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Argonne National Laboratory

PHYSICS DIVISION SUMMARY REPORT

Annual Review

1 April 1965—31 March 1966

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PHYSICS DIVISION SUMMARY REPORT

Annual Review
1 April 1965—31 March 1966

Lowell M. Bollinger, Division Director

Preceding Summary Reports:

ANL-7179, January-February 1966
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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 1966. 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 1965 through 31 March 1966 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, as in the past, 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 categories formed in this way are the following:

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

(2) Neutron and charged-particle-induced reactions at the 4-MeV Van de Graaff.

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

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

(5) Various 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 REACTORS CP-5 AND JUGGERNAUT

The Physics Division program at the reactors CP-5 and Juggernaut 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 experiments with neutron-capture gamma rays.

The first category includes a recently-completed measurement of the electron-neutron interaction and a continuing study of the decay of polarized neutrons.

Neutron cross sections are measured by the time-of-flight method with a fast chopper. Recently this system has been used principally to measure total cross sections and to study the gamma-ray spectra that result from the capture of neutrons in resonances.

The largest area of investigation is concerned with the study of nuclear structure by various measurements on the thermal-neutron-capture gamma rays. Most of the experiments of this kind have been revolutionized recently by the development of the lithium-drifted germanium-diode gamma-ray spectrometer. As a result of the excellent resolution and relatively high efficiency of this new spectrometer, the data required to construct refined nuclear level diagrams and decay schemes can now be obtained with ease.

All parts of the program based on CP-5 were seriously hampered during 1965 by a four-month shutdown of the reactor.

1. FUNDAMENTAL PROPERTIES OF THE NEUTRON

a. Instrumentation for Measurements of the Symmetry Properties of Neutron Decay

E. Bieber, D. Blatchley, V. E. Krohn, and G. R. Ringo

The importance of these measurements to the theory of weak interactions calls for substantially more accurate measurements than those done previously. To reduce statistical uncertainty by raising the neutron beam intensity, a new polarizing mirror is being built.

Another goal is to reduce the uncertainty in the measurement of neutron polarization to less than 2%. There are two principal difficulties: (a) The large range of neutron wavelengths in the beam from the polarizer raises the possibility that certain parts of the spectrum are unduly weighted at the expense of other parts in the polarization measurement. (b) The small-angle multiple scattering in the steel depolarizing foil used in the earlier measurement is not known with a sufficient accuracy. In order to avoid these difficulties the measurement will be made by the Stern-Gerlach method, and the magnet to do this is now being built.

A further improvement has been attempted by constructing a new proton detector for the neutron decay apparatus. It is hoped that the apparatus can all be assembled and that useful measurements can be made at CP-5 before the end of 1966.

b. Measurement of the Electron-Neutron Interaction by the Asymmetrical Scattering of Thermal Neutrons by Noble Gases

V. E. Krohn and G. R. Ringo

The electron-neutron interaction has been obtained from measurements of thermal-neutron scattering by argon, krypton, and xenon. In terms of the slope of the electric structure factor of the neutron at zero momentum transfer, the values obtained were 0.0196 ± 0.0013 F^2 from Ar, 0.0197 ± 0.0007 F^2 from Kr, and 0.0190 ± 0.0005 F^2 from Xe. The final result is 0.0193 ± 0.0004 F^2, which corresponds to an electron-neutron scattering length of $-1.34 \pm 0.03 \times 10^{-16}$ cm and an effective potential of -3720 ± 90 eV.

During the course of the experiment, the neutron absorption cross sections of krypton and xenon (at 2200 m/sec) were measured by transmission and found to be 25.0 ± 0.8 b and 25.1 ± 1.0 b, respectively. Also, some free-atom thermal-neutron scattering cross sections were measured. The results were 2.415 ± 0.010 b for neon, 0.647 ± 0.003 b for argon, 7.61 ± 0.04 b for krypton, 4.30 ± 0.02 b for xenon, 73.7 ± 0.4 b for ^{36}Ar, 1.705 ± 0.009 b for ^{22}Ne, and 5.1 ± 0.3 b for ^{21}Ne.

2. SLOW-NEUTRON RESONANCES

Slow-neutron resonances are studied at CP-5 by means of a fast-chopper time-of-flight neutron spectrometer. During the past year the chopper has been used exclusively for the study of gamma rays that arise from the resonance capture of neutrons. All of the γ-ray spectra were measured with a 4-cc lithium-drifted germanium-diode spectrometer. Because of the low efficiency of this detector (in comparison with that of a large NaI scintillator), the measurements were made with a neutron flight path of only 6.5 m. The spectra were stored on magnetic tape by use of the Argonne 3-parameter analyzer, which has been modified to provide 1024 channels for each pulse-height spectrum.

a. Distribution of Partial Radiation Widths

H. E. Jackson and G. E. Thomas

To study the distribution of partial radiation widths, the high-energy gamma rays from the capture of neutrons in resonances of Pt^{195} and U^{238} were observed with a Ge diode. In Pt^{195}, the resonances at 12, 19, and 69 eV were studied. The results are in excellent agreement with those previously obtained at Argonne in measurements with a large NaI scintillator and they are in obvious disagreement with most other measurements made with NaI. In addition, the presence of a strong 6513-keV transition in the spectra of the 12- and 19-eV resonances implies the existence of a previously undetected excited state in Pt^{196} at 1407 keV.

In U^{238}, the resonances at 6.7, 21, and 36 eV were studied. The spectra exhibit the multiplicity of lines that were inferred from previously reported measurements at Argonne with a large NaI scintillator.

b. Correlation of Resonance-Capture Gamma-Ray Spectra with Deuteron Stripping Results

W. V. Prestwich and R. E. Coté

Since the resolution attainable with Ge(Li) detectors is comparable to that obtained for charged particles by means of magnetic spectrographs, it is possible to make detailed comparisons between the analogous reactions of neutron capture and deuteron stripping. In one such study, the gamma-ray spectrum resulting from capture in the 132-eV resonance of Co^{59} was measured. A comparison of this spectrum with the (d, p) spectrum allowed the identification of several transitions leading to final states exhibiting $\ell = 1$ or $\ell = 3$ characteristics. The ratio of the average reduced widths for these two classes of transitions is

$$\frac{\langle \Gamma_\gamma / E^3 \rangle_{\ell=3}}{\langle \Gamma_\gamma / E^3 \rangle_{\ell=1}} = 0.12 \pm 0.08.$$

The difference in the average widths for the two classes is consistent with a theoretical argument given by Lane and Lynn.

Studies of thermal-capture gamma-ray spectra in the region near A = 50 reveal an apparent correlation between reduced radiative widths and the corresponding (d, p) spectroscopic factor. In Mn^{56}, a relatively strong correlation of this type has been observed for thermal-neutron capture. To test whether the thermal data are characteristic of resonance capture, the spectra associated with capture in the resonances at 330 keV, 1080 keV, and 2360 keV were measured. The spectra are qualitatively different from those from thermal capture. In Fig. 1 the γ-ray reduced widths for the three resonance spectra are compared with the corresponding (d, p) spectroscopic factors.

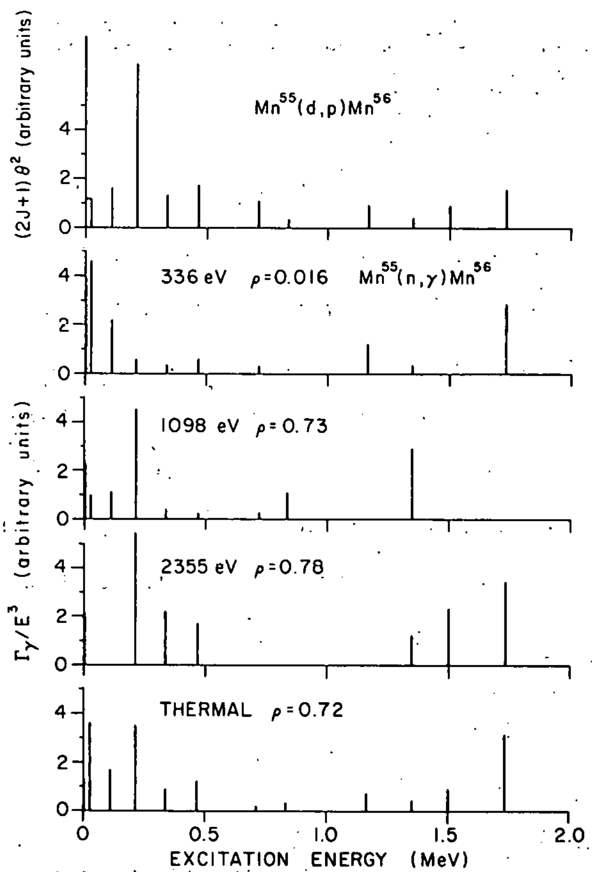

Fig. 1. Comparison between the reduced widths for the $\ell_n=1$ transitions in manganese and the reduced neutron (d, p) widths.

c. Interference Between Resonances for Radiative Transitions

R. E. Coté and W. V. Prestwich

Resonance theory predicts interference terms in the cross section for a radiative transition when two resonances of the same spin contribute to the radiative amplitude. The neutron cross section of Pt^{195} exhibits relatively well isolated resonances at 11 and 19 eV which are well suited for a study of the expected interference. Previous work[1] at Argonne with a NaI(Tl) scintillation spectrometer demonstrated the existence of this effect for the 7.914-MeV ground-state transition.

Now a study of the gamma-ray spectrum for this region of neutron energy has been undertaken with a Ge(Li) detector in the hope that the interference effect can be investigated for several transitions.

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[1] R. E. Coté and L. M. Bollinger, Phys. Rev. Letters 6, 523 (1961).

Preliminary analysis of the data indicates agreement between the NaI(Tl) and Ge(Li) results insofar as the ground-state transition is concerned.

d. Effect of Nuclear Rotation on Radiative Widths

W. V. Prestwich and R. E. Coté

Throughout the region of deformed odd-neutron nuclides, there are several examples of $K=\frac{1}{2}^-$ Nilsson orbits upon which rotational bands are built. For example, in W^{183} the ground state and the first excited state at 46 keV have been identified as members of the $[510]\frac{1}{2}^-$ rotational band. Since the capture state in this nucleus is always $\frac{1}{2}^+$, E1 transitions to either state are allowed.

The ratio Γ_1/Γ_0 of the widths of the radiative transitions to the first excited state and the ground state of W^{183} was measured by observing the gamma-ray spectra from neutron capture in several resonances of W^{182}. The values of this ratio are all found to be relatively small, and they appear to exhibit less scatter than is expected if the individual widths satisfy a Porter-Thomas distribution. Moreover, the same ratio in the spectra for thermal-neutron capture in Dy^{164}, Hf^{178}, Hf^{180}, and W^{183} (observed by others) exhibits similar effects. Statistical tests are being applied to determine whether or not these results show that E1 radiation to the rotational first excited state is somewhat inhibited and, more generally, whether or not the data are inconsistent with the simple statistical model of energy levels.

3. THERMAL-NEUTRON-CAPTURE GAMMA RAYS

The primary objective of the experimental program for the study of thermal-neutron-capture gamma rays is to obtain information about nuclear energy levels and decay schemes. Because of the extreme complexity of the spectra, until recently such measurements yielded refined results only with great effort. However, capture gamma rays now provide an easily-tapped source of information about nuclear structure—principally because of the recent development of an efficient high-resolution gamma-ray spectrometer, the Li-drifted Ge diode. Consequently, a wide variety of investigations have been undertaken.

In our program, numerous experimental techniques are used in the study of the capture gamma rays. The most powerful of these are the detection of single low-energy gamma rays with a bent-crystal spectrometer, the detection of single high-energy gamma rays with a Li-drifted Ge diode, and coincidence measurements with Ge diodes. The apparatus associated with each of these techniques is being systematically refined without seriously interrupting the program of measurements.

a. High-Sensitivity Capture-Gamma Facility

G. E. Thomas, D. E. Blatchley, and H. E. Jackson

A facility has been developed at the reactor CP-5 to take full advantage of the Ge diode for the study of the spectra of single gamma rays resulting from the capture of thermal neutrons. Basically, the system (Fig. 2) consists of a neutron-capturing gamma-ray source mounted near the reactor core in the center of a straight-through beam hole, a Ge-diode gamma-ray spectrometer mounted outside of the reactor, and a gamma-ray beam collimator that restricts the field of view of the detector so that it sees only the source in the reactor. This arrangement is believed to be optimum for obtaining a high detection sensitivity and a high signal-to-background ratio. Experience shows that one is able to measure the capture gamma-ray spectra of small samples of almost all isotopes.

Some features of the facility are the following: (a) A versatile source-handling system has been installed. It allows remotely-controlled insertion of a sample into the center of the straight-through

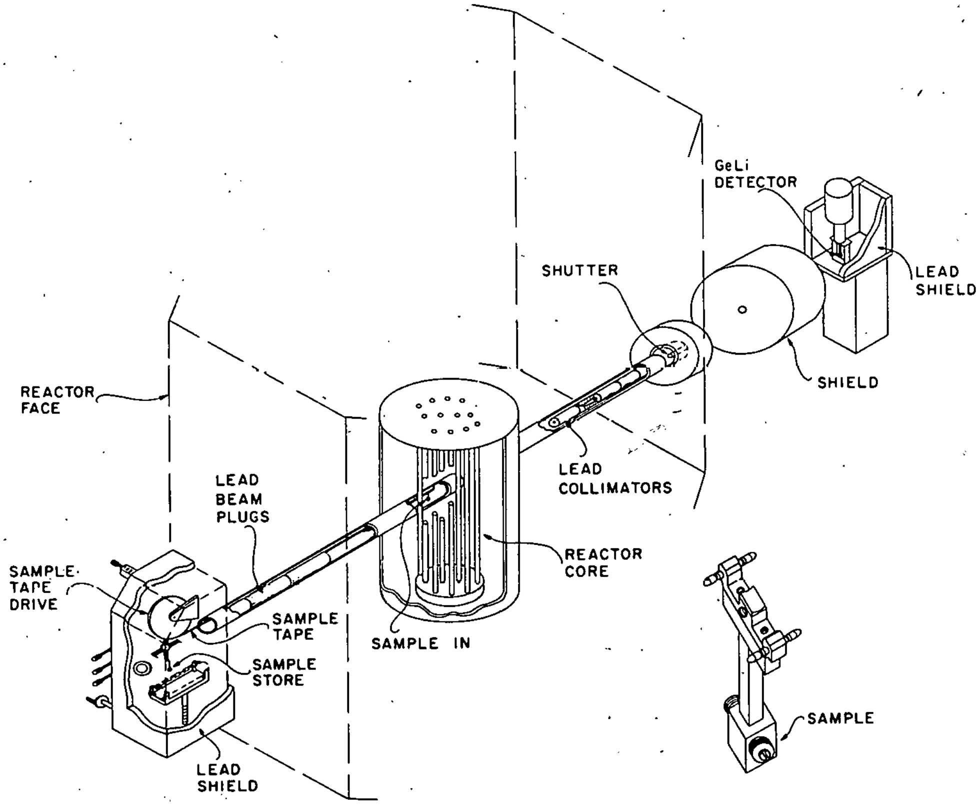

Fig. 2. The high-sensitivity capture-gamma facility at the reactor CP-5. When a sample is to be inserted, the lead beam plugs are removed and stored one on top of the other on the lift. Next, any one of four samples is taken off the storing wheel, placed on the titanium tape, and conveyed to the center of the beam tube. The lead plugs are then reinserted. The through tube is tangent to the reactor core so that the sample is exposed to a thermal flux of about 3×10^{13} neutrons/cm^2/sec. The samples range in size from a few milligrams to many grams.

hole. After irradiation the extremely active sample may be removed, temporarily stored, and reinserted for further study with no hazard to the experimenter. (b) The collimation and shielding of the facility effectively remove all sources of background that result in line spectra. (c) A 4096-channel pulse-height analyzer and a pulse-height stabilizer have been put into service. (d) The Ge-diode spectrometer used in most of the measurements to date has a volume of 4 cm^3 and a resolution width of 7 keV at 6 MeV. The NaI detectors required to operate the system in either a coincidence or an anticoincidence mode are being installed.

(e) Refined techniques for precise energy measurements have been developed. In this connection, a precision pulser (stability of one part in 10^5) is under development in the Argonne Electronics Division.

Several publications have already resulted from work performed with the high-sensitivity system and numerous experiments are in progress.

b. Neutron Separation Energies

H. E. Jackson, A. I. Namenson, and G. E. Thomas

Table I
Neutron separation energies. E_γ is the observed gamma-ray energy and E_{recoil} the value of the correction for recoil effect. The resulting separation energies E_n are compared with the values E_M derived from mass-spectrometric studies. The values for the nuclides marked with an asterisk result from measurements of the sum of two cascade γ rays.

Nuclide	E_γ (keV)	E_{recoil} (keV)	E_n (keV)	E_M (keV)
^{10}Be	6811 ± 1	2.4	6813.4 ± 1.0	6814.3 ± 2.3
^{13}C	4946 ± 1	1.0	4947.0 ± 1.0	4947.0 ± 0.8
^{15}N	10830	4.2	10834.2	10834.2 ± 0.9
^{25}Mg*	7330 ± 1	0.3	7330.3 ± 1.0	7330.6 ± 2.6
^{26}Mg*	11096 ± 1	2.1	11098.1 ± 1.0	11097.4 ± 3.4
^{27}Mg	6442 ± 1	0.8	6442.8 ± 1.0	6437.0 ± 4.3
^{28}Al	7722 ± 1	1.1	7723.1 ± 1.0	7723.6 ± 4.1
^{57}Fe	7646 ± 1	0.5	7646.5 ± 1.0	7642 ± 4

An especially easy quantity to determine from the neutron-capture gamma-ray spectra is the neutron separation energy, which is directly related to the energy of the ground-state transition. Hence, one of the first measurements with the germanium diode at the high-sensitivity gamma facility described in the preceding section was an effort to determine separation energies with precision. The 1-keV accuracy that was achieved is considerably better than has been obtained from either mass measurements or from studies of alternative nuclear reactions. Neutron separation energies obtained from the neutron-capture gamma rays have been reported for Be^{10}, C^{13}, N^{15}, Mg^{25}, Mg^{26}, Mg^{27}, Al^{28}, and Fe^{57} (Table I).

c. Spectra of Light Nuclides

D. E. Blatchley, H. E. Jackson, and G. E. Thomas

The straight-through beam-hole facility for the study of thermal-neutron-capture gamma rays is so sensitive that it is now feasible to survey the neutron-capture gamma-ray spectra of a large number of targets in a relatively short period of time.

One class of targets of particular interest is the light nuclides. The energies of the low-energy states of such nuclides are usually known from other reactions but the capture gamma rays should provide significant new information about decay schemes. To date the spectra from neutron capture in Be^{9}, N^{14}, F^{19}, Si, and Mg have been obtained.

d. Regularities in High-Energy Transitions to Rotational Levels in Odd-A Nuclei

A. I. Namenson, H. E. Jackson, and R. K. Smither

Some interesting regularities have been observed in the capture gamma-ray spectra of two odd-A isotopes of hafnium—Hf^{179} and Hf^{181}. The high-sensitivity gamma facility (Sec. I. A. 3a) at CP-5 was used to study the spectra from thermal-neutron capture in normal and isotopically enriched samples of hafnium.

Intense lines at 5720 and 5676 keV were observed in the reaction $Hf^{178}(n,\gamma)Hf^{179}$. These lines have been identified as going from the capture state of Hf^{179} to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels in the $\frac{1}{2}^-$[510] Nilsson band. The transition to the $\frac{1}{2}^-$ level is about four times as intense as the transition to the $\frac{3}{2}^-$ level; the spacing of the two levels is 44 keV.

Similar transitions were identified in the reaction $Hf^{180}(n,\gamma)Hf^{181}$. Here we observed a pair of intense lines at 5693 and 5646 keV from transitions going from the capture state to the $\frac{1}{2}^-$[510] ground state and to a previously unobserved level 47 keV above the ground state. This new level may be identified with the $\frac{3}{2}^-$ level of the $\frac{1}{2}^-$[510] Nilsson band of Hf^{181}. The transition to the $\frac{1}{2}^-$ level is again (within experimental error) about four times as intense as the transition to the level identified as $\frac{3}{2}^-$.

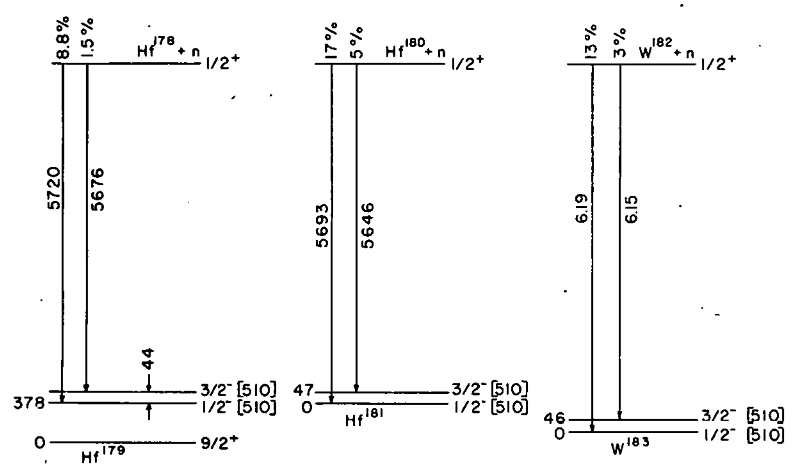

Fig. 3. A comparison of the strong (n, γ) transition from the neutron-capture state to $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of the $K=\frac{1}{2}$ rotational band associated with the [510] Nilsson configuration in Hf^{179}, Hf^{181}, and W^{183}.

The similarity between these two odd-A hafnium isotopes becomes more interesting when one compares them (Fig. 3) with known data on the odd-A isotope W^{183} (the isotone of Hf^{181}). W^{183} again shows a pair of intense transitions from its capture state to its $\frac{1}{2}^-$[510] ground state and to the $\frac{3}{2}^-$ levels in the $\frac{1}{2}^-$[510] Nilsson band, which in W^{183} is 46 keV above the $\frac{1}{2}^-$ level. Again the intensity of the transition from the capture state to the $\frac{1}{2}^-$ level is about four times that of the transition to the $\frac{3}{2}^-$ level. Other nuclides will be studied in a search for similar regularities.

e. Further Development of the Level Scheme of Hf^{178} Through $Hf^{177}(n, \gamma)Hf^{178}$ Studies

R. K. Smither, A. I. Namenson, H. E. Jackson, and A. P. Magruder

The $Hf^{177}(n, \gamma)Hf^{178}$ gamma-ray spectrum was investigated with a Li-drifted Ge-diode detector (Fig. 4). By comparing the gamma spectrum from an enriched sample (80% Hf^{177}) with that from a natural-abundance sample, 25 gamma transitions in the range 5.5 MeV $\leq E_\gamma \leq$ 7.5 MeV were shown to come from this reaction. Nine of these gamma lines were identified as transitions from the neutron-capture state to previously proposed levels. Since the neutron-capture state has a spin of 3^- or 4^-, the levels reached directly by E1 transitions from the capture state have spins in the range from 2 to 5. The

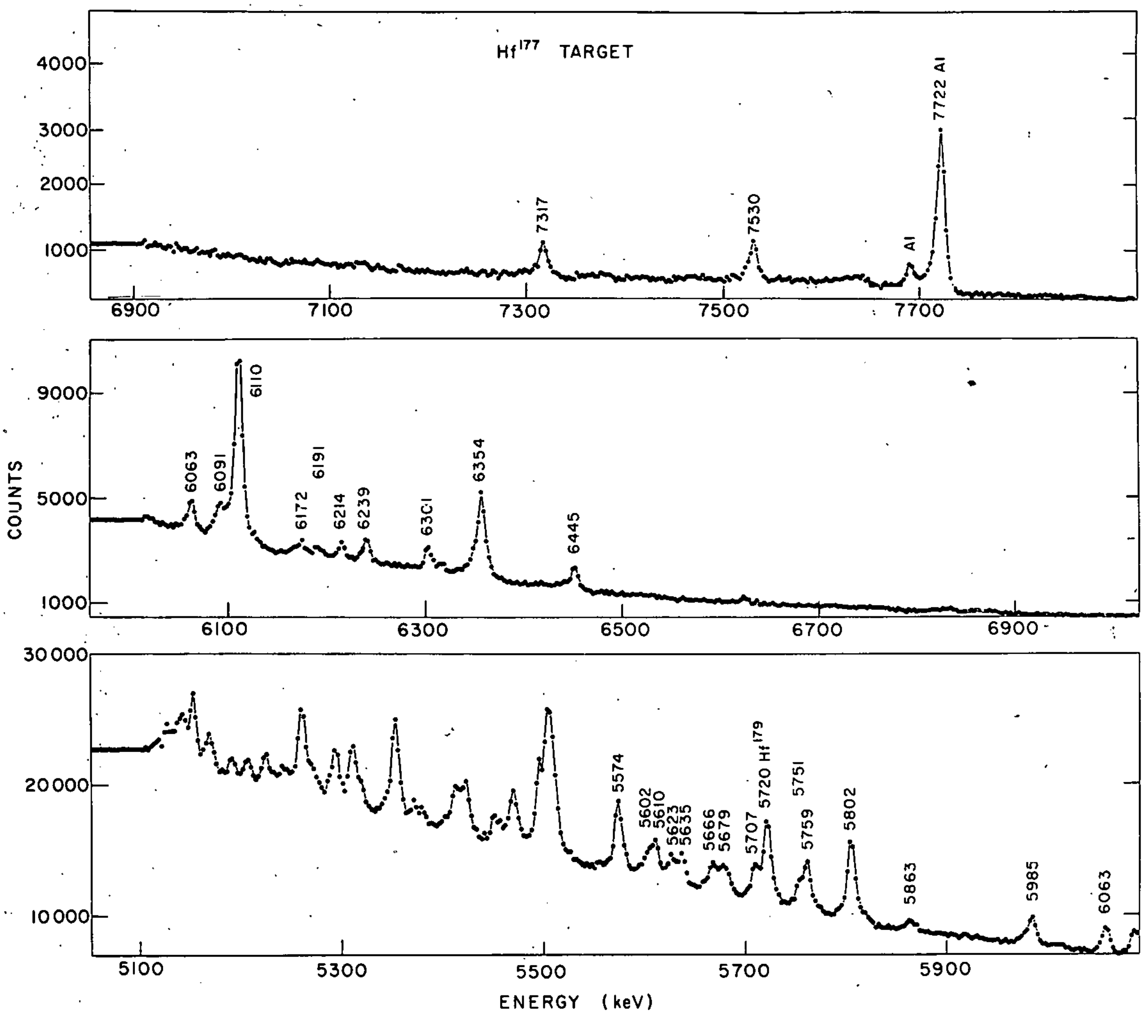

Fig. 4. Neutron-capture gamma-ray spectrum with enriched Hf^{177} target. Except where otherwise noted, all the lines labeled with energies are in Hf^{178}. The energies are in keV.

intensities of eight of the nine transitions to known levels agree well with what is expected on the basis of the spins previously proposed from the bent-crystal work of Smither and the Compton-spectrometer and conversion-electron measurements of Groshev. In addition, fifteen new levels were proposed.

To refine and extend the gamma-decay pattern, the high-energy results are being combined with the earlier bent-crystal data for the region from 50 keV to 2 MeV. The γ-ray energy measurements in the 1—2 MeV region were improved through the use of the newly-developed combination spectrometer that places the Ge-diode detector in the diffracted gamma beam of the bent-crystal spectrometer. The high precision of the bent-crystal measurements of energy is essential in this interpretation.

The most interesting feature of the Hf^{178} level scheme is the presence of many overlapping rotational bands at excitation energies between 1 and 2 MeV. The strong enhancement of E2 transitions between members of the same band relative to other competing transitions is clearly evident.

f. Development of the Level Scheme of Hf^{180} Through $Hf^{179}(n,\gamma)Hf^{180}$ Studies

R. K. Smither, A. I. Namenson, H. E. Jackson, and A. P. Magruder

The γ-ray spectrum resulting from thermal-neutron capture in Hf^{179} was investigated with a Li-drifted Ge-diode detector. Thirteen lines between 5 and 7 MeV were identified with this reaction through a comparison of spectra from enriched (84% Hf^{179}) and natural-abundance samples. The two highest energy lines were identified as direct transitions from the neutron-capture state to the 4^+ and 6^+ members of the ground-state rotational band in Hf^{180}. The remaining eleven transitions were used to identify new levels in Hf^{180}. These levels were correlated with the gamma lines in the region from 50 keV to 2 MeV in the neutron-capture spectrum from the crystal diffraction work of Smither and Namenson in order to define the γ-decay pattern in the level scheme and to generate new levels.

The analysis of the level scheme is still in progress. It appears to be quite similar to that of Hf^{178}, with many overlapping rotational bands above 1 MeV.

g. Modification of the Bent-Crystal Spectrometer

R. K. Smither and A. I. Namenson

A number of important modifications of the bent-crystal spectrometer have been completed or are currently under way.

(i) A new source-handling system has been installed. It allows samples (even highly radioactive ones) to be rapidly inserted in or removed from the reactor without exposing personnel to radiation. Brief experiments with limited objectives can now be performed without excessive loss of running time.

(ii) The spectrometer has been modified so that one bent crystal can be replaced with another in less than two hours with no loss of precision in the measurements. The experimenter can now choose between two Ge crystals measuring $3\frac{1}{2} \times 3 \times 0.16$ in. (one only recently bent and tested) and three quartz crystals measuring $12 \times 11 \times 0.080$ in. (not yet bent), $12 \times 12 \times 0.160$ in., and $6 \times 4 \times 0.240$ in. to fit his needs. For example, the 0.080-in. quartz crystal for measurement of a 40-keV gamma could be quickly followed by a 0.16-in. Ge crystal for a 4-MeV gamma.

(iii) Two newly constructed collimators extend the usable energy range of the crystal spectrometer. Removing the material that formerly obstructed the beam moves the lower limit from 40 down to 15 keV, and improving the collimation raises the upper limit from 2 MeV to 6 MeV. The very thin ($0.018 \times 6 \times 6$ in.) Pb plates of the smaller of these collimators (to be placed ahead of the bent crystal) sagged appreciably with time and are being replaced with stainless steel; but the larger collimator (placed after the crystal, just in front of the detector) with the thicker plates is nearly perfect (Fig. 5).

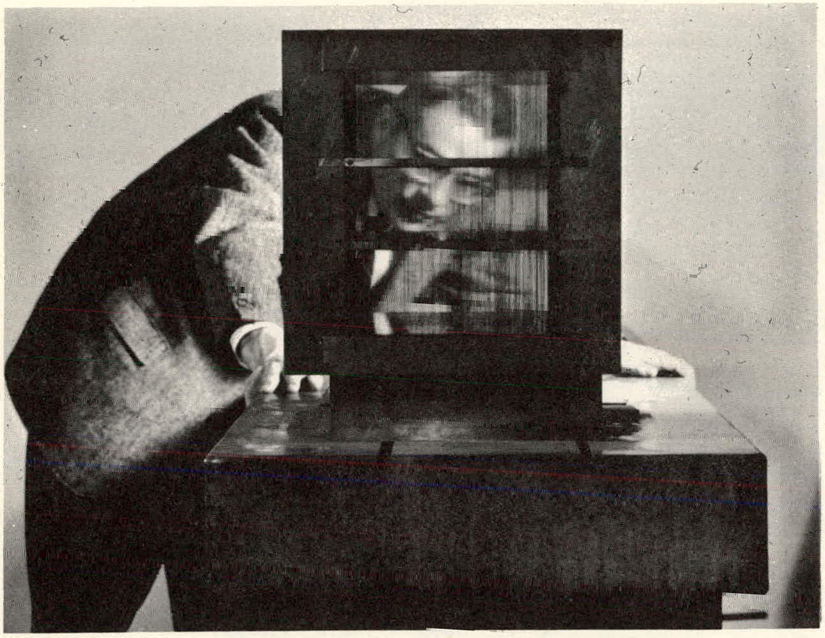

Fig. 5. The larger of the two new multislit collimators for the bent-crystal spectrometer. The high transmission of this collimator is evident from the photograph. The two collimators must be aligned so that the plates of the larger one occupy the shadows of the plates of the smaller.

h. The $Cd^{113}(n,\gamma)Cd^{114}$ Reaction and Associated Energy Levels in Cd^{114}

R. K. Smither, A. I. Namenson, and A. P. Magruder

The gamma-ray spectrum resulting from $Cd^{113}(n,\gamma)Cd^{114}$ was investigated in the 2—9 MeV region with a Li-drifted Ge-diode detector (Fig. 6a) and in the region from 40 keV to 2 MeV with the improved Argonne 7.7-m bent-crystal spectrometer. In the region from 40 keV to 2 MeV (Fig. 6b), the new crystal-diffraction data increase the precision of the γ energies to 1 part in 10^4 (a factor of 2—3 improvement over the previous results). The very difficult region of spectral energies between 1 and 2 MeV was examined with the newly developed combination bent-crystal spectrometer and Ge-diode gamma-ray spectrometer. These three (n,γ) experiments were coupled with a series of $Cd^{113}(d,p)Cd^{114}$ angular-distribution experiments to extend the level scheme of Cd^{114}.

Eighteen previously proposed levels were confirmed and 24 new levels were suggested. The rather unusual features of the $Cd^{113}(d,p)Cd^{114}$ reaction (the fact that odd values of ℓ_n are associated

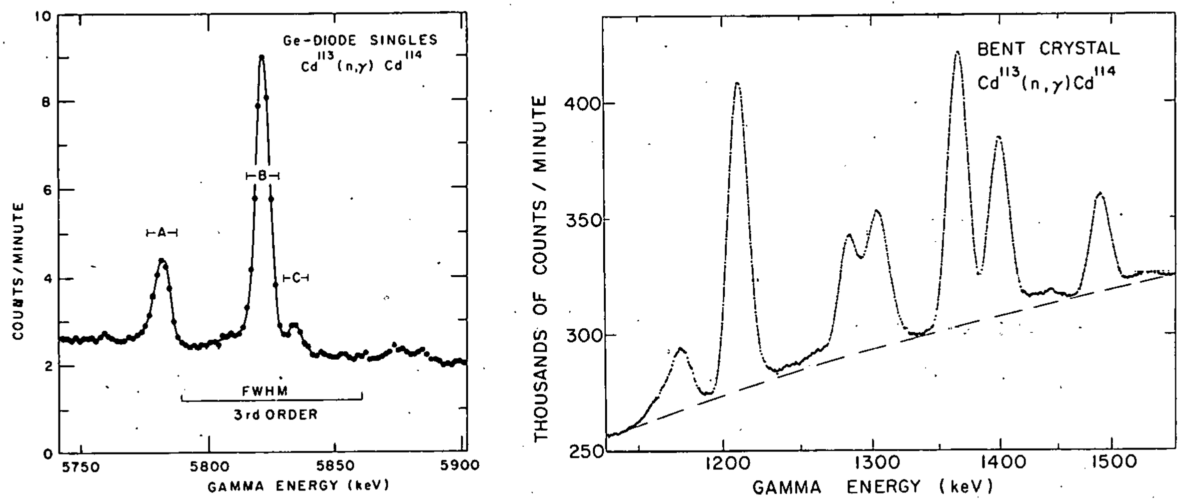

Fig. 6. The gamma-ray spectrum from the $Cd^{113}(n,\gamma)Cd^{114}$ reaction. (a) High-energy spectrum taken with the Ge diode looking directly at the (n, γ) source. The bar below the large peak indicates the resolution width in the third-order diffraction spectrum of the bent-crystal spectrometer. (b) Low-energy spectrum from the bent-crystal spectrometer. It was obtained in first-order diffraction from the (310) planes of the quartz crystal. The dashed line is the undiffracted background.

with negative parity, even values with positive parity) permit the parity of each state to be determined from the observed value of ℓ_n. By combining information about the gamma transitions to and from a level, the value of ℓ_n from the (d, p) work, and the conversion-electron work of Groshev et al., it is possible to define the spins of most levels as well. The level structure of Cd^{114} becomes very complicated above 2 MeV (average level spacing about 25 keV); the improved precision and resolution in the measurements of gamma energies were essential to the development of the level scheme. The Ge-diode work on the $Cd^{113}(n,\gamma)Cd^{114}$ reaction gave a neutron binding energy of 9039 ± 1 keV.

i. Energy Levels and Decay Schemes of Odd-Odd Nuclides

H. H. Bolotin and A. Namenson

This experimental program seeks to provide information concerning the energies and decay schemes of low-lying states in selected odd-odd nuclides. Several experimental systems are used to unravel the complex spectra. The high-energy gamma-ray transitions from the capture state are observed with the high-sensitivity gamma facility at CP-5 (p. 8). These transitions establish the energies of excited states close to the ground state of the product nucleus under investigation. The low-energy gamma-ray transitions between these excited states are studied at the Juggernaut reactor. Here targets are placed in an external neutron beam with a flux of about 5×10^6 neutrons cm^{-2} sec^{-1}. Singles and coincidence spectra are obtained with Ge(Li) detectors and an eight-fold digital coincidence system used in conjunction with an 800-channel pulse-height analyzer. If a new external-beam facility now being established at CP-5 proves to be satisfactory, the work at Juggernaut will be terminated.

(i) Levels in Ta^{182} from the Reaction $Ta^{181}(n,\gamma)Ta^{182}$.

The low-energy levels of odd-odd deformed nuclei provide significant information about the interaction between the odd nucleons when collective motion is present. For Ta^{182}, spectra observed at the high-sensitivity capture-gamma facility at CP-5 show that high-energy transitions from the capture state populate many of the low-lying states that have been observed in (d,p) stripping studies. However, the excitation energies of these levels are determined with higher accuracy in the present experiment. Also, the capture-gamma spectra reveal low-lying states that have not been reported in the (d,p) work. The decay scheme of the low-lying states has been established from coincidence studies at the Juggernaut reactor. These data are being analyzed within the framework of the collective model. Preliminary results have led to probable assignments for several observed rotational bands.

(ii) Low-Lying Levels in Ag^{108}, Ag^{110}, Sb^{122}, and Sb^{124}.

The low-lying excited states of these nuclides offer tests of the extension of the pairing-force-interaction approach to odd-odd spherical nuclei.

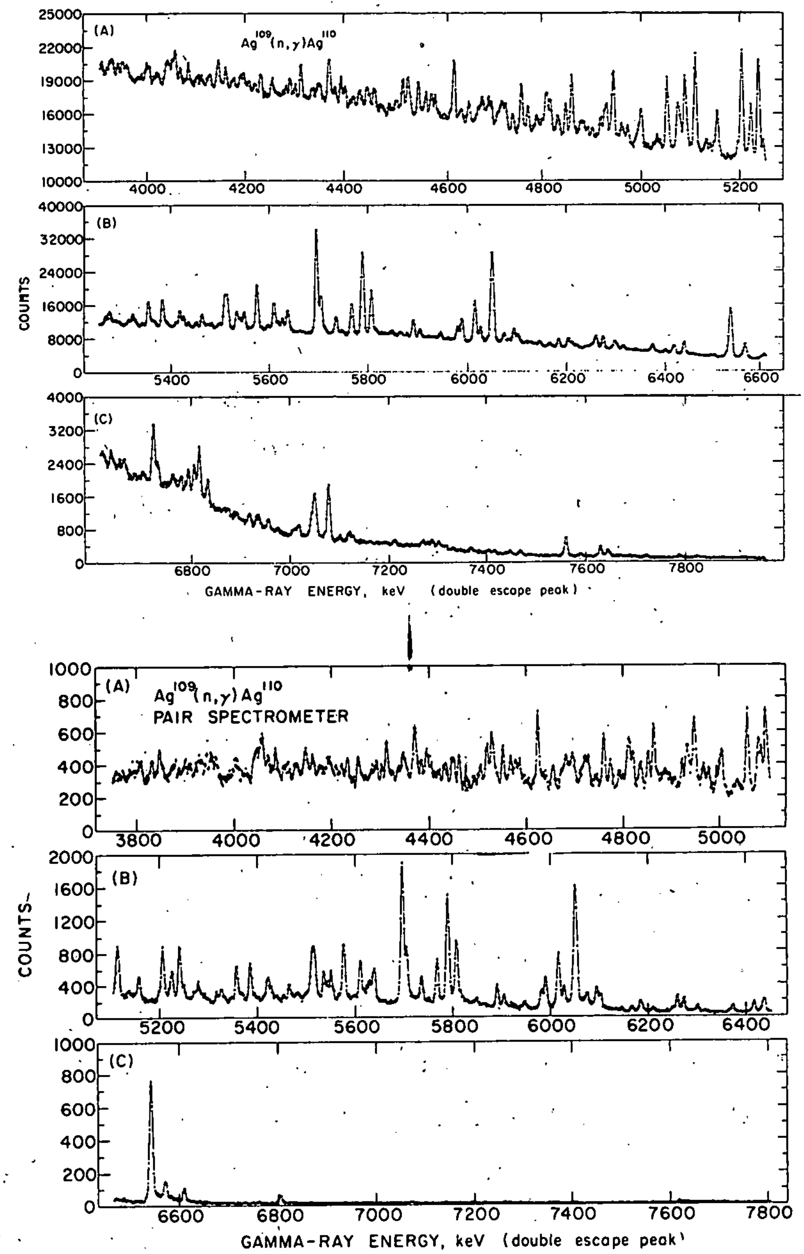

Fig. 7. Spectra of high-energy primary gamma rays following thermal-neutron capture in Ag^{109}. The gamma-ray energies associated with the double-escape peaks observed in the spectra are measured along the abscissa. Upper: singles spectrum. Lower: pair-spectrometer spectrum, in which only double-escape peaks are observed. The pair spectrum is seen to be distinctly simpler than the singles spectrum, especially in the vicinity of 6800 keV.

The neighboring Sn and Cd isotopes have already been shown to be describable by this model. The low-energy spectrum of Sb^{122} has been studied at the Juggernaut reactor. Both high- and low-energy capture gamma-ray measurements are in progress at CP-5. The spectra of the high-energy gamma rays following the reaction $Ag^{109}(n,\gamma)Ag^{110}$ arc shown in Fig. 7.

(iii) Levels in Ga^{70} and Ga^{72}. The gamma rays resulting from the capture of thermal neutrons in highly enriched samples of Ga^{69}

and Ga^{71} have been studied at the Juggernaut reactor as part of a continuing study of the Ga isotopes. The measurements will be extended at the new external-beam facility that is being established at CP-5.

(iv) Levels in Cu^{64} and Cu^{66}. The low-lying levels in these odd-odd Cu isotopes have been investigated at the high-sensitivity capture-gamma-ray facility at CP-5 by use of highly enriched samples of Cu^{63} and Cu^{65}. Many of the transitions observed have abnormally high strengths and several primary transitions that populate low-lying states in these nuclides have been resolved for the first time in the neutron-capture gamma-ray spectra. These data provide a highly sensitive and accurate determination both of the neutron-separation energies and of the low-lying excited states up to ~2 MeV excitation.

j. Gamma-Ray Spectra from Resonance Capture of Neutrons

L. M. Bollinger and G. E. Thomas

The high-sensitivity capture-gamma facility (Sec. I. A. 3a) is being used in an effort to observe the gamma-ray spectra resulting from the capture of neutrons in resonances. The basic idea of the experiment is that the energy of the observed gamma ray depends on the energy of the captured neutron and that the Ge-diode spectrometer now makes it feasible to detect the weak lines (at higher energy than for thermal capture) that are expected to result from resonant capture.

The first target studied was carbon, for which one hoped to see an 8.329-MeV gamma-ray line associated with capture in the 156-keV resonance of C^{13}. The line was not observed. However, the spectra obtained in this first measurement suggest that the basic idea of the experiment is valid and that lines from resonance capture will be observable when various forms of background have been reduced. The work is continuing.

B. RESEARCH AT THE 4-MEV VAN DE GRAAFF ACCELERATOR

The experimental program with the 4-MeV Van de Graaff accelerator is proceeding along much the same lines as in previous years. Experiments with fast neutrons are emphasized, especially measurements of the polarization of scattered neutrons. There has also been a revival of interest in the use of the 4-MeV machine for the study of charged-particle reactions, particularly for the measurement of the lifetimes of nuclear states by a Doppler-shift method. A continuing program is directed toward the improvement of the accelerator.

1. OPERATION OF THE 4-MEV VAN DE GRAAFF ACCELERATOR

J. R. Wallace

The 4-MeV accelerator has operated 3402 hours in the period from 1 April 1965 to 31 March 1966. It is currently operating on a schedule of 80 hours per week.

To meet the needs of most of the experiments being performed at this accelerator, emphasis has been placed on obtaining higher beam currents. Proton beam currents as high as 60—70 μA are being delivered to the target in some experiments.

The system for changing gases in the ion source has been improved, a new low-ripple 60-kV focus supply has been installed, and the pumping speed of the main vacuum pumps has been increased. A highly regulated power supply for the electrostatic analyzer has been designed, built, and tested by the Electronics Division and is being installed. A new water-cooling system has been designed and is now out for construction bids.

2. NEUTRON CROSS SECTIONS OF B^{10} FOR ENERGIES BETWEEN 10 AND 500 KEV

F. P. Mooring, J. E. Monahan, and C. M. Huddleston

The neutron total and absorption cross sections of B^{10} have been measured[1] for energies between 10 and 500 keV (Fig. 8). Our values for the absorption cross section are larger (by an average of 275 mb over the neutron-energy interval from 160 to 500 keV) than the values of the $B^{10}(n,\alpha)Li^7$ cross section measured earlier. The (n, α) cross section has often been used in shielding and reactor-design

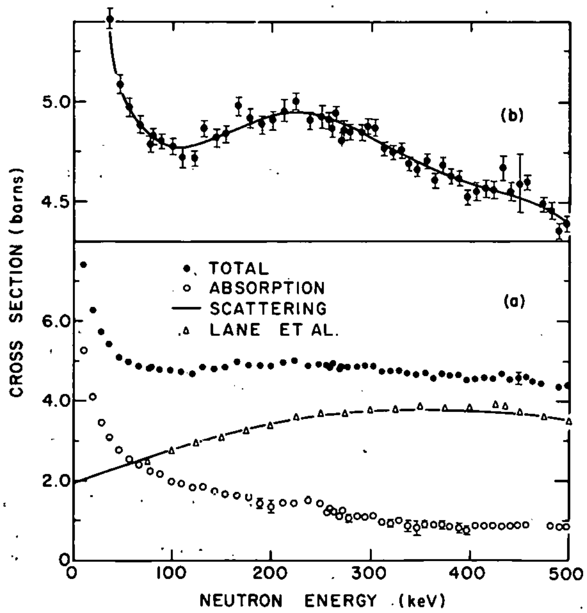

Fig. 8. The neutron cross sections of B^{10}. (a) The total, absorption, and scattering cross sections. The upper set of points (closed circles) represents the total cross section. For the absorption cross section (open circles), error bars are shown only at those energies at which the uncertainties in the measurement exceed the size of the circle. The scattering cross section of B^{10} (solid curve) is a plot of the difference between the smooth curves drawn through the points representing the total cross section and the absorption cross section. The triangles are values of the scattering cross section obtained by integrating the differential scattering measurements of R. O. Lane, A. Elwyn, F. P. Mooring, and J. E. Monahan (Sec. I. B. 4). (b) The total neutron cross section of B^{10} on an expanded scale.

calculations where it is further assumed that the (n, α) cross section is equal to the absorption cross section. Other measurements of the other possible neutron-absorbing processes indicate that the (n, α) and the absorption cross section are indeed very nearly equal in this energy interval. Also, a measurement of the scattering cross section of B^{10}

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

confirms our values for the absorption cross section. We believe that the earlier generally accepted values for the $B^{10}(n,\alpha)$ cross section are in error (by as much as 30%) in the interval from 160 to 500 keV.

3. THE 20.8-KEV RESONANCE IN B^{11}

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

The total neutron cross section of natural boron has been investigated in the vicinity of the 20.8-keV resonance in B^{11} by use of self-indication techniques. A neutron energy spread of 910 ± 80 eV was used in the measurements. The usual area analysis was extended to take account of the effects of self-indication and the absorption of neutrons by the detector samples. Preliminary results give a cross section of 60 ± 15 b at the resonance and 7.0 ± 1.0 eV for the level width. The measurements eliminate both J = 0 and J = 3 as possible values for the angular momentum of the excited state in B^{12}.

4. POLARIZATION AND DIFFERENTIAL CROSS SECTIONS FOR NEUTRONS SCATTERED FROM BORON

R. O. Lane, A. J. Elwyn, F. P. Mooring, and J. E. Monahan

The polarization $P(\theta)$ and the differential cross section $\sigma(\theta)$ for neutrons scattered from B^{10} and B^{11} at five angles have been measured in the energy interval $0.075 \leq E_n \leq 0.50$ MeV with the Argonne 4-MeV Van de Graaff. The results for B^{11} + n indicate that on the resonance at $E_n = 0.43$ MeV the Legendre polynomial expansion for $\sigma(\theta)$ contains only the terms $\sigma(\theta) = B_0 + B_1 P_1 (\cos\theta)$. The observation that $B_2 = 0$ on resonance does not agree with the assignment of channel spin 1 for this resonance.[1] We are now investigating the parameters of this state and properties of the background scattering up to 0.500 MeV. In particular, we are employing the R-matrix formalism for two channels (S = 1, 2) and one level plus a background R^0 term. The effects of bound states must be included. We have extended our measurements of $\sigma(\theta)$ and $P(\theta)$ up to ~2 MeV in order to obtain a more complete account of the polarization effects and hopefully to determine the parity of the state at E_n = 1.78 MeV.

The data on B^{10} up to 0.5 MeV showed negligible $P(\theta)$ and a very smooth variation of $\sigma(\theta)$ with E_n. We have also extended these data up to ~2 MeV to assist in the interpretation of the data for B^{10} + n discussed in Sec. I. B. 2.

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[1] H. B. Willard, J. K. Bair, and J. D. Kington, Phys. Rev. 98, 669 (1955).

5. NEUTRON SCATTERING FROM NUCLEI NEAR A = 20

J. E. Monahan, A. J. Elwyn, R. O. Lane, and F. P. Mooring

An analysis of the resonance-like peaks observed[1] in the differential cross section and polarization of neutrons scattered from F has been almost completed. Most of the structure observed in the neutron energy interval from 0.2 to 2.2 MeV can be explained within the experimental uncertainties in terms of states with spin and parity 1^-. The description of these resonances in terms of states with definite spin and parity is natural if this structure is interpreted in terms of the doorway-state model of nuclear reactions.

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[1] A. J. Elwyn, J. E. Monahan, R. O. Lane, and A. Langsdorf, Jr., Nucl. Phys. 59, 113 (1964).

This model pictures the formation of a compound nucleus as a stepwise process in which each successive step excites a more complex shell-model configuration. The state vectors for the actual compound states in a given energy interval then have as a common component the simple configuration (doorway) through which they are formed. If the amplitude of this component is sufficiently large and if the spreading of the simple configurations among the actual compound states is not so great that the associated structures overlap each other, the simple configuration would be observable as a resonance of intermediate width that forms an envelope for the more complex compound-nucleus resonances. This qualitative behavior is evident in the present data. A comparison of these results with explicit calculations[2] based on a particle-hole description of doorway states should provide a more nearly definitive test of the value of this model.

It seems reasonably clear that the same type of intermediate structure is not observed in the scattering of neutrons from heavy nuclei, at least at incident energies greater than 2 MeV. Since there is a kind of continuity in the properties of the simple configurations between light and heavy nuclei, it is of interest to determine the regions of mass number and energy in which the doorway states are observable. The present investigation is part of a program that was initiated for this purpose.

[2] R. Lemmer (private communication).

6. POLARIZATION AND DIFFERENTIAL CROSS SECTIONS FOR NEUTRONS SCATTERED FROM Cr, Fe, Tb^{159}, AND Ho^{165}

A. J. Elwyn, R. O. Lane, A. Langsdorf, Jr., F. P. Mooring, and J. E. Monahan

As part of a continuing program in the investigation of the scattering of neutrons with energies of less than about 2 MeV from various nuclei throughout the periodic table, we have recently measured

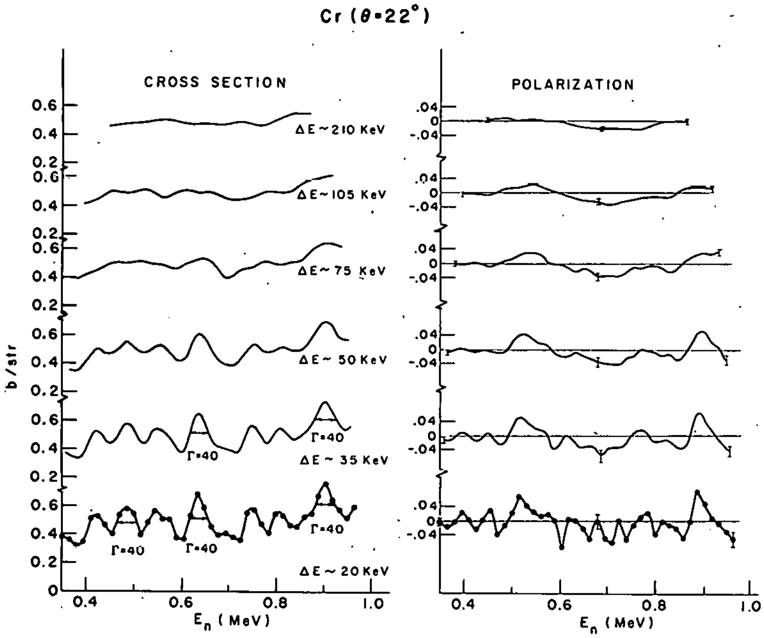

Fig. 9. The differential cross section and polarization for neutrons scattered from Cr at $\theta = 22^{\circ}$ for neutron energies between 0.35 and 0.97 MeV. The lowest curves are the actual data obtained with an energy spread of about 20 keV. Structure having widths on the order of 40 keV is observed. The other curves are numerical averages of the original data over larger and larger averaging intervals.

both the polarizations and the differential cross sections for 0.3—1.5-MeV neutrons scattered from the nuclei Cr, Fe, Tb^{159}, and Ho^{165}.

For the rare-earths Tb^{159} and Ho^{165}, neutron data have previously been scarce or nonexistent in this energy range. In the energy range between 0.3 and 0.4 MeV, the scattering from Ho^{165} revealed some small polarization effects; aside from this, neither nuclide showed any significant polarization over the entire energy interval from 0.3 to 1.5 MeV. The energy dependence of $\sigma(\theta)$ and the total scattering cross section were quite smooth throughout the energy range investigated. In particular, the measurements revealed no structure resolvable with the energy spread of 30—40 keV employed in the experiment. The data are currently being interpreted in terms of an optical-model description of the neutron-nucleus interaction.

The measurements on the elements Cr and Fe with incident energy spreads of 20—30 keV revealed a number of broad bumps of the order of 40—50 keV wide in the energy dependence of both the polarization and the differential cross section at each of the five angles at which the experiment was performed. An example of the observed structure is shown in Fig. 9. It is not yet clear to what extent an optical model may be used to interpret data that have been numerically averaged over an energy interval large enough to average out the observed structure. A phase-shift analysis has been undertaken in order to see if the structure itself can be adequately interpreted in terms of energy levels of the compound system formed by adding a neutron to the target nucleus, and to determine the spins and parities that might be associated with such states.

7. SMALL-ANGLE SCATTERING OF NEUTRONS BY URANIUM

A. J. Elwyn, J. E. Monahan, R. O. Lane, F. P. Mooring, and A. Langsdorf, Jr.

As discussed in last year's report, both the polarization and the differential cross section in the scattering of 0.83-MeV neutrons from U^{238} have been measured[1] at angles of 1.65°, 2.35°, 4.6°, and 10.0°. Calculations based on a potential that contains terms representing the nuclear interaction, the interaction between the neutron magnetic moment and the nuclear Coulomb field, and the interaction between an induced electric dipole moment (polarizability) of the neutron and the electric field of the nucleus were compared with the data. The results of this analysis lead to the conclusion that for values of the polarizability of the neutron close to the theoretical prediction (10^{-42} cm^3), the measured differential cross sections exhibit a small-angle behavior that suggests the existence of an additional and as yet unknown long-range neutron-nucleus interaction. Furthermore, the results of the polarization measurements lead to the conclusion that this new interaction is nonpolarizing.

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[1] A. J. Elwyn, J. E. Monahan, R. O. Lane, A. Langsdorf, Jr., and F. P. Mooring, Phys. Rev. 142, 758 (1966).

Further experimentation is planned in order to study these effects in more detail. In particular, a study of the detailed energy dependence of the small-angle scattering of neutrons from fissionable (and nonfissionable) nuclei—especially in energy intervals just above and just below the fission threshold—may prove useful in determining the nature of the anomalous scattering.

Some modification of the existing experimental arrangement in order to minimize systematic errors and to increase the detection efficiency is planned. In particular, we expect to utilize more than one detector so that the scattering at a number of small angles can be measured simultaneously. Our neutron detectors must therefore have characteristics that remain stable over reasonably long periods of time. Preliminary investigation of various kinds of pulse-shape-discrimination circuitry is in progress.

8. LIFETIME MEASUREMENTS

Since electromagnetic transitions depend only upon the properties of the nuclear states (the radiation field is understood from electromagnetic theory), electromagnetic transition rates are of particular value in the study of nuclear structure. Low-lying levels of nuclei can decay only by gamma emission and therefore the measured lifetimes of these levels, combined with gamma-ray branching ratios, provide a direct measure of gamma-ray transition rates.

a. Lifetime Measurements by Doppler-Shift Methods

R. E. Segel, R. H. Siemssen, A. E. Blaugrund, G. C. Morrison, D. Youngblood, S. I. Baker, and P. P. Singh

A program of lifetime measurements by the Doppler-shift attenuation method has been undertaken with the aid of high-resolution lithium-drifted Ge detectors fabricated by the ANL Electronics Division. The recoils are generated by nuclear reactions initiated by a beam from the Van de Graaff.

The first and third excited states of Ca^{41} have been populated by the $K^{41}(p,n)Ca^{41}$ reaction. Both of these states are $\frac{3}{2}^-$ and represent the splitting of the single-particle state that is described as a $p_{3/2}$ neutron orbiting a Ca^{40} core. The lifetime of the first excited state was found to be $4.5 \pm 1.0 \times 10^{-13}$ sec. The lifetime of the third excited state was found to be greater than 7×10^{-13} sec. Work by Lee, Schiffer, Kennedy, and Segel[1] at Argonne has shown that the E2 transition to the ground state represents less than 1% of the decays of the third excited state. Combining the result of Lee et al. with the present work leads to the conclusion that the reduced matrix element for the E2 transition from the upper $\frac{3}{2}^-$ state is less than 0.3% of that for the transition from the lower $\frac{3}{2}^-$ state.

Observations on the 1.042-MeV level in F^{18}, the first state with isotopic spin 1, seem to show a slight attenuation of the Doppler shift. This implies a quite short lifetime—about 5×10^{-15} sec. The γ rays from the first isotopic-spin-1 state in Al^{26}, formed in the $Na^{23}(\alpha,n)$ reaction, have been observed and the attenuation of the Doppler shift has been measured. Coincidences between particles and gammas from the $Si^{28}(d,p)Si^{29}$ reaction have been used to observe the γ ray from the first and third excited states of Si^{29}. An attenuation of the Doppler shift has been observed for each of these states.

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[1] L. L. Lee, Jr., J. P. Schiffer, E. F. Kennedy, and R. E. Segel (unpublished results).

b. Improved Timing with NaI(Tl)

F. J. Lynch

The improved time resolution we have recently obtained with NaI(Tl) at 300°K is somewhat superior to that previously reported for pure NaI at 77°K. For example, the time distribution for x rays (31.6 keV) relative to the conversion electrons from a Cs^{137} source, shows a full width at half maximum of 1.6 nsec and a slope corresponding to a half-life $T_{1/2} = 0.63$ nsec. This implies that τ/R is much smaller than commonly believed, where τ is the mean life of the scintillator and R is the average number of photoelectrons per event.

This small value is not due to a small τ because only the usual slow component is observed when the shape of the scintillation is measured by a probability technique. Therefore R must be larger than expected; the observed time resolution requires at least 8.7 photoelectrons per keV. This is consistent with values obtained by two other independent techniques. Thus, the improved resolution is primarily due to improved conversion efficiency and the low thermionic current of the bi-alkali photocathode.

c. Pulsed-Beam Measurements of Lifetimes of Nuclear States

R. E. Holland, F. J. Lynch, and A. E. Blaugrund

Investigations of transitions between $\frac{3}{2}^+$ and $\frac{7}{2}^-$ levels have been continued. In Ca^{41}, the second excited state (the 2.014-MeV level believed to be a $d_{3/2}$ hole state) was found to have a mean life of 1.0 ± 0.1 nsec. The lifetime of the second excited state in K^{39} at 2.82 MeV, which is believed to be the $f_{7/2}$ particle state, is measured to be 0.010 ± 0.015 nsec.

In Sc^{45}, the model of Lawson and Macfarlane predicts that the $\frac{3}{2}^+$ first excited state at 12.5 keV should de-excite to the $\frac{7}{2}^-$ ground state by an M2 transition; but according to the model of de Shalit, the de-excitation should proceed by an E3 transition. Our measurement of the K conversion coefficient agrees within experimental error with the value calculated for an M2 transition. A measurement of the cross section for the inverse process, in which the $\frac{3}{2}^{+}$ state is Coulomb excited by bombarding with chlorine ions, is being attempted.

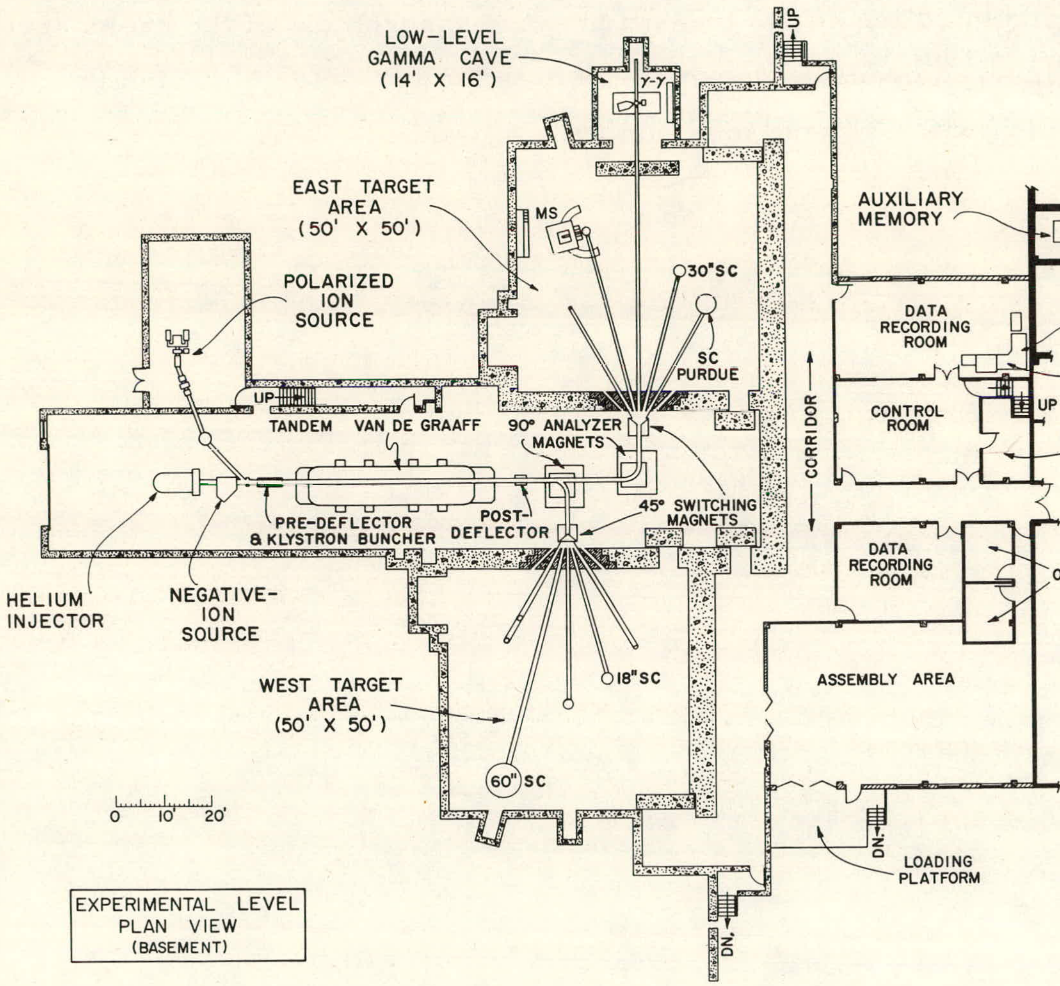

Fig. 10. Floor plan of the Tandem Van de Graaff facility. There are two nearly-identical well-shielded target areas, each with its own associated data-recording room. Experiments are usually scheduled to alternate from one area to the other. Most of the large pieces of equipment are indicated: MS—magnetic spectrometer, SC—scattering chamber, γ-γ—gamma-ray angular-correlation spectrometer. Some of the outside users bring their own equipment (e.g., the Purdue scattering chamber in the East Target Area). An on-line computer complex records and analyzes data as an experiment progresses.

C. RESEARCH AT THE 12-MEV TANDEM VAN DE GRAAFF ACCELERATOR

The Tandem Van de Graaff accelerator (Fig. 10) which was installed in 1962, is now used to its full capacity on an operating schedule of 24 hours daily. The machine (an EN-model Tandem) provides the principal research tool of 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.

The research carried out at the Tandem under the Low-Energy Physics Program is very broad in scope, reflecting the diverse interests of the physicists involved. Most of the program is concerned with various aspects of charged-particle-induced nuclear reactions. Recently, studies of direct reactions, the giant-dipole resonance, and isobaric-spin analogue states have received special emphasis.

An integral part of the program is a continuing effort to provide up-to-date equipment for use in experiments at the Tandem. Apparatus now in use includes an on-line computer system, a broad-range magnetic spectrograph, a large angular-correlation apparatus for gamma-ray measurements, a pulsed-beam facility, and several scattering chambers. Major apparatus under development includes a polarized-ion source, an automatic plate reader, and a 65 000-word core-storage memory. The accelerator itself will be converted into an FN-model Tandem in 1967.

1. OPERATION OF THE TANDEM

Jack R. Wallace

The tandem has operated 6434 hours in the period from 1 April 1965 to 31 March 1966. This makes a total of 21 147 hours to date. The machine is operating on a schedule of 168 hours per week (24 hours per day, 7 days per week).

Changes and improvements in the past year include installation of a kit from High Voltage Engineering to increase the transmission of the beam, of an assembly to make the electrical connections from the voltage-dividing column to the acceleration tube, and of beam-steering systems for the target rooms; improving the ion source by further stabilizing the extraction voltage, by adding a plasma-expansion cone and additional vacuum pumps, and by installing new pole pieces and a vacuum chamber for the 20° bending magnet; improving the circuitry of the beam-pulsing system; arranging for all ion-source components to be remotely controlled from the control console; and designing and constructing an assembly to permit use of a carbon foil as the ion stripper in the high-voltage terminal. A new 30-in. scattering chamber has been added to the experimental facilities.

During 1967 the present EN tandem Van de Graaff will be converted into an FN machine in order to increase the particle energy and beam current. The construction and testing of a polarized-ion source are well advanced.

2. EXPERIMENTS ON THE LIGHTER NUCLEI

a. Interference Effect Between the 16.62- and 16.92-MeV Levels in Be^8

C. P. Browne* and J. R. Erskine

An investigation of the $B^{10}(d, \alpha)Be^8$ reaction at $E_d = 12$ MeV has revealed an unusual property of the two levels in Be^8 at 16.63 and 16.92 MeV excitation. The α spectrum from the above reaction shows an interference effect (Fig. 11) between these two levels, each of which has a width Γ of about 100 keV. Instead of appearing as two independent Breit-Wigner distributions, the α groups corresponding to these levels have distinctly distorted shapes indicative of some sort of interference. This is not too surprising since it was previously known that the wave functions of these levels are closely related. Efforts to learn the nature of this interference phenomenon are continuing.

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*University of Notre Dame.

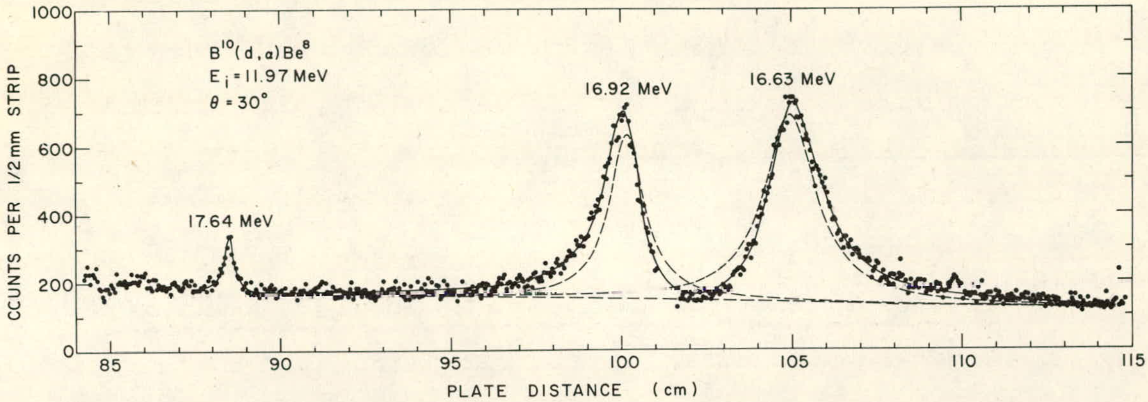

Fig. 11. Alpha spectrum showing interference between the 16.63- and 16.92-MeV levels in Be^8 from the $B^{10}(d,\alpha)Be^8$ reaction. In addition to these two peaks, whose asymmetric shapes indicate the interference, the data show an alpha-particle group corresponding to the transition to the 17.64-MeV excited state in Be^8. The data were fitted with a two-level Breit-Wigner formula (solid curve) by minimizing χ^2. The dashed curves show the shapes the levels would have had without interference.

b. Studies of B^{10}

R. E. Segel, P. P. Singh, and R. H. Siemssen

When B^{10} was bombarded by protons with energies up to 12 MeV, the yield curves to various channels fell into two distinct categories depending upon whether or not one of the reaction products is in a state with isotopic spin 1. Most of these yield curves were obtained from Argonne work on reactions to γ-ray-emitting states, but some are from charged-particle experiments at other laboratories. For a $(0,\frac{1}{2})$ final state, in which the isotopic spin of one of the final particles is 0 and that of the other is $\frac{1}{2}$, the yield is dominated by a resonance several MeV broad centered at a bombarding energy of about 7 MeV. This broad resonance is absent for the $(1,\frac{1}{2})$ final states. A plausible explanation is that the resonance is in the system consisting of a proton plus the clusters $\alpha + \alpha + d$. Since the clusters are all $T = 0$, such a state can decay directly only to $(0,\frac{1}{2})$ states.

In a successful search for the transition from the 5.16-MeV state to the 3.58-MeV state, alpha particles from the 2-MeV

Van de Graaff were employed to excite the 1.17-MeV resonance in the $Li^6(\alpha,\gamma)$ reaction. The radiation width was found to be in very good agreement with the theoretical calculations of Cohen and Kurath.[1]

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

c. Isospin Selection Rule in the $C^{12}(d,\alpha)B^{10}$ Reaction

L. Meyer-Schützmeister, D. von Ehrenstein, and R. G. Allas

The violation of the isospin selection rule has been studied in the reaction $C^{12}(d,\alpha)B^{10}$ with deuteron energies between 9 and 12.5 MeV. The differential and total cross sections of the isospin-forbidden transition to the first T=1 state in B^{10} (the $J^\pi = 0^+$ state at 1.74 MeV excitation) has been compared with the cross sections of the isospin-allowed transition to the ground state ($J^\pi = 3^+$, T = 0), the first excited state ($J^\pi = 1^+$, T = 0 at 0.72 MeV), and the third excited state ($J^\pi = 1^+$, T = 0 at 2.14 MeV). Mostly the intensity of the T=1 alpha group is less than 1% of the yield of the α groups leading to the neighboring T=0 states. This reduction is due not only to isospin forbiddenness but also to angular-momentum and parity selection rules which apply in this particular (d,α) reaction for which both the initial and the final state have $J^\pi = 0^+$. The small yield is ascribed to the isospin selection rules that influence this T=1 transition.

In the energy range from 9 to 11 MeV, the angular distribution of the T=1 state stays fairly constant and is nearly symmetric around 90°. The yield decreases steadily. At deuteron energies higher than 11.5 MeV, the angular distribution changes drastically and becomes strongly forward peaked and asymmetric around 90° and the total yield increases slightly. We assume that this behavior indicates a direct-interaction mechanism in which the process of mixing the isospins takes place at the surface of the nucleus. Coulomb excitation during the process of d capture or α emission might be responsible for the isospin violation at higher deuteron energies. The final report has been submitted for publication.

d. Angular-Correlation Measurements in Nuclear Reactions

L. Meyer-Schützmeister and T. H. Braid

Recently we have started to measure angular correlations (Fig. 12) of nuclear reactions in an arrangement which allows the population of only a few substates in the detected residual nucleus,

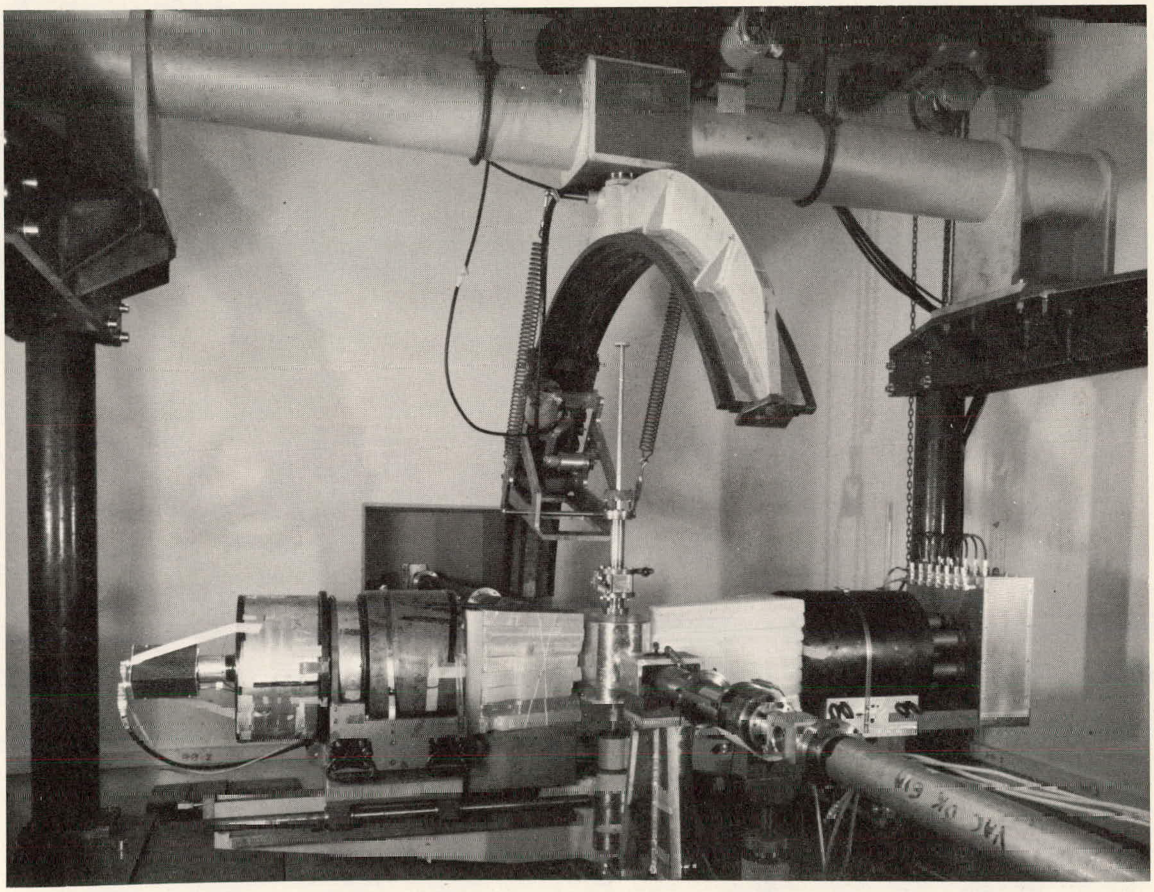

Fig. 12. Apparatus used for particle-gamma and gamma-gamma angular correlations. Three large NaI crystals can be accommodated. The two in the horizontal plane that includes the beam line are shown; the third (not in use when the photograph was taken) can be mounted on the carriage and positioned anywhere on the upper hemisphere. The crystals can be operated independently in singles measurements so as to decrease the running time in low-yield reactions.

independent of its spin. In our first example we studied the reaction $Mg^{24}(He^3,\alpha)Mg^{23}$. The outgoing alpha is measured with a surface-barrier detector in the form of an annular ring, placed at 180° to the incoming beam. The different gamma rays emitted from the Mg^{23} nucleus are measured in coincidence with the preceding alpha as a function of the angle between the alpha and the gamma ray. This method has the great advantage of being independent of the process leading to the residual nucleus.

The analysis of the angular correlations is relatively simple. In our case, in which the alphas populate only the substates $m = \pm\frac{1}{2}$ in the Mg^{23} nucleus, the angular correlations depend only on the spins of the Mg^{23} states that are involved in the reaction and on the multipolarity of the emitted γ ray. So far, we have studied the first three excited states in Mg^{23}, which are isolated well enough to allow a good determination of the angular correlations.

We are in the process of comparing these results with those obtained in the mirror nucleus Na^{23} and other nuclei (e.g., Ne^{21} and Na^{21}) which should have similar level schemes for the first few excited states. For example, we have confirmed that the three lowest excited states in Mg^{23} and Na^{23} have the same spin assignments, but we have obtained a markedly different branching ratio for the two gammas that are emitted from the third excited state in each of the nuclei. This last result indicates a different charge distribution of the involved excited states in Mg^{23} and Na^{23}. It is hoped that this comparison of the spin assignments, branching ratios, and multipolarities of the emitted gammas will give a good handle by which to check and improve the theoretical assumptions.

3. RADIATIVE CAPTURE

a. Radiative-Capture Studies of the Giant Dipole Resonance

L. Meyer-Schützmeister, R. E. Segel, and Z. Vager

We have continued our investigations of the giant dipole resonance through α capture (induced by the 12-MeV tandem generator) by studying the reactions $Mg^{26}(\alpha,\gamma)Si^{30}$, $Si^{28}(\alpha,\gamma)S^{32}$, and $Mg^{24}(\alpha,\gamma)Si^{28}$. In all three reactions it could be shown experimentally that the γ-ray transition to the ground state is predominantly of dipole character and that therefore the reactions proceed mainly through the giant electric-dipole resonances in Si^{30}, S^{32}, and Si^{28}, respectively. In Table II the integrated cross sections of these reactions are compared with our earlier measurement[1] of the reaction $Al^{27}(p,\gamma_0)Si^{28}$. A detailed analysis of the α capture in Mg^{24} and Mg^{26} shows that both reactions go strongly through compound-nucleus resonances with an average width of 60 keV. This is in contrast to the $Al^{27}(p,\gamma)$ reaction which also exhibits the 60-keV-wide structure but has the bulk of the cross section in the fast components which vary only smoothly with energy. We conclude that the fast components are strongly suppressed in the formation of the giant dipole resonance by α capture in

TABLE II. Comparison of the alpha and proton decays of the giant resonance in three nuclei. These integrated cross sections were obtained by detailed balance; they include most of the giant dipole resonance.

	$\int\sigma(\gamma,\alpha_0)dE$ (mb-MeV)	$\int\sigma(\gamma,p_0)dE$ (mb-MeV)
Si^{28}	4.3	52
Si^{30}	2.4	. . .
S^{32}	≈ 0.8	. . .

[1] P. P. Singh, R. E. Segel, L. Meyer-Schützmeister, S. S. Hanna, and R. G. Allas, Nucl. Phys. 65, 577 (1965).

the two target nuclei Mg^{24} and Mg^{26}. This indicates that the isospin-mixing procedure is not alone responsible for the compound-nucleus formation.

The small cross section for the α capture and the suppression of its fast components indicate that the arrangement of the nucleons in the giant dipole resonance only slightly resembles a configuration that consists of a core (either Mg^{24} or Mg^{26}) plus an alpha. The relatively large cross section and the fast components in the proton capture can then be taken as an indication that the nucleon configuration of the giant resonance is well described in terms of a core plus a proton, a picture which agrees well with the particle-hole theory that is currently used to describe the giant dipole resonance.

b. Search for $T=\frac{3}{2}$ States in $T_z = -\frac{1}{2}$ Nuclei

G. C. Morrison, R. E. Segel, and D. Youngblood

By looking at the β^+ decay of the final nucleus, the (p,γ) reaction is being used to locate the positions of the $T=\frac{3}{2}$ analogue states in $T_z = -\frac{1}{2}$ nuclei in the 1d-2s shell. Because the formation of a $T=\frac{3}{2}$ state can proceed only by isobaric-spin impurity in the entrance channel and the only allowed decay is by gamma emission, $T=\frac{3}{2}$ states should give rise to very narrow resonances. The position of the lowest $T=\frac{3}{2}$ analog state in each such nucleus has been experimentally observed[1] in the super-allowed β^+ decay of delayed-proton precursors, e.g., $Si^{29}(\beta^+)Al^{29}$.

In the initial experimental arrangement, the β^+ activity was detected by observing coincident annihilation quanta in two NaI detectors at 180°. In the final arrangement, the background was further reduced by detecting the β^+ in a plastic scintillator and requiring that it be in coincidence with the annihilation quanta and that it have more than a

[1] J. C. Hardy and B. Margolis, Phys. Letters 15, 276 (1965).

certain energy. With this arrangement, resonances in the $Ca^{40}(p,\gamma)Sc^{41}$ reaction have been observed in good agreement with previous experiment.[2] In preliminary results on the $Si^{28}(p,\gamma)P^{29}$ reaction, the analogues of the ground state and possibly the first excited state of P^{29} have been observed.

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[2] D. Youngblood, thesis, Rice University, 1965.

4. EXPERIMENTS ON ELASTIC SCATTERING OF CHARGED PARTICLES AND ON DIRECT-REACTION MECHANISMS

a. $B^{10}(d,d)B^{10}$, $B^{10}(d,p)B^{11}$, and $B^{11}(p,p)B^{11}$ Reactions

R. H. Siemssen and L. L. Lee, Jr.

Our investigation of the $B^{10}(d,p)B^{11}$ and $B^{10}(d,d)B^{10}$ reactions at the Argonne Tandem has been supplemented by measurements of the elastic proton scattering from B^{11} at several bombarding energies between 12 and 21 MeV. The proton scattering has been measured with the Boulder cyclotron in cooperation with Dr. M. E. Rickey. An optical-model analysis of the elastic deuteron scattering indicates that a spin-orbit coupling for the deuteron is required. Possibly also the spin of the target nucleus B^{10} has to be taken into account. A final analysis of the elastic scattering and of the (d,p) process has not yet been made.

b. Evidence for a Dependence of Single-Proton Transfer Reactions on Isobaric Spin

R. H. Siemssen, G. C. Morrison, B. Zeidman, and H. Fuchs

Relative spectroscopic factors from the (He^3,d) reaction are compared with those from the (d,n) reaction leading to the low T=0 states and first T=1 states in the odd-odd nuclei B^{10}, N^{14}, and Al^{26}. It is widely accepted that the (He^3,d) and the (d,n) reactions are analogous processes involving proton transfer and that they should therefore yield the same spectroscopic factors. In contrast, in each case studied, the relative spectroscopic factor for the T=1 state deduced from the (d,n) reaction is less than the spectroscopic factor from the (He^3,d) reaction, the spectroscopic factors for the T=0 states being normalized to each other for the two reactions. This difference is independent of the incident energy. It is found to be largest for B^{10}, for which it is approximately a factor of 3.

c. J Dependence in (d,p) Reactions

L. L. Lee, Jr., A. Marinov, C. Mayer-Böricke, and J. P. Schiffer

These effects[1] have been studied in somewhat more detail. More experimental information has been accumulated for light nuclei by measuring the (d,p) reaction on B^{10}, C^{12}, O^{16}, F^{19}, Si^{28}, S^{32}, and S^{34}. J dependence was found for ℓ=1 transitions in the 1p shell, a hitherto unobserved effect (Fig. 13). Additional evidence was accumulated for J-dependent effects in the 1d shell.

We are now using these effects in experiments to assign spins and parities to excited states.

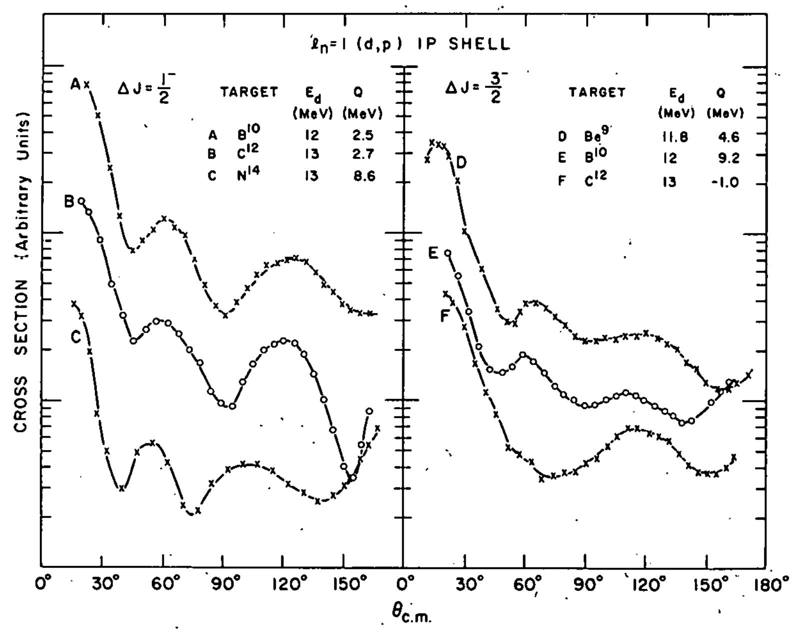

Fig. 13. J-dependent effects for (d,p) reactions in the 1p shell.

[1] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. 136, B405 (1964).

d. A Study of the $Si^{28}(d,n)P^{29}$ and $Mg^{24}(d,n)Al^{25}$ Reactions

S. Buccino,* D. S. Gemmell, L. L. Lee, Jr., J. P. Schiffer, and A. B. Smith*

These (d,n) reactions were studied by use of the pulsed deuteron beam of the tandem Van de Graaff. Bombarding energies of 7 and 9 MeV were used. The resultant angular distributions were analyzed in terms of the DWBA formulas and then compared with the results obtained for the mirror nuclei Si^{29} and Mg^{25}. A J-dependent effect in the $\ell=2$ transition was found, similar to that seen in the (d,p) reaction.[1] A final report on this work is being prepared for publication. The information on spectroscopic factors is summarized in Table III.

TABLE III. Spectroscopic factors from (d,n) reactions.

Reaction	Excitation energy (MeV)	ℓ_p	Spectroscopic factor
$Mg^{24}(d,n)Al^{25}$	g. s.	2	0.58
	0.45	0	0.85
	0.95	2	0.45
	1.79	2	0.20
$Si^{28}(d,n)P^{29}$	g. s.	0	1.00[a]
	1.36	2	1.29[a]
	1.96	2	0.24[a]

[a]Relative to the ground state.

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*Reactor Physics Division, ANL.

[1] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. 136, B405 (1964).

e. Energy Dependence of Deuteron Scattering

C. Mayer-Böricke and R. H. Siemssen

The elastic scattering of deuterons was studied at 1-MeV intervals in the range from 6 to 13 MeV for a Mg^{24} target and from 6 to 11 MeV for Ti^{48}. For Mg^{24}, the angular distribution for inelastic scattering to the first excited state was also obtained, as well as yield functions at 90° and 150° in 50-keV steps. In the energy region from 11 to 13 MeV, the elastic deuteron scattering shows an anomalous behavior. Instead of the maximum moving in from 180°, a new maximum is formed by the splitting of a broad maximum at 110°. In this range of energies and angles, the Blair phase rule does not hold for the inelastic deuteron scattering.

In spite of fluctuations in the yield functions, the optical-model parameters for the deuteron scattering from Mg^{24} (with the exception of the imaginary depth W of the potential well) vary smoothly with energy. With the angular distributions calculated with these parameters, the main features of the experimentally observed angular distributions (including the splitting of the maximum at 110°) can be reproduced reasonably well. The optical-model analysis of the Ti^{48} data yields parameters which change only little with energy, especially if fixed geometrical parameters are chosen.

f. Analysis of Elastic Scattering of Protons and Deuterons by Isotopes of Ca, Ni, and Cu

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

The angular distributions of 9- and 12-MeV protons elastically scattered from $Ca^{42,44,48}$ (present work), $Ni^{58,60,62,64}$, and $Cu^{63,65}$ (earlier work[1]) were analyzed in terms of an optical potential.

[1] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. 134, B765 (1964).

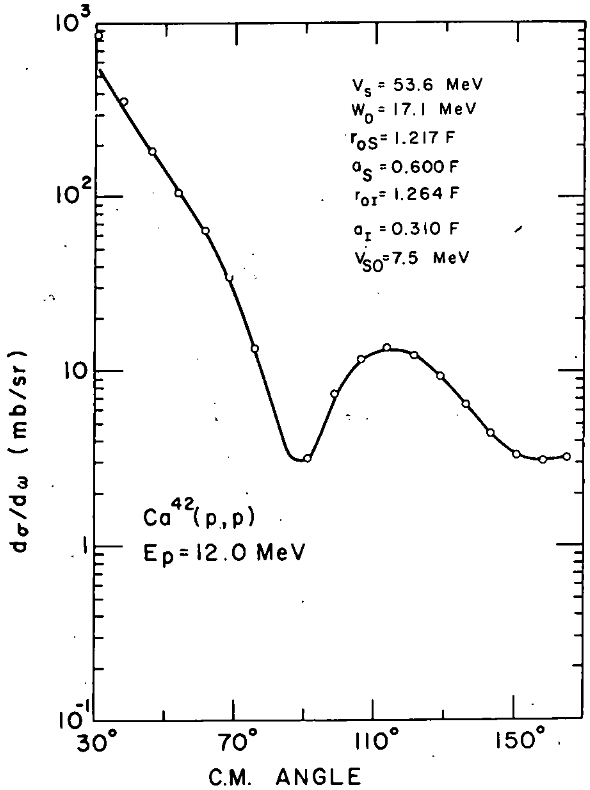

Fig. 14. Angular distribution for the elastic scattering of protons by Ca^{42}. The line corresponds to the calculated scattering from a potential with the parameters given in the figure.

The results for Ca^{42} are shown in Fig. 14. Particular care was taken to investigate the dependence of the optical potential on neutron excess. While the results show some systematic trends, the results are far from clearcut. This may be because of the relatively low bombarding energies used. The final report on this work has been submitted for publication.

g. Proton Reaction Cross Sections and Strength Functions

A. J. Elwyn, A. Marinov, and J. P. Schiffer

When a (p, n) reaction on a given target element is induced by protons with energies sufficiently below the Coulomb barrier, the emission of charged particles is inhibited and the compound nucleus decays almost entirely by neutron emission. Under these circumstances, therefore, the total neutron yield integrated over all angles of emission

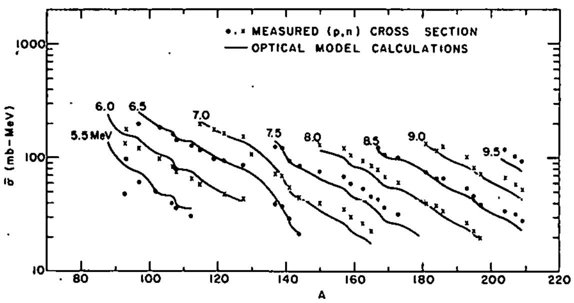

Fig. 15. The cross section (at each indicated incident-proton energy) as a function of atomic weight A. The points (circles and crosses) are measured (p,n) reaction cross sections. The compound-nucleus cross sections (curves) were calculated on the basis of Perey's optical model (Ref. 2).

is a good approximation to the total reaction cross section. In a series of experiments, begun in 1964, about 33 elements in the mass range $90 \lesssim A \lesssim 209$ were bombarded by monoenergetic protons from the Argonne tandem accelerator. Total (p,n) reaction cross sections were obtained from the measured neutron yields; and "reduced cross sections," which are closely related to the proton strength function, were determined[1] by dividing the total neutron yields by the weighted sum of the penetrability factors of the Coulomb and centrifugal barriers.

Measured (p,n) cross sections were compared with optical-model calculations of proton reaction cross sections, as shown in Fig. 15. The calculations were based on Perey's surface-absorption optical potential[2] which had been obtained from a systematic analysis of proton elastic-scattering data in the energy range between 9 and 22 MeV. Agreement between the calculations and the measurements is remarkably good—especially in the mass regions $100 \lesssim A \lesssim 150$ and $180 \lesssim A \lesssim 195$. But as might be expected, in the intervening range from $A \approx 150-180$ (a region of strongly deformed nuclei) the data are in less good agreement with calculations based on a spherical optical model.

The reduced cross sections from the present series of measurements as well as from previous measurements[1] in the mass region $37 \leqslant A \leqslant 130$ were also compared with optical-model calculations.

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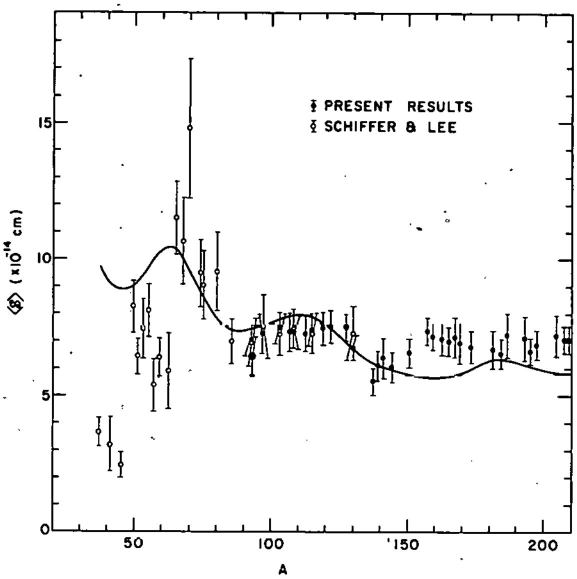
[1] J. P. Schiffer and L. L. Lee, Jr., Phys. Rev. 109, 2098 (1958).

[2] F. G. Perey, Phys. Rev. 131, 745 (1963).

Fig. 16. Comparison between the mean reduced cross sections (points) and the curve calculated on the basis of Perey's optical model (Ref. 2). The calculated curves were obtained by dividing the computed compound-nucleus cross sections integrated over energy by the weighted sum of the Coulomb penetrability factors.



This is shown in Fig. 16. Although some of the actual details in the data are not reproduced by the calculations (notably in the region of strongly deformed nuclei), the disagreement between calculations and measurements is not worse than 10—15%, at least for $A \geq 90$.

On the basis of further calculations, in which the optical-model results were decomposed into their partial-wave components, we conclude that the P-wave proton strength function peaks at about $A = 105$, and that S- and D-wave strength functions dominate near $A \approx 65$ and for $155 \leq A \leq 200$. In the mass region $150 \lesssim A \lesssim 180$, it is likely that specific properties of deformed nuclei play an important role for the proton strength function, as has previously been shown to be the case for the neutron strength function.

5. NUCLEAR-STRUCTURE STUDIES WITH DIRECT REACTIONS

a. A Study of Ca^{40} with the $K^{39}(He^3,d)Ca^{40}$ Reaction

J. R. Erskine

The single-particle nature of energy levels in Ca^{40} has been investigated with the $K^{39}(He^3,d)Ca^{40}$ reaction.[1] Spectroscopic

[1] J. R. Erskine, Phys. Rev. 149, 854 (1966).

factors and ℓ values were extracted with a DWBA analysis of the measured angular distributions. The major components of the $(d_{3/2}^{-1} f_{7/2})_{T=0,1}$ and $(d_{3/2}^{-1} p_{3/2})_{T=0}$ configurations have been identified. The data show that the calculations of Gillet and Sanderson overestimated the effects of Coulomb mixing of T=0 and T=1 states in Ca^{40}.

b. A Study of the $Ca^{48}(He^3,d)Sc^{49}$ Reaction

J. R. Erskine, A. Marinov, and J. P. Schiffer

The states of the nucleus formed by adding a proton to the doubly-closed-shell nucleus of Ca^{48} have been studied at low excitation energies.[1] An analysis of the angular distributions has yielded information on single-particle energies in Sc^{49}. Some information was also obtained with the $Ca^{48}(He^3,\alpha)Ca^{47}$, $Ca^{48}(d,t)Ca^{47}$, $Ca^{48}(d,p)Ca^{49}$, and $Ca^{48}(\alpha,p)Sc^{51}$ reactions. The final report on this work has been published.[1]

[1] J. R. Erskine, A. Marinov, and J. P. Schiffer, Phys. Rev. 142, 633 (1966).

c. Excited States in Cu^{62} from the $Ni^{61}(He^3,d)$ Reaction

G. C. Morrison and J. P. Schiffer

As part of the program of investigation of the (He^3,d) reaction on separated Ni isotopes with the 18-MeV He^3 beam of the Argonne tandem Van de Graaff (Sec. I.C.6c), we have made measurements on the $Ni^{61}(He^3,d)Cu^{62}$ reaction. Deuteron energy spectra were obtained with the broad-range magnetic spectrograph at enough forward angles to differentiate clearly between $\ell=1$ and $\ell=3$ angular-momentum transfer in the stripping reaction. Levels were observed at excitation energies of 0.0, 0.042, 0.288, 0.426, 0.550, 0.638, 0.675, 0.698, 0.910, and 0.982 MeV with an uncertainty of ±5 keV. Preliminary analysis shows that all the levels listed are predominantly populated by $\ell=1$ proton transfer with the exception of the $\ell=3$ state at 0.982 MeV.

At higher excitation energies, many further levels are observed as would be expected from the odd-odd nature of Cu^{62}. At excitation energies of 4.623 and 5.79 MeV, the analogues of the ground state and first excited state of Ni^{62} are clearly observed. The position of the ground-state analogue leads to a Cu^{62}—Ni^{62} Coulomb-energy difference of 9.36 MeV.

d. (d,p) Reactions on $Zn^{64,66,68,70}$

J. P. Schiffer, D. von Ehrenstein, and L. L. Lee, Jr.

Angular distributions have been measured between 5° and 160° in steps of 5° for the (d,p) reactions on $Zn^{64,66,68,70}$ with 10-MeV deuterons from the Argonne tandem Van de Graaff. Spins and parities of the final states were determined with the help of the previously established J-dependence rules.[1] The data were acquired with solid-state detectors and—mainly in the forward direction—with the broad-range magnetic spectrograph.

From the $Zn^{70}(d,p)Zn^{71}$ reaction we obtained the previously unknown Q value of the ground state and several dozens of excited states up to about 4 MeV excitation energy. In the spectra of the other Zn isotopes investigated, we also found a number of new levels. The spins and parities of many of the newly discovered levels were determined (Fig. 17), and previously assigned spin values[2] were verified or corrected. The most striking examples of corrections on the basis of the J dependences[1] are the spins of the low-lying levels at 0.09 MeV and 0.18 MeV in Zn^{67} from the $Zn^{66}(d,p)Zn^{67}$ reaction. To these levels we assign $J = \frac{1}{2}^{-}$ and $\frac{3}{2}^{-}$, respectively, instead of the previous $J = \frac{3}{2}^{-}$ and $\frac{5}{2}^{-}$.

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[1] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. 136, B405 (1964).

[2] Nuclear Data Tables, compiled by K. Way et al. (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D.C.); E. K. Lin and B. L. Cohen, Phys. Rev. 132, 2632 (1963).

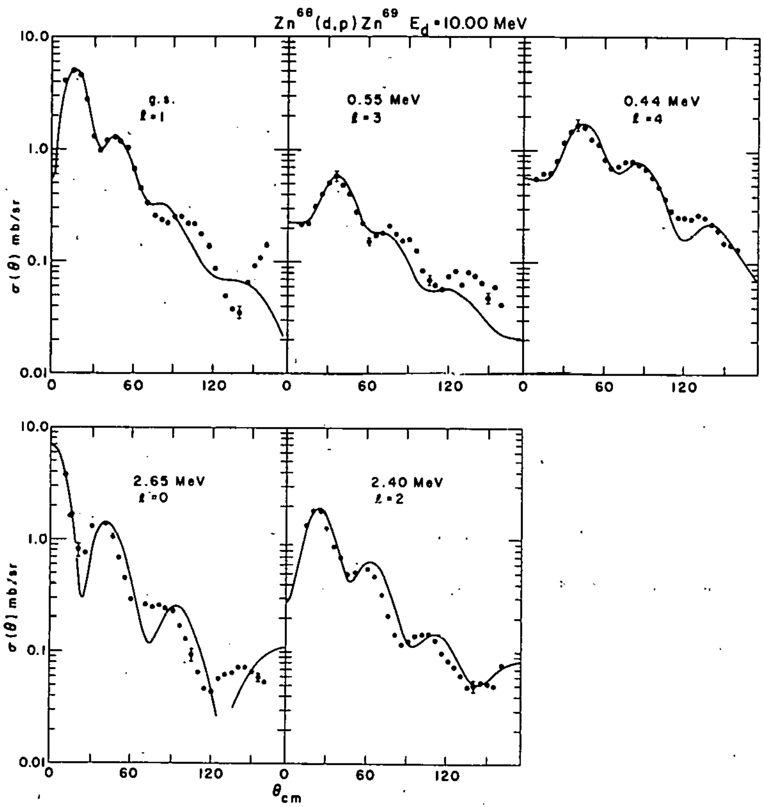

Fig. 17. Some measured angular distributions for the (d, p) reactions on Zn^{68}. The solid curves are calculated with the distorted-wave Born approximation.

A reinvestigation[3] of the β decay involving these two levels, undertaken as a result of the spin reassignment, agrees with our findings.

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[3] M. S. Freedman, F. T. Porter, F. Wagner, Jr., Phys. Rev. (in press).

e. Study of (He^3, d) Reactions in the 1f-2p Shell

B. Zeidman, R. H. Siemssen, L. L. Lee, Jr., and G. C. Morrison

While shell-model neutron states have been extensively studied by means of the (d, p) reaction, our knowledge of proton states is still sparse. The (He^3, d) reaction provides a method for precise spectroscopy in proton states. This reaction, initiated by 18-MeV He^3 ions from the tandem Van de Graaff, was used to study the nuclei $Ga^{65,67,69,71}$ by bombardment of separated Zn isotope targets in the 18-in. scattering chamber. Many new levels up to about 4-MeV excitation were observed in all these nuclei. Angular distributions provided a means of identifying spin and parities. The lack of sizable $g_{9/2}$ neutron admixture in $Zn^{64,66,68}$ was inferred from the lack of interaction with the $g_{9/2}$ proton state which has almost constant excitation energy and reduced width. Analysis is continuing.

f. Energy Levels in Cd^{114} from the $Cd^{113}(d,p)Cd^{114}$ Reaction

R. K. Smither, A. I. Namenson, and J. R. Erskine

The angular distribution of the proton groups from $Cd^{113}(d,p)Cd^{114}$ has been measured with the magnetic spectrograph. From these data (Fig. 18), the value of ℓ_n was identified for 24 of the proton groups. In many cases, spin and parity assignments for the levels could be deduced from the combination of these ℓ_n values with the (n,γ) data obtained with the bent-crystal spectrometer. Further analysis is under way to obtain spectroscopic factors for the proton groups.

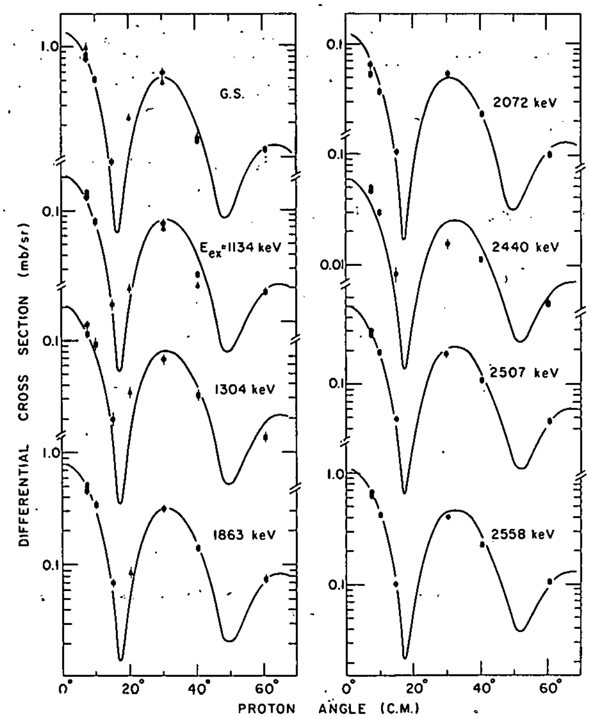

Fig. 18. Angular distribution of the first eight ℓ_n=0 proton groups from the reaction $Cd^{113}(d,p)Cd^{114}$ reaction induced by the 12-MeV deuteron beam from the Argonne Tandem Van de Graaff. The smooth curve in each case results from a DWBA calculation based on the published parameters of C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).

g. $W^{182}(d,p)W^{183}$ Reaction at 12 MeV

R. H. Siemssen and J. R. Erskine

Additional exposures with the spectrograph were taken[1] to obtain improved data on the weak transitions to the ground state of W^{183}. This transition is of particular interest for the study of two-step stripping processes. The angular distributions of the $W^{182}(d,p)W^{183}$ reaction for states up to 450 keV excitation have been compared with DWBA calculations with different distorting potentials, and spectroscopic factors have been extracted. The ratios of the experimental spectroscopic factors agree quite well with those predicted by the Nilsson model, when band mixing is included in the calculation of the theoretical spectroscopic factors. Absolute spectroscopic factors, on the other hand, may disagree by as much as a factor of 2—3.

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[1] R. H. Siemssen and J. R. Erskine, Phys. Rev. 146, 911 (1966).

h. A Study of Actinide Nuclei by Means of Charged-Particle Reactions

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

New data taken with (d,t) reactions have been added to earlier data taken with (d,p) and (d,d') reactions on actinide nuclei. The

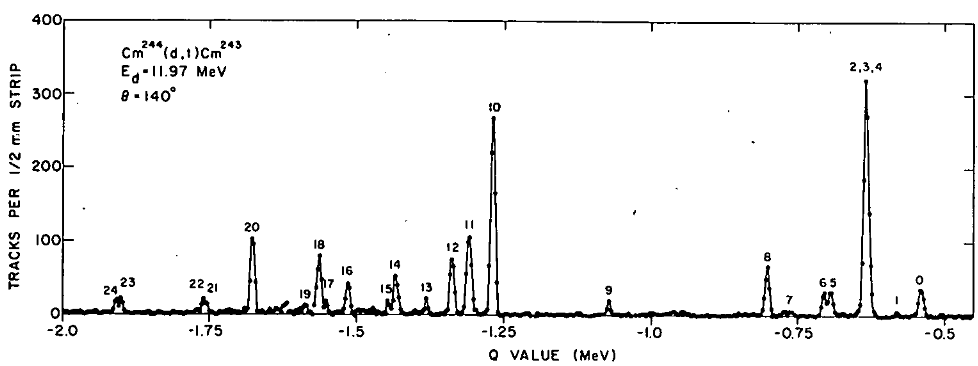

Fig. 19. Triton spectrum from the $Cm^{244}(d,t)Cm^{243}$ reaction. The intensely radioactive target—several micrograms of Cm^{244} ($\tau_{1/2}$ = 18 y) deposited on a self-supporting carbon film—had an activity of about 10^9 alpha particles per second. The triton groups Nos. 0—8 correspond to previously unknown rotational levels built on the $[622]\frac{5}{2}$, $[631]\frac{1}{2}$, and $[624]\frac{7}{2}$ intrinsic states of Cm^{243}.

combination of the (d,p) and (d,t) data enables us to distinguish between particle, hole, and collective excitations. We have been able to identify and label large numbers of intrinsic excitations in odd-A nuclei. The nuclei studied to date are Th^{229}, Th^{231}, Th^{233}; U^{233}, U^{235}, U^{237}, U^{239}; Pu^{239}, Pu^{241}, Pu^{243}; Cm^{243} (Fig. 19), Cm^{245}, and Cm^{247}. A preliminary report has been published[1] and work is continuing.

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[1] T. H. Braid, J. R. Erskine, and A. M. Friedman, Phys. Letters 18, 149 (1965).

6. STUDIES OF ISOBARIC-SPIN ANALOGUE STATES

a. The Study of Isobaric Analogue States in Sc^{49} by Ca^{48} + p Scattering

K. W. Jones,* L. L. Lee, Jr., A. Marinov, and J. P. Schiffer

The states of the nucleus formed by scattering a proton from the doubly-closed-shell nucleus of Ca^{48} have been studied at high excitation energies. The isobaric analogues of low-lying levels in Ca^{49} were thus observed as resonances in the Sc^{49} compound nucleus. The properties of these resonances were subjected to detailed analysis; in particular the energies of the analogue resonances have been used to calculate charge radii in the various Ca isotopes. The final report on this work has been submitted for publication.

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*Brookhaven National Laboratory.

b. (He^3,α) Measurements on Medium-Weight Nuclei

T. H. Braid and L. Meyer-Schützmeister

These continuing measurements employ the magnetic spectrograph and the 13-MeV beam from the Tandem. In collaboration with a group from Rochester, we measured a complete angular distribution for $Co^{59}(He^3,d)Co^{58}$. Measurements have also been made on Sc^{45}. In addition to the analogues of $1f_{7/2}$ states in a number of elements, we see the analogues of $2s_{1/2}$ and $1d_{3/2}$ hole states in such nuclides as Ti^{45} and Ti^{47}. These states in Ti^{45} are more highly excited with respect to the $f_{7/2}$ analogue of the ground state of Sc^{45} than the corresponding states of Sc^{45} are with respect to that ground state, the difference being 50—100 keV. This difference may be mainly due to the different wave functions in the Coulomb field of a uniformly charged sphere; a calculation on this assumption leads to an estimated difference of slightly more than 100 keV.

c. Excitation of Isobaric Analogue States by the (He^3,d) Reaction on Ni Isotopic Targets

G. C. Morrison and J. P. Schiffer

The 18-MeV He^3 beam of the ANL Tandem Van de Graaff is being used in conjunction with the broad-range spectrograph in a high-resolution study of the energy levels of Cu^{59}, Cu^{61}, Cu^{63}, and Cu^{65} by means of the (He^3,d) reaction on separated Ni isotopes. Deuteron energy spectra obtained at several forward angles sufficed to establish whether the stripping reactions to particular energy levels were of $\ell = 1$ or $\ell = 3$ nature. The excitation-energy region corresponding to the expected low-lying analogue states has been studied with particular care. In Cu^{59}, where Blair and Armstrong[1] have identified analogue states, many more strong levels are resolved as shown in Fig. 20. In Cu^{61}, where the

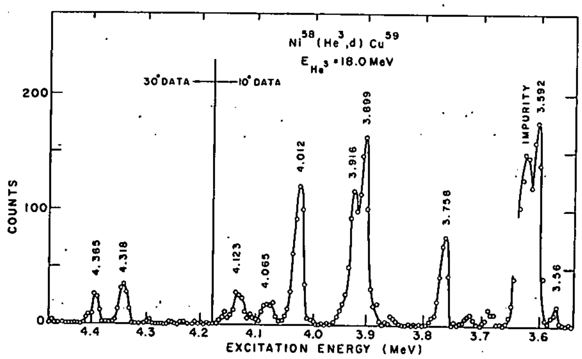

Fig. 20. Composite deuteron spectrum of the $Ni^{58}(He^3,d)Cu^{59}$ reaction in the region of the expected analogue states. Peaks labeled "impurity" were from the C backing or O surface contaminants. The 10° and 30° sections of the spectrum are not normalized to each other.

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[1] A. G. Blair and D. D. Armstrong, Phys. Letters 16, 57 (1965).

ground-state analogue is unbound by 1.68 MeV, only two levels are weakly excited at positions approximate to the expected analogue states. This is in agreement with Ref. 1. In Cu^{63} and Cu^{65}, whose ground-state analogues are unbound by 2.51 and 3.12 MeV, respectively, no levels are observed in the expected region of excitation energy.

d. Isobaric-Analogue States from Proton Scattering on Barium Targets

G. C. Morrison and Z. Vager

The isobaric analogues of some low-lying states in Ba isotopes have been observed as compound-nucleus resonances in elastic and inelastic proton scattering on Ba^{134}, Ba^{135}, Ba^{136}, Ba^{137}, and Ba^{138} targets. Excitation curves for elastic proton scattering at 170° are shown in Fig. 21. The positions of the corresponding resonances in different isotopes are observed to vary systematically as a function of

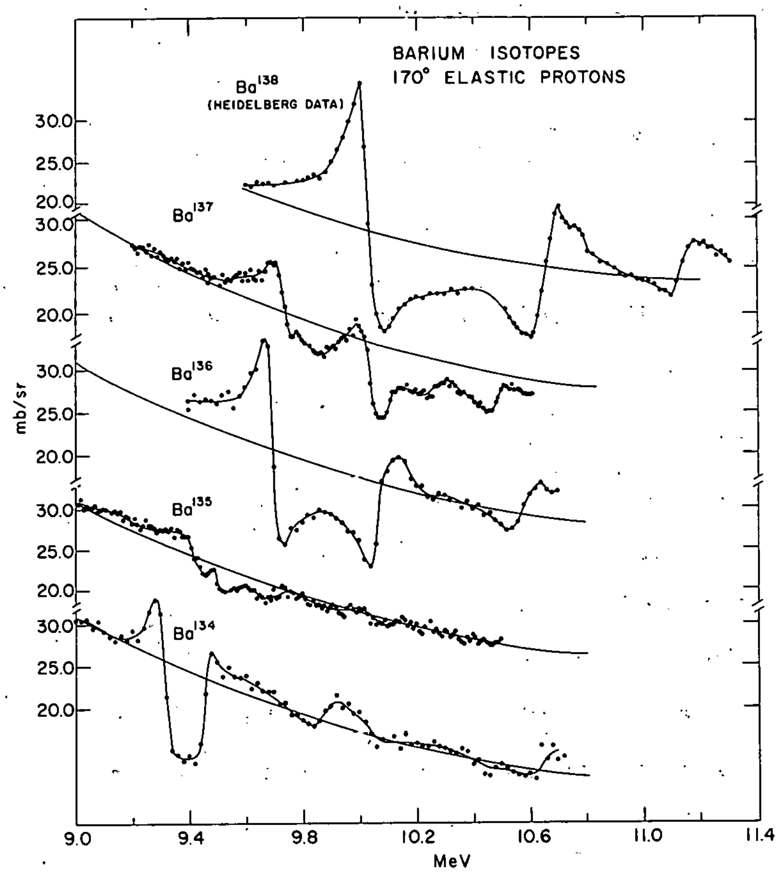

Fig. 21. Cross sections at 170° for elastic proton scattering from Ba isotopes. The three resonances shown for Ba^{138} + p at about 10.0, 10.6, and 11.1 MeV are identified as $f_{7/2}$, $p_{3/2}$, and $p_{3/2}$, respectively. The smooth lines are calculated optical-model cross sections.

energy. For example, the even-A isotopes show a strong $f_{7/2}$ resonance at about 10 MeV. Only for the Ba^{138} target does this correspond to the ground-state analogue.[1] For Ba^{136} and B^{134} targets, the ground-state analogue resonances are predicted and have been observed at energies of about 8.0 MeV. Targets of the odd-A isotopes show composite resonances at about the same incident energy. These can be interpreted as a splitting of the $f_{7/2}$ resonancc coupled to the $\frac{3}{2}^+$ ground states of Ba^{135} and Ba^{137}. Such resonances correspond to states at about 4.0 MeV excitation in the analogue nucleus. At resonances in the even-A isotopes, strong inelastic scattering is observed to the first 2^+ excited states; this scattering increases in intensity as A decreases. Little inelastic scattering is observed at resonances in the odd-A isotopes. These studies are continuing.

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[1] P. von Brentano, N. Marquardt, J. P. Wurm, and S. A. A. Zaidi, Phys. Letters 17, 124 (1965).

7. EFFECTS IN COMPOUND NUCLEI

a. Study of the $K^{39}(p,\alpha)Ar^{36}$ Reaction

D. von Ehrenstein, L. Meyer-Schützmeister, and R. G. Allas

The reaction $K^{39}(p,\alpha)Ar^{36}$ was investigated in the incident-proton energy range 10.0—13.0 MeV in steps of 20 keV and 100 keV at eight angles from 25° to 160°. The excitation functions of the α groups leading to different final states in Ar^{36} exhibit strong fluctuations in forward and backward angles. These fluctuations usually are not correlated. The analysis was made in terms of Ericson's statistical model. The coherence width Γ is around 10—15 keV. There are some indications for nonfluctuating contributions (direct interaction). Tentative spin assignments of the first two excited states in Ar^{36} were suggested on the basis of the (2I + 1) rule. The final report on this has been published.[1]

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[1] D. von Ehrenstein, L. Meyer-Schützmeister, and R. G. Allas, Nucl. Phys. 79, 625 (May 1966).

b. The Scattering of Protons by Ni^{58}

A. J. Elwyn, J. E. Monahan, R. E. Segel, P. P. Singh, and Z. Vager

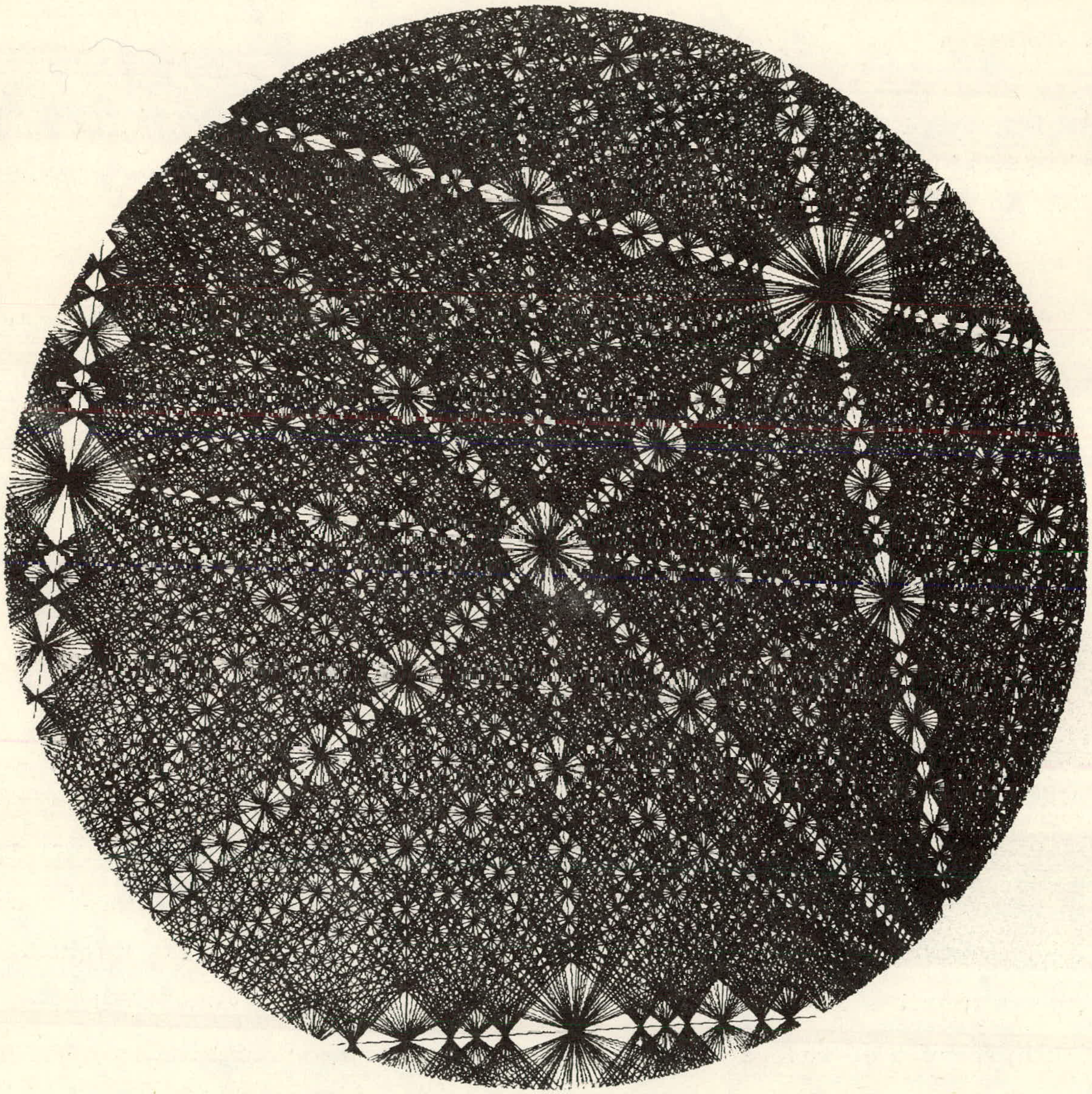
The search for intermediate structure in the $Ni^{58}(p,p')$ data has been continued. A large number of both autocorrelations and cross correlations have been computed for both the differential and the total cross-section data. From these analyses it has become apparent that intermediate structure cannot be found in the data by statistical means.

This result does not bar the presence of intermediate structure, but does rule out the most dramatic kind of structure wherein the cross section is dominated by intermediate structure of a characteristic width. However, there is nothing in the intermediate-structure picture which requires all of the doorway states to be of similar width. Visual examination of the data suggests that some of the large peaks might have the properties of doorway states. The possibility that some of these bumps could be analyzed as single states superimposed upon an optical-model background has been discussed with Stamp and Feshbach of M.I.T. and with Izumo of Illinois. They have undertaken such calculations but have not as yet communicated any definite results to us.

8. BLOCKING EFFECTS IN SINGLE CRYSTALS

D. S. Gemmell and R. E. Holland

We have measured the energy and spatial distributions of charged particles scattered from a highly collimated beam incident on



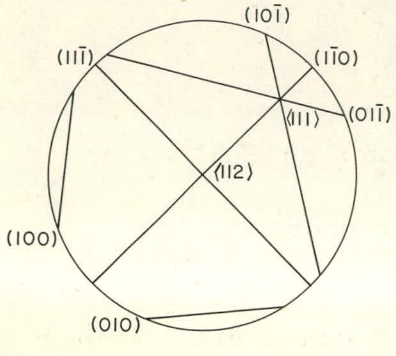


Fig. 22. The result of calculations in connection with experiments on channeling and blocking of charged particles passing through single crystals. Patterns similar to those shown above are observed experimentally, although none as complex as the larger figure have been seen. A line in the figure represents the intersection of a plane in a single crystal with a plane placed perpendicular to the $\langle 112 \rangle$ axis of a cubic crystal. The small figure shows the projection of low-order planes (no index larger than 1). The large figure shows the intersections of all planes with indices of 9 or less.

single crystals of Si, Ge, and MgO. The scattering patterns were observed both with photographic emulsions and with a highly collimated solid-state detector. The detector measurements were highly automated by using on-line computer control of the apparatus. The data show evidence for both channeling[1] and blocking effects.[2] The energy dependence of the angular widths of blocking lines was determined to be closely proportional to $1/\sqrt{E}$, but the absolute magnitude is only about a tenth of that expected from a simple model. Detailed measurements on the orientation dependence, the temperature dependence, etc. of the effects have been made and are continuing. At the same time, many of the effects seen (Fig. 22) have been quantitatively reproduced by detailed computer calculations.

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[1] R. S. Nelson and M. W. Thompson, Phil. Mag. 8, 1677 (1963).

[2] D. S. Gemmell and R. E. Holland, Phys. Rev. Letters 14, 945 (1965).

9. DEVELOPMENT OF INSTRUMENTATION AT THE TANDEM

a. Pulsed-Beam Apparatus

F. J. Lynch

A wide-range time analyzer for measuring lifetimes from 1 μsec to 30 min by use of pulsed-beam techniques has been installed at the Tandem. The beam is directed onto the target for an appropriate period of time and then deflected away electrostatically by means of the post-acceleration deflection plates. Then the address of the analyzer is advanced at a rate of from 1/8 μsec to 8.38 sec per channel. Two-parameter operation is provided so that the energy of the gamma rays can be observed as a function of time after bombardment. Usually a lithium-drifted germanium detector will be used and the data will be stored sequentially on magnetic tape, with the ASI-210 as a buffer, and analyzed later. The data will normally include 1024 channels of energy information and 256 channels of time information. This system complements the previously constructed fast system which employs a time-to-pulse-height converter and beam bursts of <1 nsec duration.

b. Precision Scattering Chamber at the Tandem

J. L. Yntema

The installation of the precision scattering chamber is expected to be completed before 1 August 1966. The scattering chamber will permit remote control of the target angle, distance from detector to target, and the angular positions of the four detector arms and of the target. Work on programmed control of the angular position of the detector arms is in progress.

c. A New Magnetic Spectrograph

J. R. Erskine

In preparation for the projected increase in the energy of the Argonne Tandem, a more advanced type of broad-range magnetic spectrograph (a split-pole spectrograph designed by H. A. Enge[1]) will be purchased. In addition to having the ability to handle particles with energies more than twice the maximum that could be handled by the older spectrograph (e.g., protons with energies up to 95 MeV), this new instrument will be superior in having a larger solid angle of acceptance, higher resolving power, and a broader range of energy acceptance at a given magnetic field.

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[1] H. A. Enge, Nucl. Instr. Methods 28, 119 (1964); H. A. Enge and J. E. Spencer, Rev. Sci. Instr. (to be published).

d. Automatic Plate-Scanning Machine

J. R. Erskine, R. H. Vonderohe,* L. Amiot,* and N. Sobel*

A machine to automatically scan nuclear track plates has become necessary to handle the large quantity of data which can be collected with a broad-range magnetic spectrograph, especially in view of the forthcoming replacement of the present spectrograph with one of the new split-pole type. It appears that such a machine can be made 50—100 times as fast as a human scanner.

The development and construction of the Argonne machine are well advanced; in fact, the machine has been scanning limited areas of test emulsions for some time. The results to date are very encouraging. The interface between the scanning tube and the PDP-7 digital computer exists, and computer programs to do the pattern recognition have been written. The system electronically scans an area of emulsion measuring 0.5 mm $\times$ 11 mm in about 1 sec. The work on both hardware and software is continuing.

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*Applied Mathematics Division, ANL.

e. Construction of the Source of Polarized Ions

D. von Ehrenstein, D. C. Hess, and C. W. Schmidt

During the past year, most major components of the polarized ion source for the Tandem have been finished and various combinations of them are being tested. The dissociator to produce hydrogen atoms from molecules in an rf discharge has been working for several months; its efficiency was recently improved. The 6-pole magnets seem to deliver the expected high field, and in tests of their focusing properties they gave very satisfying real images (Fig. 23) of specially shaped patterns of the atomic-beam source (dissociator). A preliminary version of the ionizer to generate positive ions in a strong magnetic field is working and is being used for the tests.

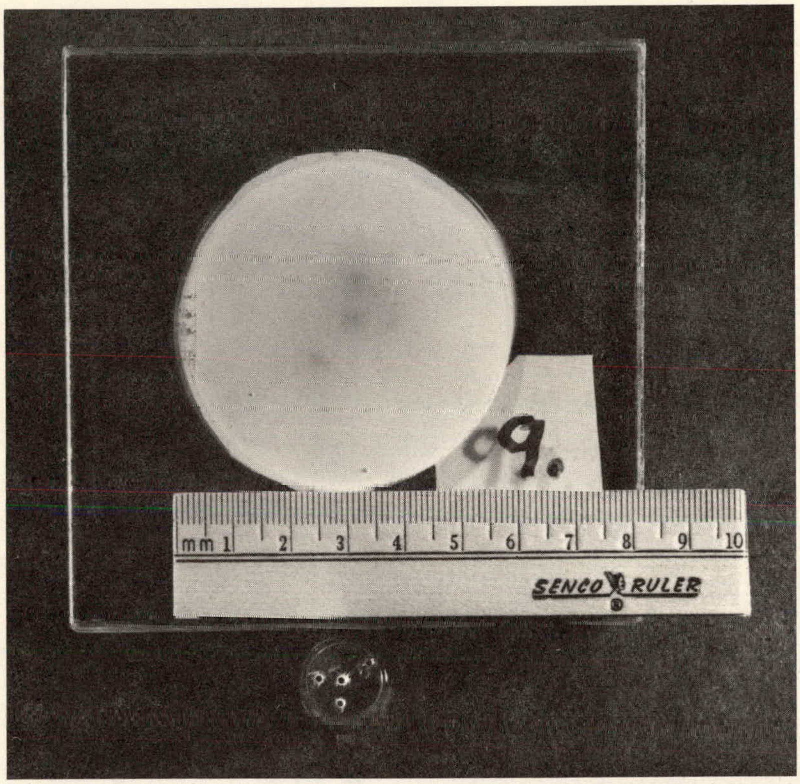

Fig. 23. The real image (shown above the scale) formed when the 6-pole magnet of the polarized ion source focuses the beam of neutral atomic hydrogen from a special beam source (shown below the scale). As usual, the target is coated with yellow molybdenum oxide which is reduced to a blue oxide when struck by atomic hydrogen but not when struck by H_2.

The first attempt to effect the adiabatic-passage transition needed to produce or increase polarization succeeded and gave an efficiency of about 80%. The polarization of the positive ions was successfully tested with the T(d, α)n reaction at around 100 keV. Both the tests of the transition and the polarization with a strong-field ionizer were greatly facilitated by the unique design of our source incorporating two separated 6-pole magnets.[1] None of the operations have been properly optimized yet. The components of the charge exchanger to convert to negative ions for injection into the Tandem are yet to be tested.

We have assisted in the testing of the polarization of the negative-ion source constructed by Dr. B. L. Donnally of Lake Forest College.

European polarized-ion sources were described in Argonne Report ANL-7118.

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[1] D. von Ehrenstein, D. C. Hess, and G. Clausnitzer, Phys. Letters 19, 114 (1965).

10. UNIVERSITY USE OF THE 12-MEV ARGONNE TANDEM

J. P. Schiffer and F. P. Mooring

The program of providing running time on the Argonne Tandem Van de Graaff to scientists from various universities is continuing. During the past year, the outside users have used 16% of the total experimental time available. A list of the outside groups with their starting dates is appended. Projects terminated during the year are marked with asterisks.

a. Multiple Coulomb Excitation and the Reorientation Effect
   (R. P. Scharenberg, Case Institute of Technology and Purdue University, December 1963)

b. Studies of Energy Levels in Light Nuclei with the Magnetic Spectrograph
   (C. P. Browne, Notre Dame University, September 1963)

c. Alpha-Gamma Correlation Studies of the Reaction $C^{12}(O^{16},\alpha)Mg^{24*}$
   (W. W. Eidson, J. G. Cramer, Jr., and R. D. Bent, Indiana University, August 1964)

d. Magnetic Spectrograph Studies of the Reactions (He^3,α) and (He^3,d)
   (W. P. Alford, L. M. Blau, D. Cline, and J. J. Schwartz, University of Rochester, May 1964)

e.* Study of Reaction Cross Sections with Alpha Particles
   (L. Haskin, University of Wisconsin, December 1964)

f.* Short Nuclear Lifetimes by Doppler-Shift Techniques
   (R. D. Bent and P. P. Singh, Indiana University, November 1964)

g.* Investigation of Ca^{49} Isobaric-Analog States in Sc^{49}
   (K. W. Jones, Brookhaven National Laboratory, September 1964)

h.* (d,p) Reactions on Au and Cd
   (C. K. Bockelman, P. D. Barnes, and K. J. Wetzel, Yale University, July 1964)

i.* Inelastic Proton Scattering from Cu and Zn
   (R. R. Johnson, University of Minnesota, April 1965)

j. Study of the Reaction $Ca^{40}(He^{3}, p\gamma)Sc^{42}$

(H. E. Gove and D. Cline, University of Rochester, May 1965)

D. RESEARCH AT THE 60-IN. CYCLOTRON

The 60-in. cyclotron is one of the low-energy accelerators operated by the Chemistry Division. It accelerates α particles to 43.2 MeV, He^3 to 33 MeV, deuterons to 21.6 MeV, and protons to 10.8 MeV. For all four of these projectiles, it can produce external beams at the shutter in excess of 0.1 mA. In addition, it accelerates Li^6 to an energy of 66 MeV with usable external beams of the order of 0.01 μA.

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

A beam-analyzing magnet system was installed and placed in operation in the fall of 1965. The analyzer provides a resolution width of 0.1% or less. To make good use of this analyzed beam, a broad-range magnetic spectrograph is being acquired.

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

1. THE 60-IN. SCATTERING CHAMBER AT THE CYCLOTRON

The 60-in. scattering chamber was moved to tunnel No. 2. Installation of a new vacuum system and work on a cooling system to permit cooling of the detectors to temperatures below -40°C are in progress.

a. (d,t) and (d, He^3) Reactions

J. L. Yntema

The analysis of the (d,t) reaction on the Ca isotopes and the (d, He^3) reaction on Ca^{42}, Ca^{43}, and Ca^{44} has been completed (Fig. 24). A number of $\ell=0$ transitions observed in $Ca^{40}(d,p)Ca^{41}$ at excitation energies of 3.4 MeV and above are only weakly excited in the (d,t) reaction. The second $\frac{3}{2}^-$ state at 2.47 MeV is considerably weaker than would be

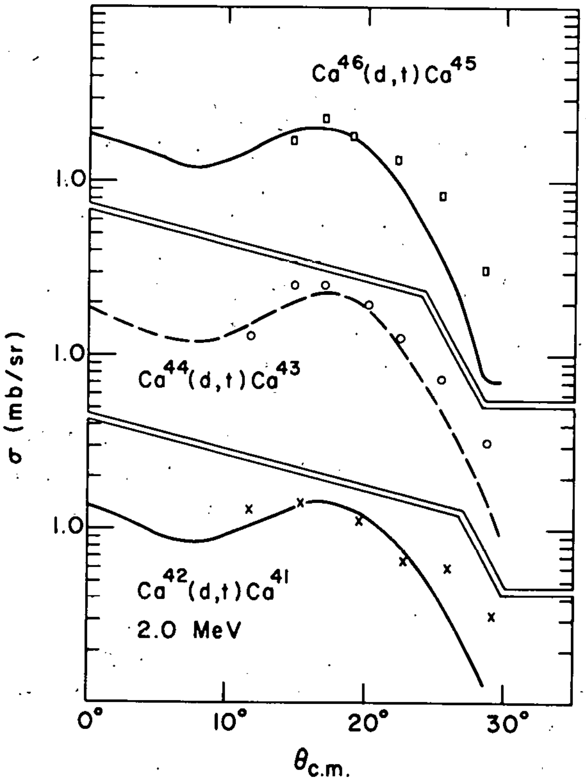

Fig. 24. Transitions to the $2s_{1/2}$ neutron-hole states. In the case of the Ca^{42}(d,t)Ca^{41} reaction, the irregularity of the curve near 27° indicates a contribution from the transition to the first $\frac{3}{2}^-$ state in Ca^{41}.

expected from the (d,p) reaction on Ca^{40}. These results indicate that the structure of Ca^{40} requires a more complicated admixture than a 2-particle 2-hole configuration. In K^{42} the $d_{3/2}$ hole strengths of the three lowest states are in the ratio of 4:7:9 which, if the 2j+1 rule holds, would give spin assignments of 2^-, 3^-, 4^- for the sequence rather than the 2^-, 4^-, 3^- sequence indicated by the energies of the high-energy capture γ rays. Both excited states indicate admixture of $s_{1/2}$ neutron hole configurations. In Ca^{47} a second $s_{1/2}$ neutron hole state was observed about 260 keV above the $\frac{1}{2}^+$ state near 2.6 MeV.

The Mo^{92}(d,t)Mo^{91} reaction is being studied to obtain information on the possibility of seniority mixing in the $g_{9/2}$ shell. The Mo^{92}(d,He^3)Nb^{91} reaction has been investigated to obtain a comparison with a number of theoretical predictions on the proton configuration of Mo^{92} as well as the proton hole spectrum of Nb^{91}.

b. (α, α') Scattering

J. L. Yntema

The inelastic scattering of 43-MeV alpha particles by the Ti isotopes has been studied in more detail. A dozen preferentially excited states in the even-A Ti isotopes were observed and a distorted-wave analysis of the results is in progress in collaboration with G. R. Satchler of Oak Ridge.

c. Transition to the $J^{\pi} = \frac{7}{2}^{+}$ State in Al^{27} from the $Mg^{26}(\alpha,t)$ and the $Mg^{26}(He^3,d)$ Reactions

D. Dehnhard and J. L. Yntema

Angular distributions of tritons from the (α,t) reaction to the ground state and to the $J^{\pi} = \frac{7}{2}^{+}$ state at 2.212 MeV in Al^{27} have been compared with DWBA calculations. The value S(2.212 MeV)/S(g. s.) $\approx$ 0.06 obtained for the relative spectroscopic factor is in contrast with the value of approximately 0.01 which A. G. Blair extracted from his results on the $Mg^{26}(He^3,d)$ reaction at $E(He^3) \doteq 22.0$ MeV. Our preliminary results on the latter reaction at $E(He^3) = 33.0$ MeV yield an upper limit of approximately 0.02, in confirmation of Blair's estimate. The discrepancy between the (α,t) and (He^3,d) reactions, both of which involve transferring a proton to the target, is much larger than the uncertainties in the DWBA calculations.

The wave function of the 2.212-MeV state (which is understood either as a rotational state based on the $\frac{5}{2}^{+}$ ground state or as a state formed by a $1d_{5/2}$ hole coupled to a 2^{+} excited state of Si^{28}) is believed to contain only a very small admixture of $1g_{7/2}$ amplitude. This explains the rather weak transition to this state and suggests that the discrepancy may be due to a multiple excitation process, which would be more probable in the (α,t) than in the (He^3,d) reaction.

d. Single-Nucleon Pickup Reactions on Mg^{26}

D. Dehnhard and J. L. Yntema

The $Mg^{26}(He^3,\alpha)$ reaction was studied at $E(He^3) = 33.0$ MeV (Fig. 25) and 12.0 MeV. Only two states, the ground state and a state at 7.75 MeV (where the isobaric analog of the ground state of Na^{25}

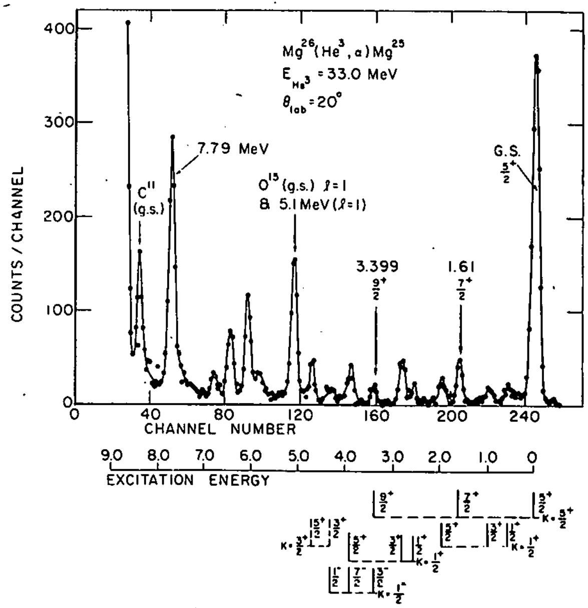

Fig. 25. Spectrum of α-particle energies.

is expected), were found to be strongly excited. The $Mg^{26}(d,t)$ reaction was also investigated at E_d = 21.6 MeV to obtain absolute spectroscopic factors for comparison with the results from the $Mg^{26}(He^3, \alpha)$ reaction. The transitions to the first $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states of Mg^{25} give markedly different angular distributions (Fig. 26). The fact that the cross section for the transition to the $\frac{9}{2}^+$ state is smaller than the one proceeding to the $\frac{7}{2}^+$ state, together with the different angular distribution, indicates that multiple excitation plays an important role in the excitation of these two states.

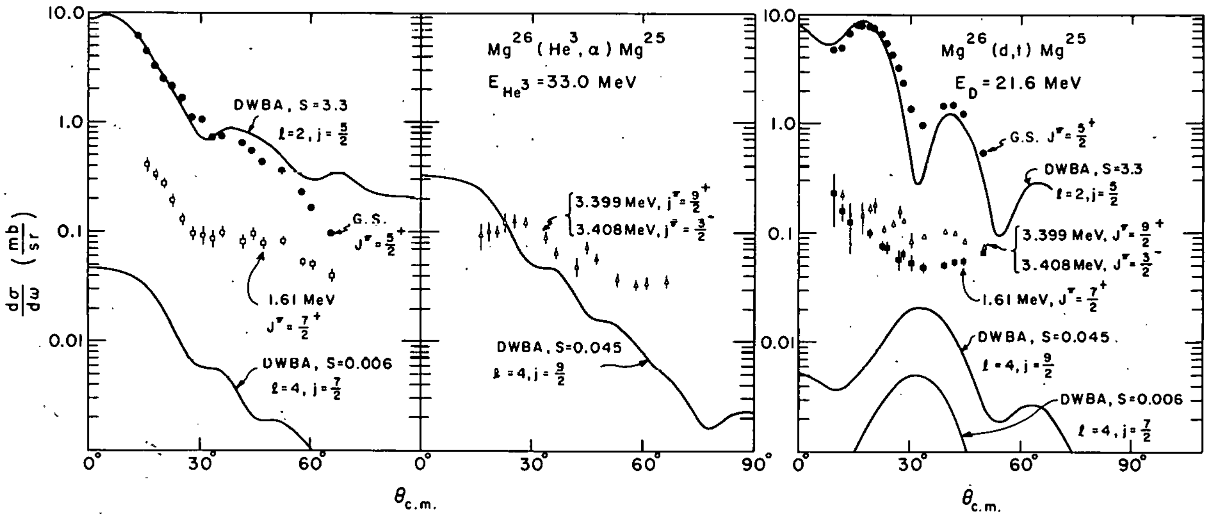

Fig. 26. Experimental and calculated differential cross sections.

e. The $Si^{30}(He^3,\alpha)Si^{29}$ Reaction

D. Dehnhard and J. L. Yntema

To determine the position of the isobaric analogue of the ground state of Al^{29}, we studied the $Si^{30}(He^3,\alpha)$ reaction at $E(He^3) = 33.0$ MeV. A strongly excited state was observed at 8.2 MeV, which is the approximate excitation energy of the analogue state.

f. J Dependence in (α,t) and (α,He^3) Reactions on Mg^{24} and Mg^{26}

D. Dehnhard

Differential cross sections of the (α,t) and (α,He^3) stripping reactions on Mg^{24} and Mg^{26} at an incident energy $E_\alpha = 42.8$ MeV have been measured at forward angles. The angular distributions for $\ell=2$ transitions leaving the final nuclei in $J=\frac{3}{2}$ and $J=\frac{5}{2}$ states show strongly different shapes between 45° and 70°, the $J=\frac{5}{2}$ transition having an additional oscillation that is missing in the $J=\frac{3}{2}$ transition. In contrast to this, previous data on the $Mg^{25}(He^3,\alpha)$ reaction at $E(He^3) = 33.0$ MeV (corresponding to an energy $E_\alpha = 49.8$ MeV for the inverse reaction) show no additional oscillation for the pure $J=\frac{5}{2}$ transition to the ground state of Mg^{24}. The $J=\frac{5}{2}$ distribution at this higher incident energy is thus similar to the $J=\frac{3}{2}$ distribution at $E_\alpha = 42.8$ MeV.

2. ELASTIC SCATTERING OF 33-MEV He^3 ON Mg^{25}

D. Dehnhard

To provide optical-model parameters for DWBA calculations for (He^3,α) and (α,He^3) reactions on Mg isotopes, the angular distributions of the elastically scattered He^3 particles have been measured between $Q = 18°$ and 70°. The search code JIB 3 (F. G. Perey) was used to extract optical-model parameters, which were found to be close to those suggested by R. H. Bassel.

3. K^{47} MASS FROM THE REACTION $Ca^{48}(d,He^3)K^{47}$

E. Newman,* J. C. Hiebert,* and B. Zeidman

The Q value for the reaction $Ca^{48}(d,He^3)K^{47}$ was measured at the Oak Ridge cyclotron to establish the mass of K^{47}. The Q value was found to be -10.304 ± 0.012 MeV, which implies a K^{47} mass excess of -35 707 ± 21 keV (C^{12} = 0). In addition, the first excited state of K^{47} was established at 370 ± 15 keV and is tentatively identified as an s-hole state. A final report has been published.[1]

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*Oak Ridge National Laboratory.

[1] E. Newman, J. C. Hiebert, and B. Zeidman, Phys. Rev. Letters 16, 28 (1966).

4. THE SCATTERING OF 33-MEV He^3 ON THE EVEN-A NICKEL ISOTOPES

R. H. Siemssen, T. H. Braid, D. Dehnhard, and B. Zeidman

In view of the increasing importance of the He^3-induced reactions as a spectroscopic tool, systematic studies of He^3 scattering in terms of the nuclear optical model are of interest. For this investigation, we have chosen the scattering of He^3 from the even-A Ni isotopes. In addition to providing a test of the optical-model description of He^3 scattering, it was hoped that the study of the scattering from different isotopes might yield information on the nuclear symmetry term in the optical potential.

In the experiment, 33-MeV He^3 particles from the Argonne 60-in. cyclotron were scattered from isotopically enriched targets of Ni^{58}, Ni^{60}, Ni^{62}, and Ni^{64}, rolled to a thickness of approximately 1 mg/cm^2. The ability to use a single set of parameters to fit the major differences in the angular distributions from one isotope to another over an angular range in which the differential cross sections vary by four orders of magnitude is a striking success of the optical model of He^3 scattering. Except for Ni^{58}, both the magnitude and the sign of the observed variation in the real potential from one isotope to the other are consistent with the predicted (N - Z) term in the nuclear optical potential. A final report has been published.

5. REACTIONS INDUCED BY 33-MEV He^3 IONS

D. D. Borlin and T. H. Braid

The 18-in. scattering chamber and the 33-MeV analyzed beam from the cyclotron are being used to study (He^3,α) reactions on nuclei in the $1f_{7/2}$ region. States with both $T = T_z$ ("normal" states) and $T = T_z - 1$ (isobaric analogue states) have been observed in Cr^{49} and Sc^{44} in preliminary measurements. The measurements supplement and extend similar measurements made at 13 MeV.

6. STUDIES OF PICKUP REACTIONS

B. Zeidman and T. H. Braid

A magnetic analyzing system has recently been installed on the external beam of the cyclotron. This has enabled us to narrow the experimental resolution width in our (d,He^3) spectra to about 100 keV (limited mainly by target thickness) and therefore to resolve levels which could not previously be seen. For example, the d and s hole states in Fe^{54}(d,He^3)Mn^{53} are clearly resolved, as are a large number of states in Sc^{45}(d,He^3)Ca^{44}. This improved resolution has also been used in measurements on isotopes of Cr, Fe, Co, and Ni. In V^{49}, the $1d_{3/2}$

and $2s_{1/2}$ hole states (in particular) have been found. In addition to its direct value, the information on the positions and strengths of $1d_{3/2}$, $2s_{1/2}$, $1f_{7/2}$, and $2p_{3/2}$ states is useful for comparison with their highly excited isobaric analogues formed by neutron pickup on the same targets.

7. ELASTIC SCATTERING FROM HEAVY ELEMENTS

D. D. Borlin and T. H. Braid

With the magnetically analyzed 33-MeV He^3 beam and the 43-MeV α beam from the cyclotron, we have used the 18-in. scattering chamber to study the angular distributions of helium ions elastically scattered from targets of Au^{197} and U^{238} in the range 10°—100°. The ratio of the cross section to the Rutherford cross section is close to unity up to 50° for He^3 on U^{238}, falls off smoothly (showing practically no structure) until roughly 75°, and then shows several rather flat oscillations up to 100°. The data are being analyzed to find the optical-model parameters that will fit the measurements. Such parameters are needed because of the current Argonne work on heavy-element reactions. Very little information is available at the present time.

8. DELAYED PROTONS

T. H. Braid, D. D. Borlin, and A. M. Friedman*

A superconducting solenoid (designed to remove the background due to electrons and positrons) has been constructed and tested. It will supply a maximum field of 30 kG at the center of an 8-cm-diameter tube at room temperature. The final apparatus needed to make use of this magnet in the measurements is under construction.

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*Chemistry Division.

9. ANALYZING MAGNETS FOR THE 60-IN. CYCLOTRON

J. J. Livingood, W. J. Ramler,* G. W. Parker,* R. Benaroya,* J. Aron,* M. C. Oselka,* F. Cilyo,† P. J. Basnar,‡ and T. E. Sterling‡

The ~1% energy spread of particles from the 60-in. cyclotron has become increasingly detrimental to the sophisticated experiments now being performed. Hence, it was decided to design

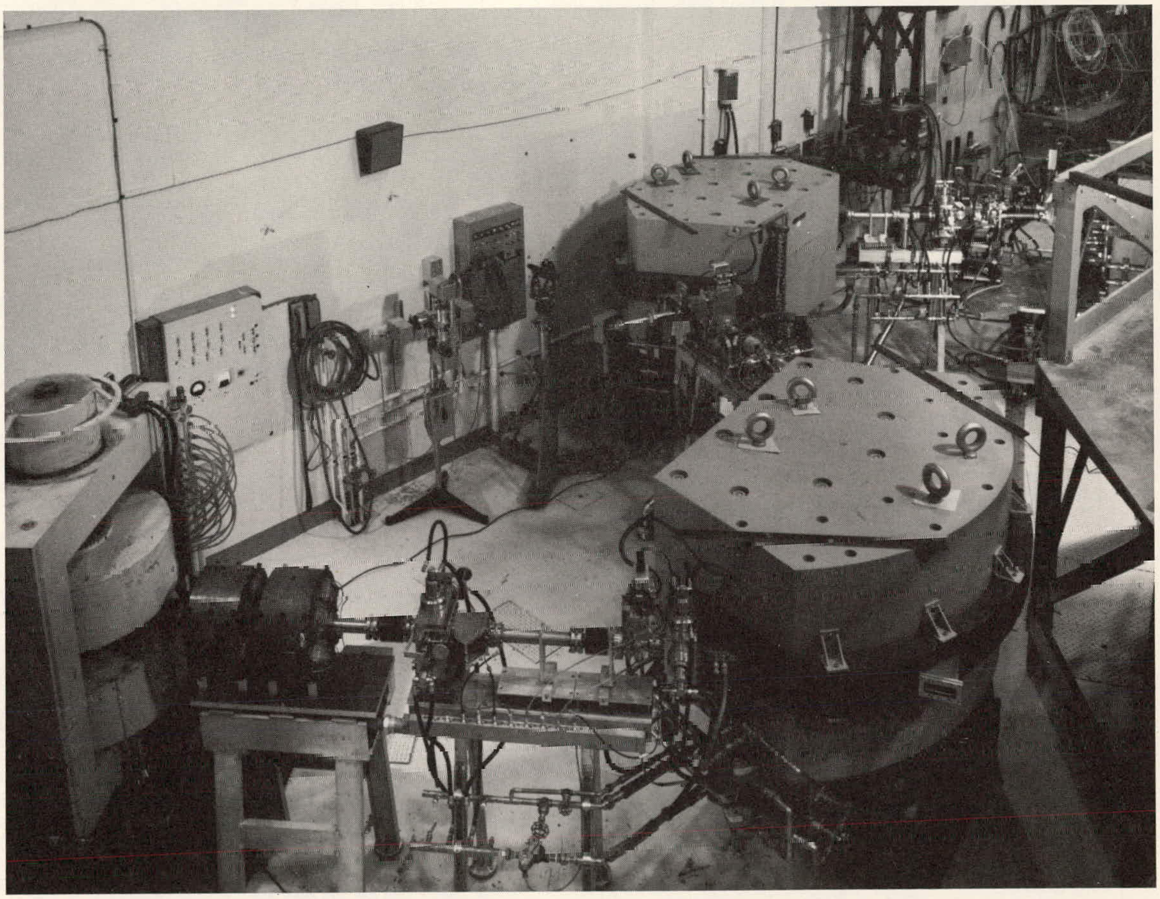

Fig. 27. The two 120° analyzing magnets at the 60-in. cyclotron. The switching magnet (far left) directs the analyzed beam to any one of three stations in the target room.

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*Chemistry Division, ANL.

†Electronics Division, ANL.

‡Central Shops, ANL.

analyzing magnets subject to the constraints imposed by the direction of the extracted beam, the available floor space, and the location of the final target area. Design calculations indicated that two uniform-field 120° magnets, which bent the beam on arcs of 40-in. radius in opposite directions and whose edge angles supplied the vertical focusing, should give a combined first-order energy spread of 0.075% (full width at half maximum) when used at unity magnification with 3-mm slits. Uncorrectable aberrations were expected to deteriorate this figure somewhat.

The magnets (Fig. 27) and power supplies built by Spectromagnetic Industries gave an energy spread within the guaranteed 0.1% (FWHM). The installation and testing of the complete system and of the components has been completed.

10. PROPOSED CONVERSION OF THE 60-IN. CYCLOTRON

J. J. Livingood, W. J. Ramler,* T. K. Khoe,† R. Benaroya,* and K. W. Johnson*

A design study has shown that the Argonne fixed-frequency 60-in. cyclotron can be converted into a 71-in. variable-energy cyclotron of excellent quality. The present 60-in. cyclotron, now 14 years old, is of the "classical" variety and is capable of producing only 10.8-MeV H^+, 21.6-MeV D^+, 34.5-MeV $^3He^{2+}$, and 43.2-MeV $^4He^{2+}$. Energy variation, now so much in demand by the users, is possible only by employing energy-degrading foils, which reduce the intensity and increase the energy spread of the beam. The projected conversion will increase the pole-tip diameter to 71 in. and will introduce sector-focusing to raise

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*Chemistry Division, ANL.

†Particle Accelerator Division, ANL.

the energy and permit energy variation downward from maxima of 60-MeV H^+, 36-MeV D^+, 93-MeV $^3He^{2+}$, 72-MeV $^4He^{2+}$, and 126-MeV $^{14}N^{5+}$.

Components which can be retained from the 60-in. machine are the magnet yoke, pole bases, and the main exciting coils and their power supply; the power supplies for the radio-frequency system, the deflector, and the ion source; the vacuum pumps, the cooling system, and most of the control and power circuitry; the beam-transport and energy-analyzing system; the present cyclotron vault, the two target rooms, and the existing shielding.

Major components that must be designed and constructed include the spiral pole tips; the auxiliary magnet coils and their power supplies; the dee and tuning system with their vacuum envelopes and a new oscillator-amplifier complex; a new deflector system with additional power supplies; a new ion source; an additional vacuum pump; and further control and power wiring.

Necessary development work, prior to final design, will involve magnet studies (which can be carried out on a modification of an existing model magnet) and the construction of a scaled plywood-and-sheet-copper model of the dee and tuning system. Most of the design and construction of final components can be accomplished with the 60-in. machine still in operation. The shutdown period to effect the conversion is estimated at 10—12 months.

Major Parameters

Magnet: 71-in. diameter; 4 sectors with 60° maximum spiral angle and valley gap of 15.85 in.; hill gap varying from 10 to 9.08 in. Maximum orbit radius = 29.5 in.

Dee: Single, 180°, at 150 kV, with aperture varying from 2 to 1 in. Frequency variable from 7.51 to 22.54 Mc/sec by means of a coaxial tuner.

11. A REVIEW OF DISPERSIVE AND ACHROMATIC PASSAGE OF CHARGED PARTICLES THROUGH ONE, TWO, OR THREE MAGNETS

J. J. Livingood

This review, which is being prepared as an ANL topical report, presents a single unified approach to the various uses of bending magnets and expresses the results in equations and curves which may be applied readily when a magnet system is to be designed. (1) First-order matrix coefficients of radial displacement are computed and tabulated for the passage through three magnets with field indices between 0 and +1 and with arbitrary edge angles. Simple procedures are given to convert these to axial coefficients, and the double-focusing conditions are derived. (2) The expressions for resolution, magnifications, and object and image distances are given for a variety of single magnets, with graphs for representative bending angles. (3) The dispersion and resolution of a chain of magnets are considered, with bends in one or the other direction. (4) Phase-space-ellipse methods are used to compute radial and axial beam envelopes, with tabulation of the ellipse coefficients through three magnets. The basic relations between ellipse and displacement coefficients are developed. (5) Chromatic aberrations and achromatic arrays are considered. The distinction is drawn between systems in which both the slope and the image are achromatic and those in which only the image is nondispersive. (6) The concepts of emittance and of the effective edge of a magnet are developed. (7) Methods for eliminating one of the most serious aberrations are quoted without proof. And (8) a limited Bibliography is included.

E. OTHER NUCLEAR EXPERIMENTS

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

1. LEVELS POPULATED BY BETA DECAY

The activities studied were produced at the Argonne 60-in. cyclotron. A versatile counting system, in which as many as eight digital coincidence gates were employed in conjunction with an 800-channel pulse-height analyzer, was used to record gamma-gamma coincidences. One member of the coincidence system employed a Li-drifted Ge-diode gamma-ray detector, while the second member was either another Ge detector or a 3 × 3-in. NaI(Tl) scintillator, as dictated by the complexity of the experimental situation. The internal-conversion-electron spectra and positron spectra were studied with the Argonne toroidal-field electron spectrometer.

a. Level Structure in Cr^{52} Populated in the 5.7-day Decay of Mn^{52}

H. H. Bolotin, M. S. Freedman,* F. T. Porter,* and F. Wagner*

The level structure of Cr^{52} below an excitation energy of 4 MeV has been viewed in terms of the complex of seniority-labeled shell-model states, representing the recoupling of two and four $f_{7/2}$ protons. Several questionable facets of previously reported investigations led to a re-examination of this decay. The complex gamma-ray spectrum required the use of high-resolution Ge detectors. When the internal-conversion coefficients obtained were coupled with the measured gamma-ray

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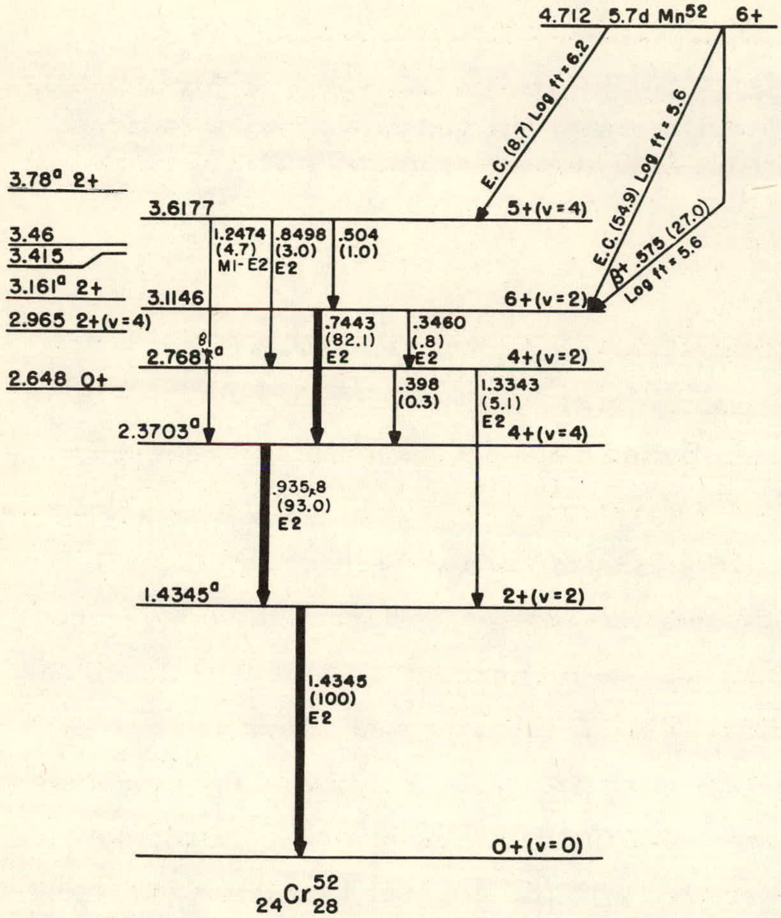

Fig. 28. Proposed decay scheme of Mn^{52}. All levels shown, including those at the left, are seen in (p, p') and (p, α) reactions; those labeled a are seen in (α, α') scattering.

intensities, a revised and simplified decay scheme (Fig. 28) resulted. The level structure of Cr^{52}, as determined from this completed investigation, has been interpreted in terms of states with seniorities 2 and 4. The branching ratios for the decay of several interesting levels have been examined within this framework.

b. Levels in Fe^{55} from the β^+ Decay of Co^{55}

H. H. Bolotin, H. Fischbeck, M. S. Freedman,* F. T. Porter,* and F. Wagner*

The low-lying excited states of Fe^{55} are expected to reflect the interesting coupling between extra-core nucleons and phonon states of the even-even nuclear core. Since previous experimental

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*Chemistry Division, ANL.

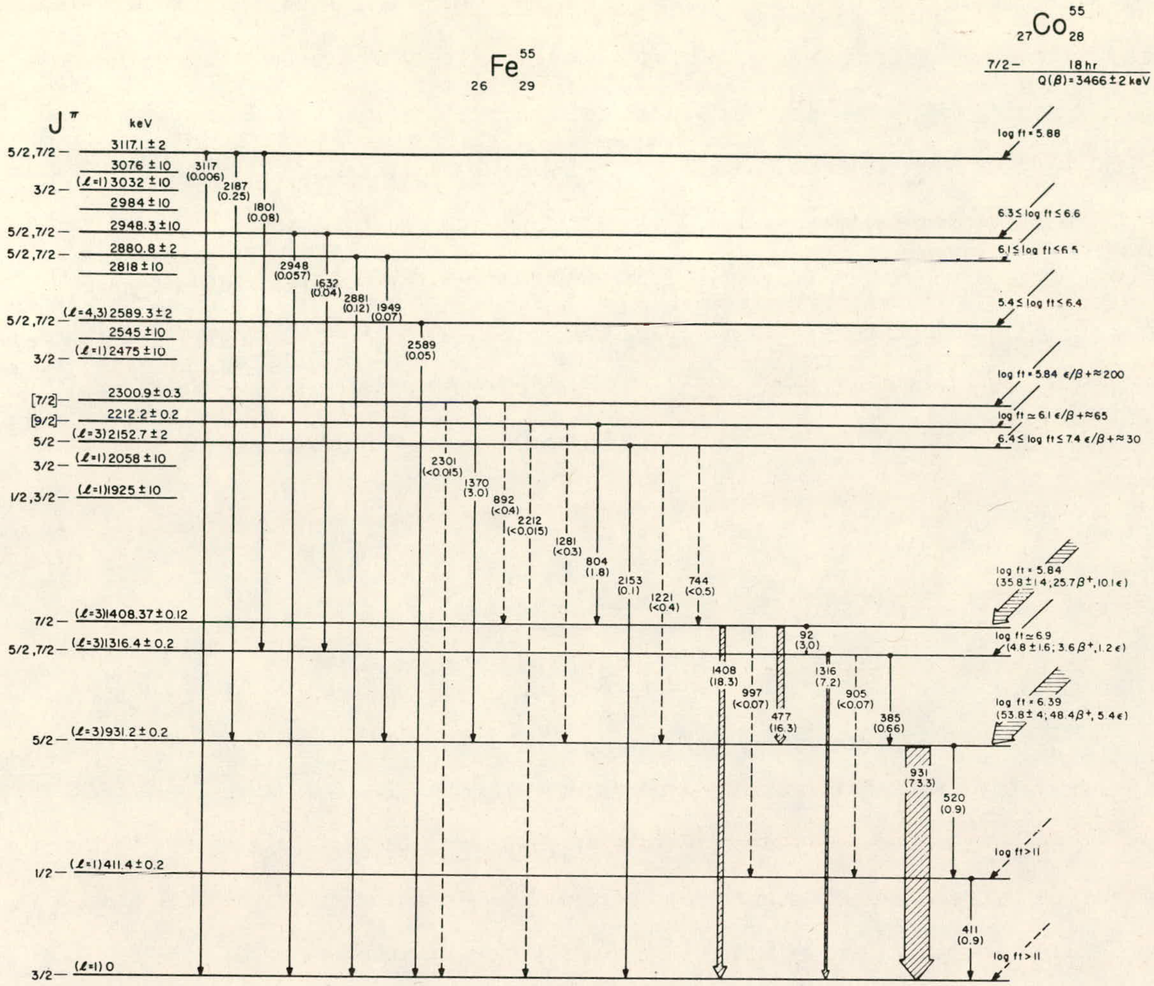

Fig. 29. Decay scheme of Co^{55} and energy levels in Fe^{55}. The energy given at the left is taken from the decay information if the level is populated in the decay, from nuclear-reaction data otherwise. The spin and parity assignments are based on a variety of data. For the 2212.2- and 2300.9-keV levels, the selected spins (shown in brackets) are based on arguments from the intensities of the gamma rays depopulating the states and should be viewed as tentative. The ℓ value is the orbital angular momentum of the transferred nucleon in (d, p) and (p, d) excitations. Numbers in parentheses are intensities in per-cent per decay. The beta feed intensities are derived from the gamma intensity balances. The total electron capture ϵ and the positron partition are theoretical. Transitions indicated by dashed lines were not observed; upper limits for their intensities are given. The ranges of log ft values given for some of the levels indicate that the sum of the upper limits for the missing transitions is significant in comparison with the observed transition intensities.

studies of the highly complex decay of Co^{55} were incomplete and sometimes mutually inconsistent, we undertook a thorough study involving γ-γ coincidences, internal-conversion coefficients, and the positron groups populating the lowest levels in Fe^{55}. Levels up to an excitation energy of 3.116 MeV were observed. The revised decay scheme (Fig. 29) and level parameters disagree with earlier reports in several important particulars. The decay is shown to populate only those states that are excited in charged-particle reactions. Since the initial report of this work, at least two theoretical efforts to explain the observed level structure have been initiated.

c. The Decay of Cu^{61}

H. J. Fischbeck and H. H. Bolotin

The low-lying levels in Ni^{61}—populated in the Cu^{61} decay—are of considerable theoretical interest since the Ni^{61} nucleus with 28 protons and 33 neutrons is tractable to shell-model calculations. However, several serious discrepancies were found when the experimental data available from nuclear-reaction studies were compared with the spectroscopic information from the Cu^{61} decay. The 3.3-h β^+ decay of Cu^{61} has therefore been reinvestigated with the aid of high-resolution Ge detectors and Ge-Ge coincidence techniques. The Cu^{61} activity was produced by an (α, 2n) reaction on Co^{59}. The sources were prepared by separating the Cu from the Co target either chemically or by use of the Argonne isotope separator.

In addition to the previously observed eight γ lines, nine new γ rays were observed. A level at 910 keV, which had been observed in (d, p) reactions, was found to be populated by β decay. Ge-Ge coincidence studies revealed that the corresponding 910-keV γ ray is indeed a ground-state transition and not, as was previously assumed, a stop-over transition from the 1186-keV level. Although the energy difference between Ni^{61}

and Cu^{61} is 2.23 MeV, no levels above 1186 keV had been observed in the earlier investigations. We have, however, identified 1.46-, 1.61-, and 1.73-MeV gamma rays corresponding to levels in Ni^{61} observed in (d, p) reactions. With the information gathered in this investigation, it becomes possible to construct a decay scheme which is in excellent agreement with nuclear-reaction data.

d. Ga^{66} Levels Populated by the Decay of 2.4-h Ga^{66}

H. H. Bolotin

The doublet at 182 and 189 keV (previously reported from this research) has been observed in coincidence spectra obtained by use of two Ge(Li) detectors, and each member of this doublet has been assigned in the decay scheme. These γ rays are not in coincidence with each other, a result which could not be established by the use of NaI(Tl) detectors. The internal-conversion-electron spectrum has been measured with the Argonne six-gap "orange" spectrometer. The internal-conversion coefficients coupled with the existing Ge(Li) coincidence data are expected to establish the spins and parities of most of the levels populated in the decay to the odd-odd Ga daughter.

2. ARGONNE SIX-GAP BETA-RAY SPECTROMETER

G. T. Wood and H. H. Bolotin

The six-gap (Copenhagen "orange" type) beta-ray spectrometer is being developed for conversion-electron and electron-gamma coincidence spectroscopy of radioactive nuclei. Because of the high transmission of the instrument, it is also particularly suitable for the study of electron-conversion spectroscopy following nuclear reactions. Beam ports in the vacuum chamber permit connection to the ANL tandem accelerator. The basic spectrometer (consisting of the iron pole pieces and yokes) and the vacuum chamber were purchased from the University of Pennsylvania and brought to ANL in September 1965. It has now been mechanically aligned, the vacuum system has been improved, source and detector assemblies have been constructed, the electronic system has been installed, and some of the performance has been tested. The spectrometer now operates manually, and the electronic circuitry for automatic programming is under construction.

The first nuclide studied was Ge^{66}, whose decay is also being investigated by gamma-gamma coincidence measurements.

3. MAGNETIC PERTURBATION OF γ-γ ANGULAR CORRELATIONS

G. T. Wood and C. F. Dam

The gamma-gamma angular-correlation system recently completed by S. B. Burson is being used to study the magnetic perturbation of the gamma-gamma correlations from radioactive nuclei incorporated as dilute impurities in Fe (or Co or Ni) hosts. Large internal magnetic fields have been reported at the nuclei of such impurities, and are qualitatively explained by the mechanism of polarization of the conduction electrons. These internal fields, which are aligned by magnetizing the Fe host, may be studied by the angular-correlation method and possibly may be usable as a tool in the determination of the magnetic moments of short-lived nuclear excited states. Initial measurements involve Te^{127m} imbedded in an iron foil by the Argonne isotope separator.

4. PATTERN RECOGNITION FOR NUCLEAR EVENTS

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

The mechanization of the procedure for identifying 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.

By use of the special processing unit DAPHNIS, completed in 1964, the speed of the computing involved has been greatly increased. In the past year it has been shown that a first-level association layer which works well with one set of learning patterns is apt to work well with others, but it has also been found that what is learned is more dependent on the learning set than on the first-level associators. The optimum size of learning set has been found to be around 500 patterns. Some critical tests of the general strategy should be completed soon.

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*Applied Mathematics Division, ANL.

5. MICROSCOPIC LOCATION OF O^{17}, O^{18}, AND N^{15}

G. R. Ringo and J. P. Schiffer

Biologists have expressed the desire for a technique by which the tracer isotopes O^{17}, O^{18}, and N^{15} could be located (possibly simultaneously) within a resolution diameter of 1 micron or better. It is proposed to do this by sweeping a proton beam about 1μ in diameter over a thin specimen of interest and using a semiconductor counter to detect the alpha particles from (p, α) reactions on the three isotopes mentioned.

The past year has been spent on such engineering details as getting a proton beam of 1-micron diameter—a project which is not yet successful. Since no protons of over 2 MeV will be needed in this work, the microscope is now being set up at the 2-MeV Van de Graaff where there is a considerable gain in scheduling freedom as compared with the 4.0-MeV machine where the work has been done hitherto.

6. MUONIC x RAYS

R. E. Coté, R. Guso, J. P. Marion, W. V. Prestwich, F. R. Taraba, R. A. Carrigan, A. Gaigalas, R. B. Sutton, S. Raboy, and C. C. Trail

The study of muonic x rays has continued at the synchrocyclotron at the Carnegie Institute of Technology, where a lithium-drifted germanium gamma-ray spectrometer is used at the muon channel. The primary goal has been to measure and analyze the effects of nuclear-quadrupole hyperfine structure in muonic atoms with highly deformed nuclei. However, since the experimental arrangement was more easily optimized for more simple spectra, several nearly spherical nuclei were studied first. The nuclides for which portions of the muonic x-ray spectra should be 175 Lu REu

were observed were $Ag^{107,109}$, In^{115}, I^{127}, Cs^{133}, La^{139}, Pr^{141}, $Ce^{140,142}$, $Eu^{151,153}$, Tb^{159}, Ho^{165}, Tm^{169}, La^{175}, Ta^{181}, $Re^{185,187}$, Au^{197}, natural Pb, Bi^{209}, Th^{232}, $U^{235,238}$, and Pu^{239}. These spectra showed several examples of gamma rays emitted after muon capture, higher order K transitions, and full K, L, M, N, O, and P x-ray spectra.[1] The data[2] on Au^{197} led to the first observation of the quadrupole splitting of the $2p_{3/2} \rightarrow 1s_{1/2}$ transition in this nuclide and were qualitatively in agreement with the spectrum predicted by Wheeler. A similar (though smaller) splitting was observed in Bi^{209}, whose spectrum shows a general line broadening due to the rather large magnetic dipole-dipole interaction.

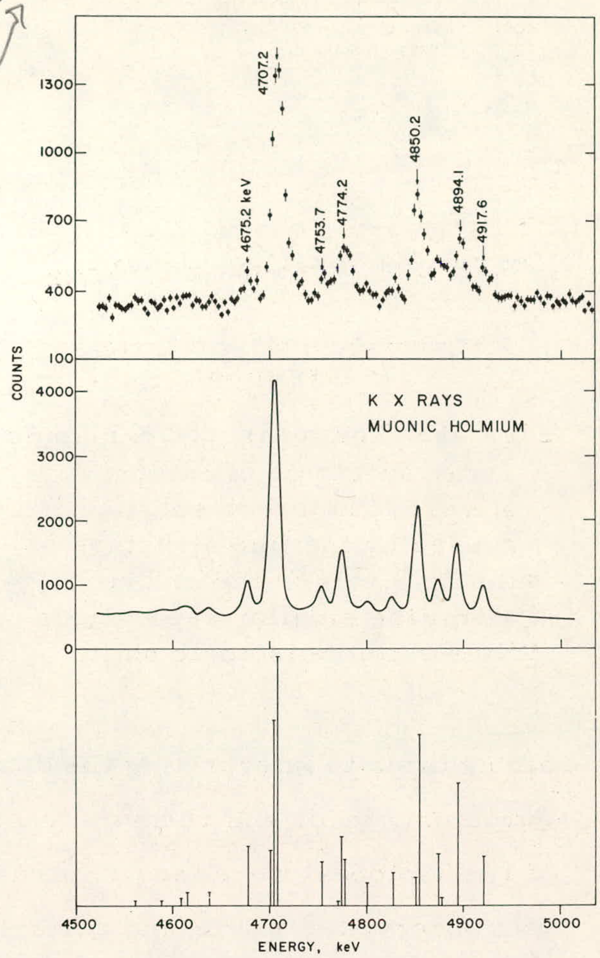

Fig. 30. The K muonic x-ray spectrum of Ho^{165}. Bottom: computed spectrum based on the first three excited states of Ho^{165}. Center: same computed spectrum with the line shape folded in. Top: measured spectrum.

The dramatic static and dynamic quadrupole effects in the highly deformed nuclides (e.g., Ho^{165} and Th^{232}) were shown in great detail. The spectrum of K x rays from Ho^{165} is shown in Fig. 30.

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[1] R. E. Coté, W. V. Prestwich, S. Raboy, C. C. Trail, R. A. Carrigan, Jr., A. Gaigalas, and R. B. Sutton, Proceedings of the Williamsburg Conference on Intermediate Energy Physics, February 10—12, 1966, edited by H. O. Funsten (The College of William and Mary, Williamsburg, Virginia, 1966), Vol. I, p. 51.

[2] R. E. Coté, R. Guso, S. Raboy, R. A. Carrigan, Jr., A. Gaigalas, R. B. Sutton, and C. C. Trail, Phys. Letters 19, 18 (1966).

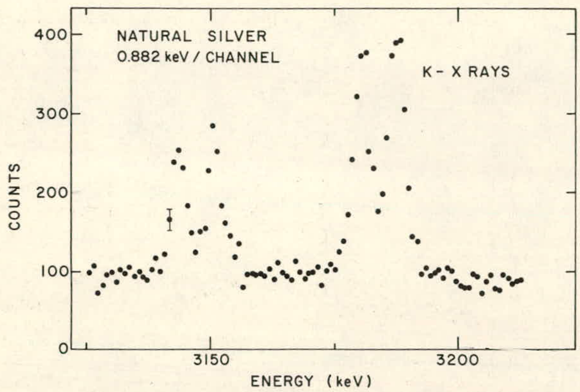

Fig. 31. The measured K muonic x-ray spectrum of natural silver. The broad splitting is caused by the fine structure of the 2p levels in the muonic atom; the smaller separations illustrate the isotopic shift.

These spectra are excellently described by the theory of Wilets and Jacobsohn. A computer program written to analyze these data is based on this theory, and in addition it takes account of the finite size of the nucleus and of vacuum-polarization effects on the potential used in solving the Dirac equation for the muon in the field of the nucleus.

Although the studies were mostly confined to mono-isotopic elements (to avoid ambiguities in interpreting the data), the elements silver, cerium, europium, lead, and rhenium (each of which consists almost exclusively of two isotopes) were investigated for special reasons. The isotope shift was observed in silver and cerium, although it had previously been measured only in separated isotopes. The spectrum of K x rays from silver is shown in Fig. 31. The results on lead were inconsistent with the intensity ratio $I(K_\alpha)/I(K_\beta) = 2$ that follows from the assumption of purely statistical populations for the $2p_{3/2}$ and $2p_{1/2}$ levels.

The continuing effort will place more emphasis on the lighter elements and on a more detailed study of the L x rays of the heavier nuclides. Improved apparatus and techniques (such as preamplifiers with the new cooled field-effect transistors, and the use of larger germanium diodes and pulse-shape discrimination) should materially increase the resolution and the statistical quality of the data.

II. THEORETICAL PHYSICS

INTRODUCTION

The theoretical group consists of permanent staff and long- and short-term visitors. Over the past two years, a post-doctoral training program in nuclear theory has been initiated. At the present time, the group includes four young nuclear theorists in their post-doctoral years.

The largest theoretical effort goes into studies of nuclear structure and reactions. There is a major program which directs itself to the nuclear matter problem. Research is also carried out in the areas of statistical mechanics, applied mathematics, elementary-particle theory, quantum field theory, and superconductivity theory.

Activities of the group include several regular seminars. The general theoretical physics seminar draws in theorists from other divisions at Argonne and from nearby universities. The nuclear physics seminar is shared with experimental physicists at Argonne and with physicists from the University of Chicago and from Northwestern University. These formal programs are supplemented by a variety of informal contacts with the above-mentioned groups, with many research collaborations. Members of the Argonne Theoretical Group also offer occasional courses at neighboring universities.

The theoretical group continues to attract large numbers of well-qualified applicants for temporary and permanent positions. Only a small number of these can be accepted for stays of a year or more. An active summer program makes it possible to accommodate others on a short-term basis. These are supported by Argonne National Laboratory, by Associated Midwest Universities, and by various outside agencies.

1. THEORETICAL NUCLEAR SPECTROSCOPY

S. Cohen, D. Kurath, R. D. Lawson, M. H. Macfarlane, S. P. Pandya, M. Soga, and J. M. Soper

The system of programs for doing shell-model calculations has been rewritten so that the energy calculations as now carried out include a named-storage feature which facilitates the handling of the large blocks of information involved. It is also now possible to extract coefficients of fractional parentage which are of interest for nuclear-transfer reactions. These programs have been used extensively during the past year. Some of the problems are discussed in the following items.

a. 1p-Shell Nuclei

S. Cohen and D. Kurath

It was apparent in an earlier survey of the 1p-shell nuclei that electromagnetic transitions and beta decay provide sensitive tests of the shell-model wave functions. Additional information is obtained by comparison with single-particle-transfer reactions, which relate states in adjacent nuclei.

There is a large amount of experimental information about transitions in B^{10}, so correlation of the model calculations with observation was used to place rather stringent conditions on the wave functions. Values for E2 transitions were also extracted, and the comparison of strong observed E2 transitions with calculated values is quite encouraging.

The coefficients of fractional parentage were extracted for comparison with the transfer reactions. Here the experimental results relating the Be^9 ground state to states of B^{10} confirmed the nature of the B^{10} states deduced from the gamma-decay comparison. There is also good agreement with strengths observed in (p, d) reactions on various 1p-shell targets under bombardment with 150-MeV protons at Orsay.

b. Projection from Nilsson Orbitals

D. Kurath

The technique of projection from Nilsson orbitals was applied to two problems. One concerns the effect on the magnetic octupole moments, measured recently in elastic electron scattering on 1p-shell nuclei at Stanford. Here the effect of extending the basis states by projection is to produce either enhancement or suppression factors for the M3 moment, depending on the nucleus in question. There is some evidence for the need of such factors to reproduce the experimental evidence.

The second problem concerns the probability of exciting states in one-particle-transfer reactions when such an excitation is not theoretically possible within the basic configuration. Again the projection technique extends the basis, and seems to show a marked difference between the two cases wherein a $J = \ell \pm \frac{1}{2}$ level is produced in a reaction on an even-even nucleus. The small amount of experimental evidence does not show such a difference, so the mechanism of excitation is presumably more complicated than the simple single-nucleon transfer. This interesting point warrants more detailed study.

c. Nickel Isotopes

S. Cohen, R. D. Lawson, M. H. Macfarlane, S. P. Pandya, and M. Soga

The low-lying states of the nickel isotopes are assumed to arise from putting neutrons in the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ single-particle states. An excellent fit to the spectra (Fig. 32) was obtained by assuming that the residual two-body interaction can be characterized by an eight-parameter potential—i.e., a conventional central singlet, a central triplet, a tensor and a two-body spin-orbit force, and four additional parameters which characterize the interaction when the two interacting particles are in relative s states. In addition, by endowing the neutron with an effective charge of 1.7 e many of the E2 properties are properly predicted.

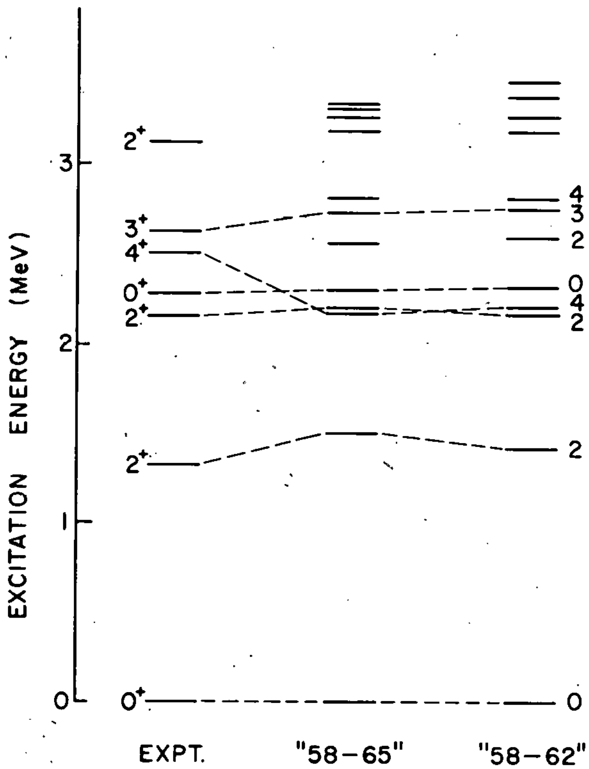

Fig. 32. Spectrum of Ni^{60}. The experimentally observed spectrum together with the spins of the states is shown on the left. All states below 3 MeV except the 3^+ state were included in the data fitting. The set of results obtained when all the nickel data are considered is labeled "58—65." The theoretical level scheme that results when only the data in Ni^{58}, Ni^{59}, Ni^{60}, Ni^{61}, and Ni^{62} are fitted is designated by "58—62."

However, the magnetic moments of the low-lying states are badly reproduced by the theory. Further, the stripping strength is almost entirely concentrated in the lowest state of each angular momentum. This latter result, which is characteristic of all shell-model calculations that have been performed to date, is at complete variance with experiment and clearly illustrates the limitation of shell-model calculations made with such truncated Hilbert spaces.

d. Measurement of $d_{3/2}$ Core Excitation in Ca^{45} from Beta Decay[1]

S. Cohen and R. D. Lawson

The beta decay of Ca^{45} to the $\frac{3}{2}^+$ hole state in Sc^{45} can proceed only if the $d_{3/2}$ shell is not filled in the ground state of Ca^{45}. The log f_1t for this unique-first-forbidden transition has recently been measured at Argonne.[2] The beta-decay matrix element connecting the

[1] S. Cohen and R. D. Lawson, Phys. Letters 17, 299 (1965).

[2] M. S. Freedman, F. T. Porter, and F. Wagner, Jr., Phys. Rev. 140, B563 (1965).

$d_{3/2}$ and $f_{7/2}$ single-particle states can be taken from the ${}_{17}Cl^{38}_{21} \rightarrow {}_{18}A^{38}_{20}$ decay. From this in combination with the measured log f_1t for the Ca^{45} decay, one concludes that the probability that there are two $d_{3/2}$ proton holes in the ground state of Ca^{45} is between 10% and 20%.

e. Concealed Configuration Mixing and the Spectroscopy of the Pseudonium Nuclei

S. Cohen, R. D. Lawson, and J. M. Soper

On the basis of a simple configuration assignment, it is often possible to correlate binding energies of nuclei relative to closed shells, interpret excitation energies of low-lying states, predict selection rules for beta and gamma decay, and to understand certain static multipole moments of nuclei. If the consequences of assuming a simple, pure configuration are quantitatively borne out by experiment, it is tempting to say that this confirms the hypothesis that the shell is fairly pure. We have shown that this conclusion is not warranted.

This is done by exactly solving the problem in which neutrons are filling two isolated single-particle levels which, under the influence of the residual two-body forces, mix strongly. The properties of these pseudo-nuclei are given by the exact solution of the two-level problem and are called "pseudo-experimental results." In our case, the two levels considered are the $1d_{3/2}$ and $1f_{7/2}$ single-particle states; our pseudo-nuclei consist of from zero to twelve particles in these levels. Despite the fact that the $d_{3/2}$ shell is only 9% closed for N = 4, we find that the properties of the low-lying states of the pseudo-nuclei with $N \geq 5$ can be explained by taking as a model the simple configuration $(d_{3/2})^4(f_{7/2})^{N-4}$, i.e., a model in which $f_{7/2}$ particles move outside a closed $d_{3/2}$ shell. A final report has been published.[1]

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[1] S. Cohen, R. D. Lawson, and J. M. Soper, Phys. Letters 21, 306 (1966).

f. M2 Selection Rule for Nuclear Transitions

D. Kurath and R. D. Lawson

An examination of all the existing experimental data on M2 transitions between low-lying states shows that with few exceptions this type of transition is always inhibited by at least two orders of magnitude. For deformed nuclei it is easy to show that for large deformation there is a selection rule which inhibits this type of transition. The M2 operator can only produce transitions between deformed oscillator states which differ in n_z by no more than one unit. A low-lying state with "wrong" parity usually corresponds to a particle in a Nilsson orbit whose n_z differs from that of the "normal" orbits by more than one unit; from this follows the selection rule. As was illustrated in the case of the scandium isotopes,[1] even when one projects states of good angular momentum from deformed oscillator orbitals this selection rule inhibits the transition, although it no longer leads to an exact vanishing of the matrix element.

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[1] R. D. Lawson and M. H. Macfarlane, Phys. Rev. Letters 14, 152 (1965).

2. NUCLEAR EXCITATION AS SEEN BY GAMMA RADIATION FROM INELASTIC ALPHA SCATTERING

D. R. Inglis

When certain deformed even-even nuclei are excited to their first 2^+ state by inelastic alpha scattering, the orientation of the angular pattern of the subsequent gamma rays in the reaction plane (Fig. 33) exhibits a very remarkable behavior in its dependence on scattering angle.[1] Although experiments being carried out on the Argonne

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[1] D. K. McDaniels, D. L. Hendrie, R. H. Bassel, and G. R. Satchler, Phys. Letters 1, 295 (1962); J. G. Cramer, Jr., W. W. Eidson, and D. E. Blatchley, Nuclear Spectroscopy with Direct Reactions. I. Contributed Papers, Argonne National Laboratory Report ANL-6848, p. 153; J. G. Wills and J. G. Cramer, Jr., ibid., p. 147.

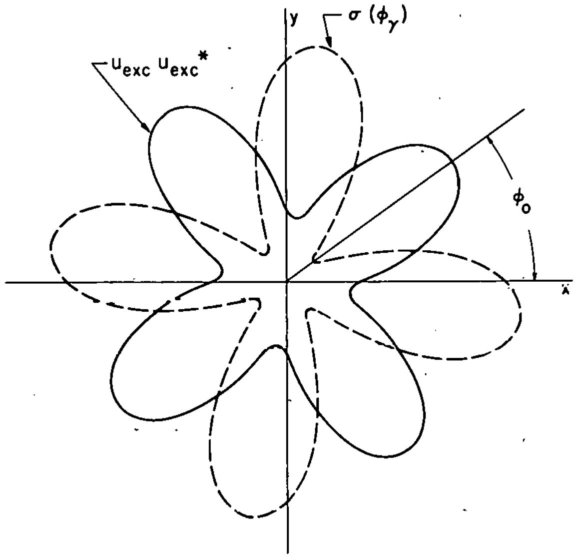

Fig. 33. The angular pattern of the gamma radiation (dashed) and of the probability distribution of the major axis of the elliptical nucleus in the excited state L = 2. The phase difference between the two patterns is determined semiclassically by the fact that a varying current element radiates preponderantly in a direction normal to itself.

tandem generator by investigators from Indiana University show that this behavior has a marked energy dependence, the salient feature remains a reverse rotation of the gamma pattern as the scattering angle is increased.

In an earlier phase of this research, it was suggested[2] that this behavior could be clarified in graphic fashion by relating it to the "beats" formed at the edges of the nucleus by the superposition of the incoming and outgoing waves. Since then this idea has been successfully developed in a two-dimensional analysis.[3] In its essential features, the model used has only two free parameters—one representing the width of the effective regions of overlap of the two waves at the two edges of the nucleus, the other specifying the relative weakness of the waves as they curve around the shaded side. By adjusting these two parameters within reasonable limits it is possible to fit the vagaries of the rotation curve rather well (Fig. 34), except at small scattering angles.

To fit the observation that the rotation stops at these small angles, it is necessary to take account of the alpha-particle waves not only where they graze past the edges of the nucleus but also where they

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[2] D. R. Inglis, Phys. Letters 10, 336 (1964).

[3] D. R. Inglis, in Preludes in Theoretical Physics in Honor of V. F. Weisskopf, edited by A. de Shalit, H. Feschbach, and L. van Hove (North-Holland Publishing Co., Amsterdam, 1966); Phys. Rev. 142, 591 (1966).

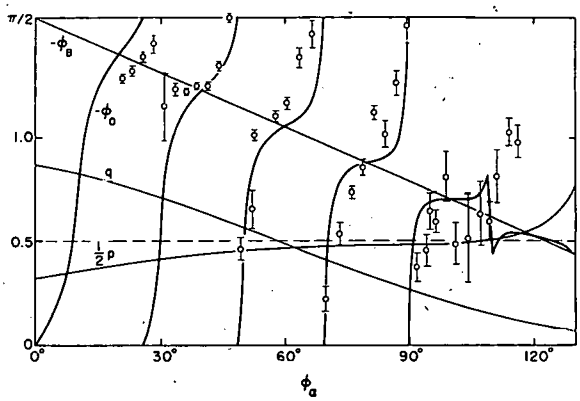

Fig. 34. The experimental results showing the reverse rotation for Mg^{24} at E_α = 22.5 MeV [from W. W. Eidson, J. G. Cramer, Jr., D. E. Blatchley, and R. D. Bent, Nucl. Phys. 55, 613 (1964)], as compared with theoretical curves for favorable values of the parameters.

come to a focus at the far side. The purpose of this stripped-down treatment of a complicated phenomenon by a simple model is to explore and understand essential physical ideas that would otherwise be hidden in the intricacies of complete machine computations.

3. THE EFFECT OF LONG-RANGE PERTURBATIONS IN SCATTERING

J. E. Monahan and A. J. Elwyn

As reported previously, several measurements of the scattering of neutrons from heavy nuclei indicate a contribution at small angles ($\theta \lesssim 5^\circ$) that cannot be explained in terms of conventional long-range interactions between the neutron and the target nucleus. A possible explanation of these results has been given in terms of an anomalously large value of the polarizability α_n of the neutron. Although there seems to be evidence that this increased small-angle scattering cannot be explained in terms of the structure of the neutron,[1,2] a direct measurement of α_n would be of interest.

The insensitivity of the differential cross section (averaged over many resonances) to values of α_n less than $\sim 10^{-40}$ cm^3 can be

[1] A. J. Elwyn, J. E. Monahan, R. O. Lane, F. P. Mooring, and A. Langsdorf, Jr., Sec. I. B.7.

[2] A. J. Elwyn, J. E. Monahan, R. O. Lane, A. Langsdorf, Jr., and F. P. Mooring, Phys. Rev. 142, 758 (1966).

traced to the fact that for heavy target nuclei there is destructive interference between the nuclear scattering and that due to the polarizability of the neutron. Since the imaginary part of the phase shift from nuclear scattering changes sign at a resonance energy, it may be possible to eliminate this destructive interference by making measurements over an isolated resonance in the compound system.

We have calculated the differential cross section and polarization of neutrons scattered from Pb^{208} in the neighborhood of a resonance at ~ 0.5 MeV. The results show that it would be possible to detect values of $\alpha_n \gtrsim 10^{-41}$ cm^3 from measurements at scattering angles between 10^o and 15^o, provided the nuclear phase shifts were known. Such a measurement is about an order of magnitude more sensitive to the value of α_n than the corresponding energy-averaged measurements. The theoretical value of α_n is about 10^{-42} cm^3 and it seems improbable that neutron scattering measurements of this sensitivity can be achieved.

4. AVERAGE PROPERTIES OF ATOMIC AND NUCLEAR STATES, TRANSITIONS, AND CROSS SECTIONS

N. Rosenzweig

The investigation of the statistical properties of the highly excited states of atoms and nuclei has continued with two main goals: (1) to define the limits of validity of Wigner's model, which has been very successful in the description of the "local" properties of the most complex systems, such as the distributions of level spacings in heavy nuclei, and (2) to formulate more advanced statistical theories which will reflect structural details of the systems, such as approximate constants of the motion and the energy dependence of the nuclear level density.

a. Nuclear Level Density

An earlier calculation of the nuclear level density has been generalized by removing the g-fold degeneracy of the independent-particle levels in the form of a uniformly spaced cluster of single-particle levels. The result has a simple analytical form and serves to illustrate that gaps, partially filled shells in the ground state, and other distinctive features of the single-particle spectrum find expression as additive corrections to the excitation energy in the standard level-density formula. Furthermore, it was found very recently that the major part of the additive correction is precisely of the same form as a term (arising from shell structure) in the semiempirical mass formula recently developed by Swiatecki and collaborators. An attempt is now under way to generalize the above work still further by allowing the independent-particle levels within a cluster to have arbitrary degeneracies and spacings. A cluster could then be identified with a major shell in the nuclear shell model.

b. Finite-Sample Effects in the Spacing Distributions of Nuclear Levels

(with J. E. Monahan)

The consequences of Wigner's invariant Gaussian ensemble of real symmetric matrices of high dimensionality were studied further in order to detect statistically significant deviations between measured spacings and Wigner's model. In particular, the first and second moment of a new statistic have been estimated on the basis of the random-matrix model, and comparisons with experimental results for U and Th will be undertaken in the near future.

c. Average Properties of Complex Atomic Spectra

(with B. G. Wybourne)

We conclude from the study of some theoretical examples that although the properties of the individual states of a complex atomic spectrum depend in a very intricate way upon the atomic parameters (Slater integrals, spin-orbit parameters, etc.), the same quantities, when averaged over a large set of states, have a relatively simple but striking dependence upon the parameters. A specific example is the square of the gyromagnetic ratio averaged over the fifty $J=\frac{7}{2}$ states of the f^7 configuration. The main features of the dependence of that quantity on the value of the spin-orbit parameter can be understood qualitatively in terms of a general inequality for orthogonal matrices, selection rules, the degeneracies of the jj coupling limit, and the statistical model that has been applied successfully to heavy nuclei. Although this particular study is completed, it is expected that the study of the atomic case will continue to be a helpful guide in the formulation of more advanced statistical theories of the nucleus.

d. Dyson's Brownian-Motion Model of a Random Matrix

This model represents the only analytical approach to a statistical theory of the energy states of a complex quantum system whose states are characterized not only by a few quantities (such as spin and parity) that are conserved exactly, but also by some other quantities (such as total orbital and total spin angular momentum) that are conserved only approximately. The atomic spectrum considered above is an example of this very common situation in nuclear and atomic spectroscopy. Although the mathematical development of Dyson's model is not yet sufficiently advanced to allow applications to experimental results, work has progressed toward that goal.[1] The formal solution to Dyson's equation has been given and analyzed in some special cases. More recently, the distribution of the eigenvectors, defined by the Brownian motion of the energy matrix, has been studied, and the results will be reported in the near future.

[1] N. Rosenzweig, Nuovo Cimento 38, 1047 (1965).

5. THE GROUND STATE OF NUCLEAR MATTER

F. Coester and B. Day

The mathematical problem of finding the binding energy and the ground-state wave function of a many-nucleon system is fundamental to any attempt at understanding nuclear structure in terms of realistic nucleon-nucleon forces. The limiting case of infinite nuclear matter is relatively more accessible to systematic approximation than are finite nuclei. Qualitative and semiquantitative results obtained for nuclear matter retain their significance for finite nuclei.

The approximations are based on the following properties of the nuclear forces and the ground-state wave function. The two-body potential contains a strong repulsion (whose range is short compared with the average distance between nucleons) and a smooth attractive tail which is too weak to excite nucleons out of the Fermi sea with large probability. Either feature alone or the combination of both produces correlation corrections to the pure Fermi-gas ground state, which are small over most of the configuration space. The first-order approximation in this scheme is the Brueckner approximation or, in the absence of strong repulsions, the Hartree-Fock approximation. For realistic nuclear forces, higher order corrections must be considered. The established procedure is to expand the solution of the Schrödinger equation in a perturbation series and selectively sum those terms that are believed to be important.

We derive integral equations for higher order terms for the binding energy of nuclear matter and the correlation corrections to the wave functions directly from the second quantized Schrödinger equation without series expansion. Known results, namely the Brueckner approximation and Bethe's integral equations for the sum of all three hole-line diagrams, are derived in a concise and direct way. We expect to obtain other corrections that may be needed and estimates on the remainder.

6. PHENOMENOLOGICAL α-α POTENTIALS

S. Ali* and A. R. Bodmer

Phenomenological ℓ-dependent α-α potentials are obtained for ℓ = 0, 2, and 4 from fitting the relevant phase shifts for c.m. energies $\lesssim$ 12 MeV. For the nuclear part of the potentials, a superposition of repulsive and attractive Gaussian shapes was used. Following theoretical indications, we try to obtain fits with an ℓ-independent attractive part having a longer range than the repulsive parts. Further, we attempt to obtain, at first, the attractive part from just the ℓ=4 phase shift in view of the effect of the large ℓ=4 centrifugal barrier in masking the inner repulsive part.

It is, in fact, found possible to obtain acceptable potentials with a common attractive part. These potentials are, however, strongly ℓ-dependent through the repulsive part which becomes weaker as ℓ increases. For ℓ = 4, only a quite weak repulsive part is found to be permissible. Our potentials are in good agreement with those recently obtained by Darriulat et al.[1] The interesting possibility is pointed out and discussed that the attractive tail of the α-α potential may be a good selective probe into just the central, spin-independent, isospin-independent attractive part of the nuclear force. A more careful study of this possibility is in progress. A final report on this work has been published.[2]

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*The University, Manchester; now with the Pakistan Atomic Energy Commission.

[1] P. Darriulat, G. Igo, H. G. Pugh, and H. D. Holmgren, Phys. Rev. 137, B315 (1965).

[2] S. Ali and A. R. Bodmer, Nucl. Phys. 80, 99 (1966).

7. STUDIES OF HYPERNUCLEI AND THE INTERACTIONS OF Λ PARTICLES

A. R. Bodmer

This program attempts to make a comprehensive theoretical interpretation of all experimental information concerning hypernuclear states. It is carried out by using the techniques of modern nuclear-structure theory.

a. Excited State of $_{\Lambda}Be^9$ and the Λ-N Interaction

S. Ali,* A. R. Bodmer, and J. W. Murphy†

One expects two close-lying states of $_{\Lambda}Be^9$ with $J = \frac{3}{2}$ and $\frac{5}{2}$ that correspond to the first excited state of Be^8 with J = 2. With an α-particle model for the Be^8 core and central Λ-α interactions, these states of $_{\Lambda}Be^9$ will be degenerate. If the excitation energy E^* is greater than 3.4 MeV, then $_{\Lambda}Be^{9*}$ will be particle unstable for $_{\Lambda}Be^{9*} \rightarrow {}_{\Lambda}He^5 + \alpha$. Rather detailed calculations of E_{Λ}^* have been made with a 3-body model consisting of two α particles and the Λ. This model has proved very successful and consistent for the ground state of $_{\Lambda}Be^9$.[1] The calculations were made with an extension of the method developed earlier.[1] A number of ℓ=2 α-α potentials (appropriate to the J=2 state of Be^8) were used, some of which give an excellent fit to the ℓ=2 phase shifts.

The rearrangement energy and rms separation of the α particles in $_{\Lambda}Be^{9*}$ were also calculated and were found to be quite similar to the corresponding values for the ground state. It was found that E^* depends somewhat on the (Yukawa) range μ^{-1} of the attractive part of

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[1] A. R. Bodmer and S. Ali, Nucl. Phys. 56, 651 (1964).

the Λ-N interaction. (For a given μ, the α-Λ potential was chosen to give the experimental binding energy of ${}_{\Lambda}He^{5}$.) For $\mu^{-1} = 0.7$ F, corresponding to two pion masses, it was found that $E^{*} = 2.7$ MeV and thus ${}_{\Lambda}Be^{9*}$ is particle stable, whereas for a shorter range $\mu^{-1} = 0.4$ F one obtains $E^{*} = 3.5$ MeV so that ${}_{\Lambda}Be^{9*}$ is barely particle unstable. A recently reported event[2] has been interpreted as the decay of a ${}_{\Lambda}Be^{9*}$ which was particle unstable by 0.6 ± 0.4 MeV. If this event should be confirmed then our results would indicate a quite short range, $\mu^{-1} < 0.4$ F, for the attractive part of the Λ-N interaction. Such a range would be consistent with what one expects from one-particle-exchange models of the interaction. The final report on this work has been published.[3]

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[2] R. J. Piserchio, J. J. Lord, and D. Fournet Davis, Bull. Am. Phys. Soc. 10, 115 (1965).

[3] S. Ali, J. W. Murphy, and A. R. Bodmer, Phys. Rev. Letters 15, 534 (1965).

b. Hypertriton with an S' State and the Λ-N Interaction

A. R. Bodmer

In continuation of the work reported last year, the hypernuclear results have been rather completely compared with the much improved low-energy Λ-p scattering data now available. If one makes the most economical and reasonable assumption that the singlet Λ-N interaction is well determined from the hypernucleus ${}_{\Lambda}H^{3}$ (which is very loosely bound), then the comparison indicates that the free triplet interaction is rather larger (but not very much larger) than the effective interaction in hypernuclei obtained especially from ${}_{\Lambda}He^{5}$.

The interesting possibility is suggested that in a hypernucleus the triplet interaction in particular can be suppressed relative to the free interaction as a result of suppression of the strong coupling of the Λ-N with the Σ-N channel. Thus for ${}_{\Lambda}He^{5}$, because of isospin conservation, the α particle must be excited to T=1 states for any coupling with the Σ-N channel; such excitations (> 20 MeV) are comparable with the Σ-Λ mass difference (≈ 80 MeV). Estimates of this effect for ${}_{\Lambda}He^5$ show that it could account for an appreciable part (and possibly all) of the difference between the free and the effective triplet interaction. Other possibilities which could also contribute are due to possible tensor and three-body forces. The comparison with the scattering data also tentatively indicates the existence of a hard core in the Λ-N interaction if one believes mainly theoretical indications (described in the preceding subsection) that the attractive part of the interaction has a rather short range. The final report on this work has been published.[1]

[1] A. R. Bodmer, Phys. Rev. 141, 1387 (1966).

c. An Alpha-Deuteron-Lambda Model of the Hypernucleus ${}_{\Lambda}Li^7$

J. W. Murphy* and A. R. Bodmer

The hypernucleus ${}_{\Lambda}Li^7$ has been studied with a three-body model consisting of the Λ and an undistorted α particle and deuteron. The interactions between the constituents are obtained by making use of the basic α-N and Λ-N interactions. However, the strengths of these are adjusted to give the observed binding energies of the two isolated pairs α-d (i.e., Li^6) and α-Λ (i.e., ${}_{\Lambda}He^5$). The strength of the d-Λ interaction is not fixed but is determined as a function of the binding energy of ${}_{\Lambda}Li^7$ by our calculations for this hypernucleus. For Li^6, a 2s relative α-d wave function was used. The 1s α-d component ψ_{1s} is assumed to be entirely spurious both for Li^6 and ${}_{\Lambda}Li^7$. Variational calculations for ${}_{\Lambda}Li^7$ are made with flexible trial wave functions and with particular effort given to reducing the amplitude of ψ_{1s} as much as possible.

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In achieving this, some interesting new features arise in our variational calculation.

Our results confirm the indications of a previous study[1] with a two-body model that there is a strong α-Λ correlation together with only a slight distortion of the Li^6 core by the Λ. They also indicate that comparing (as a function of the range of the Λ-N interaction) the strength of the Λ-d interaction obtained from $_\Lambda H^3$ with that from $_\Lambda Li^7$ could give information about the range of the Λ-N interaction. However, no conclusive results could be obtained in this respect; although we obtain the major part of the binding energy of $_\Lambda Li^7$, there is nevertheless a sufficient discrepancy to indicate that our model is not completely adequate. In particular, the probable need to consider correlations of the Λ with the individual nucleons of the deuteron indicates the use of a four-body, α-n-p-d-Λ model for further studies of $_\Lambda Li^7$. A final report on this work has been published.[2]

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[1] A. R. Bodmer and J. W. Murphy, Nucl. Phys. 73, 664 (1965).

[2] J. W. Murphy and A. R. Bodmer, Nucl. Phys. 83, 673 (1966).

8. INTERNAL SYMMETRIES IN A COUPLED-CHANNEL SOLUBLE MODEL WITH INELASTICITY

James T. Cushing

The conjecture that an internal symmetry group may be selected by a bootstrap mechanism was studied within the framework of a closed, exactly soluble model. In order to have two-body unitarity and crossing without necessarily identically zero amplitudes, two types of particles of different mass (each possessing internal quantum numbers corresponding to an unspecified internal symmetry group and each assigned to irreducible representations of this group) are allowed to scatter in a two-dimensional world. The symmetry group makes its appearance explicitly only through the crossing matrix characterized by a parameter which is to be determined self-consistently. All two-body channels, both elastic and inelastic, are treated exactly. Unitary, crossing-symmetric, analytic scattering amplitudes corresponding to the various processes are constructed for continuous ranges of the parameter of the crossing matrix. Even with the additional constraint of a self-consistency requirement in the form of Levinson's theorem, an internal symmetry group is not selected by the bootstrap mechanism in this model. Also, a technique was developed for converting a coupled set of singular, linear Cauchy integral equations into an equivalent uncoupled Fredholm set.

9. LOCALITY IN FIELD THEORY

H. Ekstein

The usual statement of locality is that local observables commute if they belong to space-like positioned spacetime volumes. The present discussion rejects this as unacceptable because it does not express an operational statement. The alternative statement says (in loose language) that any observation in V_1 is compatible with any observation in V_2, if V_1 and V_2 are spacelike. It has been shown that the new and the conventional statement are not mathematically equivalent. It is hoped that a richer relativistic field theory will become possible with the new statement. Work is continuing.

10. GENERAL THEORY OF SCATTERING

H. Ekstein

A projected book on the general theory of scattering emphasizes modern time-dependent Hilbert-space methods rather than the usual method of non-square-integrable solutions of partial differential equations. Fifteen skeletal chapters have been written, but the competition of more exciting present-day research has limited the progress. A contract for its publication has been proposed by John Wiley & Sons, Inc.

11. RELATIVISTIC COMBINATION OF INTERNAL AND SPIN SYMMETRIES IN S-MATRIX FORMULATION

H. Ekstein

A nonrelativistic combination of spin symmetry and internal [SU(6)] symmetry for the "elementary" particles has had a partial success. The attempt to make this theory conform to the principle of relativity raised some perplexing questions as to the nature of symmetries other than space-time. The present investigation gives a compact and consistent redefinition of symmetry. In particular, the question as to whether a nonrelativistic symmetry theory can be made relativistic is answered by an unqualified affirmative. However, the constraints imposed on the scattering operator by the principle of relativity make the S operator trivial, so that agreement with experiment can be secured only by breaking the symmetry. The final report on this work has been published.[1]

[1] H. Ekstein, Phys. Rev. 141, 1560 (1966).

12. THE ART OF EDUCATED GUESSING IN QUANTUM MECHANICS

H. Ekstein

If the initial wave function or density matrix of a system is not known exactly (the usual situation), then, generally and strictly speaking, physics has no predictive power. The lacking knowledge must be supplemented by educated guessing, and this can be done either by common sense or in a systematic way. The theory of systematic guessing, sometimes called generalized statistical mechanics, is in an unsatisfactory state: (1) its basic assumptions seem unconvincing and arbitrary and (2) it gives divergent results even for some very simple cases, unless some more or less judicious tampering is performed. The present effort tends to (a) put the theory of physical conjecturing on a sounder basis and (b) make it unambiguously applicable to the (realistic) case of infinite-dimensional Hilbert space. A paper is in preparation.

13. QUANTUM MECHANICS OF RELATIVISTIC PARTICLES

F. Coester and G. Roepstorff

It is generally recognized that there are three distinct levels of hadron interactions, namely weak, electromagnetic, and strong interactions. If the hadrons are to be understood as strongly bound compounds of heavy quarks, a fourth level of super-strong interactions must be added. The known local field theories do not provide an adequate basis for a plausible description of strongly bound quarks. The existence of a macroscopically causal relativistic description of a finite number of interacting particles was demonstrated in an earlier paper.[1] We apply that scheme to the super-strong interactions of quarks. A plausible and useful quark model requires at least the introduction of electromagnetic and weak interactions into such a scheme. The problems involved and the consequences for hadron form factors are being investigated.

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[1] F. Coester, Helv. Phys. Acta 38, 7 (1965).

III. EXPERIMENTAL ATOMIC PHYSICS

INTRODUCTION

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

A. 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 Fe^{57}, Sn^{119}, K^{40}, Kr^{83}, Cs^{133}, Xe^{129}, Xe^{131}, I^{129}, Sb^{121}, and Np^{237}, and others are being considered.

1. MÖSSBAUER EFFECT IN Cs^{133}

G. J. Perlow, A. J. F. Boyle, and G. L. Montet

The Mössbauer effect in cesium metal has been observed. The recoilless fraction is very small, 5.5×10^{-5}, and produces a resonant fractional dip of 1.9×10^{-4} in the velocity spectrum. It required about 2×10^{8} counts in each of about 200 channels to delineate the dip adequately in order to use it as a basis for calibration of the isomer shift. As a result of the calibration it appears that the source, which is an alloy of Ba^{133} plus inactive barium and aluminum, produces the unusual species Cs^{-} in its decay. The characteristic temperature of the cesium metal is measured in the experiment as $\theta_M = 49 \pm 1^\circ K$. The spectrum of cesium metal might be expected to furnish evidence for the existence of static spin-density waves, but no such indication was found.

2. THE DEBYE-WALLER FACTOR FOR THE CESIUM ION IN THE CESIUM HALIDES BY MEASUREMENT OF THE MÖSSBAUER EFFECT IN Cs^{133}

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

The recoilless fraction in cesium halides was measured by the method of line-width determination. Absorbers with several thicknesses were employed. The characteristic temperatures θ_M for the halides are found to be $109^\circ K$ for CsF, $106^\circ K$ for CsCl, $104^\circ K$ for CsBr, and $96^\circ K$ for CsI.

3. COMPARISON OF IODINE AND XENON COMPOUNDS BY THE MÖSSBAUER EFFECT

G. J. Perlow and M. R. Perlow

Additional isomer shifts were measured in iodine compounds by use of stable I^{127} and in xenon compounds by use of stable Xe^{129}. A report is in preparation.

4. MÖSSBAUER STUDIES WITH Kr^{83}

S. L. Ruby and H. Selig*

The fundamental parameters of Kr^{83} make it as suitable as the famous Fe^{57} for Mössbauer investigations of chemical and solid-state interactions. It has been almost completely neglected, however, because of technical difficulties and because of a smaller range of interesting environments. During this year we have utilized one unusual environment—namely the only compound of krypton, KrF_2—to study the nuclear quadrupole moment of this nucleus, as well as the electric field gradient generated by the asymmetric electronic distribution around the krypton in this molecule. Some of the "technical difficulties" referred to above were diminished by the use of a new parent activity. In addition, we were able to measure the change in proton radius between the $\frac{9}{2}^+$ and $\frac{7}{2}^+$ levels of this nucleus.[1]

Plans for the coming year include measurement of the magnetic moment of the excited state of Kr^{83} (probably by use of a superconducting magnet) and the use of this isotope in studies of lattice dynamics.

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*Chemistry Division, ANL.

[1] S. Ruby and H. Selig, Phys. Rev. 147, 348 (1966).

5. MÖSSBAUER-EFFECT STUDIES WITH Sb^{121}

S. L. Ruby, G. M. Kalvius,* G. B. Beard,† and R. E. Snyder†

The first experiments with this isotope, which is new to Mössbauer investigations, have been aimed at the nuclear properties.

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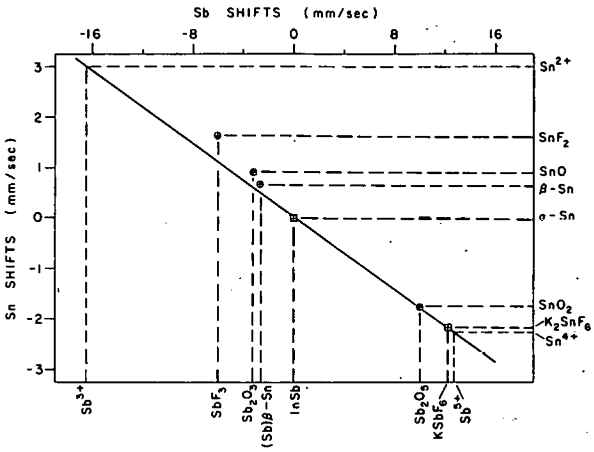

Fig. 35. Comparison between tin and antimony for pairs of compounds in which the metal atoms are thought to be isoelectronic.

A paper on the nuclear quadrupole moments has been completed, and most of the data needed for an analysis of the magnetic moments and also for the isomer shifts have already been taken. The continuing attempt to understand the latter more fully will apparently require a comparison with isoelectronic tin compounds (Fig. 35), and some good analyses of the electronic wave functions of these atoms.

A result will be the first measurement of the ratio $\delta r/r$ for nuclei of different elements. This work will be greatly facilitated by the strong sources resulting from the high-flux neutron bombardments recently made available at Savannah River.

6. MÖSSBAUER EFFECT IN THE ACTINIDE ELEMENTS

S. L. Ruby, G. M. Kalvius,* M. B. Brodsky,† and D. J. Lam†

In recent experiments we have found that Np^{237} is a very suitable nucleus for Mössbauer investigations; its magnetic behavior is easy to measure. We have already shown that neptunium metal becomes neither ferromagnetic nor antiferromagnetic at 4.2°K, despite anomalous specific-heat data.

We recently have attempted to demonstrate the existence of a Mössbauer effect in U^{235}, the necessary excited state being produced

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by Coulomb excitation in a target at the 4-MeV Van de Graaff. The effect was several times smaller than anticipated—probably because of lattice dynamical effects of the recoil. There are some five or six other nuclei in this region of the periodic table that also are suitable for such work. In addition to making Mössbauer studies practical on new isotopes, the Coulomb-excitation technique enforces interest in nanosecond radiation-damage effects in both metals and insulators.

7. MÖSSBAUER LINE BROADENING IN POWDERED CRYSTALS

Murray Peshkin

A theoretical treatment gives theorems that relate the centroid and the moments of Mössbauer lines to the electric and magnetic interactions of the nucleus with its crystal environment. A final report has been published.[1]

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[1] M. Peshkin, Phys. Rev. 139, A717 (1965).

8. MÖSSBAUER ANALYSIS OF IRON IN STONE METEORITES

E. L. Sprenkel-Segel and S. S. Hanna

The resonant absorption of gamma rays by Fe^{57} has been used in the analysis of iron in stone meteorites. By comparison with absorption patterns of terrestrial reference minerals, the meteoritic compounds may be identified and the relative amount of iron in each mineral determined. Typical minerals analyzed are olivine and pyroxene (ferromagnesian silicates), troilite (a sulfide), and kamacite (an iron-nickel alloy). Iron analysis plays an important role in both the classification of meteorites and the investigation of their preterrestrial history. Important inferences concerning the evolution of meteorite bodies can be deduced from the relative proportions of oxidized and reduced iron in stone meteorites. A manuscript has been prepared for publication in the book Mössbauer Effect Methodology, Vol. II.

9. METEORITIC IRON MINERALS AND THE ORIGIN OF METEORITES

E. L. Sprenkel-Segel, G. J. Perlow, and J. D. Oyler

A Mössbauer velocity spectrometer has been used to investigate the resonance absorption of gamma rays by Fe^{57} in meteoritic minerals. Since the elemental abundances of the chondritic stones are remarkably similar, these meteorites are classified on the basis of the most outstanding variable quantity: the relative proportion of oxidized to reduced iron. Six groupings are observed, ranging from nearly complete reduction (all iron present as iron-nickel alloys and as the sulfide, troilite) to complete oxidation (all iron present as ferrous and ferric minerals). Analysis of the characteristic absorption patterns for the various iron-bearing minerals should make it possible to decide whether the six groups represent (1) fragments from six different parent bodies, each with an almost unique ratio of oxidized to reduced iron or (2) six segments in a continuous sequence of oxidation-reduction ratios indicating formation of the chondrites at various stages during the progressive oxidation (or reduction) of a parent magma.

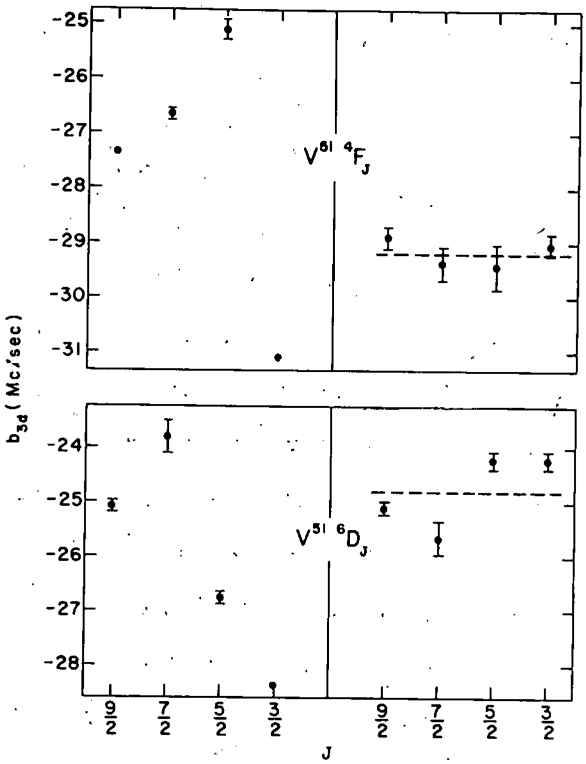

Fig. 36. Plot of the values of $b_{3d} = e^2 Q \langle r^{-3} \rangle_{3d}$ both before and after correction for off-diagonal hfs in two multiplets of V^{51}. The data for $3d^3 4s^2$ $^4F_{9/2, 7/2, 5/2, 3/2}$ are given at the top, and for $3d^4 (^5D) 4s$ $^6D_{9/2, 7/2, 5/2, 3/2}$ at the bottom of the figure. The values obtained from the raw data are shown at the left and the values determined after correction for off-diagonal hyperfine interactions at the right. For each multiplet, applying the correction gives a dramatic improvement in the consistency of the results. The results are consistent within experimental error for the ^4F term, and very nearly so for the ^6D levels.

B. ATOMIC-BEAM RESEARCH

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

The Mark II atomic-beam machine has been used for further studies of the hyperfine interaction in free atoms. Most of our effort this year has gone into research on V^{51} and Ni^{61}, both of which have several low-lying atomic states in each of two electronic configurations. One aim was to determine the extent to which the Sternheimer shielding of the nuclear electric quadrupole moment differs between the two configurations. Other results of the work are precision measurements of the electronic g factors and magnetic-dipole and electric-quadrupole hyperfine-interaction constants of each state. Certain details of the electronic wave functions and estimates of the degree of electron-core polarization are also obtained. The most valuable aspect of the work is that studying the hyperfine interaction in several different states and configurations leads to a more systematic and detailed understanding of the atomic and nuclear properties (Fig. 36) than can be attained if only a single state is investigated. The work on V^{51} is nearly complete and that on Ni^{61} is perhaps one-third complete. Values for the ground-state electric-quadrupole moments were found for both nuclei.

The energies of the levels of the ground ($2p^2$) configuration of the neutral carbon atom have long been regarded as indicative of the presence of large amounts of configuration interaction; the spin-orbit and Coulomb interactions within the p^2 configuration lead to very poor agreement with the observed term values. Since the electronic g factors of these levels should be very sensitive to the presence of most types of configuration interaction, we are attempting precision measurements of the g factors. The experiment is difficult because of the problem of producing a steady, reasonably intense beam of carbon atoms. The measurement appears possible, however, and work is continuing.

A new atomic-beam machine for work with transuranic isotopes is under development.

C. HIGH-FREQUENCY PLASMAS

The central purpose of this research is to advance the understanding of the basic properties of low-pressure gaseous discharges and plasmas produced by high-frequency fields. The two lines of experimental and theoretical investigation being pursued are studies of plasmas produced (1) in the approximately uniform rf electric field between plane parallel electrodes and (2) in the nonuniform standing-wave fields in resonant cavities.

1. PLASMAS IN UNIFORM ELECTRIC FIELDS*

A. J. Hatch, B. A. Tryba, and N. M. Uss

An analytic and experimental study of the substitution method used to measure the complex admittance of high-frequency discharges between plane-parallel electrodes showed that the method (a modification of the standard Hartshorn-Ward method used for solid dielectrics) was valid but that correction factors of 1.3 to 1.6 due to the effects of residual lead impedances had to be applied to the previously measured values of the admittance components. The corrected values are now considered to be publishable.

Another study was an attempt to validate the use of a Langmuir probe to measure the density n and the temperature T of electrons in the high-frequency discharges. The density is of special interest because it is involved in the correlation between measured values of admittance and values calculated from a quasi-bound-electron theory of admittance. This work led to the conclusion that the densities of our plasmas ($\sim 10^6 - 10^8$ cm^{-3}) are at least an order of magnitude below the value that would make the ratio of plasma-sheath thickness to probe

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*During the past year, the work under this heading was done as student projects in the Argonne Semester Program of the Associated Colleges of the Midwest.

dimensions small enough to satisfy the requirements of probe theory. Thus, in our old system operated at 15 MHz, the Langmuir probe is incapable of measuring n and can provide only approximate ($\sim \pm 50\%$) values of T. In the new system to be operated at $\sim$50 MHz, the densities are expected to be increased by an order of magnitude; and this may make possible the needed measurements of n and T. In addition, the new system will employ ultra-high vacuum techniques to permit studies with pure gases.

2. PLASMAS IN NONUNIFORM (CAVITY) ELECTROMAGNETIC FIELDS

A. J. Hatch, M. Hasan, S. Halverson,* and J. Wenger†

A theoretical and computational analysis of potential wells for the steady-state confinement of plasmas in the quadrupole field modes (TM_{011}, TE_{012}) of cylindrical cavities has been completed. The results include (a) determination of optimum dimensions of cavities for maximum depth of potential wells, (b) establishment of a frequency-scaling law, and (c) calculation of absolute depths and contour levels of the wells. Thus for typical conditions at which our UHF system can be operated (900 MHz, 2kW), the maximum depth of the well for low-density plasmas (TM_{010} mode) is 82 eV, and that for high-density plasmas (TE_{012} mode) is 70 eV. In the latter case, theory indicates that our system should have the capability of maintaining a small volume ($\sim$0.6 liter) of fully ionized hydrogen of density $\sim 10^{10}$ cm^{-3} in stable steady-state confinement. A silver plated cylindrical cavity with an internal vacuum liner will be used for studies of the basic properties of such plasmas under various conditions of pressure and power. Figure 37 is a photograph of the cavity plasma facility to be used in this work.

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*Electronics Division, ANL.

†Applied Mathematics Division, ANL.

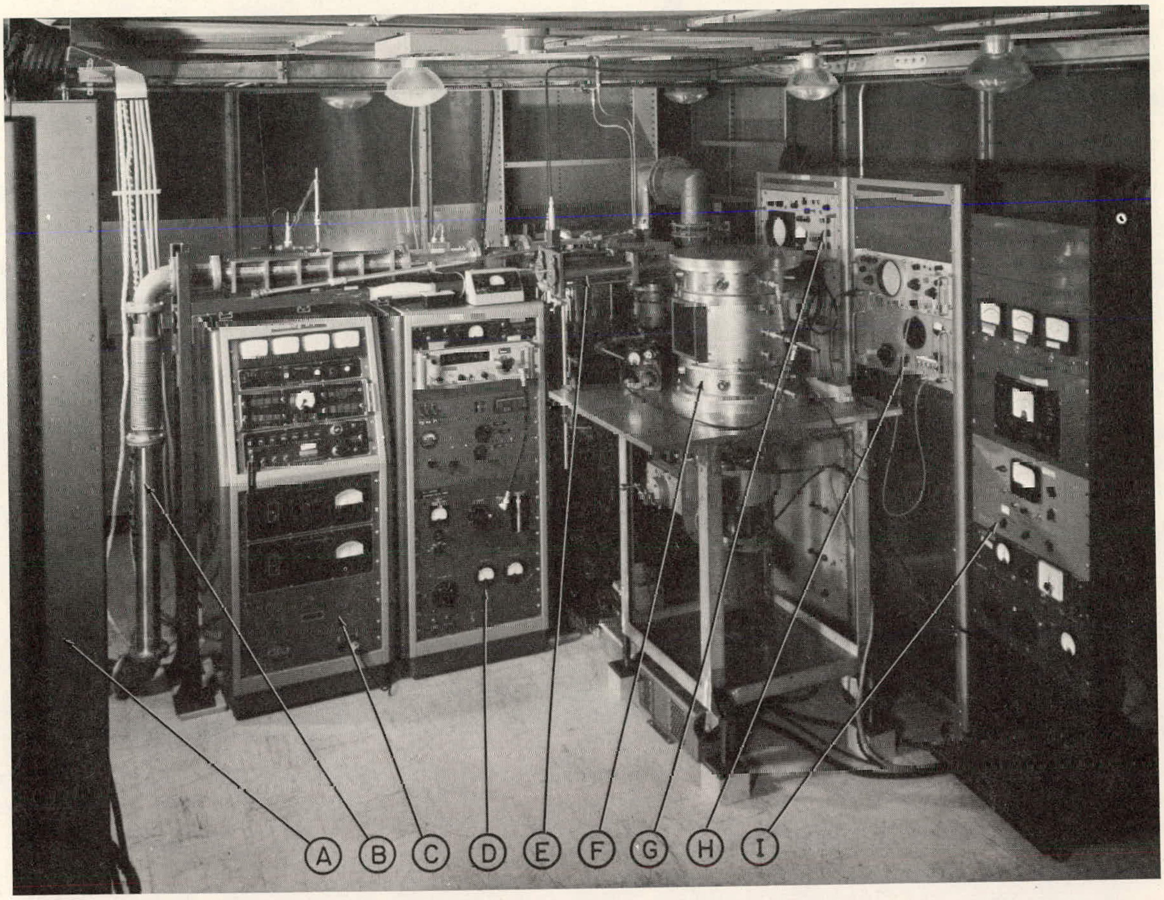

Fig. 37. Photograph of microwave-cavity plasma facility. From left to right the major components are (A) 2-kW cw uhf power amplifier built around a 4-cavity klystron (type 4KM3000LR), (B) $3\frac{1}{8}$-in. rigid coaxial line, including a slotted line and bi-directional couplers, (C) klystron control console, (D) master (driver) oscillator console, (E) tuning stubs, (F) cavity (inside height 42 cm, inside diameter 33 cm) with screened viewing window in central sector, (G) automatic impedance plotter, (H) diagnostic rack, and (I) control rack for vacuum system. Microwave power is coupled from the coaxial line into the cavity by a capacitance-loaded loop. A 3-port ferrite circulator (hidden by amplifier cabinet) functions as an isolator to protect the klystron against the deleterious effects of high standing-wave ratio due to possible sudden changes in plasma loading. The uhf microwave power system is continuously tunable from 610 to 985 MHz with uhf power output maintained within ± 3 db at any desired power level up to 2 kW.

D. MASS-SPECTROMETRIC INVESTIGATIONS

The mass-spectrometric investigations employ seven instruments, each designed for specific fields of activity. Mass spectrometer MA-15B is used primarily in the study of the molecular composition of high-temperature vapors but is also used together with MA-18 for gas-phase molecular reactions and dissociations. Extensive studies of photodissociation in complex molecular species are carried out on MA-24, which is provided with a vacuum ultraviolet monochromator. The spectrometer MA-17 is equipped with an energy analyzer and is being used to study the kinetic energy liberated in molecular reactions and fragmentations. Two additional instruments, MA-25 and MA-27, are in use in molecular and ionic sputtering experiments and similar investigations involving surface properties and reactions. Replacing MA-27 by a new spectrometer (MA-28, now under construction) will provide higher resolution and greater sensitivity. An old instrument MA-16A has been used in the recent past to study the properties and quality of ionic beams in connection with the design of ion sources, but is at present on a stand-by basis.

The results of these investigations are applicable to problems encountered in such diverse fields as nuclear reactor technology, radiation damage, materials for rocket engines, and certain phases of the re-entry of space vehicles. However, the main emphasis is on providing fundamental information on the thermodynamics and kinetics of chemical reactions, and on molecular structure and similar aspects of the properties of matter.

1. IONIZATION AND FRAGMENTATION OF GAS MOLECULES

J. Berkowitz, W. Chupka, K. Refaey, and W. Jivery

a. Photoionization Studies

The operation of mass spectrometer MA-24 with its associated vacuum ultraviolet monochromator has been greatly improved. An ion-counting detection system with a very low background is now in operation and has made possible useful measurements with ion beams as weak as a few counts per minute. Several photon sources are being used—especially the many-line hydrogen source and the helium-continuum source, which together provide useful intensities over most of the range from 3500 Å down to 600 Å.

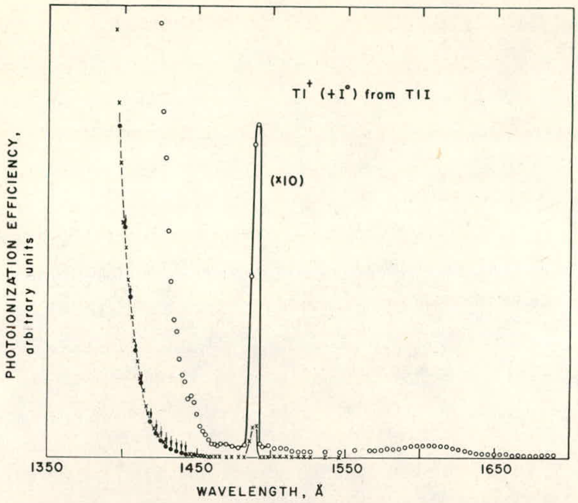

Fig. 39. Threshold region of the photoionization-efficiency curve for dissociative ionization of TlI to give Tl^+ and I^0 (in the $^2P_{3/2}$ state). The curve is plotted on two scales differing by a factor of 10. The higher magnification reveals a 1610-Å peak not visible at the lower magnification, but still maintains good statistics. The peaks at 1610 and 1490 Å are due to atomic thallium, which was present in trace quantities (0.001%). The feature beginning at about 1440 Å is due to the dissociative ionization process. The arrows point to the thresholds for ionization from successively less excited vibrational levels of neutral TlI as the photon wavelength is decreased. In this way, the ionization proceeding from the ground vibrational state can be deduced.

(ii) Kinetics of Fragmentation of Polyatomic Molecular Ions. Photoionization-efficiency curves for all significant ions have been measured for a series of alkanes (ethane, propane, and butane) and a series of alcohols (methyl, ethyl, n-propyl, and isopropyl). The data were treated to give breakdown curves describing the relative probability of the important fragmentation modes as a function of internal energy. In general, the data support the validity of the statistical theory of mass spectra which has been applied extensively to these two groups of compounds.

(iii) Free Radicals. Measurement of the photoionization-efficiency curve for the free radical CF_3 has cleared up a long-standing discrepancy. The shape of the curve shows conclusively that the configurations of CF_3 and CF_3^+ are very different, the former probably being pyramidal and the latter planar. The vertical ionization potential is about 11.0 eV while the adiabatic ionization potential is certainly less than 9.5 eV and is probably about 9.2 eV. The very unfavorable Franck-Condon factor for the adiabatic transition makes the direct determination of the ionization potential almost impossible and accounts for the

(i) High-Temperature Vapors. Several metal halide molecules and the Te_2 molecule have been studied by photoionization techniques (Fig. 38). The measured thresholds for formation of fragment as well as parent ions yield very accurate values for ionization potentials and some bond dissociation energies (Fig. 39). The ionization potentials determined were 8.469 eV in TlI, 7.64 eV in NaI, 7.64 eV in Na_2I_2, 9.57 eV in MgI_2, and 8.22 eV in Te_2. The bond energies determined were 2.770 eV in TlI and 2.64 eV in Te_2. Energies of formation were also obtained for some diatomic and polyatomic fragment ions. These results, which are much more accurate than those obtained heretofore by thermochemical or electron-impact techniques, are important in understanding the behavior of matter at high temperatures. The new light sources extend such measurements to many molecules of great interest at high temperatures.

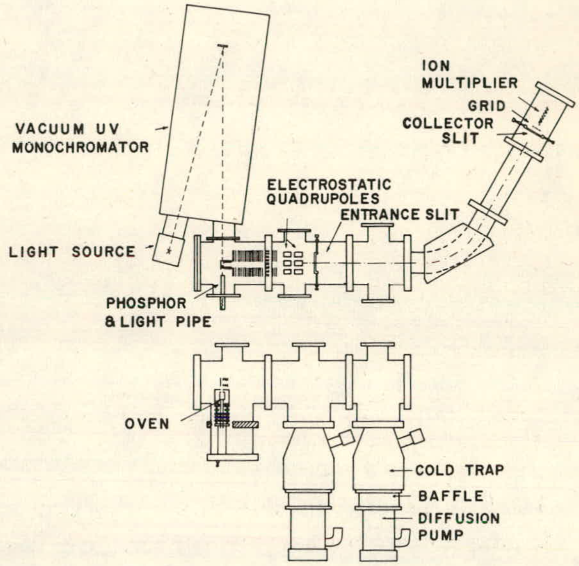

Fig. 38. Schematic diagram of the apparatus for photoionization mass spectrometry. The top view shows the path of photons and ions; the side view indicates the direction of the molecular beam. The near-normal-incidence monochromator used here enhances the photon intensity in the ionization region by an order of magnitude over that in designs used previously. The transmission of ions through the mass spectrometer is nearly 100%, again substantially higher than attained in earlier designs. This increase in sensitivity enables the experimenter to sacrifice light intensity by narrowing the entrance and exit slits of the monochromator in order to obtain significantly higher energy resolution in the ionization-efficiency curve. This not only gives more accurate threshold values for reactions, but also reveals fine structure not otherwise visible.

discrepancies among earlier measurements. The ionization potential of CF_3 is being measured indirectly by producing CF_3^+ as a fragment from other molecules. These measurements are necessary for the determination of certain bond energies of fluorocarbon molecules.

In the study of the photoionization of the methyl radical CH_3, the most important result has been the measurement of the threshold for the process $CH_3 + h\nu \rightarrow CH_2^+ + H + e^-$. This threshold together with Herzberg's spectroscopic value for the ionization potential of CH_2 gives the value 88 ± 2 kcal/mole for the heat of formation of CH_2. This is the most reliable and accurate measurement of this quantity, whose value has been in dispute for decades; and with further refinement of technique the error can be made negligible.

b. Dissociation of Polyatomic Ions by Collision

The cross sections for dissociation and ion-molecule reactions observed in collision of molecular ions with various neutral gas molecules have been measured. In many cases, the cross sections for collision-induced dissociations were found to be surprisingly large (ca. 10^{-16} cm^2) at energies only a few volts above threshold in the center-of-mass system. In addition, thresholds for some endoergic processes and the kinetic energy released in some decompositions have been measured. These experiments are part of an effort to understand the details of ion-molecule reactions at energies well above thermal.

2. STUDY OF FRAGMENTATION PROCESSES

H. E. Stanton

A method of interlacing the kinetic energy distribution of an unknown ion with the distribution of a known ion many times during a single sweep in kinetic energy has been developed and the necessary equipment has been installed in mass spectrometer MA-17. The interlacing is accomplished by switching the high voltage so that first one ion and then the other is tuned in, and at the same time the energy-selector voltage is slowly swept over the energy range. This has improved the stability of the instrument by reducing the effects of time variations and increasing the precision of the kinetic energy measurements.

The fragmentation of molecules by electron impact under varying source conditions continues to be studied with the energy-selecting mass spectrometer MA-17. Since the kinetic energies of the fragments are almost always quite small in the center-of-mass system, it has been necessary to develop methods of analyzing the distributions to separate the energies of formation from thermal motions and possible instrumental effects. Further efforts are being devoted to a mathematical process of stripping off the effects of instrumentation and thermal kinetic energies to give the intrinsic kinetic energy distribution of the reaction itself in the center-of-mass coordinate system.

3. HIGH-TEMPERATURE STUDIES OF EQUILIBRIA AND CHEMICAL KINETICS

D. Bayer, J. Berkowitz, and W. A. Chupka

The saturated vapor of tellurium was analyzed mass spectrometrically and found to consist predominantly of Te_2 molecules, as inferred by earlier workers. However, significant amounts of Te_5 are present as well as lesser amounts of other polymers. The heat of formation of Te_5 and the free energies of formation of Te_6 and Te_7 have been determined. It will be of interest to compare the stability of the polymers of tellurium with those of the related elements sulfur and selenium.

4. ATOMIC AND IONIC IMPACT PHENOMENA ON METAL SURFACES

M. Kaminsky

a. Atomic Impact Phenomena at Thermal Energies

By means of a recently developed technique of combining modulated atomic and/or molecular beams of alkali metals and alkali halides with phase-sensitive mass-spectrometric detection, the mean residence times τ_i of alkali ions on atomically clean surfaces of polycrystalline wolfram have been studied as a function of the composition of the incident beam. These precise measurements of τ_i and the desorption energies E_i of the ions (Table IV) showed that the atomic and molecular composition of the beam significantly affected both E_i and the quantity $\tau_i{}^0$ in Frenkel's equation $\tau_i = \tau_i{}^0 \exp E_i/kT$.

In addition, the function $\tau_i(T)$ was measured for the desorption of Na^+, K^+, and Rb^+ from an atomically clean polycrystalline wolfram surface and for the desorption of Li^+, Na^+, K^+, and Rb^+ from strongly gas-covered wolfram surfaces and precise values of E_i were

TABLE IV. Values of $\tau_i{}^0$ and E_i for the desorption of alkali ions from clean polycrystalline tungsten surfaces bombarded by atomic or molecular beams of known composition.

Desorbing ion	Composition of beam	Surface coverage degree Θ due to incident beam	$10^{13}\ \tau_i{}^0$ (sec)	E_i (eV)
Na^+	Atomic sodium	2×10^{-3}	0.85 ± 0.15	2.69 ± 0.03
	45% Na, 24% NaCl, 31% Na_2Cl	2×10^{-3}	2.00 ± 0.50	2.55 ± 0.03
K^+	Atomic potassium	2×10^{-4}	0.59 ± 0.10	2.41 ± 0.03
	70% K, 11% KCl 15% K_2Cl	2×10^{-4}	6.20 ± 1.00	2.30 ± 0.03
Rb^+	Atomic rubidium	2×10^{-4}	0.47 ± 0.10	2.12 ± 0.02
	85% Rb, 5% RbCl, 10% Rb_2Cl	2×10^{-4}	15.5 ± 0.80	2.05 ± 0.02

obtained.[1] These results, together with those for desorption of neutral particles, will serve to ascertain whether or not the adsorbate may exist on the surface in two different long-lived states (the atomic and the ionic states). The experiments will be extended to monocrystalline targets.

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[1] M. Kaminsky, Advances in Mass Spectrometry 3, 295 (1966); Ann. Physik 18, 53 (1966); Proceedings of the 25th Annual Conference on Physical Electronics, MIT, 1965, p. 173.

b. Ionic-Impact Phenomena in the Rutherford Collision Region

(i) Species of Charged and Uncharged Particles Emitted from Monocrystalline Targets under High-Energy Ion Impact. These studies have been continued with the aid of the portable mass spectrometer MA-27 and the 2-MeV Van de Graaff. When the (111) planes of Al and Cu monocrystals were bombarded with deuterons with energies from 0.2 to 1 MeV, the most abundant species of charged sputtered particle was the singly-charged ion. As in the earlier observations[1] on the (110) and (100) planes of Cu and Ag crystals, the yield of singly charged ions decreases with increasing energy—partly because of the corresponding decrease of the cross section for displacement of a lattice atom. Diatomic ions were about a thousandth as abundant as the atomic species; and an increasing number of doubly-charged ions are observed above 500 keV for Al and above 850 keV for Cu. For both target materials, the most abundant species of uncharged sputtered particles was found to be monatomic. The observed large value of the ratio of charged to uncharged sputtered particles in this energy region is incompatible with the surface-ionization models used by some authors; the suggested model[1] involving charge-changing collisions successfully explains the data. The study will be extended to other target materials and to other energies and species

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[1] M. Kaminsky, Advances in Mass Spectrometry 3, 69 (1966).

of incident ions, partly with the aid of a larger (15-in. radius, 90° sector field) spectrometer MA-28 now being designed. A vacuum system for use in preparing monocrystalline foils is being purchased. Such foils will be used in studies of "forward sputtering," of charge-transfer of the transmitted primary particles, and of stopping power.

(ii) Positive Ion Emission from Metal Monocrystals under High-Energy Deuteron Bombardment. The total yield S_i of secondary positive ions has been measured[2] for atomically clean (111) surfaces of Al, Cu, and Ag monocrystals bombarded by 0.4—1.6-MeV mass-analyzed D^+ beams at angles of incidence of 0° and 45°. At these energies, S_i decreases slightly with increasing deuteron energy E_d at normal incidence, but at 45° incidence it increases. The ratio of positively charged to uncharged sputtered particles is large (of the order of 30%—75%) and increases with increasing E_d, in accordance with the suggested model of charge-changing collisions between energetic recoil atoms and quasi-stationary lattice atoms. For these target materials, S_i decreases from Ag to Cu to Al (Fig. 40), in contrast to recent observations[3] with

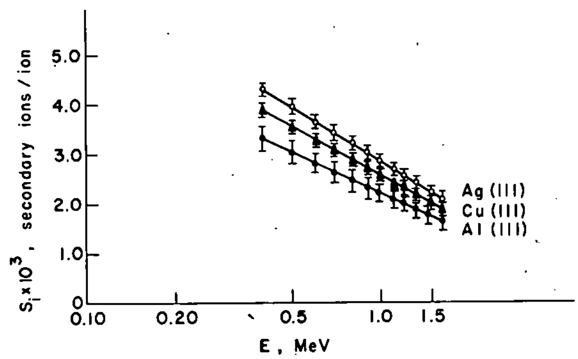

Fig. 40. The total yield S_i of secondary ions leaving the (111) planes of aluminum, copper, and silver monocrystals under deuteron bombardment at normal incidence.

[2] M. Kaminsky and K. Swenson, Proceedings of the 26th Annual Conference on Physical Electronics, MIT, 1966, p. 316.

[3] H. Beske, Z. Naturforsch. 19a, 1627 (1964).

polycrystalline samples in the hard-sphere collision region. Mass-spectrometric data[4] indicate that the value of S_i is determined predominantly by the emission of sputtered charged particles of the target material.

(iii) Electron Emission from Metal Monocrystals under High-Energy Ion Impact. (a) Dependence on the crystallographic orientation of the crystal. We established recently[5] that, in contrast to theoretical predictions,[6] the yield γ in the Rutherford collision region shows a significant dependence on the crystal plane bombarded. For deuteron bombardment (Fig. 41a) we observed that at normal incidence

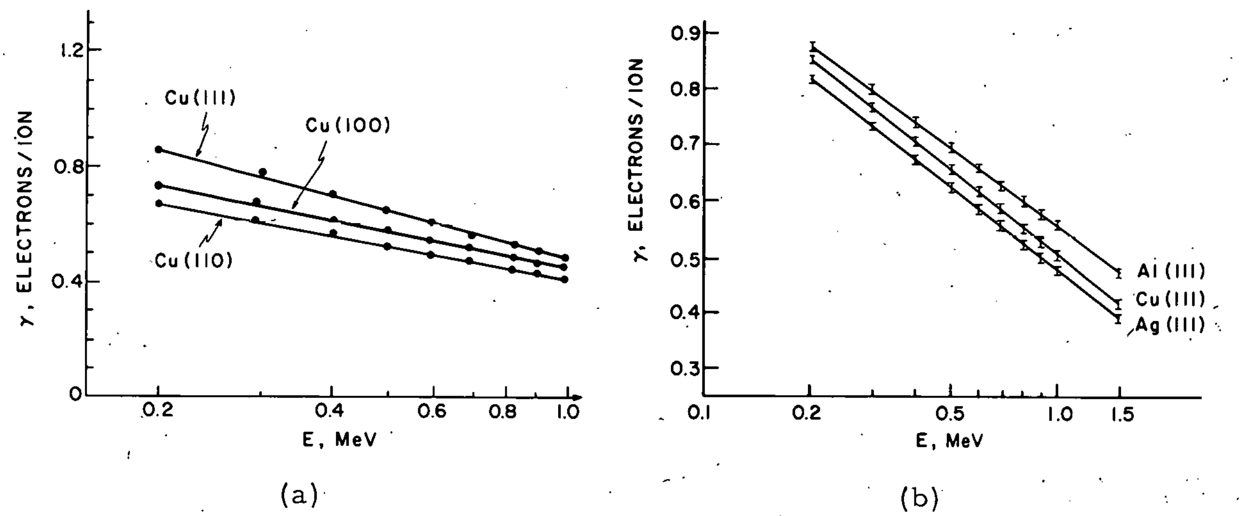

Fig. 41. Energy dependence of the total secondary-electron yield γ for monocrystals bombarded by D^+ ions incident normal to the surface. (a) Effect of crystal plane: plots for the (111), (100), and (110) planes of Cu monocrystals. (b) Effect of target material: plots for the (111) planes of Al, Ag, and Cu monocrystals.

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[4] M. Kaminsky, Advances in Mass Spectrometry 3, 69 (1966).

[5] M. Kaminsky and G. Goodwin, Proceedings of the 25th Annual Conference on Physical Electronics, MIT, 1965, p. 213.

[6] E. J. Sternglass, Phys. Rev. 108, 1 (1957), especially p. 6.

the yields for the low-index planes of copper decrease in the order $\gamma(111) > \gamma(100) > \gamma(110)$, and for aluminum and silver $\gamma(111) > \gamma(100)$. Both the relative yields from the different crystal planes and the variation of yield with angle of incidence indicate that the number of secondary electrons per incident ion was least when the ions were directed along channels formed by rows and planes of atoms and greatest when the ion path was most obstructed by lattice atoms. These measurements will be extended to other fcc and bcc metals.

(b) Dependence on the target material. In contrast to theoretical predictions[6] that the yield γ in the Rutherford collision region should be practically independent of the target material, measurements[7] on atomically clean surfaces of monocrystals of Al, Cu, and Ag showed a dependence on the target material. For deuterons at normal incidence (energy range 0.2—1.5 MeV) the yield values (Fig. 41b) decreased in the order $\gamma[Al(111)] > \gamma[Cu(111)] > \gamma[Ag(111)]$. This behavior reflects the dependence of the cross section for ionizing a lattice atom by ion impact on the target material. As a surface became gas covered, the yield increased significantly and the distinctions between different target material became less apparent. The dependence of γ on the target material is found to exist also for H^+, H_2^+, and for He^+ bombardment.

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[7] M. Kaminsky and P. Eastman, Proceedings of the 26th Annual Conference on Physical Electronics, MIT, 1966, p. 331.

5. OPERATION OF THE 2-MEV VAN DE GRAAFF ACCELERATOR

Jack R. Wallace and W. Evans

The 2-MeV Van de Graaff accelerator has operated 1674 hours from 1 April 1965 to 31 March 1966. It currently is operating 40 hours per week. Protons, molecular hydrogen ions, deuterons, and alphas have been accelerated to energies from 150 keV to 2 MeV.

During the past year the vacuum has been improved by changing from a 4-in. oil diffusion pump to a 6-in. mercury diffusion pump and a convenient valve system has been installed. The corona system to stabilize the high voltage has been modified and a new design of the voltage-dividing column has been installed. The vacuum chamber of the analyzing magnet has been modified to give higher beam transmission. A better-regulated focus supply has been installed. The new water-cooling system being built for the 4-MeV Van de Graaff will also serve this machine.

6. SEARCH FOR FRACTIONALLY-CHARGED PARTICLES

W. A. Chupka, J. P. Schiffer, and C. M. Stevens*

Recent theoretical developments indicate that elementary particles may be built up of particles with charges of $\frac{1}{3}$ e and $\frac{2}{3}$ e. An experimental search is being made to investigate the possibility that such particles may exist freely in nature in very small concentrations. Samples of meteorites, of the atmosphere, and of sea water have been examined with no positive indications. To escape detection in these measurements, the mass of such "quarks," if they exist at all as free particles, must be greater than 20—30 BeV/c^2. The measurements are being further refined.

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*Chemistry Division, ANL.

IV. PUBLICATIONS FROM 1 APRIL 1965 THROUGH 31 MARCH 1966

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. THE ELECTRON-NEUTRON INTERACTION FROM THE SCATTERING OF NEUTRONS BY NOBLE GASES
   V. E. Krohn and G. R. Ringo
   Phys. Letters 18, 297-299 (1 September 1965)

2. BORON-LOADED NEUTRON DETECTOR WITH VERY LOW γ-RAY SENSITIVITY
   H. E. Jackson and G. E. Thomas
   Rev. Sci. Instr. 36, 419-425 (April 1965)

3. NEW VALUES OF NEUTRON SEPARATION ENERGIES
   H. E. Jackson, A. I. Namenson, and G. E. Thomas
   Phys. Letters 17, 324-325 (15 July 1965)

4. LOW-LYING EXCITED STATES OF Sc^{46} POPULATED IN THE THERMAL-NEUTRON CAPTURE REACTION $Sc^{45}(n,\gamma)Sc^{46}$
   H. H. Bolotin
   Phys. Rev. 138, B795-B803 (24 May 1965)

5. MEASUREMENTS OF NEUTRON CROSS SECTIONS OF Fe, Al, AND CF_2 BY A RATIO METHOD
   A. Langsdorf, Jr., J. E. Monahan, R. O. Lane, and A. J. Elwyn
   Phys. Rev. 142, 643-656 (18 February 1966)

6. POLARIZATION AND DIFFERENTIAL CROSS SECTIONS IN THE SMALL-ANGLE SCATTERING OF NEUTRONS BY URANIUM
   A. J. Elwyn, J. E. Monahan, R. O. Lane, A. Langsdorf, Jr., and F. P. Mooring
   Phys. Rev. 142, 758-767 (18 February 1966)

7. ISOBARIC-SPIN SELECTION RULE IN THE $B^{10}(d,\alpha)Be^{8}$ REACTION AT 7.5 MEV
   C. P. Browne* and J. R. Erskine
   Phys. Rev. 143, 683-687 (18 March 1966)

8. GAMMA DECAY OF THE 5.16-MEV STATE IN B^{10}
   R. E. Segel and R. H. Siemssen
   Phys. Letters 20, 295-297 (15 February 1966)

9. STATES IN C^{12} BETWEEN 16.4 AND 19.6 MEV
   R. E. Segel, S. S. Hanna, and R. G. Allas
   Phys. Rev. 139, B818-B830 (23 August 1965)

10. THE 1^- STATE AT 4.45 MEV IN O^{18}
   B. Zeidman and T. H. Braid
   Phys. Letters 16, 139-141 (15 May 1965)

11. PROTON-CORE EXCITATION IN THE GROUND STATE OF O^{18}
   J. R. Erskine, R. E. Holland, R. D. Lawson, M. H. Macfarlane, and J. P. Schiffer
   Phys. Rev. Letters 14, 915-918 (31 May 1965)

12. STUDY OF THE $F^{19}(He^3,d)Ne^{20}$ REACTION
   R. H. Siemssen, L. L. Lee, Jr., and D. Cline†
   Phys. Rev. 140, B1258-B1266 (6 December 1965)

13. SEARCH FOR A SECOND STATE IN Ne^{20} NEAR 4.97 MEV
   L. Meyer-Schützmeister and R. E. Segel
   Nucl. Phys. 71, 343-347 (September 1965)

14. GIANT RESONANCES AND FINE STRUCTURE IN Si^{28} FROM THE $Al^{27}(p,\gamma)Si^{28}$ REACTION
   P. P. Singh, R. E. Segel, L. Meyer-Schützmeister, S. S. Hanna, and R. G. Allas
   Nucl. Phys. 65, 577-601 (1965)

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*University of Notre Dame.

†University of Rochester.

15. $Ca^{40}(d,p)Ca^{41}$, A TEST OF THE VALIDITY OF THE DISTORTED-WAVE BORN APPROXIMATION
L. L. Lee, Jr., J. P. Schiffer, B. Zeidman, G. R. Satchler,* R. M. Drisko,* and R. H. Bassel*
Erratum: Phys. Rev. 138, AB6-AB7 (28 June 1965)

16. ^{47}K MASS FROM THE REACTION $^{48}Ca(d,^{3}He)^{47}K$
E. Newman,* J. C. Hiebert,* and B. Zeidman
Phys. Rev. Letters 16, 28-30 (3 January 1966)

17. ENERGY LEVELS IN Sc^{49} FROM $Ca^{48}(He^{3},d)Sc^{49}$, AND OTHER REACTIONS PROCEEDING FROM Ca^{48}
J. R. Erskine, A. Marinov, and J. P. Schiffer
Phys. Rev. 142, 633-637 (18 February 1966)

18. INELASTIC ALPHA-PARTICLE SCATTERING BY Mn^{55} AND Co^{59}
H. W. Broek
Phys. Rev. 139, B1160-B1163 (6 September 1965)

19. WIDE-ANGLE SCATTERING OF 43-MEV ALPHA PARTICLES BY Ni^{58}
H. W. Broek, J. L. Yntema, B. Buck,* and G. R. Satchler*
Nucl. Phys. 64, 259 (1965)

20. THE SCATTERING OF 33-MEV He^{3} ON THE EVEN-A NICKEL ISOTOPES
R. H. Siemssen, T. H. Braid, D. Dehnhard, and B. Zeidman
Phys. Letters 18, 155-157 (15 August 1965)

21. COLLECTIVE EXCITATIONS IN THE ZIRCONIUM ISOTOPES
H. W. Broek and J. L. Yntema
Phys. Rev. 138, B334-B339 (26 April 1965)

22. DECAY OF $_{55}Cs^{129}$
E. B. Shera and S. B. Burson
Phys. Rev. 140, B531-B536 (8 November 1965)

23. HIGH-RESOLUTION STUDY OF (d,p) REACTIONS ON TARGETS OF W^{182}, W^{184}, AND W^{186}
J. R. Erskine
Phys. Rev. 138, B66-B77 (12 April 1965)

*Oak Ridge National Laboratory.

24. LEVELS OF Tl^{206} AS OBSERVED AT HIGH RESOLUTION WITH THE $Tl^{205}(d,p)Tl^{206}$ REACTION
J. R. Erskine
Phys. Rev. 138, B851-B856 (24 May 1965)

25. COULOMB EXCITATION AND THE SCATTERING OF 43-MEV ALPHA PARTICLES BY Pb^{208}
G. R. Satchler,* H. W. Broek, and J. L. Yntema
Phys. Letters 16, 52-53 (1965)

26. ENERGY LEVEL STRUCTURE OF Th^{231}, U^{235}, U^{237}, Pu^{241}, AND Pu^{243} AS OBSERVED AT HIGH RESOLUTION WITH (d, p) REACTIONS
T. H. Braid, R. R. Chasman (Chemistry), J. R. Erskine, and A. M. Friedman (Chemistry)
Phys. Letters 18, 149-154 (15 August 1965)

27. PROPOSAL FOR A SOURCE OF COMPLETELY POLARIZED DEUTERONS
D. von Ehrenstein, D. C. Hess, and G. Clausnitzer†
Phys. Letters 19, 114-116 (1 October 1965)

28. BLOCKING EFFECTS IN THE EMERGENCE OF CHARGED PARTICLES FROM SINGLE CRYSTALS
D. S. Gemmell and R. E. Holland
Phys. Rev. Letters 14, 945-948 (7 June 1965)

29. MEASUREMENT OF X-RAY SPECTRA OF MUONIC ATOMS IN THE INTERMEDIATE REGION
J. A. Bjorkland (Electronics), S. Raboy, C. C. Trail, R. D. Ehrlich,‡ and R. J. Powers‡
Nucl. Phys. 69, 161-172 (July 1965)

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64. CHARGE RADII FROM COULOMB ENERGIES OF ANALOG STATES
J. P. Schiffer and K. W. Jones*
Bull. Am. Phys. Soc. 10, 1084 (1965)

65. ALPHA DECAY OF THE 5.16-MEV STATE IN B^{10}
R. E. Segel, P. P. Singh,† and M. A. Grace‡
Bull. Am. Phys. Soc. 10, 1115 (1965)

66. LIFETIME OF THE 1.95-MEV LEVEL IN Ca^{41}
P. P. Singh, R. H. Siemssen, R. E. Segel, and S. I. Baker
Bull. Am. Phys. Soc. 10, 1115-1116 (1965)

67. GIANT RESONANCE IN $Mg^{26}(\alpha,\gamma)Si^{30}$
Z. Vager, L. Meyer-Schützmeister, R. E. Segel, and P. P. Singh
Bull. Am. Phys. Soc. 10, 1084 (1965)

68. DECAY OF 5.7-DAY Mn^{52}
F. Wagner, Jr. (Chemistry), M. S. Freedman (Chemistry), F. T. Porter (Chemistry), and H. H. Bolotin
Bull. Am. Phys. Soc. 10, 1116 (1965)

69. STUDY OF $Zn^{66,68}(He^3,d)Ga^{67,69}$ REACTIONS
B. Zeidman, R. H. Siemssen, and L. L. Lee, Jr.
Bull. Am. Phys. Soc. 10, 1126 (1965)

American Physical Society, Los Angeles, California, 20—22 December 1965.

70. QUADRUPOLE RESONANCE IN KrF_2 USING THE MÖSSBAUER EFFECT
S. L. Ruby and H. Selig (Chemistry)
Bull. Am. Phys. Soc. 10, 1202 (1965)

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*Brookhaven National Laboratory.

†Indiana University.

‡Oxford University.

American Physical Society meeting, New York, 26—29 January 1966.

71. INTERNAL SYMMETRIES ALLOWED IN A MANY-CHANNEL MODEL
J. T. Cushing
Bull. Am. Phys. Soc. 11, 22 (1966)

72. $Ti^{48}(d,d)Ti^{48}$ FROM 6 TO 11 MEV
C. Mayer-Böricke and R. H. Siemssen
Bull. Am. Phys. Soc. 11, 82 (1966)

73. x RAYS FROM MUONIC BISMUTH
S. Raboy, R. E. Coté, R. Guso (Special Materials and Services), R. A. Carrigan, Jr.,* A. Gaigalas,* R. B. Sutton,* and C. C. Trail†
Bull. Am. Phys. Soc. 11, 129 (1966)

74. $Zn^{64,66,68}(d,p)$ REACTIONS
J. P. Schiffer, D. von Ehrenstein, and L. L. Lee, Jr.
Bull. Am. Phys. Soc. 11, 100 (1966)

75. MÖSSBAUER QUADRUPOLE RESONANCE IN Sb^{121}
R. E. Snyder,‡ G. B. Beard,‡ S. L. Ruby, and G. M. Kalvius (Solid State Science)
Bull. Am. Phys. Soc. 11, 51 (1966)

76. CONCEALED CONFIGURATION MIXING IN THE NUCLEAR SHELL MODEL
J. M. Soper| and R. D. Lawson
Bull. Am. Phys. Soc. 11, 102 (1966)

77. ENERGIES OF x RAYS FROM MUONIC TANTALUM
C. C. Trail,† R. A. Carrigan,* A. Gaigalas,* R. B. Sutton,* R. E. Coté, S. Raboy, and R. Guso (Special Materials and Services)
Bull. Am. Phys. Soc. 11, 129 (1966)

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*Carnegie Institute of Technology.

†Brooklyn College.

‡Wayne State University.

|A. E. R. E., Harwell, England.

C. ANL TOPICAL REPORT

1. SURVEY OF POLARIZED ION SOURCES IN EUROPE
   D. C. Hess and D. von Ehrenstein
   Argonne National Laboratory Topical Report
   ANL-7118 (November 1965)

D. PHYSICS DIVISION INFORMAL REPORTS

1. USERS' MANUAL FOR THE SPEAK-EASY PROGRAM
   S. Cohen and M. Kraimer (Applied Mathematics)
   Physics Division Informal Report PHY-1965A
   (September 1965)

2. A COMPUTER PROGRAM FOR AUTOMATIC DECOMPOSITION OF SPECTRA FROM CHARGED-PARTICLE REACTIONS
   P. Spink and J. R. Erskine
   Physics Division Informal Report PHY-1965B
   (December 1965)

3. MONTE CARLO CALCULATION OF THE EFFICIENCY OF THE COMPTON POLARIMETER IN DETECTING THE LINEAR POLARIZATION OF GAMMA RAYS
   G. T. Wood
   Physics Division Informal Report PHY-1965C
   (December 1965)

V. STAFF MEMBERS OF THE PHYSICS DIVISION

The Physics Division staff for the year ending 31 March 1966 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 1965 through 31 March 1966, there were 33 temporary staff members (22 staff members from universities and other laboratories and 11 post-doctoral fellows), 6 graduate students (including 4 doing thesis research), and 25 undergraduates (4 in the Argonne Semester program of the Associated Colleges of the Midwest, 7 co-op technicians, 8 CSUI-ANL Honor Students, and 6 on summer appointments).

RESEARCH AT THE REACTOR CP-5

Permanent Staff

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

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

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

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

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

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

†Sol Raboy, Ph.D., Carnegie Institute of Technology, 1950

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

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*Director of Physics Division.

†No longer at Argonne as of 31 March 1966.

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

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

Resident Research Associates

Erhard Bieber, Dr. rer. nat. in Physics, Technische Hochschule, 1965
(On leave from Technische Hochschule, München, Germany)

Donald Blatchley, Ph. D., Indiana University, 1964
(On leave from University of Iowa)

†Michael D. Crisp (RSA, summer, Washington University)

†Patrick D. Doherty, Ph. D., St. Louis University, 1962
(On leave from Santa Clara University)

†Harnam S. Hans, Ph. D., Aligarh Muslim University, 1953
(On leave from Texas A & M University)

Arthur I. Namenson, Ph. D., Columbia University, 1963
(On leave from Columbia University)

William V. Prestwich, Ph. D., McMaster University, 1963
(On leave from McMaster University, Hamilton, Ontario, Canada)

†George Rieke (RSA, summer, Harvard University)

FAST-NEUTRON REACTIONS

Permanent Staff

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

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

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

Alexander Langsdorf, Jr., Ph. D., Massachusetts Institute of Technology, 1937

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

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†No longer at Argonne as of 31 March 1966.

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

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

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

J. L. Yntema, Ph. D., Free University of Amsterdam, 1952

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

Resident Research Associates

Samuel I. Baker (RSA, thesis, Illinois Institute of Technology)

A. E. Blaugrund, Ph. D., University of Utrecht, 1960
(On leave from Weizmann Institute of Science)

David D. Borlin (RSA, thesis, Washington University)

Dietrich Dehnhard, Ph. D., University of Marburg/Lahn, 1964
(On leave from Universität Marburg, Germany)

†Amnon Marinov, Ph. D., Hebrew University, 1962
(On leave from Hebrew University, Jerusalem, Israel)

Rolf H. Siemssen, Ph. D., University of Hamburg, 1963
(On leave from University of Hamburg, Germany)

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*Associate Director of Physics Division.

†No longer at Argonne as of 31 March 1966.

†P. Paul Singh, Ph.D., University of British Columbia, 1959
(On leave from Indiana University)

†Zeev Vager, Ph.D., Weizmann Institute of Science, 1952
(On leave from Weizmann Institute of Science)

Norman Williams, Ph.D., Manchester University, 1965
(On leave from Manchester University)

Dave Youngblood, Ph.D., Rice University, 1965
(On leave from Rice University)

DEVELOPMENT OF EQUIPMENT AND ACCELERATORS

Permanent Staff

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

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

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

Resident Research Associate

Dieter von Ehrenstein, Ph.D., University of Heidelberg, 1960

GAMMA- AND BETA-RAY SPECTROSCOPY

Permanent Staff

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

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

G. T. Wood, Ph.D., Washington University, 1956

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†No longer at Argonne as of 31 March 1966.

Resident Research Associates

†George B. Beard, Ph. D., University of Michigan, 1955
(On leave from Wayne State University)

Cecil F. Dam, Ph. D., Ohio State University, 1956
(On leave from Cornell College)

†Helmut J. Fischbeck, Ph. D., Indiana University, 1960
(On leave from University of Michigan)

†Teymoor Gedayloo, M. S., University of Washington, 1960
(On leave from Lawrence College)

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

MÖSSBAUER STUDIES

Permanent Staff

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

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

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

Stanley Ruby, B. A., Columbia University, 1947

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†No longer at Argonne as of 31 March 1966.

Resident Research Associates

†A. J. F. Boyle, Ph. D., Australian National University, 1957
(On leave from University of Western Australia)

†Michael A. Grace, Ph. D., Oxford University, 1950
(On leave from Oxford University)

Esther L. Segel, Ph. D., University of Rochester, 1959
(On leave from Illinois Institute of Technology)

†Richard E. Snyder (RSA, thesis, Wayne State University)

MUONIC X RAYS

Permanent Staff

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

Resident Research Associate

†Carroll C. Trail, Ph. D., Texas A & M College, 1956
(On leave from Brooklyn College)

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

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†No longer at Argonne as of 31 March 1966.

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

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

†Morton Hamermesh, Ph. D., New York University, 1940

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

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

†Donald Lang, Ph. D., Australian National University, 1961

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

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

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

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

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

Resident Research Associates

James T. Cushing, Ph. D., State University of Iowa, 1963

Benjamin Day, Ph. D., Cornell University, 1963

†Harry J. Lipkin, Ph. D., Princeton University, 1950
(On leave from Weizmann Institute of Science)

†Bernard Margolis, Ph. D., Massachusetts Institute of Technology, 1952
(On leave from McGill University)

Gert Roepstorff, Ph. D., University of Hamburg, 1964
(On leave from University of Hamburg, Germany)

John M. Soper, Ph. D., Trinity College of England, 1958
(On leave from A. E. R. E., Harwell, England)

†L. J. Tassie, Ph. D., University of Melbourne, 1957
(On leave from Australian National University)

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*Associate Director of Physics Division.

†No longer at Argonne as of 31 March 1966.

MASS SPECTROMETRY

Permanent Staff

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

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

Manfred Kaminsky, Ph. D., University of Marburg, Germany, 1957

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

Resident Research Associates

†Thomas C. Ehlert, Ph. D., University of Wisconsin, 1963
(On leave from Marquette University)

†Chava Lifshitz, Ph. D., Hebrew University, Jerusalem, Israel, 1961
(On leave from Hebrew University, Jerusalem, Israel)

Kamel M. A. Refaey (RSA, thesis, Illinois Institute of Technology)

RADIOFREQUENCY PLASMAS

Permanent Staff

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

Resident Research Associate

†Mazhar Hasan, Ph. D., Illinois Institute of Technology, 1959
(On leave from Northern Illinois University)

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†No longer at Argonne as of 31 March 1966.

ADMINISTRATIVE

Permanent Staff

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

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

USAEC Division of Technical Information Extension, Oak Ridge, Tennessee