long-time averages of lattice energy, magnetization, and specific heat for previous settings of kT.

In order that the time development of a (hypothetical) lattice of spins may be observed directly, a new computer program has been developed for simulating a finite two-dimensional Ising lattice which is in contact with an infinite heat reservoir at a well defined temperature. It is possible to vary this temperature, and in addition to simulate the application of an external magnetic field whose strength may also be varied. The most significant improvement over previous computer simulations of an Ising lattice is the explicit calculation of the time interval between successive spin configurations of the lattice.

All of the interesting thermodynamic and statistical mechanical quantities may be calculated from the time averages over many configurations at particular settings of temperature and external field. Because it is possible to display the instantaneous configuration of the spins on an on-line cathode-ray tube (Fig. 53), one can also watch the microscopic time development of the system. The inclusion of a realistic time scale in the cinematographic display gives the viewer a more meaningful insight into the time development than would a simple, regularly spaced succession of images of different configurations. The computed results for the thermodynamic functions have been found to be consistent with the exact results, except that there are no real infinite singularities because the simulated system is not infinite. In view of this success, the program will be modified to simulate a three-dimensional lattice for which no exact mathematical results exist.

c. The Mössbauer Effect in Short-Lived Isotopes

A. J. F. Boyle and G. J. Perlow

(i) Miniaturized System for Very Small Samples

In a typical Mössbauer experiment, both the source and the absorber of the gamma radiation have had areas of a few square centimeters, and the absorbers have either been of stable isotopes or long-lived ones (commonly a million years or longer). The problem in using radioactive absorbers is to have a sufficient number of the atoms without the radioactivity becoming so intense that it obscures the transition of interest. The details of the solution (if there is one) depend on the properties of the nucleus in question, such as the attainable activity per unit area in source and absorber and the amount of atomic absorption by the isotope of interest and by any other material mixed with it. The limit to the total activity typically restricts the area of both source and absorber to a few square millimeters or less. The

resulting scaling down of the conventional Mössbauer apparatus necessitates careful alignment of source and absorber, and the amplitude of the relative motion between them must be kept small so that the source can be placed close to the absorber. A miniaturized system that satisfies these requirements has been developed.

(ii) Mössbauer Effect in ^{133}Ba (7.2 yr)[1]

The use of the small-area technique for studies of short-lived radioisotopes was demonstrated in an experiment with 7.2-year ^{133}Ba as the absorbing nucleus and the 37-hour isomer of this nucleus as the source. To produce sufficiently active source material, it was necessary to bombard ^{133}Cs with deuterons so that the 37-hour isomer of ^{133}Ba formed in the nuclear reaction could be extracted as a pure isotope. Even though the Argonne cyclotron is ideal for this purpose, only a few millicuries can be produced in a reasonable time; and consequently the absorber area was limited to a few square millimeters. In an experiment with ~2 μg of ^{133}Ba, a usable velocity spectrum (Fig. 54) could be obtained at liquid helium temperature (4°K) in one half-life (37 hours) of the source. When the experiment was performed in a strong magnetic field, the magnetic moments of the ^{133}Ba nucleus both in its ground state and in its 12.3-keV excited state could be measured. In addition, all the usual chemical

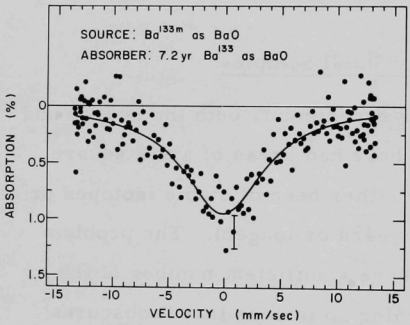

Fig. 54. Velocity spectrum obtained in one source half-life at liquid-helium temperature with the oxide source and absorber.

[1] A. J. F. Boyle and G. J. Perlow, Phys. Rev. 180, 625 (1969).

and solid-state properties usually associated with the Mössbauer effect can now be studied with barium (the only alkaline earth in which the Mössbauer effect has been observed).

(iii) Extension to Other Short-Lived Radioisotopes

The success of the ^{133}Ba experiment leads to the realistic expectation that Mössbauer absorption may be detectable in some 30 radionuclides with half-lives less than a thousand years. The small-area technique, using as it does only a few micrograms of absorber material, also opens the way to numerous applications in which only very small amounts of material are available. In addition to the nuclear, chemical, and solid-state problems such as those suggested above, it may find application with monocrystalline and biological specimens.

(iv) The Mössbauer Effect in an Absorber Produced by Neutron Capture

A. J. Boyle, L. M. Bollinger, G. J. Perlow, R. K. Smither, and G. E. Thomas

The success of the small-sample technique [Sec. IV. 1c(i)] for the study of radioactive absorbers suggested that even the very short-lived nuclides produced by neutron capture could be used as absorbers in Mössbauer experiments if the source were strong enough. For many materials a source of the required strength may be obtained by neutron capture in a sample in the interior of a reactor. However, the radiation from such an intense source could not be used in a conventional counting experiment, because the detector would be paralyzed by the intense flux of unwanted radiation from both the source and the absorber. We have overcome this problem by using a crystal-diffraction technique to separate out the γ rays associated with the transition of interest. Figure 55 is a schematic diagram of the experimental arrangement.

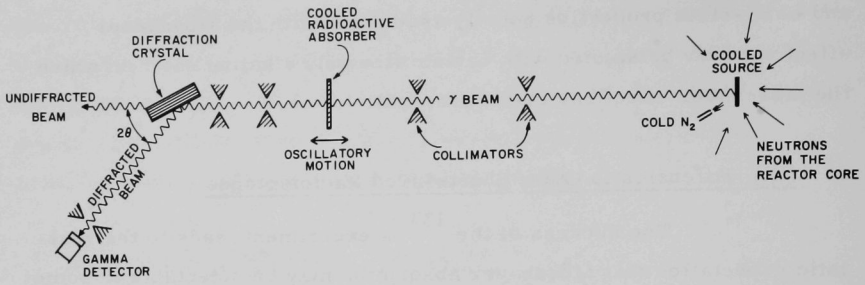

Fig. 55. Schematic drawing of the apparatus used to measure the Mössbauer effect in ^{153}Sm. Thermal neutrons from the reactor core are captured in the liquid-nitrogen-cooled ^{152}Sm sample on the right, which is located in the center of a tube passing through the high-flux region of the Argonne research reactor. The resultant γ beam is collimated as it leaves the reactor, passes through the cooled radioactive ^{153}Sm absorber and further collimating slits, and then impinges on the diffraction crystal which separates the 35.84-keV gamma ray from the rest of the (n, γ) spectrum. The intensity of the diffracted 35.84-keV γ ray is then measured as a function of the velocity of the cooled radioactive ^{153}Sm absorber to obtain the velocity spectrum of Mössbauer absorption.

The 35.8-keV state in ^{153}Sm was studied as a test of the suggested use of neutron capture to form both the source and absorber. The source was 140 mg/cm^2 of $^{152}Sm_2O_3$ mounted in the center of a tube that passes near the core of the reactor CP-5. The absorber, 4×10^{17} atoms of 47-h ^{153}Sm per cm^2, was formed by irradiating $^{152}Sm_2O_3$ (140 mg/cm^2) to saturation. This highly active absorber, attached to the vibrator, was outside of the reactor in the direct beam from the source. Both the source and the absorber were cooled to liquid nitrogen temperature.

With a Cu crystal to select the 35.8-keV gamma ray, the background in the counting channel included a 17% contribution from the source and 38% from the fresh absorber. The counting rate was 170 sec^{-1}. The velocity spectrum accumulated in 50 h showed a small (0.4%) Mössbauer effect with a line width of 10 mm/sec.

Although only marginally successful because of the scarcity of absorber nuclei and other unfavorable circumstances, the experiment showed that the attempted measurement and others of the same kind are entirely feasible. With some effort the technique could be improved enough to produce data of good quality.

2. ATOMIC-BEAM RESEARCH

a. Hyperfine Structure of Stable Isotopes

W. J. Childs and L. S. Goodman

Our program of measuring hyperfine structure (hfs) in the nuclear ground state of stable isotopes is continuing. Emphasis is placed on making measurements in a number of different metastable atomic states, since it is well known that conclusions drawn from a measurement in a single state can be grossly in error if the composition of the state is not accurately known. Detailed comparison of the hfs of many levels with the theory should lead not only to a better understanding of the atomic structure, but also to a more reliable value for the electric-quadrupole moment of the nucleus of the atom.

Studies of this type were made on about a dozen metastable atomic levels of the $5d6s^2$ and $5d^26s$ electron configurations in ^{139}La. Because of poor intensity, however, completion of the work has had to be postponed pending development of an exciter for the beam atoms. At the present stage of the interpretation, no single set of atomic parameters can be found to fit all the quadrupole hfs constants to better than about 20%. It is hoped that further theoretical work will lead to a substantial refinement in our knowledge of these parameters. The results already obtained illustrate well the dangers of evaluating a quadrupole moment from the hfs of a single atomic state.

Similar studies are being carried out on ^{159}Tb, the only neutral atom with $Z < 97$ for which the ground electron configuration

is not yet known. Levels of both $4f^9 6s^2$ and $4f^8 5d6s^2$ are populated thermally in the atomic beam, and hfs constants have been determined for three levels of the former and for fourteen of the latter.[1] Although the work is not yet complete, it appears to be even more difficult to obtain a good fit to the measured electric-quadrupole hfs constants B than in the case of ^{139}La.

In addition to the hyperfine-interaction constants A and B, high-precision values of the electron g factor g_J can be obtained for all atomic states populated in the beam. Such a study was made in ^{140}Ce, and good values of g_J were obtained for 33 levels. Since the value of g_J for a state depends strongly on its composition, such studies are of great use in understanding the atomic structure.

It is felt that continuation of the present program should lead to substantially more accurate values for nuclear ground-state quadrupole moments and also to a far more detailed understanding of the structure of medium and heavy atoms.

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[1] W. J. Childs and L. S. Goodman, J. Opt. Soc. Am. 59, 875 (1969).

b. Investigations of Radioactive Isotopes

J. A. Dalman, H. Diamond,* L. S. Goodman, and H. E. Stanton

Several runs with 5-h ^{243}Pu were carried out. This work will be resumed when CP-5 becomes available again. Plans have been made to measure g_J values for one or two states in ^{254}Fm in the near future.

Further work in 1969 is planned with francium isotopes, especially ^{223}Fr, and with ^{141}Ce and ^{143}Ce. The work with the Ce isotopes is of interest both for studies of the nuclear moments and for the determination of the electronic angular momentum of a particular atomic state.

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*Chemistry Division.

The value of the electronic angular momentum J for the first excited state (228 cm^{-1}) of Ce I is in doubt. The indication from optical spectroscopy is J = 2, while that from atomic-beam investigations is J = 4. We are hopeful that further atomic-beam experiments with the odd-A isotopes of cerium may resolve this long-standing discrepancy.

A small mass-spectrometer detector is being constructed for installation on the present machine. This will allow one to monitor the stable atoms in the beam and will also allow us to study long-lived radioactive species.

Several modifications during the past year have improved the operation and utility of the machine. These include an improved system for loading radioactive samples into the machine, improved rf structures for inducing transitions, an improved power regulator for heating our ovens, and a modification of the vacuum system.

3. RADIO-FREQUENCY PLASMAS

The central purpose of this research is to advance the understanding of the basic properties and mechanisms of low-pressure plasmas produced by rf fields, with special emphasis on aspects relevant to controlled thermonuclear research. The two lines of experimental and theoretical investigation being pursued are studies of plasmas produced (a) in the approximately uniform rf electric field between parallel-plate electrodes and (b) in the nonuniform standing-wave electromagnetic fields in resonant cavities.

a. Plasmas in Uniform rf Electric Fields

A. J. Hatch

The main goal of this work is to elucidate the basic mechanisms involved in resonant plasma phenomena (e.g., rf plasmoids) that occur at pressures in the vicinity of and below the collision-frequency transition ($\sim 10^{-2}$ Torr). The present approach is to correlate

measurements of impedance Z_p with a one-dimensional slab-model theory. Earlier measurements of Z_p at 15 MHz by use of a quasi-substitution method revealed highly nonlinear effects that require more detailed study under a wide range of circuit tuning conditions. A pair of papers describing this earlier work is in preparation. More recently a four-probe method (the long-wavelength equivalent of a slotted line) has been used to measure Z_p at 45 MHz, and a machine computation program has been written to reduce the rather large errors inherent in the use of the conventional graphical (Smith chart) method of data reduction. Extensive measurements using this more sophisticated method through a wide range of pressure and rf power are planned.

b. Plasmas in Nonuniform Cavity Fields

A. J. Hatch, S. L. Halverson,* and J. L. Shohet

The main goal of this work is to investigate the basic phenomena and mechanisms of plasmas produced in the standing-wave fields of resonant cavities at UHF frequencies (600—1000 MHz) and at pressures well below the collision-frequency transition (~0.5 Torr). Special emphasis is placed on the plasma confinement capabilities resulting from time-average drift forces in quadrupole modes.

Experimental work during the past year has been concerned mainly with the plasma-loading characteristics of a cylindrical cavity at intermediate pressures (~0.02 Torr). A highly significant result of this work is the demonstration of a frequency-shifting method of exciting a plasma in a resonant cavity. This new method has given plasma densities ~7 times those obtainable by exciting the cavity at its empty frequency. To obtain such an increase at fixed excitation frequency would require an increase in input power by a factor of

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*Electronics Division.

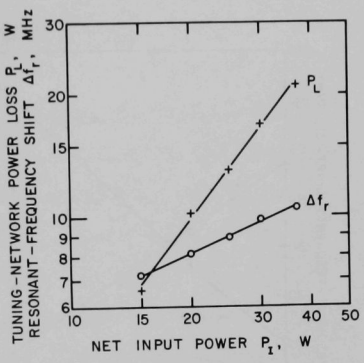

Fig. 56. Results of conventional method of increasing plasma density by increasing input rf power P_I to a resonant cavity at a fixed excitation frequency. The plasma density (proportional to Δf_r) increases approximately as $P_I^{1/2}$ whereas the power loss P_L in the impedance-matching network increases approximately as $P_I^{3/2}$. The maximum plasma density here (at P_I = 36 W) is $n \approx 0.52 \times 10^9$ cm^{-3}.

$\sim 7^2 \approx 50$. This result is explained on the basis that the presence of the plasma causes the cavity to become detuned and this in turn causes a substantial loss of power to the impedance-matching network. Therefore, when the plasma-loaded cavity is excited at its empty frequency both the detuning and the matching network losses increase as input power is increased, with the result that a decreasing fraction of the input power is available to the plasma, as shown in Fig. 56. However, when the excitation frequency is increased ("frequency chasing") both the detuning (with respect to the excitation frequency) and the matching-network losses decrease, thereby making an increasing fraction of the input power available to the plasma, as shown in Fig. 57. A paper describing this work has been published.[1]

Theoretical work during the past year has been concerned mainly with a computation of the frequencies of the first ten fundamental modes of a cylindrical cavity as a function of the nonuniform radial density of a central axial column of plasma. The radial density distribution used was obtained from an Abel inversion of the lateral luminosity profile of a plasma column excited by the TM_{010} mode. This work represents a substantial refinement of the simpler conventional problem in which a small plasma rod of uniform density is assumed;

[1] S. L. Halverson and A. J. Hatch, Appl. Phys. Letters 14, 79 (1969).

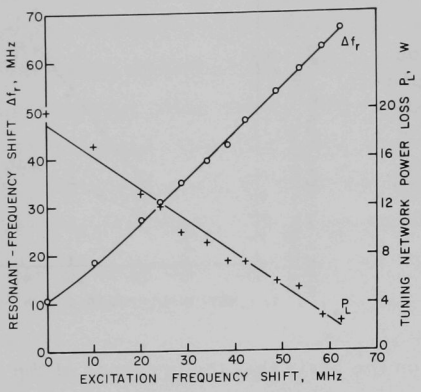

Fig. 57. Results of new method of increasing plasma density by shifting excitation frequency while maintaining input power P_I constant at 36 W (corresponding to maximum in Fig. 56). The plasma density (proportional to Δf_r) increases approximately linearly with the shift Δf_x in excitation frequency, whereas the power loss P_L in the matching network decreases at a rate that is also approximately proportional to Δf_x. The maximum plasma density here is $n \approx 3.4 \times 10^9$ cm^{-3}, or $\sim 6\frac{1}{2}$ times that in Fig. 56 at the same input power.

and it is especially useful as a diagnostic aid for the present experimental studies. A paper describing this work is in preparation.

4. MASS-SPECTROMETRIC AND RELATED INVESTIGATIONS

Two broad areas of investigation can be distinguished here: (1) the interaction of radiation with gaseous or vapor species and (2) the interaction of particle beams (charged and neutral) with solids. In the former type of study, electron and (more recently) photon impact has been used to study the thresholds for ionization and dissociative ionization, the phenomenon of autoionization, and the rates of chemical reactions in which the reactants can be formed in well-defined energy states. From these experiments, rather precise values of ionization potentials, bond-dissociation energies, and electron affinities have been obtained. Recently, these studies have been extended to examine the kinetic energies of electrons ejected in the photoionization process.

Two instruments are in use in molecular and ionic sputtering experiments and similar investigations involving surface properties and reactions. A portable mass spectrometer is used at various accelerators in studies of the phenomena involved in ion bombardment of polycrystalline and monocrystalline foils and thick targets. The effect of channeling on the charge distributions of beams penetrating monocrystalline foils has engaged particular attention recently.

a. Photoelectron Spectroscopy of Autoionization Peaks[1]

J. Berkowitz and W. A. Chupka

A vacuum ultraviolet monochromator has been combined with a retarding-field electron-energy analyzer to study the distribution of photoelectrons from autoionizing states of hydrogen and nitrogen. In most cases involving hydrogen, the photoelectrons produced are monoenergetic and correspond to autoionizing transitions in which Δv is a minimum, i.e., the ejected electrons have the minimum kinetic energy. There is one possible exception to this generalization.

Different mechanisms appear to be operative in the nitrogen autoionizations. In general, several bundles of electrons, corresponding to the formation of several ionic states, are observed. Whereas vibrational relaxation of the core appears to explain the results with hydrogen, an alternative mechanism involving configuration interaction has been examined in an attempt to rationalize the nitrogen results. This proposed mechanism implies that relative transition probabilities in the autoionization process are dominated by Franck-Condon factors connecting the quasi-discrete state and the ionic state. The ratio of Franck-Condon factors is very sensitive to the choice of internuclear distance for the quasi-discrete state. In many cases, it is possible to find a plausible internuclear distance for which the ratio of Franck-Condon factors agrees with experiment. If the Franck-Condon factors are indeed the major determinant of relative transition probabilities, photoelectron spectroscopy offers a method for determining the internuclear distances of the quasi-discrete states. One autoionizing transition in nitrogen, as yet unassigned, does not seem to fit this mechanism.

Plans are under way to improve and extend the above measurements, with the aid of a more intense photon source. Included in these plans are experiments to measure the angular distribution of photoelectrons from various states.

[1] J. Berkowitz and W. A. Chupka, J. Chem. Phys. 51, 2341 (1969).

b. Photoionization Mass Spectroscopy of Gases[1]

J. Berkowitz and W. A. Chupka

A careful examination of the photoionization of HCN has revealed two processes, $HCN + h\nu \rightarrow H^+ + CN^-$ and $HCN + h\nu \rightarrow H^+ + CN + e$, not previously reported by other workers. The difference in threshold values for the two processes leads directly to the electron affinity 3.82 ± 0.02 eV for CN. The threshold for the second process leads to $\Delta H_{f_0}{}^0(CN) = 105.5 \pm 2$ kcal/mole, but $\Delta H_f{}^0(HCN)$ remains a major source of uncertainty. The best value for the ionization potential of CN, as obtained from this work, is 14.03 ± 0.02 eV.

The photoionization efficiency of CH_2CO (ketene) has been examined, partly to obtain an independent measurement of the heat of formation of the radical CH_2 from the reaction $CH_2CO + h\nu \rightarrow CH_2{}^+ + CO + e$. The threshold for this process has tentatively been determined to be 13.75 ± 0.02 eV. This implies $\Delta H_f{}^0(CH_2) = 87—90.5$ kcal/mole, the accuracy being limited by uncertainty in $\Delta H_f{}^0(CH_2CO)$. The ionization potential of CH_2CO has been determined to be 9.61 ± 0.01 eV.

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[1] J. Berkowitz and W. A. Chupka, J. Chem. Phys. 50, 1497 (1969).

c. Photoionization of High-Temperature Vapors[1]

J. Berkowitz and W. A. Chupka

From the thresholds for photodissociative ionization of cesium halide molecules, the dissociation energies of these diatomic molecules have been obtained. The values obtained are $D_0(CsCl) = 105.6 \pm 1.6$ kcal/mole, $D_0(CsBr) = 96.2 \pm 1$ kcal/mole, and $D_0(CsI) = 82.3 \pm 1$ kcal/mole. For $D_0(CsF)$ the interpretation is in doubt. The dissociation energies of the molecular ions $CsBr^+$ and CsI^+ have

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[1] J. Berkowitz and W. A. Chupka, J. Chem. Phys. 50, 3503 (1969); 50, 4245 (1969).

also been measured, as have the heats of formation of Cs_2F^+, Cs_2Cl^+, and Cs_2Br^+.

Several autoionization peaks have been observed in the ionization efficiency curves of the cesium halides, somewhat displaced in energy from their positions in atomic cesium. In particular, the $(5p)^6\ 6s \rightarrow (5p)^5\ (6s)^2$ transition, which occurs at 12.306 eV in atomic cesium, is shifted to 12.1, 12.4, 12.5, and 12.6 eV for CsF, CsCl, CsBr, and CsI, respectively. These "chemical shifts" are in accord with the "modified free ion" model which has been used to explain chemical shifts in the binding energies of inner electrons.

Since autoionization in metal atoms is quite common, one may anticipate the occurrence of chemical shifts in the autoionization of metal compounds. Further work is planned along these lines, and also to directly measure the chemical shift in the inner-electron binding energy by photoelectron spectroscopy.

The ionization potentials of Se_2 and Te_2, as obtained from their photoionization thresholds, are 8.88 ± 0.03 and 8.29 ± 0.03 eV, respectively. The threshold for formation of S^+ from S_2 leads to $D_0{}^0(S_2)$ = 101.0 ± 0.2 kcal/mole, in general agreement with other techniques. The corresponding process from Te_2 yields $D_0{}^0(Te_2)$ = 62.3 ± 0.2 kcal/mole, distinctly favoring one of two proposed thermochemical values. The experimental result for Se_2, $D_0{}^0$ = 78.6—83.2 kcal/mole, has considerable uncertainty but tends to favor the highest of three spectroscopic possibilities. Evidence was also found for a splitting of 0.35 ± 0.04 eV between the 0_g^+ ground state of Te_2 and the 1_g state.

d. Charge-Transfer and Collision Studies

J. Berkowitz and W. A. Chupka

Rare gas atoms produced in known highly excited electronic states by photon absorption were found to transfer an electron

to the SF_6 molecule to form an ion pair. The cross section for this process has been studied as a function of the state of excitation of the rare gas atom. Rare gas atoms in Rydberg states lying just below the ionization limit have been found to be ionized by collision with normal atoms, the cross section rising very rapidly as the excitation energy approaches the ionization limit. This phenomenon, detected for some molecules also, is apparently quite general and indicates the complexity of ionization studies carried out at all but the lowest pressures. It is also of considerable importance to such phenomena as ionization in shock tubes.

Negative ions such as I^- and F^- have been prepared in exceptionally clean fashion and with very low kinetic energies by photon absorption processes. Endoergic charge-transfer processes such as $I^- + I_2 \rightarrow I_2^- + I$ and $F^- + F_2 \rightarrow F_2^- + F$ have been studied as a function of kinetic energy. Preliminary measurements of the energy thresholds give reasonable values for the electron affinities of F_2 and I_2. The method is capable of considerable improvement and promises to become a fairly general technique for the determination of electron affinities of stable molecules.

e. Reactions of Ions in Prepared States

W. A. Chupka and J. Berkowitz

Fairly pure preparations of H_2^+ ions in vibrational states from v = 0 to v = 5 were made by photoionization and the cross sections for their reactions with helium to form $HeH^+ + H$ and $H^+ + H + He$ were measured as a function of both vibrational and kinetic energy independently. The reaction forming HeH^+ is endoergic by very nearly three vibrational quanta of H_2^+ ($\sim$0.7 eV). All vibrational states were found to react at kinetic energies above the thermochemical threshold but with cross sections which increase very rapidly with vibrational energy. The data provide the first direct and conclusive

proof that vibrational energy is very much more effective than kinetic energy in causing chemical reaction. The reactions of the HD^+ ion with helium and hydrogen show strong isotopic effects which help elucidate the reaction mechanism. The simplicity of this reaction makes it amenable to theoretical calculations which are being carried out by workers elsewhere for comparison with these results. The photoionization technique makes feasible the detailed study of reactions of ions in prepared electronic, vibrational, and even rotational states, particularly as more intense sources of photons, such as synchrotron radiation, become available.

f. Experiments Utilizing Synchrotron Radiation

J. Berkowitz and W. A. Chupka

Experiments designed to exploit the unique character of the synchrotron radiation at the MURA electron storage ring have been under preparation throughout the past year and are about to begin. The synchrotron radiation is a smooth continuum, which is most desirable when one is looking for structural features in absorption or photoionization spectroscopy. It fills in a gap between the helium continuum and hydrogen many-line laboratory light sources, and extends well below the short-wavelength helium limit (ca. 600 Å). In addition the radiation is highly polarized.

The storage ring, designed to have a circulating electron current of 1 A, is presently operating routinely at 2.5—5 mA. (The operators of this device plan to gradually increase the current to design specifications.) Preliminary measurements indicate that at its present level, it provides a light intensity equal to, or slightly higher than the conventional light sources. With this intensity, it already becomes attractive for certain measurements, such as the angular distribution of photoelectrons as a function of wavelength. The polarized character of the radiation can be exploited in such measurements. Of particular

interest is the photoelectron angular distribution from helium, which cannot readily be investigated with the available light sources.

As the intensity of radiation is increased, many other experiments will become attractive, including the angular distribution of electrons produced by autoionizing transitions, the reaction of ions in selected states (electronic, vibrational, and rotational) with other gases, the angular distribution resulting from the interaction of ionic and molecular beams (elastic, inelastic, and reactive scattering), the photoionization and absorption of H_2, HD, and D_2 at higher resolution than heretofore attained, and the photoionization and photoelectron energy analysis of high-temperature vapors (for which the intensities are weak).

The experimental system being prepared for these experiments consists of a high-resolution vacuum-ultra-violet monochromator, a scattering chamber, and an electron-energy analyzer.

g. Kinetic Energy Distributions of Fragmentation Products

H. E. Stanton

The investigation of the release of kinetic energy in the fragmentations of molecules of varying complexity has been carried forward during the past year, but with reduced effort. The emphasis has been on the improvement of the effective energy resolution of the mass spectrometer. Some changes in instrumentation which promise to make for greater accuracy in experimental measurements have been instituted, and quasi-theoretical developments in the interpretation of experimental findings will make the determination of the kinetic energy distributions much more precise and meaningful. These improved results may be expected to find application in understanding fragmentation processes in molecules under electron impact as well as the distribution of the internal energy in these molecules.

h. Atomic-Impact Phenomena on Metal Surfaces

M. Kaminsky

Studies of atomic impact phenomena on surfaces with the pulsed molecular-beam mass spectrometer (MA-25) were given low priority during the last year; the existing manpower was entirely occupied with the extensive experimental program described in Sec. IV.4i. Should more personnel become available, it is intended to start with three important experiments on mean residence times and negative-ion formation.

i. Atomic and Solid-State Effects Associated with the Penetration of Energetic Ions Through Solids

When energetic charged particles penetrate through a monocrystalline solid, their trajectories can under certain conditions be influenced by the regular arrangement of the lattice atoms. In particular, they may be guided through the spaces between low-index lattice planes (planar channeling) or along the open channels in the low-index directions (axial channeling). In such cases, the impact parameters of successive collisions can become correlated (channeled) and their distribution is not random as in the case of motion through amorphous solids.

The group of experiments reported below is concerned with the processes that take place when energetic ions (p, d, ^{3}He, α) from the 2-MeV Van de Graaff penetrate thin metal foils (e.g., Cu, Ni, Ag, and Au). Both monocrystalline and polycrystalline foils were used; in some cases they were magnetized. The energies of the incident ions were varied over the range from approximately 0.15 to 2.00 MeV. The incident beam was highly collimated (angular spread $< 0.01^\circ$) and its direction deviated less than 0.1° from one of the low-index directions of the monocrystal (e.g., the [100] direction) and was perpendicular (within 0.1°) to the surface of the polycrystalline targets. The energy spectrum of the beam emerging from a monocrystalline foil consisted of two well-separated peaks, the mean energy $\overline{E}_n$ of the lower one corresponding to the normal energy loss observed with polycrystalline targets while the mean energy $\overline{E}_{ch}$ of the high-energy peak reflects the reduced loss rate for channeled ions.

(i) Effect of Channeling on the Charge-Changing Collisions

M. Kaminsky

This program, which was started in 1968, deals with measurements of the equilibrium charge distribution of energetic ions penetrating through polycrystalline or monocrystalline metal foils. In the past, most studies of charge-changing collisions were conducted in gaseous targets and in a few polycrystalline solid targets. For light ions ($Z \leq 2$) penetrating through metal monocrystal foils, information was completely lacking. Such studies in monocrystalline foils promise, however, to yield information on the way in which the electron density distribution in the lattice and especially along certain lattice channels affects the process of electron capture and electron loss by the penetrating ions. The development of an adequate energy-loss theory for energetic ions would be greatly aided by such information.

Channeling Effect on the Electron Stripping Reaction $^3He^+ \rightarrow {}^3He^{++} + e$ (M. Kaminsky). In these experiments Cu(100) foils and polycrystalline Cu foils were bombarded by $^3He^+$ ions. The emerging ions with mean energies $\overline{E}_n$ characteristic of the low-energy peak and $\overline{E}_{ch}$ characteristic of the high-energy peak were analyzed according to their charges. The ratio R(emergent beam) $\equiv {}^3He^{++}/{}^3He^+$ was measured for both $\overline{E}_n$ and $\overline{E}_{ch}$ over a range of primary $^3He^+$ energies. For the low-energy peak, the R values normalized to equal emergent energy were close to those for polycrystalline Cu foils; for the high-energy peak the R values were only $\frac{1}{3} - \frac{1}{2}$ of the value for the low-energy peak as shown in Fig. 58. These results agree qualitatively with our observations reported in 1968 for $^3He^+$ ions penetrating through Au(100) foils. The result implies a lower stripping probability for ions traversing and escaping from regions of lower electron density, as for instance in the center of lattice channels.

It is planned to continue this program to study such important parameters as the lattice channel spacing (corresponding to different crystallographic axes), the angle of incidence of the primary

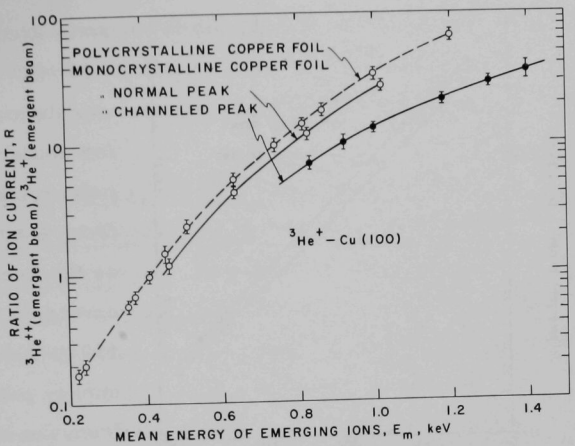

Fig. 58. The ratio $R = {}^3He^{++}/{}^3He^+$, both measured in the emergent beam as a function of the mean energy of the emerging ions. The curves are for $^3He^+$ ions incident normal to the surface of a Cu(100) foil and of a polycrystalline Cu foil.

ion with respect to the channel axis, the Z dependence of the target material, and the effect of target temperature (partial channel closing by phonon vibrations), and surface-layer impurities (discussed further in the last paragraph of this subsection).

For these measurements a high-resolution mass spectrometer (MA-28) was used in conjunction with the 2-MeV Van de Graaff and its associated beam-handling equipment. It is intended to modify the present target chamber to facilitate the insertion of targets, collimator systems, and solid-state detectors.

Channeling Effect on the Electron Capture Reactions $D^+ + e \rightarrow D^0$ and $H^+ + e \rightarrow H^0$ (M. Kaminsky). In these experiments the distribution of charge states of hydrogen or deuterium particles emerging from monocrystalline or polycrystalline Ni foils of various thicknesses were measured under ultrahigh-vacuum conditions for ions emerging with energies in the range 0.10—1.20 MeV. Over four times the area actually struck by the beam, each foil thickness varied $\leq 3\%$. The particle emerging from a Ni(110) foil (H^+, H^0, D^+, and D^0, and a negligible concentration of H^- and D^- in the energy region studied) were electrostatically analyzed according to their charge state, and the

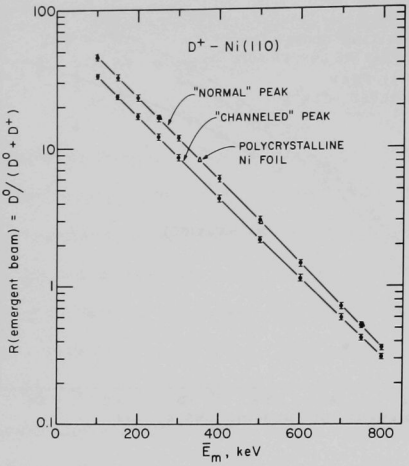

Fig. 59. The ratio $R = D^0/(D^0 + D^+)$, both measured in the emergent beam, as a function of the mean energy of the emerging ions. The curves are for D^+ ions incident normal to the surface of a Ni(110) foil and of a polycrystalline Ni foil.

ratio R(emergent beam) $= H^0/(H^0 + H^+)$ or $D^0/(D^0 + D^+)$ was determined. For example, for deuterons penetrating through polycrystalline Ni foils, R varied from 4.80×10^{-1} to 4.6×10^{-3} as the average energy of the emergent beam increased from 150 to 900 keV. For the low-energy peak in the energy spectrum from the monocrystalline foil, the R values normalized to equal emergent energy were close to those for polycrystalline foils; for the high-energy peak, which is due to channeled ions, R was significantly lower, as shown in Fig. 59. This implies a lower electron capture probability for ions traversing and escaping from regions of lower electron density (e.g., the centers of lattice channels).

This program will be continued. The projected studies include measurements of the formation of negative ions (important for operation of the tandem Van de Graaff), the dependence of the R values on the crystallographic orientation of the monocrystalline foil (e.g., on variation of the angle of incidence and on the exposure of different axial channels by using foils whose surfaces are parallel to different crystal planes), on the target material, on impurity layers (electron donor materials) deposited on monocrystalline foils, and on the type of incident ion.

Planned improvements of the apparatus include construction of a better electrostatic analyzer (with well-regulated power supplies) and modification of the vacuum system to facilitate opening and closing the system.

Effect of Impurity Layers Deposited on Metal Monocrystalline Foils on the Charge Distribution of the Emergent Beam (M. Kaminsky and K.-O. Groeneveld). New studies of the charge distribution of energetic particles emerging from metal foils onto which impurity layers have been deposited under controlled conditions (known thickness and composition, e.g., KCl on Ni, Li on Ni) have been initiated. These measurements are designed to resolve an existing controversy over the question whether or not impurity layers on target foils can influence the "equilibrium" charge states of the emerging particles. If such an influence can indeed be demonstrated, the next step will be to investigate combinations of electron-donor layers and monocrystalline metal foils in the hope of finding some for which the fraction of negative ions emerging from the "sandwich" will be high enough in a certain convenient energy region to make them useful as "electron-adder foils" for a tandem Van de Graaff. An evaporator system (including an electron gun and devices to monitor the deposition rate and the thickness of these thin films) will be needed to prepare such sandwich foils.

(ii) Anomalous Energy Loss of Ions Penetrating Through Metal Monocrystals

M. Kaminsky

The effort to determine how channeling influences the energy loss of energetic ions penetrating through metal monocrystalline foils of various orientations was continued during the past year. The energy loss of protons and deuterons penetrating through both magnetized and unmagnetized Ni(110) foils and through polycrystalline Ni foils was measured for primary-ion energies from 0.5—2.0 MeV for various

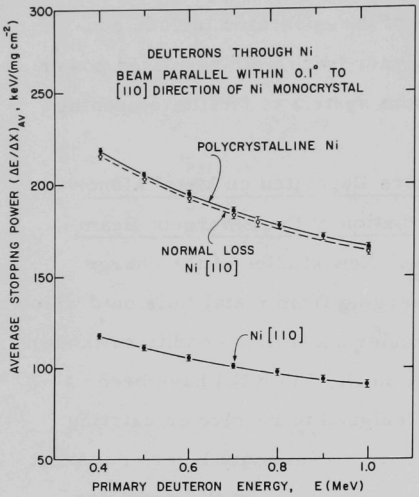

Fig. 60. Values of the mean stopping power for D^+ ions incident normal to the surface of a Ni(110) foil and of a polycrystalline Ni foil at incident deuteron energies E up to 1.0 MeV.

angles of incidence under ultrahigh-vacuum conditions. Figure 60 illustrates such results for D^+ ions incident normal to the surface of a Ni(110) foil and of a polycrystalline Ni foil. Furthermore, the energy loss of $^3He^+$ ions penetrating through monocrystalline and polycrystalline Cu and Au foils was determined over the same primary-ion energy range.

Preliminary results for the energy loss of deuterons going through magnetized Ni(110) foils (direction of magnetization perpendicular to the direction of the channel followed by the ion) reveal that the average stopping power is $\sim 7-10\%$ higher than for the unmagnetized Ni(110) foil. Future experiments are planned to determine (a) the degree to which the observed "dechanneling" effect (increased stopping power) can be related to the magnetic deflection of the ions within the magnetized solid and to magnetostrictive effects and (b) the angular-energy distribution $d^2N/d\theta dE_{out}$ of particles emerging at angle θ with energy E_{out} after traversing metal monocrystals of different structures (hcp, bcc, fcc) and orientations. Such data will not only provide better insights into the phenomena connected with the slowing down of charged particles in matter, but will also provide valuable information for the production of suitable electron-adder or electron-stripping foils (for tandem Van de Graaff operation) with greatly increased intensity per unit solid angle (emittance).

(iii) Studies of the Polarization of Deuterons Emerging from Magnetized Monocrystalline Metal Foils; Development of a New Type of Polarized Ion Source

M. Kaminsky

A new program has been initiated to determine if energetic deuterons can be polarized by passage through a monocrystalline Ni foil that is magnetized to saturation.

In these experiments, a highly collimated D^+ ion beam (angular spread $<0.01^\circ$) strikes a magnetized Ni(110) foil parallel to the [110] direction within 0.1°. The incident ion energy is chosen such that the mean energy of the emerging deuterium particles (D^+, D^0) is in the range 110—130 keV. The reasons for this choice are twofold: (a) In this energy range a rather large fraction (approximately 50%) of the penetrating deuterons will pick up polarized electrons. (b) The tensor polarization P_{33} of the polarized deuterium atoms D^0 can be readily measured by use of the $T(d,n)He^{++}$ reaction, which has a large cross section over a rather broad energy region (width ≈ 140 keV) and a maximum value at about 107 keV (5 barns for an unpolarized beam).

The deuterons that have picked up a polarized electron and emerge from the foil as deuterium atoms D^0 are then sent through a region of weak magnetic field (~10 gauss). The transit time in this region is $\sim 5 \times 10^{-8}$ sec, which is enough larger than the Larmor precession time to permit nuclear polarization by hyperfine interaction. The emergent D^+ ions are deflected electrostatically so that only the polarized deuterium atoms strike a thick Ti-T target. According to the theory, the cross section for the reaction $T(d,n)^4He^{++}$ is expected to be proportional to $1 - \frac{1}{4} P_{33} (3 \cos^2 \theta - 1)$, where θ is the center-of-mass angle of emission of the alpha particle relative to the polarization axis of the deuterium atoms. In our experiments (Fig. 61), three surface-barrier solid-state detectors have been placed at $\theta = 7^\circ$ (detector 1) and $\theta = 90^\circ$ (detectors 2 and 3). Then the ratio n_1/n_2

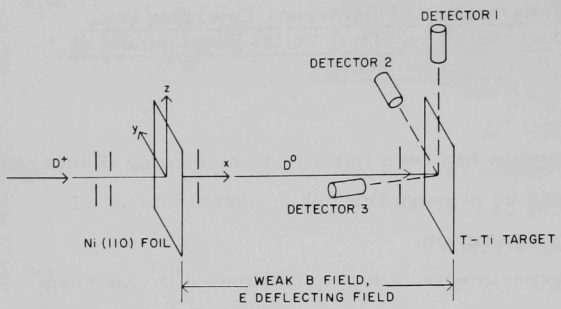

Fig. 61. Schematic diagram of the experimental arrangement to measure the polarization of channeled deuterium particles.

of the counting rates of two detectors (detectors 1 and 2 or detectors 1 and 3) is determined for the polarized beam and normalized to the same ratio for the unpolarized beam. Measurements of this kind are in progress.

If this process indeed produces a useful degree of polarization, the next step will be to convert the polarized neutral deuterium atoms into negative ions by passing the polarized D^0 beam through a thin nonmagnetized monocrystalline foil. No depolarization is expected if the transit time between the second foil and the Ti-T target is kept small ($<10^{10}$ sec).

The process promises to be very efficient, since a large fraction of the primary D^+ beam can be converted into polarized atoms, and our monocrystalline foils (without cooling) have withstood current densities of 10 $\mu A/cm^2$. Furthermore, the utilization of the axial channeling effect (beam alignment with respect to, say, the [100] axis) results not only in a strong reduction in beam depolarization (since large-angle scattering inside the foil is greatly reduced) but also in greatly improved values for the intensity per unit solid angle. Therefore it appears that this may form the basis of a very simple, practical, and inexpensive source of polarized ions for the tandem Van de Graaff.

Most of the electronic equipment now in use has been borrowed on a short-term basis. If the new process proves feasible,

it would be an attractive approach to the development of a source of negative polarized ions at the tandem Van de Graaff. (A U.S. patent has been applied for.)

(iv) Preparation of Thin Monocrystalline Metal Foils

M. Kaminsky, K.-O. Groeneveld, and G. Goodwin*

In order to provide the monocrystalline target foils needed for the measurements listed above, we have engaged in an extensive development program.

Thin wafers ($\frac{1}{2} \times \frac{1}{2} \times 0.001$ in.) were cut from monocrystalline blocks of Ni, Cu, and W by eloxing (done in Metallurgy) and were further thinned by repeated electropolishing and etching. Many of the well known etching solutions could not be used to thin our monocrystalline wafers because of preferential etching along certain crystallographic planes, leading often to pinholes. Therefore the polishing and etching solutions were modified for some of the materials and thinning procedures were established in order to obtain thin homogeneous foils with the desired high degree of monocrystallinity. We were able to obtain foils with usable areas of approximately 10 mm^2 and a thickness of approximately 0.00 008 in.

Since thinner foils could not readily be obtained by this method, we started a new program of growing thin monocrystalline Au and Cu films epitaxially.

In conjunction with our ultrahigh-vacuum bell jar, we tested 180° and 270° electron beam guns, film-thickness monitors, deposition-rate meters, and residual-gas analyzers loaned by various manufacturers and assessed their applicability to our special requirements. The 270° electron beam gun seems to come closest to our specifications. Using heated monocrystalline NaCl substrates, we deposited approximately 5000-Å-thick Cu films with a fair degree of monocrystallinity (mosaic spread of approximately 0.5°).

*Deceased.

We intend to proceed with our research on the epitaxial growth of monocrystalline films and with production of "sandwich foils" (in which impurity layers of, say, donor materials are deposited on thin metal foils to form an electron adder).

(v) Relocation of Equipment Used in Conjunction with the 2-MeV Van de Graaff

G. Goodwin,* R. Amrein, and M. Kaminsky

The 2-MeV Van de Graaff used in the above experiments on energetic particles penetrating metals was shut down on 15 June 1968 and was moved from the basement to the first floor, where a new vault was built and the existing control room was remodeled. At the same time, our target chambers, high-resolution mass-spectrometer system, electronic control units, and other equipment used with this accelerator were disassembled, parts were modified, and all were moved to the new location. The reassembly, which began on 15 September included several major improvements. (a) A new goniometer arrangement for more precise target movements was built and assembled. In contrast to the old system, the majority of the parts of the new goniometer are outside the vacuum system, thereby improving the ultimate vacuum of the system and (by greatly reducing backlash, for example) permitting easy adjustments of the goniometer. (b) The beam collimator system was greatly improved by extending the beam drift region by approximately 10 ft (total distance from analyzing magnet to target is now 45 ft) and by adding additional apertures. The accurate alignment of the apertures was facilitated by the aid of a laser beam. (c) The beam-line vacuum system was greatly improved. (In the beam line, the residual gas pressure is $\sim 2 \times 10^{-7}$ Torr; in the target chamber, $1-2 \times 10^{-8}$ Torr can be reached without baking.) (d) The alignment of the high-resolution spectrometer was improved. After some major work in aligning the

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*Deceased.

system, the performance of the new apparatus significantly exceeded that of the old system; e.g., we now obtain almost 100% transmission through our spectrometer and the beam spread is less than 0.01°. After rewiring all units and testing the connections between vault and control room, the complete new machine was put into operation by 15 October 1968.

j. Operation of the 2-MeV Van de Graaff Accelerator

Jack R. Wallace

The 2-MeV Van de Graaff accelerator has operated 1273 hours from 1 April 1968 to 14 March 1969. It is operated 40 h per week.

The accelerator was dismantled, moved from the basement to the first floor, and reassembled to make way for the Dynamitron. It is now located where the former 4-MeV Van de Graaff was located. This required an interruption of only two months in the experimental program of this installation.

The shielding, interconnecting control wiring, experimental wiring, and component alignment were greatly improved at its new location. New vacuum pumps have also been installed. Greatly improved operations have resulted from these changes.

V. PUBLICATIONS FROM 1 APRIL 1968 THROUGH 31 MARCH 1969

The papers listed here are those whose publication was noted by the reporting unit of the Laboratory in the 1-year period stated above. The dates on the journals therefore often precede this period, and some dated within the period will be listed subsequently. The list of "papers and books," which also includes letters and notes, is classified by topic; the arrangement is approximately that followed in the Table of Contents of this Annual Review. The "reports at meetings" include abstracts, summaries, and full texts in volumes of proceedings; they are listed chronologically.

A. PUBLISHED PAPERS AND BOOKS

1. MEASUREMENT OF A AND B COEFFICIENTS IN THE DECAY OF POLARIZED NEUTRONS
   C. J. Christensen, V. E. Krohn, and G. R. Ringo
   Phys. Letters 28B(6), 411-412 (6 January 1969)

2. STUDY OF THE $Nb^{93}(n_{res},\gamma)Nb^{94}$ REACTION
   W. V. Prestwich, R. E. Coté, and Hla Shwe
   Phys. Rev. 174, 1421-1426 (20 October 1968)

3. NUCLEAR SPECTROSCOPY WITH AVERAGE SPECTRA FROM NEUTRON RESONANCE CAPTURE
   L. M. Bollinger and G. E. Thomas
   Phys. Rev. Letters 21, 233-237 (22 July 1968)

4. NEUTRON RESONANCES OF Th^{230}
   R. E. Coté, H. Diamond (Chemistry), J. E. Gindler (Chemistry), and Hla Shwe
   Phys. Rev. 176, 1421-1423 (20 December 1968)

5. p-WAVE RESONANCES OF U^{238}
   L. M. Bollinger and G. E. Thomas
   Phys. Rev. 171, 1293-1297 (20 July 1968)

6. LEVEL STRUCTURE OF LOW-LYING EXCITED STATES OF Sc^{46}
   H. H. Bolotin
   Phys. Rev. 168, 1317-1330 (20 April 1968)

7. LOW-LYING EXCITED STATES OF ^{64}Cu AND ^{66}Cu POPULATED IN THERMAL-NEUTRON CAPTURE REACTIONS
E. B. Shera* and H. H. Bolotin
Phys. Rev. 169, 940-950 (20 May 1968)

8. AN OPTICAL MODEL FOR THE SCATTERING OF NUCLEONS FROM ^{4}He AT ENERGIES BELOW 20 MeV
G. R. Satchler,† L. W. Owen,† A. J. Elwyn, G. L. Morgan,‡ and R. L. Walters‡
Nucl. Phys. A112(1), 1-31 (1968)

9. RELATION BETWEEN FINE AND INTERMEDIATE STRUCTURE IN THE SCATTERING OF NEUTRONS BY Fe
J. E. Monahan and A. J. Elwyn
Phys. Rev. Letters 20, 1119-1122 (13 May 1968)

10. POSSIBLE DOORWAY-STATE STRUCTURE IN THE SCATTERING OF NEUTRONS BY Fe
A. J. Elwyn and J. E. Monahan
Nucl. Phys. A123(1), 33-53 (1968)

11. SMALL-ANGLE SCATTERING OF NEUTRONS BY HEAVY NUCLEI
F. T. Kuchnir, A. J. Elwyn, J. E. Monahan, A. Langsdorf, Jr., and F. P. Mooring
Phys. Rev. 176, 1405-1415 (20 December 1968)

12. LIFETIMES OF THE FIRST FOUR EXCITED STATES IN Si^{29}
S. I. Baker and R. E. Segel
Phys. Rev. 170, 1046-1050 (20 June 1968)

13. SEVERELY INHIBITED E2 TRANSITION IN ^{41}Sc
R. C. Bearse, D. H. Youngblood, and R. E. Segel
Nucl. Phys. A111, 678-680 (1968)

14. COMPTON SPECTROMETERS
T. H. Braid
Chap. V in Scintillation Spectroscopy of Gamma Radiation, edited by S. M. Shafroth (Gordon and Breach Science Publishers, London, 1967), Vol. 1, pp. 163-182

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*Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

†Oak Ridge National Laboratory, Oak Ridge, Tennessee.

‡Duke University, Durham, North Carolina.

15. THE $^{23}Na(p,\gamma)^{24}Mg$ REACTION AND THE GIANT DIPOLE RESONANCE IN ^{24}Mg
R. C. Bearse, L. Meyer-Schützmeister, and R. E. Segel
Nucl. Phys. A116(3), 682-694 (1968)

16. GAMMA DECAY OF $T=\frac{3}{2}$ STATES IN Al^{25} AND P^{29}
G. C. Morrison, D. H. Youngblood, R. C. Bearse, and R. E. Segel
Phys. Rev. 174, 1366-1374 (20 October 1968)

17. STUDY OF THE $Ca^{48}(He^3,p)Sc^{50}$ REACTION
H. Ohnuma, J. R. Erskine, J. A. Nolen, Jr., J. P. Schiffer, and P. G. Roos*
Phys. Rev. 177, 1695-1698 (20 January 1969)

18. Erratum: STUDY OF THE (d,p) REACTIONS ON $Zn^{64,66,68,70}$
[Phys. Rev. 164, 1374-1385 (20 December 1967)]
D. von Ehrenstein and J. P. Schiffer
Phys. Rev. 170, 1174 (20 June 1968)

19. THE NEUTRON RADIUS OF ^{208}Pb
J. A. Nolen, Jr., J. P. Schiffer, and N. Williams
Phys. Letters 27B(1), 1-2 (27 May 1968)

20. EFFECTS SEEN IN THE PASSAGE OF POSITIVELY CHARGED IONS THROUGH SINGLE CRYSTALS
R. E. Holland and D. S. Gemmell
Phys. Rev. 173, 344-357 (10 September 1968)

21. STUDY OF THE $Na^{23}(He^3,d)Mg^{24}$ REACTION
R. C. Bearse and J. L. Yntema
Phys. Rev. 175, 1442-1446 (20 November 1968)

22. (d,He^3) REACTION ON THE CHLORINE ISOTOPES AT 23.35 MeV
N. G. Puttaswamy and J. L. Yntema
Phys. Rev. 177, 1624-1628 (20 January 1969)

23. EXPERIMENTAL STUDY OF THE (d,He^3) REACTION ON EVEN-A ISOTOPES OF Mo
H. Ohnuma and J. L. Yntema
Phys. Rev. 176, 1416-1421 (20 December 1968)

---

*University of Maryland, College Park, Maryland.

24. MUONIC x RAYS FROM SEPARATED ISOTOPES OF EUROPIUM
R. A. Carrigan, Jr.,* P. D. Gupta,* R. B. Sutton,* M. N. Suzuki,* A. C. Thompson,* R. E. Coté, W. V. Prestwich, A. K. Gaigalas,† and S. Raboy†
Phys. Rev. Letters 20, 874-876 (15 April 1968)
Erratum: Phys. Rev. Letters 20, 1134 (13 May 1968)

25. OBSERVATION OF A GAMMA TRANSITION INDUCED IN A TARGET NUCLEUS BY STOPPING PIONS
R. A. Carrigan, Jr.,* P. D. Gupta,* R. B. Sutton,* M. N. Suzuki,* A. C. Thompson,* R. E. Coté, W. V. Prestwich, A. K. Gaigalas,† and S. Raboy†
Phys. Rev. 169, 963-965 (20 May 1968)

26. THE MUONIC x RAYS OF ^{107}Ag AND ^{109}Ag
R. A. Carrigan, Jr.,* P. D. Gupta,* R. B. Sutton,* M. N. Suzuki,* A. C. Thompson,* R. E. Coté, W. V. Prestwich, A. K. Gaigalas,† and S. Raboy†
Phys. Letters 27B, 622-624 (14 October 1968)

27. THE OPTICS OF DIPOLE MAGNETS
John J. Livingood
(Academic Press, New York, 1969), 261 + xvii pages

28. T=0 EFFECTIVE INTERACTION IN THE sd SHELL
S. Cohen, E. C. Halbert,‡ and S. P. Pandya
Nucl. Phys. A114(2), 353 (1968)

29. T=1 EFFECTIVE INTERACTION IN THE sd SHELL
S. Cohen, R. D. Lawson, and S. P. Pandya
Nucl. Phys. A114(3), 541-550 (1968)

30. E2 TRANSITIONS IN NUCLEI
R. D. Lawson
Nucl. Phys. A116(2), 363-368 (1968)

31. PARTICLE-HOLE MULTIPLETS IN ^{208}Bi
T. T. S. Kuo
Nucl. Phys. A122, 325-342 (1968)

---

*Carnegie-Mellon University, Pittsburgh, Pennsylvania.

†State University of New York, Binghamton, New York.

‡Oak Ridge National Laboratory, Oak Ridge, Tennessee.

32. UNFOLDING MEASURED DISTRIBUTIONS
J. E. Monahan
Chap. VIII in Scintillation Spectroscopy of Gamma Radiation, edited by S. M. Shafroth (Gordon and Breach Science Publishers, London, 1967), Vol. 1, pp. 371-428

33. GENERATION AND STATISTICAL ANALYSIS OF SYNTHETIC CROSS SECTIONS
P. Hoffman-Pinther,* P. P. Singh,* and D. W. Lang
Nucl. Phys. A127(2), 241-269 (1969)

34. GIANT-DIPOLE-RESONANCE ABSORPTION AND RADIATIVE STRENGTH FUNCTION OF ^{196}Pt
N. Rosenzweig
Nucl. Phys. A118(3), 650-656 (1968)

35. EFFECTIVE-INTERACTION FORMULATION OF BOUND AND CONTINUUM SHELL-MODEL CALCULATIONS
K. W. McVoy and W. J. Romo
Nucl. Phys. A126(1), 161-180 (1969)

36. GELL-MANN—GOLDBERGER RELATION FOR REACTIONS OF THE FORM (d, pn)
C. M. Vincent
Phys. Rev. 175, 1309-1313 (20 November 1968)

37. ACCURATE CALCULATION OF THE REACTION MATRIX IN LIGHT NUCLEI AND IN NUCLEAR MATTER
A. Kallio and B. D. Day
Nucl. Phys. A124(1), 177-198 (1969)

38. SIMPLE BRANCHING RATIOS AND SUM RULES IN PERIPHERAL REACTIONS
Harry J. Lipkin
Nucl. Phys. B7(3), 321-329 (1968)

39. RELATION BETWEEN MEASUREMENT THEORY AND SYMBOLIC LOGIC
M. N. Hack
Nuovo Cimento 54B, 147-148 (11 March 1968)

40. DERIVATION OF NEWTON'S LAW OF GRAVITATION FROM GENERAL RELATIVITY
Amnon Katz
J. Math. Phys. 9, 983-985 (July 1968)

---

*Indiana University, Bloomington, Indiana.

41. GRAVITY-INDUCED ELECTRIC FIELD NEAR A CONDUCTOR
Murray Peshkin
Ann. Phys. (N.Y.) 46, 1-11 (January 1968)

42. MÖSSBAUER MEASUREMENTS WITH K^{40}
P. K. Tseng, S. L. Ruby, and D. H. Vincent*
Phys. Rev. 172, 249-258 (10 August 1968)

43. ISOMER SHIFT AND HYPERFINE SPLITTINGS OF THE 59.6-keV MÖSSBAUER RESONANCE IN ^{237}Np
B. D. Dunlap (Solid State Science), G. M. Kalvius (Solid State Science), S. L. Ruby, M. B. Brodsky (Metallurgy), and D. Cohen (Chemistry)
Phys. Rev. 171, 316-321 (10 July 1968)

44. MAGNETIC-FIELD-INDUCED QUADRUPOLE SPLITTING
R. M. Golding
Molecular Physics 14(5), 457-464 (1968)

45. SUPER-TRANSFERRED HYPERFINE INTERACTIONS AT DIAMAGNETIC IONS IN FERRIMAGNETIC INSULATORS
S. L. Ruby, B. J. Evans,† and S. Hafner†
Solid State Communications 6, 277-280 (1968)

46. CONCENTRATION DEPENDENCE OF TIN (IV) ISOMER SHIFTS IN ICE
S. L. Ruby, P. K. Tseng, Hwa-Sheng Cheng,‡ and N. C. Li‡
Chem. Phys. Letters 2(1), 39-41 (May 1968)

47. DYNAMICS OF KRYPTON ATOMS IN CLATHRATE BY THE MÖSSBAUER TECHNIQUE
Y. Hazony§ and S. L. Ruby
J. Chem. Phys. 49, 1478-1481 (15 August 1968)

48. XENON AND IODINE
G. J. Perlow
Chemical Applications of Mössbauer Spectroscopy, edited by V. I. Goldanskii and R. H. Herber (Academic Press, New York, 1968), Chap. 7, pp. 377-426

---

*University of Michigan, Ann Arbor, Michigan.

†University of Chicago, Chicago, Illinois.

‡Duquesne University, Pittsburgh, Pennsylvania.

§Princeton University, Princeton, New Jersey.

49. STUDIES OF XENON CHLORIDES AND OTHER XENON COMPOUNDS BY THE MÖSSBAUER EFFECT IN ^{129}Xe
G. J. Perlow and M. R. Perlow
J. Chem. Phys. 48, 955-961 (1 February 1968)

50. STUDIES WITH THE MÖSSBAUER EFFECT OF THE FORMATION OF XENON BROMIDES IN BETA DECAY
G. J. Perlow and Hiroyuki Yoshida
J. Chem. Phys. 49, 1474-1478 (15 August 1968)

51. INFLUENCE OF RADIO-FREQUENCY MAGNETIC FIELDS ON THE MÖSSBAUER EFFECT IN MAGNETIC Co^{57} SOURCES
Gilbert J. Perlow
Phys. Rev. 172, 319-324 (10 August 1968)

52. MAGNETIC BEHAVIOR OF THE Pt+Fe SYSTEM NEAR Pt_3Fe
D. Palaith,* C. W. Kimball (Solid State Science), R. S. Preston, and J. Crangle (Metallurgy)
Phys. Rev. 178, 795-799 (10 February 1969)

53. HYPERFINE STRUCTURE OF SEVEN LOW ATOMIC LEVELS IN Co^{59}, AND THE NUCLEAR ELECTRIC-QUADRUPOLE MOMENT
W. J. Childs and L. S. Goodman
Phys. Rev. 170, 50-63 (5 June 1968)

54. HYPERFINE-STRUCTURE STUDIES OF Ni^{61}, AND THE NUCLEAR GROUND-STATE ELECTRIC QUADRUPOLE MOMENT
W. J. Childs and L. S. Goodman
Phys. Rev. 170, 136-140 (5 June 1968)

55. MAGNETIC HYPERFINE INTERACTION CONSTANTS AND ELECTRONIC g FACTORS FOR EIGHT ATOMIC STATES OF Rh^{103}
Y. W. Chan, W. J. Childs, and L. S. Goodman
Phys. Rev. 173, 107-114 (5 September 1968)

56. FREQUENCY-SHIFTING METHOD OF EXCITING A PLASMA IN A RESONANT CAVITY
S. L. Halverson (Electronics) and Albert J. Hatch
Appl. Phys. Letters 14(2), 79-81 (15 January 1969)

57. PLASMA HEATING AND CONFINEMENT—CONTROLLED NUCLEAR FUSION
Albert J. Hatch
Chap. 5.5.3 in Microwave Power Engineering, Vol. 2. Applications, edited by E. C. Okress (Academic Press Inc., New York, 1968), pp. 347-364

---

*Northern Illinois University, DeKalb, Illinois.

58. PHOTOIONIZATION OF HIGH-TEMPERATURE VAPORS. II. SULFUR MOLECULAR SPECIES
J. Berkowitz and C. Lifshitz
J. Chem. Phys. 48, 4346-4350 (15 May 1968)

59. PHOTOIONIZATION OF HIGH-TEMPERATURE VAPORS. IV. TlF, TlCl, AND TlBr
J. Berkowitz and T. A. Walter
J. Chem. Phys. 49, 1184-1189 (1 August 1968)

60. COMMENT ON THE COMPOSITION OF SELENIUM VAPOR
J. Berkowitz and W. A. Chupka
J. Chem. Phys. 48, 5743-5744 (15 June 1968)

61. PHOTOIONIZATION OF THE H_2 MOLECULE NEAR THRESHOLD
William A. Chupka and Joseph Berkowitz
J. Chem. Phys. 48, 5726-5728 (15 June 1968)

62. PHOTOIONIZATION OF CH_3; HEAT OF FORMATION OF CH_2
W. A. Chupka and Chava Lifshitz
J. Chem. Phys. 48, 1109-1115 (1 February 1968)

63. THE PHOTOIONIZATION OF CADMIUM AND MERCURY VAPOURS
J. Berkowitz and C. Lifshitz
J. Phys. B (Proc. Phys. Soc., London) 1, 438-440 (May 1968)

64. PHOTOIONIZATION OF HCN: THE ELECTRON AFFINITY AND HEAT OF FORMATION OF CN
J. Berkowitz, W. A. Chupka, and T. A. Walter
J. Chem. Phys. 50, 1497-1500 (15 February 1969)

65. MASS-SPECTROMETRIC STUDY OF THE PHOTOIONIZATION OF METHANE
William A. Chupka
J. Chem. Phys. 48, 2337-2341 (1 March 1968)

66. PHOTOIONIZATION OF ETHYLENE WITH MASS ANALYSIS
W. A. Chupka, J. Berkowitz, and K. M. A. Refaey
J. Chem. Phys. 50, 1938-1941 (1 March 1969)

67. PHOTOIONIZATION OF THE LOWER ALIPHATIC ALCOHOLS WITH MASS ANALYSIS
Kamel M. A. Refaey and William A. Chupka
J. Chem. Phys. 48(11), 5205-5219 (1 June 1968)

68. PHOTOIONIZATION STUDY OF ION-MOLECULE REACTIONS IN MIXTURES OF HYDROGEN AND RARE GASES
W. A. Chupka and Morley E. Russell
J. Chem. Phys. 49, 5426-5437 (15 December 1968)

69. ION-MOLECULE REACTIONS OF NH_3^+ BY PHOTOIONIZATION
W. A. Chupka and M. E. Russell
J. Chem. Phys. 48, 1527-1533 (15 February 1968)

70. ION-MOLECULE AND CHEMI-IONIZATION REACTIONS IN H_2 BY PHOTOIONIZATION
W. A. Chupka, M. E. Russell, and K. Refaey
J. Chem. Phys. 48, 1518-1527 (15 February 1968)

71. TRANSFORMER COUPLING FOR THE CONTINUOUS CHANNEL ELECTRON MULTIPLIER
R. N. Lewis (Electronics), L. S. Van Loon (Electronics), T. A. Mayer (Electronics), and J. Berkowitz
Rev. Sci. Instr. 39, 1386-1387 (September 1968)

B. PUBLISHED LECTURE SERIES

Summer Institute in Nuclear and Particle Physics, McGill University, 7-18 August 1967

1. NUCLEAR DEFORMATION IN THE SHELL MODEL
D. Kurath
Nuclear and Particle Physics, edited by Bernard Margolis and C. S. Lam (W. A. Benjamin, Inc., New York, 1968), pp. 199-272

C. PUBLISHED REPORTS AT MEETINGS

International Symposium on Organic Scintillators, Argonne National Laboratory, 20-22 June 1966

1. NEW LIQUID SCINTILLATORS WITH FASTER RESPONSE AND HIGHER EFFICIENCY
   Frank J. Lynch
   Organic Scintillators, edited by Donald L. Horrocks (Gordon and Breach, New York, 1968), pp. 293-301
   Molecular Crystals 4, 293-301 (1968)

Proceedings of the Conference on Slow-Neutron-Capture Gamma-Ray Spectroscopy Held at Argonne National Laboratory, 2-4 November 1966, edited by F. E. Throw (Argonne National Laboratory, Argonne, Illinois, 1968), Report No. ANL-7282

2. INVESTIGATION OF CONVERSION-ELECTRON SPECTRA FOLLOWING NEUTRON CAPTURE
   E. Bieber
   pp. 265-278

3. STUDY OF THE $F^{19}(n,\gamma)F^{20}$ REACTION
   D. E. Blatchley and G. E. Thomas
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4. PANEL DISCUSSION SUMMARIZING THE MEETING
   L. M. Bollinger, R. E. Chrien,* J. A. Harvey,† O. W. B. Schult,‡ and J. Vervier§
   pp. 533-584

5. MEASUREMENT OF RESONANCE-CAPTURE GAMMA-RAY SPECTRA WITH A 1/E NEUTRON SPECTRUM
   L. M. Bollinger and G. E. Thomas
   pp. 523-531

6. GAMMA-RAY SPECTRAL ANALYSIS
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---

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‡Technical University, Munich and Brookhaven National Laboratory, Upton, L.I., New York.

§C.E.N.-S.C.K., Mol, Belgium.

Slow-Neutron-Capture Gamma-Ray Spectroscopy (cont'd.)

7. LOW-LYING EXCITED STATES IN Ag^{108} AND Ag^{110} POPULATED BY PRIMARY THERMAL-CAPTURE GAMMA RAYS
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16. THE USE OF CRYSTAL DIFFRACTION WITH A Ge(Li) DETECTOR FOR HIGH-RESOLUTION GAMMA-RAY SPECTROSCOPY
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17. INSTALLATION AND USE OF AN INTERNAL-TARGET FACILITY
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18. GAMMA-RAY SPECTRA FROM CAPTURE OF THERMAL NEUTRONS IN B^{10}, C^{12}, AND C^{13}
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    pp. 84-88

Conference on Semiconductor Nuclear-Particle Detectors and Circuits, Gatlinburg, Tennessee, 15-18 May 1967

19. USE OF Ge(Li) DETECTORS IN GAMMA-RAY SPECTROSCOPY: APPLICATIONS AND BASIC CONSIDERATIONS
    H. H. Bolotin
    Semiconductor Nuclear-Particle Detectors and Circuits (Proceedings of a Conference conducted by the Subcommittee on Instruments and Techniques, Committee on Nuclear Science), edited by W. L. Brown, W. A. Higinbotham, G. L. Miller, and R. L. Chase (Printing and Publishing Office, National Academy of Sciences, Washington, D.C., 1969), Publication 1593, pp. 660-683

Proceedings of the International Conference on Electromagnetic Sizes of Nuclei, Carleton University, Ottawa, Canada, 22-24 May 1967

20. COULOMB ENERGIES AND NEUTRON RADII
    J. A. Nolen, Jr.
    pp. 244-253

Eighth Conference on Carbon, State University of New York at Buffalo, Buffalo, New York, 19-23 June 1967

21. MÖSSBAUER STUDIES OF CESIUM-GRAPHITE COMPOUNDS
G. L. Montet (Solid State Science), G. J. Perlow, L. E. Campbell, G. R. Hennig (Solid State Science), and A. J. F. Boyle*
Carbon 6(2), 228 (May 1968)

Hyperfine Structure and Nuclear Radiations (Proceedings of the International Conference on Hyperfine Interactions Detected by Nuclear Radiation, Asilomar, Pacific Grove, California, 25-30 August 1967), edited by E. Matthias and D. A. Shirley (North-Holland Publishing Co., Amsterdam, 1968)

22. MAGNETIC MOMENTS OF THE FIRST EXCITED STATE IN ^{133}Cs AND ^{129}Xe BY THE MÖSSBAUER EFFECT
L. E. Campbell, G. J. Perlow, and N. C. Sandstrom
pp. 161-163

23. ISOMER SHIFTS AND HYPERFINE SPLITTINGS OF THE 59.6-keV RESONANCE IN ^{237}Np
B. D. Dunlap (Solid State Science), G. M. Kalvius (Solid State Science), S. L. Ruby, M. B. Brodsky (Metallurgy), and D. Cohen (Chemistry)

24. TABLE OF CHANGES IN NUCLEAR RADIUS
P. Kienle,† G. M. Kalvius (Solid State Science), and S. L. Ruby
pp. 971-977

Proceedings of the Third International Conference on Atomic Masses, University of Manitoba, Winnipeg, Canada, 28 August-1 September 1967, edited by R. C. Barber (University of Manitoba Press, Winnipeg, 1967)

25. NUCLEAR Q-VALUE MEASUREMENTS ON A SERIES OF ACTINIDE NUCLEI
J. R. Erskine, A. M. Friedman (Chemistry), T. H. Braid, and R. R. Chasman (Chemistry)
pp. 622-638

---

*The University of Western Australia, Nedlands, Western Australia.

†Technische Hochschule, Munich, Germany.

Proceedings of the Symposium on Direct Reactions with ^{3}He, Tokyo, September 1967, edited by K. Matsuda and H. Kamitsubo (The Institute of Physical and Chemical Research "RIKAGAKU KENKYUSHO" Yamato-machi, Saitama Pref., Japan, February 1968), IPCR Cyclotron Progress Report

26. SOME COMMENTS ON He^3-INDUCED REACTIONS
J. P. Schiffer
Supplement 1, pp. 139-145

Proceedings of the International Conference on Nuclear Structure, Tokyo, 7-13 September 1967, edited by J. Sanada (Physical Society of Japan, Suppl. J. Phys. Soc. Japan, Vol. 24, 1968)

27. PERTURBATIVE METHODS IN THE THEORY OF NUCLEAR LEVEL DENSITIES
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28. EXTENSION OF M3 MATRIX ELEMENTS
Dieter Kurath
pp. 393-396; abstract, p. 721

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---

*State University of New York, Stony Brook, New York.

Conference on Nuclear Structure, Tokyo (cont'd.)

33. PRECISE COULOMB ENERGIES OF ISOBARIC PAIRS FROM THE (He^3,p) REACTION
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34. THE LEVEL STRUCTURE OF Sc^{48}
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36. DIRECT AND COMPOUND NUCLEAR REACTIONS—EXPERIMENTAL
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37. LIFETIME OF THE 1.059-MeV STATE IN Al^{26}
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38. NUCLEON-TRANSFER REACTIONS ON Mo ISOTOPES
J. L. Yntema and H. Ohnuma
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2ème Colloque International sur les Interactions entre les Champs Oscillants et les Plasmas, Saclay, 15-19 January 1968. III. Confinement et Stabilisation par les Champs H.F. Seuls ou Associes a un Champ Magnetique Statique (L'Institut National des Sciences et Techniques Nucleaires, Saclay, 1968)

39. FREQUENCY-SHIFTING METHOD OF EXCITING PLASMAS IN FUNDAMENTAL-MODE RESONANT CAVITIES
Albert J. Hatch, S. L. Halverson (Electronics), and A. E. Froehlich
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Champs Oscillants et les Plasmas, Saclay (cont'd.)

40. POTENTIAL-WELL THEORY OF CONFINEMENT OF PLASMAS IN NONUNIFORM RADIOFREQUENCY FIELDS
Albert J. Hatch, M. Hasan, and W. E. Smith (Applied Mathematics)
pp. 949-986

Nuclear Physics and Solid State Physics Symposium, Indian Institute of Technology, Guindy, Madras 36, India, 27 February-1 March 1968

41. NUCLEAR STRUCTURE CALCULATIONS
R. D. Lawson
Proceedings of the Nuclear Physics and Solid State Physics Symposium, 1968, Nuclear Physics (Physics Committee, Department of Atomic Energy, Government of India, Bombay, 1968), pp. 17-31

Eleventh Scintillation and Semiconductor Counter Symposium, Washington, D.C., 28 February-1 March 1968

42. TIME DEPENDENCE OF SCINTILLATIONS AND THE EFFECT ON PULSE-SHAPE DISCRIMINATION
Franca T. Kuchnir and Frank J. Lynch
IEEE Trans. NS-15(3), 107-113 (June 1968)

43. NEW LIQUID SCINTILLATORS WITH HIGHER SPEED AND EFFICIENCY
Frank J. Lynch
IEEE Trans. NS-15(3), 102-106 (June 1968)

Second Conference on Neutron Cross Sections and Technology, Washington, D.C., 4-7 March 1968

44. TOTAL NEUTRON CROSS SECTIONS OF ^{6}Li, ^{7}Li, AND LITHIUM FROM 10 TO 1236 keV
C. T. Hibdon and F. P. Mooring
Neutron Cross Sections and Technology, Proceedings of a Conference, edited by D. T. Goldman (National Bureau of Standards Special Publication 299, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 1968), Vol. I, pp. 159-168

Third Symposium on the Structure of Low-Medium Mass Nuclei, University of Kansas, Lawrence, 18-20 April 1968, edited by J. P. Davidson (University Press of Kansas, Lawrence, Kansas, 1968)

45. GAMMA DECAY OF $T=\frac{3}{2}$ STATES IN Al^{25}
R. C. Bearse
pp. 124-127

American Physical Society, Washington, D.C., 22-25 April 1968

46. STUDY OF THE $Na^{23}(He^3,d)Mg^{24}$ REACTION
R. C. Bearse and J. L. Yntema
Bull. Am. Phys. Soc. 13, 652-653 (April 1968)

47. SEARCH FOR EVIDENCE OF DIRECT CAPTURE IN $Tm^{169}(n,\gamma)Tm^{170}$
L. M. Bollinger and G. E. Thomas
Bull. Am. Phys. Soc. 13, 722 (April 1968)

48. LEVEL STRUCTURE OF THE LOW-LYING EXCITED STATES OF Ni^{59}
H. H. Bolotin and D. A. McClure
Bull. Am. Phys. Soc. 13, 721 (April 1968)

49. INTERNAL-CONVERSION COEFFICIENTS OF $_{75}Re^{181,182}$ DETERMINED WITH A SUPERCONDUCTING ELECTRON SPECTROMETER
S. B. Burson, P. J. Daly,* and P. F. A. Goudsmit†
Bull. Am. Phys. Soc. 13, 673 (April 1968)

50. ELASTIC SCATTERING OF α PARTICLES BY Ca^{40} AND Ni^{58}
T. W. Conlon,‡ B. W. Ridley,‡ and T. H. Braid
Bull. Am. Phys. Soc. 13, 650 (April 1968)

51. AUTOMATIC COUNTING OF TRACKS IN NUCLEAR EMULSIONS
John R. Erskine and Robert H. Vonderohe (Applied Mathematics)
Bull. Am. Phys. Soc. 13, 700 (April 1968)

---

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‡A. E. R. E., Harwell, England.

APS, Washington, D.C. (cont'd.)

52. ENERGY VARIATION OF J DEPENDENCE IN $^{12}C(d,p)^{13}C$
H. T. Fortune, R. C. Bearse, J. L. Yntema, and H. Ohnuma
Bull. Am. Phys. Soc. 13, 699 (April 1968)

53. INELASTIC SCATTERING OF PROTONS FROM ANALOG RESONANCES WITH THE TARGET ^{96}Zr
R. R. Jones,* P. Dyer,* C. Fred Moore,* G. Morrison, and N. Williams
Bull. Am. Phys. Soc. 13, 562 (April 1968)

54. HIGH-RESISTIVITY SILICON SURFACE-BARRIER DETECTORS AS PROTON SPECTROMETERS ABOVE 15 MeV
Ernest D. Klema† and J. A. Nolen, Jr.
Bull. Am. Phys. Soc. 13, 560 (April 1968)

55. ENERGY LEVELS OF ^{103}Ru AND ^{105}Ru FROM THE $^{102,104}Ru(d,p)$ REACTION
J. A. Nolen, Jr., H. T. Fortune, P. Kienle, and G. C. Morrison
Bull. Am. Phys. Soc. 13, 584 (April 1968)

56. GAMMA-RAY DECAY IN Ca^{43}
R. E. Segel, N. Williams, and N. G. Puttaswamy
Bull. Am. Phys. Soc. 13, 697 (April 1968)

57. s- AND p-WAVE RESONANCES OF Th^{232}
Hla Shwe, G. E. Thomas, and L. M. Bollinger
Bull. Am. Phys. Soc. 13, 722 (April 1968)

58. ELASTIC SCATTERING OF ALPHA PARTICLES BY Si^{30}
P. P. Singh,‡ R. N. Verma,‡ and A. J. Elwyn
Bull. Am. Phys. Soc. 13, 649 (April 1968)

59. HIGH-ENERGY K CONVERSION COEFFICIENTS
R. K. Smither, D. J. Buss, and E. Bieber
Bull. Am. Phys. Soc. 13, 721 (April 1968)

60. HIGH-ENERGY M1 TRANSITIONS
G. E. Thomas and L. M. Bollinger
Bull. Am. Phys. Soc. 13, 721 (April 1968)

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*University of Texas, Austin, Texas.

†Northwestern University, Evanston, Illinois.

‡Indiana University, Bloomington, Indiana.

APS, Washington, D.C. (cont'd.)

61. LIFETIME OF THE FIRST EXCITED STATE IN Li^8
M. J. Throop,* G. C. Morrison, and D. H. Youngblood†
Bull. Am. Phys. Soc. 13, 606 (April 1968)

62. AVERAGE RADIATION WIDTHS FROM RESONANCE NEUTRON CAPTURE IN MANGANESE AND VANADIUM
K. J. Wetzel
Bull. Am. Phys. Soc. 13, 720 (April 1968)

63. J DEPENDENCE IN THE $Fe^{54}(d,p)Fe^{55}$ REACTION
J. L. Yntema, H. Ohnuma, and H. T. Fortune
Bull. Am. Phys. Soc. 13, 699 (April 1968)

64. (d,He^3) REACTIONS ON $Fe^{56,58}$ AND Ni^{58}
B. Zeidman, T. H. Braid, and J. A. Nolen
Bull. Am. Phys. Soc. 13, 724 (April 1968)

American Physical Society, Los Alamos, New Mexico, 17-19 June 1968

65. HYPERFINE STRUCTURE OF HIGHER METASTABLE ATOMIC STATES OF La^{139}
W. J. Childs and L. S. Goodman
Bull. Am. Phys. Soc. 13, 891-892 (June 1968)

International Symposium on Nuclear Structure, Dubna, USSR, 4-11 July 1968

66. RADIATIVE TRANSITIONS FROM HIGHLY-EXCITED NUCLEAR STATES
L. M. Bollinger
Nuclear Structure, Dubna Symposium, 1968 (International Atomic Energy Agency, Vienna, 1968), pp. 317-347

67. NUCLEAR SPECTROSCOPY WITH AVERAGE SPECTRA FROM NEUTRON-RESONANCE CAPTURE
L. M. Bollinger and G. E. Thomas
International Symposium on Nuclear Structure, Dubna, USSR, 4-11 July 1968, Contributions (Joint Institute for Nuclear Research, Dubna, 1968), Dubna publication D-3893, p. 117

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*University of Iowa, Iowa City, Iowa.

†Texas A & M University, College Station, Texas.

International Symposium on Nuclear Structure, Dubna (cont'd.)

68. MEASUREMENT OF INTERNAL-CONVERSION COEFFICIENTS OF NEUTRON-CAPTURE GAMMA RAYS WITH A SUPERCONDUCTING SPECTROMETER
S. B. Burson
International Symposium on Nuclear Structure, Dubna, USSR, 4-11 July 1968, Contributions (Joint Institute for Nuclear Research, Dubna, 1968), Dubna publication D-3893, p. 174

69. SURVEY OF SINGLE-PARTICLE AND COLLECTIVE STATES OF THE ACTINIDES BY USE OF TRANSFER REACTIONS
J. R. Erskine, A. M. Friedman (Chemistry), T. H. Braid, and R. R. Chasman (Chemistry)
International Symposium on Nuclear Structure, Dubna, USSR, 4-11 July 1968, Contributions (Joint Institute for Nuclear Research, Dubna, 1968), Dubna publication D-3893, p. 61

Proceedings of the Conference on the Electron Capture and Higher Order Processes in Nuclear Decays, Debrecen, Hungary, July 15-18, 1968, edited by D. Berényi (Eötvös Lőránd Physical Society, Budapest, 1968), Vol. 3

70. PROPERTIES OF STATES EXCITED IN $^{181}_{75}$Re AND $^{182}_{75}$Re FOLLOWING ORBITAL ELECTRON CAPTURE IN $^{181}_{76}$Os (105 m) AND $^{182}_{76}$Os (22 h)
S. B. Burson
pp. 475-479

American Chemical Society Division of Physical Chemistry, Atlantic City, New Jersey, 9-13 September 1968

71. EFFECTS OF INTERNAL ENERGY ON REACTION PROBABILITIES OF IONS PREPARED BY PHOTOIONIZATION
William A. Chupka
abstract No. 81

1968 Annual meeting of the Division of Plasma Physics of the American Physical Society, Miami Beach, Florida, 13-16 November 1968

72. PLASMA EXCITATION IN RESONANT CAVITIES
Albert J. Hatch and S. L. Halverson (Electronics)
Bull. Am. Phys. Soc. 13, 1510 (November 1968)

Division of Plasma Physics of the APS, Miami Beach (cont'd.)

73. EIGENVALUES OF A MICROWAVE CAVITY FILLED WITH A PLASMA OF VARIABLE DENSITY
J. L. Shohet* and A. J. Hatch
Bull. Am. Phys. Soc. 13, 1500 (November 1968)

American Physical Society, Miami Beach, Florida, 25-27 November 1968

74. COULOMB EXCITATION OF LEVELS IN Pd^{105}
H. H. Bolotin, D. A. McClure, and B. Zeidman
Bull. Am. Phys. Soc. 13, 1471 (November 1968)

75. EFFECT OF CHANNELING ON THE ENERGY LOSSES OF ENERGETIC PROTONS IN SILVER, GOLD, AND TUNGSTEN MONOCRYSTALS OF VARIOUS CRYSTALLOGRAPHIC ORIENTATIONS
G. Goodwin and M. Kaminsky
Bull. Am. Phys. Soc. 13, 1406 (November 1968)

76. EFFECT OF CHANNELING ON THE CHARGE-CHANGING COLLISIONS OF ENERGETIC $^3He^+$ IONS PENETRATING THROUGH Cu(100) MONOCRYSTALS
M. Kaminsky
Bull. Am. Phys. Soc. 13, 1405-1406 (November 1968)

77. GAMMA DECAY OF THE 8.31-MeV ANALOG STATE ($J^\pi = \frac{5}{2}^+$, $T = \frac{3}{2}$) IN Si^{29}
F. T. Kuchnir, L. Meyer-Schützmeister, N. G. Puttaswamy, H. Ohnuma, R. E. Holland, and D. S. Gemmell
Bull. Am. Phys. Soc. 13, 1371-1372 (November 1968)

78. INELASTIC PROTON SCATTERING FROM ^{61}Ni, ^{63}Cu, ^{65}Cu, AND ^{67}Zn
James C. Legg† and J. L. Yntema
Bull. Am. Phys. Soc. 13, 1447 (November 1968)

79. EXCITED STATES OF Ga^{66} POPULATED IN THE 2.2-h DECAY OF Ge^{66}
D. A. McClure and H. H. Bolotin
Bull. Am. Phys. Soc. 13, 1426 (November 1968)

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*University of Wisconsin, Madison, Wisconsin.

†Kansas State University, Manhattan, Kansas.

APS, Miami Beach (cont'd.)

80. MULTIPOLE DECOMPOSITION OF TWO-BODY SPECTRA
J. P. Schiffer, W. P. Alford,* and M. Moinester*
Bull. Am. Phys. Soc. 13, 1365 (November 1968)

81. NEUTRON RESONANCES OF Th^{230}
Hla Shwe, R. E. Coté, H. Diamond (Chemistry), and J. E. Gindler (Chemistry)
Bull. Am. Phys. Soc. 13, 1421 (November 1968)

82. THE $^{140}Ce(^{3}He,d)^{141}Pr$ AND $^{142}Nd(^{3}He,d)^{143}Pm$ REACTIONS AT 40 MeV
B. H. Wildenthal,† R. L. Auble,† E. Newman,† and J. A. Nolen
Bull. Am. Phys. Soc. 13, 1430-1431 (November 1968)

American Physical Society, New York, 3-6 February 1969

83. GAMMA DECAY OF $T=\frac{3}{2}$ STATES IN Na^{21}
R. C. Bearse, G. C. Morrison, J. C. Legg,‡ and R. E. Segel
Bull. Am. Phys. Soc. 14, 124 (January 1969)

84. ELECTRON g FACTORS OF LOW-LYING STATES OF Tb I
W. J. Childs and L. S. Goodman
Bull. Am. Phys. Soc. 14, 84 (January 1969)

85. NGR MEASUREMENTS WITH ^{238}U
S. L. Ruby, G. M. Kalvius (Solid State Science), B. D. Dunlap (Solid State Science), G. K. Shenoy (Solid State Science), M. B. Brodsky (Metallurgy), and D. Cohen (Chemistry)
Bull. Am. Phys. Soc. 14, 134 (January 1969)

86. NEUTRON RESONANCES OF Mo
Hla Shwe and R. E. Coté
Bull. Am. Phys. Soc. 14, 104-105 (January 1969)

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*University of Rochester, Rochester, New York.

†Oak Ridge National Laboratory, Oak Ridge, Tennessee.

‡Kansas State University, Manhattan, Kansas.

1969 Particle Accelerator Conference—Accelerator Engineering and Technology, Washington, D.C., 5-7 March 1969

87. A LOW POWER MAGNETIC CHANNEL WITH DIPOLE COMPENSATION
T. Khoe (Accelerator Division), R. Benaroya (Chemistry), J. J. Livingood, W. J. Ramler (Chemistry), and W. Wesolowski (Chemistry)
Bull. Am. Phys. Soc. 14, 219 (February 1969)

American Physical Society, Philadelphia, 24-27 March 1969

88. CURIE TEMPERATURE ANOMALY OF THE ISOMER SHIFT IN IRON
R. S. Preston, I. Goroff (Metallurgy), and F. M. Mueller (Solid State Science)
Bull. Am. Phys. Soc. 14, 386 (March 1969)

D. ANL TOPICAL REPORTS

1. NUCLEAR STRUCTURE CALCULATIONS
R. D. Lawson
Argonne National Laboratory Topical Report ANL-7439 (May 1968)

2. PROCEEDINGS OF THE CONFERENCE ON SLOW-NEUTRON-CAPTURE GAMMA-RAY SPECTROSCOPY HELD AT ARGONNE NATIONAL LABORATORY, 2-4 NOVEMBER 1966
edited by F. E. Throw
Argonne National Laboratory Topical Report ANL-7282 (November 1968)

E. PHYSICS DIVISION INFORMAL REPORTS

1. RADIATIVE TRANSITIONS FROM HIGHLY-EXCITED NUCLEAR STATES
   L. M. Bollinger
   Physics Division Informal Report PHY-1968C (June 1968)

2. THE GROUND STATE OF HOMOGENEOUS NUCLEAR MATTER AND THE FOUNDATION OF THE NUCLEAR SHELL MODEL
   F. Coester
   Physics Division Informal Report PHY-1968D (August 1968)

3. DERIVATION OF NEWTON'S SECOND LAW FROM QUANTUM MECHANICS AND INVARIANCE
   H. Ekstein
   Physics Division Informal Report PHY-1968H (November 1968)

4. THE PHYSICAL INTERPRETATION OF QUANTUM THEORIES OF GRAVITATION
   H. Ekstein
   Physics Division Informal Report PHY-1969B (March 1969)

5. PROPERTIES OF THE DEFORMED NUCLIDES PRODUCED IN THE DECAY OF ^{166}Ho, ^{166m}Ho, ^{166}Tm, ^{166}Yb, ^{180}Os, ^{180}Re, ^{181}Os AND ^{181m}Os, AND BY CAPTURE OF THERMAL NEUTRONS IN ^{181}Ta
   Pieter F. A. Goudsmit
   Physics Division Informal Report PHY-1968G (December 1968)
   Ph.D. Thesis, University of Amsterdam, Netherlands (December 1968)

6. AN EVALUATION OF THE T-M OIL DIFFUSION VACUUM PUMP
   Milton D. Machalek
   Physics Division Informal Report PHY-1968F (December 1968)

7. THE ELASTIC AND INELASTIC SCATTERING OF PROTONS FROM B^{10} BETWEEN 5 AND 16 MeV
   Bruce A. Watson
   Physics Division Informal Report PHY-1968B (June 1968)
   Ph.D. Thesis, Indiana University, Bloomington, Indiana (July 1968)

8. ANL-AUA DISCUSSION OF A MIDWEST ACCELERATOR FOR NUCLEAR CHEMISTRY AND PHYSICS (A report of a conference held at O'Hare Airport, Saturday, 11 January 1969)
Physics Division Informal Report PHY-1969A (January 1969)

VI. STAFF MEMBERS OF THE PHYSICS DIVISION

The Physics Division staff for the year ending 31 March 1969 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 1968 through 31 March 1969, there were 41 temporary staff members (19 staff members from universities and other laboratories and 22 postdoctoral fellows), 13 graduate students (including 9 doing thesis research), and 36 undergraduates (5 in the Argonne Semester program of the Associated Colleges of the Midwest, 9 co-op technicians, 11 CSUI-ANL Honor Students, and 11 on summer appointments).

SLOW-NEUTRON PHYSICS

Permanent Staff

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

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

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

Victor E. Krohn, Ph.D., Case-Western Reserve University, 1952

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

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

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

Robert K. Smither, Ph.D., Yale University, 1956

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

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*No longer at Argonne as of 31 March 1969.

†Director of Physics Division.

Temporary Staff

Duane J. Buss, Ph. D., University of Notre Dame, 1966

*Raymon T. Carpenter, Ph. D., Northwestern University, 1962
(On leave from University of Iowa, Iowa City, Iowa)

*Carl J. Christensen, M. S., Danish Technical University, Copenhagen, 1957
(On leave from Danish AEC, Research Establishment, Risø)

*William V. Prestwich, Ph. D., McMaster University, 1963
(On leave from McMaster University, Hamilton, Ontario, Canada)

*Hla Shwe, Ph. D., University of California, Berkeley, 1962
(On leave from Ripon College)

Karl J. Wetzel, Ph. D., Yale University, 1965

FAST-NEUTRON REACTIONS

Permanent Staff

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

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

Alexander Langsdorf, Jr., Ph. D., Massachusetts Institute of Technology, 193

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

Temporary Staff

*Franca T. Kuchnir, Ph. D., University of Illinois, 1965

W. Gene Stoppenhagen, Ph. D., Ohio University, 1968

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*No longer at Argonne as of 31 March 1969.

†On assignment at A. E. R. E., Harwell, England (August 1968—August 1969).

CHARGED-PARTICLE REACTIONS

Permanent Staff

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

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

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

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

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

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

George C. Morrison, Ph. D., University of Glasgow, 1957

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

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

Rolf H. Siemssen, Ph. D., University of Hamburg, 1963

J. L. Yntema, Ph. D., Free University of Amsterdam, 1952

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

Temporary Staff

Donald R. Abraham, M. S., University of Wyoming, 1963
(On leave from Kansas State University)

David L. Auton (SA, thesis, University of Chicago)

‖Robert C. Bearse, Ph. D., Rice University, 1964

Joseph Comfort, Ph. D., Yale University, 1968

Douglas J. Crozier (RSA, thesis, University of Chicago)

Ralph G. DeVoe, A. B., Harvard University, 1967
(On leave from University of Chicago)

H. T. Fortune, Ph. D., Florida State University, 1967

†On assignment at Max-Planck Institute, Heidelberg, Germany (June 1967—October 1968).

‡Associate Director of Physics Division. Joint appointment with University of Chicago.

§Joint appointment with Northwestern University.

‖Became permanent 1 September 1968.

*Gerald Hardie, Ph.D., University of Wisconsin, 1962
(On leave from Western Michigan University)

*Paul Kienle, Ph.D., Technische Hochschule München, 1957
(On leave from Technische Hochschule München, Germany)

*Ramchandra G. Kulkarni (RSA, summer, Kansas State University)

James C. Legg, Ph.D., Princeton University, 1962
(On leave from Kansas State University)

James V. Maher, Jr., Ph.D., Yale University, 1969

Richard A. Morrison (SA, thesis, University of Chicago)

*J. A. Nolen, Jr., Ph.D., Princeton University, 1965

*Hajime Ohnuma, Ph.D., The University of Tokyo, 1966
(On leave from The University of Tokyo)

*N. G. Puttaswamy, Ph.D., Stanford University, 1966

Richard Rapids (RSA, University of Chicago)

Achim Richter, Ph.D., University of Heidelberg, 1967
(On leave from Max-Planck Institute für Kernphysik, Heidelberg)

James W. Smith (AUA-ANL Predoctoral Fellow, Indiana University)

Joseph C. Stoltzfus, Ph.D., University of Iowa, 1961
(On leave from Beloit College)

*Bruce A. Watson (AMU-ANL Predoctoral Fellow, Indiana University)

*Norman Williams, Ph.D., Manchester University, 1965

DEVELOPMENT OF EQUIPMENT AND ACCELERATORS

Permanent Staff

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

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

Dieter von Ehrenstein, Ph.D., University of Heidelberg, 1960

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

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*No longer at Argonne as of 31 March 1969.

†Emeritus.

GAMMA- AND BETA-RAY SPECTROSCOPY

Permanent Staff

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

G. T. Wood, Ph. D., Washington University, 1956

Temporary Staff

*Pieter F. Goudsmit (RSA, thesis, University of Amsterdam, Netherlands)

Donald A. McClure (AUA-ANL Predoctoral Fellow, University of Missouri at Rolla)

ATOMIC-BEAM STUDIES

Permanent Staff

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

John A. Dalman

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

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

MÖSSBAUER STUDIES

Permanent Staff

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

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

Stanley Ruby, B. A., Columbia University, 1947

*No longer at Argonne as of 31 March 1969.

Temporary Staff

*Alan J. F. Boyle, Ph. D., Australian National University, 1957
(On leave from University of Western Australia, Nedlands)

*L. E. Campbell, Ph. D., Carnegie-Mellon University, 1966

Lawrence E. Conroy, Ph. D., Cornell University, 1955
(On leave from University of Minnesota)

Walter Henning, Ph. D., Technische Hochschule München, 1968
(On leave from Technische Hochschule München, Germany)

*Jerry E. Hill (SA, summer, A & T State University, Greensboro, No. Carolina)

*Duane N. Olson, Ph. D., Cornell University, 1960
(On leave from St. Olaf College, Northfield, Minnesota)

Esther L. Segel, Ph. D., University of Rochester, 1959
(On leave from Illinois Institute of Technology)

*John G. Stevens (SA, summer, North Carolina State University, Raleigh)

THEORETICAL PHYSICS

Permanent Staff

†Arnold R. Bodmer, Ph. D., Manchester University, 1953

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

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

Benjamin Day, Ph. D., Cornell University, 1963

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

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

David R. Inglis, Ph. D., 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

*No longer at Argonne as of 31 March 1969.

†Joint appointment with University of Illinois, Chicago Circle Campus.

‡On assignment at Weizmann Institute of Science, Rehovoth, Israel (June 1967—September 1968)

§Joint appointment with University of Chicago.

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

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

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

Temporary Staff

Richard N. Kimmel (RSA, thesis, University of Chicago)

*Thomas T. S. Kuo, Ph.D., University of Pittsburgh, 1964
(On leave from Princeton University)

Kiuck Lee, Ph.D., Florida State University, 1955
(On leave from Marquette University, Milwaukee, Wisconsin)

*Harry J. Lipkin, Ph.D., Princeton University, 1950
(On leave from Weizmann Institute of Science)

*James J. MacKenzie, Ph.D., University of Minnesota, 1966

Nimai C. Mukhopadhyay (RSA, thesis, University of Chicago)

William J. Romo, Ph.D., University of Wisconsin, 1967

*Carl Rosenkilde, Ph.D., University of Chicago, 1966

Agam P. Shukla, Ph.D., Princeton University, 1967

C. Martin Vincent, Ph.D., University of the Witwatersrand, 1966

CHEMICAL PHYSICS

Permanent Staff

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

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

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*No longer at Argonne as of 31 March 1969.

†Associate Director of Physics Division. On assignment at Weizmann Institute of Science, Rehovoth, Israel (July 1968—August 1969).

Temporary Staff

*Morley E. Russell, Ph.D., University of Michigan, 1958
(On leave from Northern Illinois University)

Reimar N. Spohr, Ph.D., University of Uppsala, 1968

Theodore A. Walter, Ph.D., Harvard University, 1967

SURFACE PHYSICS

Permanent Staff

Manfred S. Kaminsky, Ph.D., University of Marburg, Germany, 1957

Temporary Staff

Karl-Ontjes E. Groeneveld, Ph.D., University of Frankfurt, 1966
(On leave from Institut für Kernphysik Frankfurt, Germany)

PLASMA PHYSICS

Permanent Staff

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

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*No longer at Argonne as of 31 March 1969.

ADMINISTRATIVE

Permanent Staff

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

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

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†Assistant Director of Physics Division.

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