Argonne National Laboratory

PHYSICS DIVISION SUMMARY REPORT

Annual Review

1 April 1966—31 March 1967
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PHYSICS DIVISION SUMMARY REPORT

Annual Review
1 April 1966—31 March 1967

Lowell M. Bollinger, Division Director

Preceding Summary Reports:

ANL-7247, June-August 1966
ANL-7284, September-December 1966
ANL-7312, January-March 1967
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 1967. 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 1966 through 31 March 1967 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 REACTOR CP-5

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

In the first category, preparations for a refined measurement of the symmetry properties of neutron decay are nearly completed. Data taking in this important experiment is expected to begin in the summer of 1967.

Neutron cross sections are measured by the time-of-flight method with a fast chopper. As has been true in the recent past, most of the effort is being devoted to the study of the gamma rays that result from the capture of neutrons in resonances. The three-parameter analyzer that is used to record the spectral information is being modified to make it more effective for use with Ge-diode detectors. This Argonne-developed analyzer, which is America's first multiparameter analyzer and the model for many commercial systems, has been used continuously for six years without a single electronic failure.

The largest effort is devoted to the study of nuclear structure by means of various measurements on the thermal-neutron-capture gamma rays. The high sensitivity of the internal-target facility that was completed in the past year has been intensively used in the study of a variety of targets ranging from Li$^6$ to Pu$^{240}$. An external-target facility for coincidence measurements with Ge-diode detectors has been completed and is being used. A program of improvements in the bent-crystal spectrometer is nearing completion; the modifications will result in much higher counting rates and better energy resolution. The effectiveness of an internal-conversion spectrometer that makes use of a superconducting magnet has been demonstrated for radioactive sources; during the coming year it will be used to investigate internal conversion of neutron-capture gamma rays. The various measurements provide the complementary information that is required to deduce refined and extensive decay schemes from neutron-capture reactions.
1. FUNDAMENTAL PROPERTIES OF THE NEUTRON

a. Measurements of the Symmetry Properties of the Decay of Polarized Neutrons

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. Improvements with respect to earlier experiments\(^1\) will include better counting statistics, more precise measurements of the degree of neutron polarization, and a demonstration that undesired asymmetries in the proton detector are not causing significant systematic errors.

To reduce statistical uncertainty by raising the neutron beam intensity, a new polarizing mirror is being made. A Stern-Gerlach magnet (Fig. 1) has been built and is found to give very adequate measurements (~1%) of the degree of neutron polarization. A number of changes have been made in the proton detector; the present version is considerably better (more uniform in efficiency) than the one used

Fig. 1. Contour map of the field gradients in a model five times the size of the pole pieces used in the experiment. This model, whose cross section is shown, was made of mild steel. The contours are labeled with the field gradients \( \partial |H|/\partial z \) in arbitrary units, where \( z \) is the coordinate in the vertical direction. The vertical component of the force on a neutron is proportional to this gradient, which was measured at fields well below saturation.

\(^1\)M. T. Burgy, V. E. Krohn, T. B. Novey, G. R. Ringo, and V. L. Telegdi, Phys. Rev. 120, 1829-1838 (1 December 1960).
for the earlier measurements. Nevertheless, further improvement of this detector would be very desirable and the effort to achieve such improvement is continuing.

b. Electron-Neutron Interaction

V. Krohn and G. R. Ringo

The objective of this program was to achieve a precise measurement of the electron-neutron interaction by studying the fore-and-aft asymmetry in the scattering of thermal neutrons by noble gases. This program has now been completed and the interaction strength measured with an uncertainty of ±2.5%. The result differs from the previously accepted value by about 15%, but the greatest significance of the new measurement is that it confirms that the low-energy electron-neutron interaction is substantially larger than one would predict on the basis of extrapolating the results of high-energy electron-deuteron scattering experiments to zero four-momentum transfer.


2. SLOW-NEUTRON RESONANCES

a. Time-of-Flight Studies

R. E. Coté, J. P. Marion, H. Shwe, G. E. Thomas, and W. V. Prestwich

A major part of the program at the fast chopper has been devoted to studies of capture gamma rays at neutron resonances. The remainder of the time has been spent on transmission measurements aimed at a measurement of the neutron-electron interaction and towards a better understanding of p-wave neutron interactions.
(i) p-Wave Radiation Widths. One way in which the interaction of s- and p-wave neutrons might differ is suggested by earlier fast-chopper experiments that showed that in niobium the average total radiation width $\Gamma_\gamma$ was larger for resonances associated with p-wave capture than for those associated with s-wave capture. Studies of the well established s- and p-wave resonances in Mo$^{95}$ suggest that the latter shows the same effect. The study of resonances in the other isotopes of molybdenum has led to values of the radiation widths for resonances in Mo$^{96}$, Mo$^{97}$, Mo$^{98}$, and Mo$^{100}$—but little information on the parity dependence of these widths. This is true mainly because no p-wave resonances have been positively identified in these other isotopes. Radiation widths obtained for a definite s-wave and a possible p-wave resonance in La$^{139}$ indicate little or no difference in the values, contrary to the results of earlier work. In addition to these values of the radiation widths, it was found that the effective nuclear radius for slow-neutron scattering is very low—in agreement with predictions of the optical model. The observation that strong gamma-ray transitions to well known 2$^+$ states in La$^{140}$ are associated with capture in the 70.9-eV resonance of La$^{139}$ allowed a $J^\pi = 3^-$ assignment to this resonance.

(ii) Spin Assignments of Neutron Resonances. The general problem of determining the spins of slow-neutron resonances has been one of the more difficult problems associated with the study of such resonances. No perfectly general method exists, but a very useful technique was developed here some years ago. It involves the study of the spectra of two-step cascade gamma rays to the ground state and/or low-lying excited states. Evidence presented during the past year suggested a possible failure of the technique for one of the resonances in Hf$^{177}$. At both the 1.1- and the 2.38-eV resonance in this nuclide (one for which the method had appeared to give unambiguous results), a primary gamma ray to a 2$^+$ level in Hf$^{178}$ was observed (Fig. 2). This indicated a $J^\pi = 3^-$ assignment for both resonances.
level in Hf$^{178}$, there is no information about the final state reached in the 6357-keV transition and therefore no incompatibility with the assignment of 4 for the spin of the 2.38-eV resonance.

A careful study with the fast chopper shows that it is not the same gamma ray at both resonances, but two gamma rays differing in energy by only 7 keV. The results therefore show the existence of a new level at about 1276 keV and suggest that it is this level that has $J^\pi = 2^+$ and not the level at 1269 keV.

(iii) The 35-keV Level of Sm$^{153}$. Resonance-capture gamma-ray spectra were also used to study low-lying states excited in the Sm$^{152}$($n,\gamma$)Sm$^{153}$ reaction at the 8-eV resonance of Sm$^{152}$. A level observed at 35 keV in Sm$^{153}$ from the Sm$^{152}$($d,p$) reaction had been assigned spin and parity $J^\pi = \frac{5}{2}^+$. The resonance-neutron-capture spectrum showed a very strong transition to this level from the $\frac{1}{2}^+$ capture state. Since the systematics of primary capture gamma rays show that such transitions are primarily dipole in character, the only reasonable assignment is either $\frac{1}{2}$ or $\frac{3}{2}$ for the 35-keV level. This rules out the previous assignment that had identified this level as the $\frac{5}{2}^+$ member of the [651]$\frac{3}{2}^+$ band.
b. Average Widths of High-Energy Radiative Transitions

L. M. Bollinger and G. E. Thomas

Although the partial radiation widths of high-energy states excited by neutron capture have been studied for many years, little is known about the average widths of transitions from many initial states to individual final states. The broad statistical distribution that governs the widths of the transitions from individual initial states prevents the thermal-neutron-capture gamma rays from giving useful averages, and heretofore it has not been technically feasible to measure the spectra of enough individual neutron resonances to obtain average widths with the required accuracy. We have by-passed these difficulties by directly measuring the average spectrum resulting from capture in many neutron resonances.

Basically the method of measurement, which makes use of a Ge-diode γ-ray spectrometer, consists in observing the capture γ rays emitted by a B10-surrounded sample that is located inside a nuclear reactor. The B10 absorber selectively removes low-energy neutrons and the f/E spectrum of the incident neutrons assures a low intensity of energetic neutrons. The combination limits the energies of the neutrons absorbed in the sample to a relatively narrow band that contains many resonances. The measurements are carried out at the internal-target facility at CP-5 and are feasible only because of the high sensitivity of the facility.

The new method of measurement has been used to study several problems of physical interest:

(i) High-Energy Transitions in Even-Odd Tungsten Isotopes.

The γ-ray spectra following thermal-neutron capture in the even-even isotopes of tungsten have been reported to exhibit regularities that appear to be inconsistent with a simple statistical model of the capture reaction. In particular, for the five nuclides studied, the transitions to the 3/2^- member of the [512] Nilsson band is always weaker than the transition to the [510] band. To test whether this regular behavior results from the influence of the nuclear structure of the final state or merely from a random fluctuation, the resonance-average spectra of the reactions W182(n,γ)W183, W184(n,γ)W185, and W186(n,γ)W187 were measured. Within the accuracy of the measurements, all of the transitions were
found to be of equal intensity. This indicates that the large differences observed in thermal-neutron-capture spectra result from an uninteresting statistical fluctuation.

(ii) Energy Dependence of High-Energy Radiative Transitions in the Reaction Pt$^{195}$($n, \gamma$)Pt$^{196}$. For the Pt$^{195}$($n, \gamma$)Pt$^{196}$ reaction, transitions from the initial band of states (just above the neutron binding energy at 7.9 MeV) to eight low-energy states in the energy range 0–1610 keV were observed. All of these are thought to be E1 transitions from 1$^-$ initial states to 0$^+$ or 2$^+$ final states. If the widths are assumed to vary as $E^{a}$, where $E$ is the $\gamma$-ray energy, the data give $a = 4.9 \pm 0.6$ (Fig. 3). The error results from a 12% uncertainty in the individual widths. This result is markedly different from the $E^{3}$ dependence predicted by the widely used single-particle model. However, it is in excellent agreement with the $E^{5}$ dependence that is expected if one assumes that the Lorentzian shape of the dipole giant resonance may be extrapolated to energies in the 6–8 MeV range. These results have been published.¹

(iii) High-Energy Radiative Transitions in the Reaction $^{183}\text{W} (n, \gamma) ^{184}\text{W}$. Measurements of the resonance-average spectrum of the reaction $^{183}\text{W} (n, \gamma) ^{184}\text{W}$ show that the high-energy transitions in $^{184}\text{W}$ also vary with $\gamma$-ray energy more rapidly than $E_\gamma^3$. In addition, the data show the power of the average-spectrum method as a spectroscopic tool. In particular, a previously missed low-energy state in $^{184}\text{W}$ is found, a state previously thought to have positive parity is shown to have negative parity, and the expected dependence of $\gamma$-ray intensity on the spin of the final state is observed.

(iv) Energy Dependence of High-Energy M1 Transitions. The reaction $^{105}\text{Pd} (n, \gamma) ^{106}\text{Pd}$ was studied with the aim of obtaining information about the energy dependence of high-energy M1 transitions. Unexpectedly, in initial measurements with a thick $^2\text{B}$ absorber it was found that the dominant process in the reaction is p-wave capture followed by E1 radiation instead of the expected s-wave capture followed by M1 radiation. A preliminary analysis indicates that the energy dependence of the E1 radiation is entirely different from the $E_\gamma^5$ dependence of the transitions in $^{196}\text{Pt}$. Attempts to observe the M1 radiation in $^{106}\text{Pd}$ are continuing.

3: THERMAL-NEUTRON-CAPTURE GAMMA RAYS

a. Research with the High-Sensitivity Internal-Target Facility

(i) Operation and Development (G. E. Thomas, D. E. Blatchley, W. V. Prestwich, and L. M. Bollinger). The new internal-target facility has been intensively used throughout the past year by many investigators in the study of the neutron-capture $\gamma$-ray spectra of some 50 isotopes. The sensitivity of the system is illustrated by the $^{13}\text{C} (n, \gamma)$ spectrum shown in Fig. 4. At the same time, there has been a continuing effort to refine the facility. This effort includes a reduction of the
Fig. 4. A portion of the spectrum of gamma rays from the reaction $^{13}\text{C}(n,\gamma)^{14}\text{C}$, the only lines attributable to capture in $^{13}\text{C}$ being the double-escape peaks at 6093 and 8174 keV. The sensitivity of the system is indicated by the good statistics obtained in a 20-hour run with the small sample of $^{13}\text{C}$, which has a cross section of only $0.8 \times 10^{-3}$ b. A further measure is the ease with which a 22-ppm chlorine impurity is detected.

background, the development of an annihilation pair spectrometer in which the annihilation quanta are detected in a large NaI annulus, and the design of a system to cool the sample under investigation.

(ii) Electromagnetic Transitions in the Magnesium Isotopes (R. T. Carpenter* and D. E. Blatchley). The gamma-ray spectra resulting from thermal-neutron capture in separated-isotope targets of Mg $^{24}$, Mg $^{25}$, and Mg $^{26}$ have been investigated with a lithium-drifted germanium detector at the internal-target facility. The energies and relative intensities of primary transitions from the capture state in each of the three residual nuclei have been obtained. In addition, branching ratios for the de-excitation of levels fed by these primary transitions have been determined in many cases.

In both Mg $^{25}$ and Mg $^{27}$, the thermal-neutron-capture state is $\frac{1}{2}^+$. Each decays predominantly by means of E1 transitions

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to states of negative parity lying several MeV above the ground state. In Mg$^{25}$ the states involved are located at 3414 and 4277 keV, while for Mg$^{27}$ the states occur at 3561 and 4826 keV. The decay scheme obtained for Mg$^{27}$ is substantially different from the scheme which has been previously proposed.

(iii) Gamma-Ray Transitions in F$^{20}$ (D. E. Blatchley and G. E. Thomas). Gamma-ray transitions following thermal-neutron capture in F$^{19}$ have been studied with a lithium-drifted germanium detector at the internal-target facility. Several de-excitation branches from the capture state have been used to determine the neutron binding energy in F$^{20}$ as $6602 \pm 1$ keV.

The most prominent branch in the decay of the capture state is to a level located at 6018 keV above the ground state. From observations of gamma-ray transitions from the capture state and from the level at 6018 keV to states in F$^{20}$ lying below 1 MeV in excitation, the tentative assignments for these low-lying levels are 665 keV ($3^+$), 828 keV ($4^+$), and 984 keV ($2^+$).

b. Energy Levels and Decay Schemes of Odd-A and Odd-Odd Nuclides

This experimental program seeks to provide information concerning the energies and decay schemes of the low-lying excited states of selected odd-A and odd-odd nuclides populated in thermal-neutron capture gamma-ray reactions. Two types of experimental systems are used to unravel these complex spectra. The high-energy gamma-ray transitions that populate the low-lying states of the product nucleus from direct decay of the capture state are observed with the high-sensitivity internal-target facility at the CP-5 reactor. These transitions establish the excitation energies of states within $1-2$ MeV of the ground state. The low-energy gamma-ray transitions between these low-lying excited states are studied by means of singles and coincidence gamma-ray spectroscopic techniques in a new external-neutron-beam facility at CP-5. Here, targets are placed in the external neutron beam (flux $\approx 5 \times 10^6$ neutrons cm$^{-2}$ sec$^{-1}$). Singles and coincidence spectra are obtained with the exclusive use of Ge(Li) detectors in conjunction with a two-parameter magnetic-tape recording.
system in a pulse-height array of 1024 \times 1024 channels. These two-parameter Ge(Li)-Ge(Li) coincidence studies of the gamma-ray transitions following thermal-neutron capture are the first known successful employment of this ultra-high-resolution technique in this field.

\textbf{(i) Low-Lying Excited States of Sc$^{46}$ (H. H. Bolotin).}

The low-lying excited states of the odd-odd Sc$^{46}$ nucleus have been studied in the thermal-neutron capture $\gamma$-ray reaction Sc$^{45}$ (n, $\gamma$)Sc$^{46}$. Ge(Li) detectors were used exclusively in obtaining both the singles and the coincidence spectra. The precise energies of the high-energy primary $\gamma$ rays were determined at the high-sensitivity internal-target facility. An external beam of thermal neutrons was employed to study the low-energy singles $\gamma$-ray spectrum and to carry out two-parameter $\gamma$-ray coincidence studies with two Ge(Li) detectors. Both high-energy/low-energy (Fig. 5) and low-energy/low-energy (Fig. 6) coincidence spectra were recorded. From these data, a level diagram and $\gamma$-ray decay scheme for states up to an excitation energy of \(~1200\) keV have been established in an unambiguous way.

\textbf{(ii) Levels in Ga$^{70}$ and Ga$^{72}$ (H. H. Bolotin, J. Vervier, and J. Yntema).} Although the odd-odd Ga$^{70}$ and Ga$^{72}$ nuclides are believed to be amenable to detailed shell-model calculations, few low-lying excited states in these nuclei were known from previous charged-particle or neutron-capture investigations. The present experimental studies were therefore undertaken to provide detailed information for comparison with theoretical predictions. In the present series of investigations, the high-energy primary gamma-ray transitions following thermal-neutron capture in highly enriched samples of Ga$^{69}$ and Ga$^{71}$ were studied at the high-sensitivity gamma-ray facility at the CP-5 reactor. These data have established the excitation energies of many of the low-lying excited states of these odd-odd nuclides. Both to establish levels not observed in the thermal-neutron-capture study and to establish the angular-momentum-transfer characteristics of all states seen, the
Fig. 5. Gamma-ray spectra following the thermal-neutron reaction $^{45}\text{Sc}(n,\gamma)^{46}\text{Sc}$, as recorded with Ge(Li) detectors. Left: Singles spectrum of high-energy gamma rays. Right: Direct singles spectrum and high-energy/low-energy coincidence spectra gated, as indicated, by the cross-hatched peaks labeled A—D in the high-energy spectrum. Chance coincidences and coincidences due to the underlying continuum have not been subtracted.
low-lying levels of these nuclides were also studied by means of the (d, p) reaction. As a third approach, the Ge(Li)-Ge(Li) coincidence facility will be used in gamma-gamma coincidence studies of the transitions proceeding between these states. With the combined results from these three techniques, it is expected that detailed decay schemes can be developed for these Ga isotopes.

(iii) Low-Lying Levels in Ag$^{108}$ and Ag$^{110}$ (H. H. Bolotin and A. I. Namenson). The high-energy primary gamma-ray transitions following thermal-neutron capture in highly enriched samples of Ag$^{107}$ and Ag$^{109}$ were studied at the high-sensitivity gamma-ray facility at the CP-5 reactor. These studies have established
33 primary transitions in $^{108}\text{Ag}$ and 46 such transitions issuing from the capture state in $^{110}\text{Ag}$. In each nuclide, these transitions were used to define the low-lying states in these nuclides to an accuracy of about $\pm 1$ keV up to an excitation energy of $\sim 1300$ keV. The observed strengths of the primary transitions were examined to determine the possible presence of systematic regularities of the type reported in the rotational region of the rare-earth nuclides. These data were compared with previous (d, p) studies (Fig. 7) with a view towards establishing the parity of the states populated in both reactions.

Fig. 7. Level schemes of $^{108}\text{Ag}$ and $^{110}\text{Ag}$. In each case, the levels determined from the present investigation are shown on the left and those from previously reported (d, p), (n, γ), and isomeric-decay studies are shown on the right. The diagonally shaded areas denote the uncertainties in the positions of the states observed in the (d, p) reaction.
(iv) Levels Populated in the Thermal-Neutron Reaction $^{89}\text{Y} (n, \gamma)^{90}\text{Y}$ (H. H. Bolotin). The detailed level structure of the low-lying states of the odd-odd nuclide $^{90}\text{Y}$ is believed to be understandable on the basis of the shell model. The purpose of the present study is to provide information about $^{90}\text{Y}$ states populated in the thermal-neutron-capture reaction to confirm or extend the results of previous charged-particle investigations. Preliminary analyses of primary high-energy gamma-ray data obtained at the high-sensitivity gamma-ray facility at the CP-5 reactor have yielded accurate information about many previously unobserved transitions. In combination with the results from charged-particle experiments, the data from the final evaluation will provide detailed information for comparison with shell-model calculations.

(v) Levels in $^{182}\text{Ta}$ from the Reaction $^{181}\text{Ta} (n, \gamma)^{182}\text{Ta}$ (H. H. Bolotin). The low-lying excited states of odd-odd deformed nuclei can provide significant information about the interaction between the odd nucleons when collective motion is present. For $^{182}\text{Ta}$, the high-energy primary capture gamma rays were studied at the high-sensitivity gamma-ray facility at the CP-5 reactor. These transitions define the energies of many low-lying excited states, some of which were not observed in previous studies with the (d, p) reaction. In addition, the decay properties of these low-lying states are now being measured in gamma-gamma coincidence studies with the Ge(Li)-Ge(Li) coincidence facility included in the new external-beam setup at the CP-5 reactor. These data, supplemented with previous (d, p) data, will be analyzed within the framework of the collective model.

(vi) Thermal-Neutron-Capture Gamma-Ray Studies of the Excited States of Odd-A Hafnium Isotopes (H. H. Bolotin and A. I. Namenson). The high-sensitivity gamma-ray facility was used to investigate the primary high-energy gamma rays following
thermal-neutron capture in the even-A isotopes \(^{176}\text{Hf}\), \(^{178}\text{Hf}\), and \(^{180}\text{Hf}\). The energies, intensities, and isotopic assignments of many of these transitions were determined. The primary transitions from the capture state to the low-lying Nilsson states in \(^{179}\text{Hf}\) and \(^{181}\text{Hf}\) were found to exhibit regularities which appear inconsistent with a wholly statistical capture model. These results, together with similar findings of other investigators for the cases of \(^{183}\text{W}\), \(^{185}\text{W}\), and \(^{187}\text{W}\), were discussed in terms of both the statistical model and evidence suggestive of operational selection rules that appear to govern the radiative decay of the capture states.

(vii) Low-Lying Excited States of \(^{122}\text{Sb}\) and \(^{124}\text{Sb}\) (H. H. Bolotin). The low-lying excited states of these nuclides can be used to test the applicability of the pairing interaction in odd-odd spherical nuclei. The neighboring Sn isotopes have already been shown to be well described by the model. The high-energy primary gamma-ray transitions to these low-lying states have been studied at the high-sensitivity gamma-ray facility at CP-5. To obtain additional information on these levels, the coincidence relationships between the cascade gamma-ray transitions will be studied at the external-beam Ge(Li)-Ge(Li) coincidence facility at CP-5.

(viii) The Level Structure of \(^{64}\text{Cu}\) and \(^{66}\text{Cu}\) (H. H. Bolotin, H. J. Fischbeck, and E. B. Shera*). A combined Argonne-Los Alamos study was undertaken to investigate the properties and characteristics of the low-lying excited states of the odd-odd \(^{64}\text{Cu}\) and \(^{66}\text{Cu}\) nuclides. The high-energy primary capture gamma rays populating the low-lying levels of these nuclides were studied at the high-sensitivity gamma-ray facility at the CP-5 reactor. The targets were a sample of natural Cu and highly enriched samples of \(^{63}\text{Cu}\) and \(^{65}\text{Cu}\). Virtually all the low-lying levels up to \(\sim 2\) MeV excitation energy

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Fig. 8. Proposed energy levels and decay schemes of the states in Cu$^{64}$ (above) and Cu$^{66}$ (below) as deduced from the series of singles and $\gamma$-$\gamma$ coincidence studies of the reactions Cu$^{63}$ ($n, \gamma$)Cu$^{64}$ and Cu$^{65}$ ($n, \gamma$)Cu$^{66}$, respectively. The relative intensities of the low-energy transitions are indicated by the widths of the arrows representing them. All energies are in keV. The solid flags on the left indicate states populated by primary $\gamma$-ray transitions from the capture states. The open flags on the right denote levels observed in previously reported (d, p) studies.
in both product nuclides were defined in this phase of the experiment. The low-energy transitions between these low-lying states were studied with a Ge(Li) detector and with a Ge(Li)-NaI coincidence facility at the Los Alamos Omega West reactor. These coincidence investigations between high-energy and low-energy transitions and between low-energy and low-energy transitions were sufficient when combined with the high-energy primary gamma-ray results to define the level and decay schemes of both nuclides (Fig. 8). The combined results have established additional states not populated directly by the high-energy transitions alone nor seen in (d, p) reaction studies.

c. (n, γ) Studies with the Bent-Crystal Spectrometer

(i) Modification of the Bent-Crystal Spectrometer
(R. K. Smither, D. Buss, and D. Bushnell). Preliminary testing of a newly-bent 2-mm-thick quartz crystal (11 × 12 × 0.080 in.) has been completed. As predicted by theory, the energy resolution of the instrument was improved to twice what could be obtained with the previous crystal (4 mm thick) without any appreciable loss in efficiency (reflectivity of the crystal) of the spectrometer. The line width of the spectrometer has now been reduced to about 5 keV (FWHM) at 1 MeV and 50 eV at 100 keV. Plans to obtain a 1-mm-thick crystal and a further improvement in energy resolution are under consideration.

A new multislit collimator for the bent-crystal spectrometer has been constructed and installed. The improvement in transmission of the new collimator has quadrupled the efficiency of the bent-crystal spectrometer for 400-keV gamma rays and has increased it by a factor of 50 for 40-keV gamma rays. Work is still continuing on the multislit collimator which will be placed in front of the spectrometer crystal in order to reduce the background counting rate in the spectrometer and increase the practical upper energy limit of the spectrometer.
Further modification of the remote-control source-changing apparatus (Fig. 9) was completed in June 1967. After 2 years of service, a number of weak points in the original system had become apparent. The changes are designed to remove these weak points and to improve the general reliability of the system.

Further work is proceeding on a vacuum chamber designed to hold four Ge-diode gamma-ray detectors with a combined active volume of 50-60 cc. This system will be used in connection with the bent-crystal spectrometer and, in some experiments, will replace the NaI gamma-ray detector normally used in the spectrometer. This new arrangement will make possible crystal diffraction measurements in the 2-5 MeV range. The practical limit of the present system is 2.4 MeV.

(ii) The Level Scheme of Hf$^{180}$ (Duane Buss and R. K. Smither). The gamma spectrum resulting from the Hf$^{179}$(n,γ)Hf$^{180}$ reaction had previously been obtained with the bent-crystal spectrometer and a germanium detector. These data are now being analyzed to construct

Fig. 9. Top view (above) and side view (below) of the remote-control facility for loading and storing sources for the bent-crystal spectrometer. The tape magazines and tape controller, which were completely redesigned, constitute the major change in the system. The four tapes (two on each side of the source tube) carry the (n,γ) source to the center of the reactor. They also control the rotation of the source about a vertical axis and the tilt of the source in a forward and backward direction. The rotation of the source about the horizontal axis (symmetry axis of the tube) is controlled by the worm gear shown at the upper left in the lower picture. The tape magazines (the reels shown in the figure) are used to store the perforated aluminum tapes when the source is withdrawn from the reactor. The sources are loaded and removed through a turret facility (out of sight at the left), which can also be used for storage of a hot source recently removed from the reactor. Part of the shielding was removed for this photograph. Normally the whole system is sealed in a tight box and operates in a He atmosphere.
a level scheme for Hf$^{180}$. Further data on the 1—3-MeV region of the (n, $\gamma$) spectrum will be taken with the new internal-target facility [Sec. I.A3a(i)], whose detector is a Ge diode mounted inside a large ring of sodium iodide—made in four optically isolated quadrants. The spectrum was first taken with the Ge diode in triple coincidence with opposite quadrants of the NaI ring to enhance the double-escape peaks, then in anticoincidence with the full ring to enhance the full-energy peaks. This technique, which has already been used with considerable success for the Te$^{123}$ (n, $\gamma$)Te$^{124}$ reaction [Sec. I.A3c(vii)], is expected to resolve most of the remaining questions about the highly complex level scheme of Hf$^{180}$ in the 1—2-MeV region of excitation where many overlapping rotational bands appear to exist.

(iii) The Neutron-Capture Gamma-Ray Spectrum and Energy Levels of Ge$^{74}$ (A. P. Magruder and R. K. Smither). The gamma-ray spectrum from the reaction Ge$^{73}$ (n, $\gamma$)Ge$^{74}$ was investigated with the Li-drifted Ge-detector facility at CP-5. Data from a natural-abundance source were compared with those from an enriched source to identify 44 primary transitions above 6 MeV from the neutron-capture state of Ge$^{74}$ (Ge$^{73}$ + n). A previously unreported direct transition to a level at 2.200 MeV was observed, as well as the transitions to established levels. The absolute energies of these gamma rays are found to $\pm$ 2 keV. The neutron binding energy determined from these is 10.203 ± 0.001 MeV.

The low-energy part of the spectrum from 0.2 to 3.0 MeV was also studied to improve the measurement of transitions between the low-lying states. The result is that the energies of five of the first six states have now been determined with an error less than 1 keV. These level energies are: 0.5963 ± 0.0004, 1.2049 ± 0.0006, 1.4662 ± 0.0004, 1.6999 ± 0.0006, and 2.1683 ± 0.0005 MeV. The intensities of both high- and low-energy gamma rays have been measured.
and will be used to interpret the level scheme. A paper is being prepared for the Physical Review.

(iv) Further Development of the Level Scheme of Cd$^{114}$

(R. K. Smither and A. P. Magruder). Further analysis of the Cd$^{113}$(d,p)Cd$^{114}$ proton angular distributions (performed at the Argonne tandem Van de Graaff), combined with the recent Cd$^{113}$(n,γ)Cd$^{114}$ experiment performed with the 7.7-meter bent-crystal spectrometer and the new through-tube Ge-diode facility at the reactor CP-5, has lead to the identification (Fig. 10) of the spin and parity of approximately twenty new levels above 1.5 MeV. Four of these states fit the theoretical description of the corresponding members of the 3-phonon quadrupole vibrational quintet ($0^+$, $2^+$, $3^+$, $4^+$, $6^+$). Their energies (in keV), spins, and parities are 1731.80 ($4^+$), 1783.19 ($3^+$), 1841.46 ($2^+$), and 1863.64 ($0^+$). Their energies and energy spacings are consistent with second-order perturbation theory. The enhancement of the E2 transitions to the 2-phonon states relative to those to the 1-phonon and ground states supports these associations. Three low-lying negative-parity states with energies (in keV), spins, and parities of 1757.77 ($2^-$), 1933.04 ($3^-$), and 1957.70 ($2^-$ or $1^-$) appear to be good candidates for members of the 2-phonon quadrupole-octupole vibrational quintet ($1^-$, $2^-$, $3^-$, $4^-$, $5^-$). Their energies and energy spacings are consistent with fourth-order perturbation theory and with the value of the B(E2) for the $3^-$ 1-phonon octupole state. In Fig. 11, the proton spectrum observed with the magnetic spectrograph at $60^\circ$ is compared with one of the Ge-diode runs. The considerable contrast between the relative intensities in the two experiments emphasizes the importance of combining more than one kind of experiment in the development of this type of level scheme.

The importance of this work on Cd$^{114}$ is that it is one of the few cases in which the level scheme of an even-N even-Z nucleus
is well enough developed to allow the identification of these higher-order collective states. A paper on this work is being prepared for publication.

(v) Level Schemes of Sm$^{150}$ and Sm$^{151}$ (R. K. Smither, E. Bieber, and A. P. Magruder). The high-energy portions of the Sm$^{149}$($n,\gamma$)Sm$^{150}$ and Sm$^{150}$($n,\gamma$)Sm$^{151}$ reactions were investigated with the new through-hole Ge-diode facility at the reactor CP-5. The results are now being combined with the bent-crystal data on the low-energy portion of the ($n,\gamma$) spectrum to extend the level schemes of Sm$^{150}$ and Sm$^{151}$.

(vi) Level Scheme of Hf$^{180}$ (R. K. Smither, D. Buss, and A. Magruder)

We are continuing the analysis of the new Hf$^{179}$($n,\gamma$)Hf$^{180}$ results and on the development of the Hf$^{180}$ level scheme.

The high density of energy levels in the 1–2-MeV region makes the analysis of the data very difficult.

(vii) Capture-Gamma-Ray Spectrum of Te$^{123}$($n,\gamma$)Te$^{124}$ and the Associated Energy Levels in Te$^{124}$ (R. K. Smither, R. P. Chaturvedi, D. Bushnell, and A. P. Magruder). Precise values of the low-energy gamma-ray spectrum (up to 1.59 MeV) resulting from thermal-neutron capture in Te$^{123}$ were obtained with the Argonne 7.7-m bent-crystal spectrometer. The observed
spectrum consisted of eighty gamma-ray lines starting from 104 keV. High-energy gamma rays have been observed with lithium-drifted germanium detectors. A considerable amount of new information about the \((n, \gamma)\) spectrum in the 1-3-MeV region has been obtained with the new Ge-diode facility installed in a large ring of NaI [described in Sec. I.A3a(i)]. The use of this facility is illustrated in Fig. 12.

By use of the known energies of the first two excited states in Te\(^{124}\) and the energy of the ground-state transition, the neutron binding energy of this isotope was calculated. It is found to be \(B_n = 9419 \pm 3\) keV. Excited states of Te\(^{124}\) up to 4 MeV are then calculated by use of the relation

\[
E_x = B_n - E_\gamma
\]

where \(E_x\) is the excitation energy of the state and \(E_\gamma\) is the gamma-ray energy. The energies of these excited states have been adjusted within a few keV to meet the requirements of possible connecting gamma-ray transitions. In all, forty states are populated either through direct decay of the capture state or through cascade decay of gamma rays. These values agree with the known values of the excited states from other sources.

Fig. 11. Comparison between the proton spectrum from the \((d, p)\) work at 60° and the gamma spectrum from the \((n, \gamma)\) reaction that populates the same levels in Cd\(^{114}\). The proton spectrum (upper graph) was obtained with the magnetic spectrometer at the Argonne tandem Van-de Graaff. The horizontal scale is the excitation energy of the Cd\(^{114}\) level populated by the proton group. In the gamma spectrum, only the double-escape peaks (escape of two annihilation quanta) are labeled with the corresponding excitation energies. (The label F.E. denotes a full-energy peak and S.E. a single-escape peak.) Note that the two reactions have quite different relative sensitivities to transitions to different levels with the same spin and parity.
Fig. 12. A comparison of the coincidence spectrum (below) and anticoincidence spectrum (above) for the $^{123}\text{Te}^{(n,\gamma)}^{124}\text{Te}$ spectrum taken with the new system consisting of a Ge diode in a large NaI ring. The coincidence (Ge + NaI) spectrum enhances the double-escape peaks, while the anticoincidence spectrum enhances the full-energy peaks.

(viii) Level Scheme of Sm$^{153}$ (R. K. Smither, E. Bieber, A. P. Magruder, and T. von Egidy*). The detailed analysis of the Sm$^{152}$($n,\gamma$)Sm$^{153}$ gamma spectrum, measured both with the Argonne bent-crystal spectrometer and with the through-tube Ge-diode facility at the reactor CP-5, was combined with von Egidy's conversion-electron results on the Sm$^{152}$($n,\beta$)Sm$^{153}$ reaction and with the Sm$^{152}$(d, p)Sm$^{153}$ results of Sheline et al. to construct a level scheme for Sm$^{153}$. Most of

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the levels seen in the (d, p) work also appear in the (n, γ) studies along
with many new levels. By combining the bent-crystal (n, γ) intensities
with the conversion-electron intensities, it is possible to define the
multipolarities of the gamma rays that interconnect the low-lying levels.
These multipolarities allow one to set limits on the relative spins and
parities of the low-lying levels and require many changes in the spin
and parity assignments based on the (d, p) work alone. A paper is being
prepared for publication.
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. Recent interest in intermediate structure has prompted several investigations that have given convincing evidence of such structure and have stimulated related experiments with alpha particles. The 4-MeV machine has also been used to measure the lifetimes of nuclear states by a Doppler-shift method.

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

J. R. Wallace

The 4-MeV accelerator has operated 3220 hours in the period from 1 April 1966 to 31 March 1967. It is currently operating on a schedule of 80 hours per week.

A continued effort has been devoted to obtaining and operating with larger beam currents at this Van de Graaff. The following improvements have been made. A new water-cooling system has been installed and is now in operation. Water cooling for beam components such as slits, shutters, target assemblies, etc. has been installed. An improved rf ion-source assembly has been in use. Grooved pulleys, part of an improvement in the belt-charging system, have been installed.

Other improvements and modifications include new power supplies for the analyzing magnets, further work on beam-control hardware, additional gamma shielding over the Van de Graaff machine, controlled pre-evaporated Li targets for neutron work, and a gas-changing system for the ion source in the high-voltage terminal.

Plans for replacement of the present 4-MeV Van de Graaff with a new accelerator capable of providing much larger beam currents have been completed. The 4-MeV Dynamitron has been chosen as the machine best suited to our needs and contract negotiations for it are in progress. Hopefully the new machine will be delivered in the fall of
1968. It will be installed at the same location as the present machine and will deliver its beam to the same system of experimental apparatus as is now in use. Thus, the change of accelerators will cause only a short interruption of the experimental program.

b. Polarization and Differential Cross Sections for Neutrons Scattered from Boron

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

Measurement of the differential cross section and polarization of neutrons scattered from $^{10}$B and $^{11}$B together with high-resolution total-cross-section measurements have recently been extended from the interval $0.075 \text{ MeV} \leq E_n \leq 0.500 \text{ MeV}$ for earlier work to the interval $0.500 \text{ MeV} \leq E_n \leq 2.24 \text{ MeV}$. Preliminary analysis indicates that a 2-channel single-level expression is inadequate for a correct interpretation of results for $^{11}$B + n in terms of states in $^{12}$B. Calculations in terms of a 2-channel 3-level R-matrix formalism are now being done by one of us (R. O. L.) at Ohio University. Effects of channel spin, bound states in $^{12}$B, comparison with $T=1$ states in $^{12}$C, and assignments of spins and parities to the scattering states are objectives of the analysis. Inspection of the experimental results shows that the parity of the state at $E_{\text{ex}} = 5.00 \text{ MeV}$ in $^{12}$B is most probably positive. Polarizations for $1.25 \leq E_n \leq 2.25 \text{ MeV}$ are large ($\geq 40\%$), so that $^{11}$B should be a useful analyzer when the R-matrix interpretation is complete. The differential-cross-section data for $^{10}$B + n show pronounced anomalies corresponding to states in $^{11}$B at $E_{\text{ex}} = 12.0$ and $13.15 \text{ MeV}$, while the polarization is virtually constant for the entire region $0.50 \text{ MeV} \leq E_n \leq 2.24 \text{ MeV}$. These results should lead to a better understanding of the heretofore little-known properties of the $^{11}$B states in this region.
c. Analysis of Intermediate Structure Observed in Neutron Scattering

(i) Analysis in Terms of Level-Parameter Statistics

(J. E. Monahan and A. J. Elwyn). Recent measurements of neutron total cross sections have revealed structure having widths intermediate between the narrow widths usually associated with states of the compound nucleus and the broad ones expected for single-particle states. During the past year, we have been studying various methods of analysis in attempts to distinguish between statistical and resonance interpretations of such structure. Results from the usual methods of correlation analysis, particularly as they relate to fluctuating cross sections with average values that vary as a function of energy, are difficult to interpret. The usual analysis is strictly valid only for stationary random variables. This circumstance, along with uncertainties caused by effects of finite sample size, could mask any indication of a characteristic intermediate width. In a slightly different approach, we have been able to define an "order statistic" which under certain specified conditions can provide a test of the validity of the statistical interpretation of such structure.¹

is "small," one can infer the existence of "long-range" correlations that would not be expected on the basis of statistical fluctuations of level widths and spacings.

(ii) Structure Observed in Scattering from $^{19}$F

(A. J. Elwyn and J. E. Monahan). As previously reported,$^2$ when the differential cross section and the polarization for neutrons scattered from $^{19}$F are measured as a function of energy from $0.5 - 2.2$ MeV, both have shown the existence of a resonance-like structure that has a width intermediate between what is usually associated with the states of the compound nucleus and the widths of single-particle states. We have recently completed a phase-shift analysis of the data in an attempt to test for several general properties of the observed structure.

The analysis was performed in terms of two real parameters for each possible set of angular-momentum quantum numbers. The energy dependence of the parameters as obtained in the analysis (Fig. 13) was found to be consistent with a model in which approximately isolated resonances that have (mostly) spins and parities of $1^-$ and $0^-$ could be assigned to the peaks in the measured cross sections.$^3$ Furthermore, although there are uncertainties in the analysis, there is good reason to conclude that there exists a nonzero "damping width" for decay of these states into the more complex compound-nucleus configurations—at least for some of the peaks above $1$ MeV.

The observed structure can therefore be treated as intermediate resonances corresponding to states in $^{20}$F. Furthermore, the observation that good-resolution measurements reveal the existence of a substantial number of fine-structure peaks is consistent with the

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at least tentative interpretation of these resonances as doorway states of the compound system.

(iii) Structure in Neutron Scattering from Cr (A. J. Elwyn and J. E. Monahan). As part of a program in which we have been investigating properties of the structure observed in neutron cross sections, particularly as it might be related to intermediate resonance structure, we have performed a phase-shift analysis of both cross-section and polarization data for neutrons scattered from Cr at energies up to 1 MeV. As previously reported, the observed structure has widths of 40—50 keV and separations of 70—80 keV when measured with an energy resolution width of 20 keV.

Earlier measurements of the neutron total cross section with 1-keV energy resolution width by a group at Duke University\(^4\) have revealed the existence of fine-structure fluctuations (widths

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Fig. 14. The energy dependence of the S-wave phase-shift parameters (δ - φ) and η for neutron scattering from Cr at energies below 0.75 MeV. The solid curves represent calculations based on a single-level interpretation in the region of the observed structure in the measured cross sections; the points represent the results of the phase-shift analysis of the data.

very much less than 40 keV) in the vicinity of these 40—50-keV-wide peaks. Many of these fine-structure peaks should probably be associated with P- and D-wave neutron interactions, although a number of narrow S-wave states have also been identified.

The energy dependence of the parameters in the phase-shift analysis of the present data is consistent with the existence of four or five approximately isolated S-wave resonance states located at energies below 0.75 MeV and having widths of about 40 keV, as seen in Fig. 14. However, since only a few of the fine-structure peaks observed in the total-cross-section measurements are associated with narrow S-wave states, it does not appear to be reasonable to interpret the observed 40-keV-wide structure as intermediate resonances whose strength is shared among many fine-structure states, each having the same spin and parity.

Intermediate-width structure is also observed in the energy dependence of cross-section and polarization measurements for other nuclei in the mass region near A ≈ 50—60. Further analysis is planned in an attempt to reveal various properties of such structure.
d. Small-Angle Scattering of Neutrons: Modification of the Experimental Arrangement


A completely new neutron detection system to be used in the continuing investigation of the differential cross section and polarization in the small-angle scattering of neutrons from nuclei was designed, built, and tested. It consists of four detectors to be used at four different small scattering angles simultaneously, and three smaller detectors to monitor the neutron beam. Each of the seven detectors is a stilbene scintillator mounted on a specially selected low-noise photomultiplier. Pulse-shape discrimination (PSD), based on a technique of measuring the time of baseline crossover, is used to reduce the high gamma-ray background. This background was further reduced by improving the shielding near the detectors.

The electronics for the PSD technique were designed and built in collaboration with the Electronics Division at ANL and were tested at the 4-MeV Van de Graaff accelerator. Detailed studies of the pulse shape of the scintillation in the stilbene crystals permitted an optimum adjustment of the PSD circuit. This, in conjunction with the low noise and high quantum efficiency of the photomultipliers, resulted in excellent neutron-gamma discrimination for pulse amplitudes corresponding to recoil protons with energies as low as 300 keV. The characteristics of the seven detectors were tested and found to be reproducible over a period of several weeks. The neutron detection efficiency of each of the detectors to be used in the small-angle scattering measurements is about twice the efficiency of a single detector of identical size that has been used in previous measurements at Argonne. With this improvement and the increased number of detectors, the time of data collection is cut by a factor of 8.
The new detection system was tested under typical data-taking conditions and is operating satisfactorily. At present we are using the system for detailed studies of the small-angle scattering of neutrons from several heavy elements (fissionable and nonfissionable) and at several neutron energies in the range from 0.5—2.2 MeV.

e. Neutron Cross Sections in the keV Region

C. T. Hibdon and F. P. Mooring

The equipment and techniques that have been used to study unbound nuclear levels in the keV region by neutron transmission measurements have been used to measure the neutron cross sections of Li$^6$ and lithium in the keV region. These measurements were made with the nearly monoenergetic neutrons produced when protons from the 4-MeV Van de Graaff accelerator bombard thin lithium targets (less than 2 keV thick). Since both Li$^6$ and lithium of natural isotopic abundance were measured, the cross section of Li$^7$ could also be obtained. The measurements, which are now completed from 10 to 900 keV, yield the neutron total cross sections. The measurements are to be extended to higher neutron energies.

The 4-MeV accelerator was also used to measure the neutron absorption cross section of Li$^6$ and lithium. Measurements have been completed from 10 to 100 keV, and are to be extended to higher energies. No resonance structure was observed in the region studied.

f. Scintillation Detectors

F. J. Lynch

The variation of light intensity with time following excitation by gamma rays has been measured for various organic scintillators. By refinements in the measurement and in the data analysis, mean lives
for energy transfer from solvent to solute and for decay of the fast component have been determined with an error of \( <0.1 \) nsec. Values have also been determined for the longer decay constants. Such measurements give fundamental information about the scintillation process, i.e., the probability of transfer of excitation energy from solvent to solute molecule, the time constant for decay of the singlet and excimer states, excimer formation rates, and rates of triplet formation, diffusion, and annihilation.

Such measurements also provide a basis for comparing the expected performances of different scintillators in specific measurements. For example, new liquid scintillators in the oligophenylene series have mean lives for transfer of 0.1 nsec and decay times of 1.2 nsec. These time constants are much faster than those of scintillators hitherto available. The speed and increased light efficiency have led to corresponding improvements in time resolution. For a 300-keV energy loss in the scintillator, for example, the full width at half maximum is 250 psec for the fast-time-resolution curve; and the slope corresponds to a virtual half-life of 35 psec.

To determine the best scintillator for pulse-shape discrimination between neutrons and \( \gamma \) rays, decay times have also been measured for pulses excited by neutrons. The time between the start of the photomultiplier pulse and a fixed fraction of the final integrated pulse height is used to distinguish scintillations caused by Compton electrons from those caused by recoil protons. Probability calculations based on the measured decay curves then provide a criterion for the performance of the system. Experimental measurements indicate high stability and good discrimination down to a neutron energy of 250 keV. A system consisting of six stilbene scintillation detectors has been constructed; these detectors have a common circuit and routing pulses are used to identify the detector channel. It is now being used in scattering experiments with polarized neutrons.
g. Lifetime Measurements by the Doppler-Shift Method


The measurement of lifetimes by the attenuated-Doppler-shift method has continued. The Electronics Division has made considerable progress in improving the Ge(Li) detectors, and this has made for more accurate measurements. Measurements on the first and third excited states of $^{41}$Ca have been completed. As a by-product of this measurement, gamma-ray lifetimes for the first and third excited states in $^{41}$Sc have been measured in a radiative-capture experiment.

We have made a series of measurements on the transition from a $J=0$, $T=1$ state to the $J=1$, $T=0$ state in self-conjugate odd-odd nuclei. The matrix element for this transition is closely related to the Gamow-Teller matrix element from the analog state. It can be seen that the theory is quite well verified and that where the spin-flip part of the transition is suppressed (as evidenced by the high $\log f_t$) the orbital part is evident.

The lifetimes of the first four excited states of $^{29}$Si have been measured. Here the state is produced in the $^{28}$Si$(d,p)$ reaction, and the recoil direction is defined by coincidence with a proton counter. Of particular interest is the very fast $E2$ transition from the second excited state. This is one of the fastest $E2$ transitions in this region of the periodic table; it indicates a high degree of collective motion.
C. RESEARCH AT THE 12-MEV TANDEM-VAN DE GRAAFF ACCELERATOR

The Tandem Van de Graaff accelerator, which was installed in 1962, is now used to its full capacity on an operating schedule of 24 hours per day. 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 some aspect of charged-particle-induced nuclear reactions. Recently, studies of direct reactions, the giant dipole resonance, and isobaric-spin analog 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.

a. Operation of the Tandem Van de Graaff Accelerator

Jack R. Wallace

The tandem has operated 6618 hours in the period from 1 April 1966 to 31 March 1967. This makes a total of 27,685 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 further modifications of the ion source and vacuum system to improve the characteristics of the beam entering the tandem. The carbon-foil ion stripper in the high-voltage terminal has been modified and has been working very successfully. An automatic beam-steering system for use in the experimental area is being designed.
Preparatory work for the conversion of the EN tandem to an FN tandem is in progress. The vault which houses the tandem has been extended, and in addition the interior of the building has been modified. An addition to house the polarized ion source was completed and the source is currently being moved and reassembled there. The design of a SF₆ insulating-gas system for use with the FN tandem has been completed. Both it and the new accelerator will be installed in the summer of 1967.

An enlargement of our data-handling area is under design and it is hoped that construction will take place later this year. It will provide more efficient use of our on-line-computer system for all experimenters using the tandem facilities.

b. Radiative-Capture Studies of the Giant Dipole Resonance

(i) The Na²³(p,γ)Mg²⁴ Reaction (L. Meyer-Schützmeister, R. E. Segel, and R. C. Bearse). The Na²³(p,γ)Mg²⁴ reaction has been studied at bombarding energies from 4 to 12.8 MeV. The usual transitions to the ground state and first excited state of the daughter nucleus—in this case Mg²⁴—were observed. However, the ground-state transition is unusually weak. This weakness can be explained on the basis of a single broad state,¹ a combination of particle-hole states, dominating the giant resonance. Since Mg²⁴ and Na²³ are in the lower part of the sd shell, the nucleon configuration of the giant resonance in Mg²⁴ contains predominantly d⁵/₂ holes and the direct proton emission should lead strongly to d⁵/₂ hole states in Na²³ only. But the ground state of Na²³ with its spin ⁵/₂⁺ is a more complicated state, and direct reaction components should be suppressed. This was confirmed by analysis of the data in terms of Ericson

fluctuations. The angular distributions showed their usual near invariance, which is somewhat surprising in view of the relative importance of the compound nucleus in this reaction. The ground-state angular distribution shows a marked dip at 90°. The yield to the first excited state is about normal.

(ii) Giant Dipole Resonance in Ar36 (L. Meyer-Schützmeister, D. S. Gemmell, R. C. Barse, N. G. Puttaswamy, and R. E. Segel). The radiative capture of protons by Cl35 has been studied over the range 4 ≤ Ep ≤ 12 MeV which covers the excitation region 12.4 ≤ Ex ≤ 19.2 MeV in Ar36. The experiments were performed in a manner similar to the others previously reported by the Argonne group.2 Figure 15 shows a yield curve taken in 25-keV steps with a 1.5 mg/cm^2 BaCl2 target; the Cl35 enrichment was about 99%. Most of the yield curve in Fig. 15 was taken at 45° to the incident beam, but the portion from 7.0 to 8.5 MeV was taken at 90° and an adjustment was made for the gamma-ray angular distribution. The yield curve is dominated by the onset of the giant resonance but, because of the comparatively low Q and also because the giant resonance appears to come at a higher energy in Ar36 than in neighboring nuclides, the beam energy was not high enough to reach the peak of the giant resonance. There is a great deal of fine structure but, at least in the giant-resonance region, the direct-interaction component contributes most of the cross section.

The $\gamma_1$ yield curve is qualitatively similar to that obtained for $\gamma_0$ except that the $\gamma_1$ yield is still rising at the high-energy end. This indicates that the peak of the $\gamma_1$ giant resonance has not yet been reached. The integrated ($\gamma_0$, $p_0$) yield, obtained by detailed balance, is 0.060 MeV-b which is about 11% of the dipole sum [taken as $(2\pi e^2 M/c)(N/Z/A)$.]

Angular distributions were taken every 100 keV over the entire range; some samples are shown in Fig. 16. The angular distributions show marked variations below the giant-resonance region but then settle down to the usual near-invariance at higher energy. The greater yield in the forward direction, indicative of E1-E2 interference, is quite marked.

(i) Angular-Correlation Measurements in Nuclear Reactions

(D. Cline, L. Meyer-Schützmeister, and T. H. Braid). Some controversy about the spin of the second excited state in Ca$^{39}$ exists in the literature. We therefore intended to determine the spin by angular-correlation measurements of the reaction Ca$^{40}$($He^3$, He$^4$$\gamma$)Ca$^{39}$. As we had done before in another reaction, we applied the frequently-used counter arrangement in which the outgoing particle (the alpha) is
detected at the fixed angle of $180^\circ$ to the incoming beam and the angle of the NaI(Tl) crystal serving as the $\gamma$ detector is varied from $90^\circ$ to $25^\circ$. The coincidences of the alphas and gammas are studied as a function of this angle. Unfortunately, the second excited state of Ca$^{39}$ was so poorly populated that this spin could not be determined uniquely even when the measurements were continued for a long time. We now plan to study the mirror nucleus K$^{39}$, which will have the same spin assignments for the lower states, by means of the reaction $\text{Ar}^{36}(a,p)\text{K}^{39}$. If the cross section is large enough, we can make a more definite spin assignment.

(ii) Energy Levels of Si$^{30}$ (N. G. Puttaswamy, D. S. Gemmell, L. Meyer-Schützmeister, and H. Ohnuma). Angular-correlation studies of the Si$^{30}(a,a'\gamma)$ reaction at $E_a = 13.000$ and $13.015$ MeV have led to spin assignments for the energy levels of Si$^{30}$. Since their population depends strongly on the bombarding energy, targets about $200 \mu g/cm^2$ thick were used. They consist of SiO$_2$ (95% Si$^{30}$) evaporated on thin carbon backings. Detecting the scattered alphas by an annular silicon detector at $180^\circ$ to the beam restricted the observation to natural-parity states. The gamma detector was a 25-cc Ge(Li) counter whose angle was varied from $30^\circ$ to $90^\circ$. A two-parameter analysis of the coincidences between the gammas and the scattered alphas showed strong excitation of the Si$^{30}$ states at 2.232 ($2^+$), 3.501 ($2^+$), 3.781, 4.807, 4.819, 5.276, and 5.954 MeV, the given values of $J^\pi$ being previously known. The level energies quoted above (estimated to have an error of 5 keV) are computed from the data at all angles by taking the Doppler shift into account. Our results show $J^\pi = 2^+$ and $0^+$ for the 4.819- and 3.781-MeV states, respectively; the value $0^+$ was deduced by comparing our result with those of Broude et al.\footnote{C. Broude, P. J. M. Smulders, and T. K. Alexander, Nucl. Phys. A90, 321 (1967).}
absence of the 3.767-MeV state in our experiment favors $1^+$, one possibility suggested by Broude et al.\textsuperscript{1}

(iii) The Level Structure and Decay Scheme of Sc$^{43}$ (J. J. Schwartz, \textsuperscript{*} W. Parker Alford, \textsuperscript{*} T. H. Braid, and L. Meyer-Schützmeister). The Ca$^{40}$($a,p$)Sc$^{43}$ and Ca$^{40}$($a,p\gamma$)Sc$^{43}$ reactions have been used to study the level structure and decay scheme of Sc$^{43}$ from the ground state through 1.95 MeV in excitation. To measure the angular correlations for the ($a,p\gamma$) reaction, the coincidences between the gammas and the protons detected at $180^\circ$ to the incoming $a$ beam were studied as a function of the angle of the gamma detector. The gammas were measured with a NaI(Tl) crystal which had the usual limited energy resolution of such crystals and which consequently was incapable of untangling the complicated $\gamma$ spectrum.

In order to obtain the energy level scheme of Sc$^{43}$, we therefore studied the ($a,p$) reaction in the magnetic spectrograph with a rather good energy resolution width of about 10 keV. In addition, we restudied the $p-\gamma$ coincidences with a Ge(Li) detector for the gammas. This gives a much better energy resolution for the gammas but the counting efficiency was small and the detector had to be placed directly behind the target. No angular correlation could be studied. All the results combined allowed us to observe previously unreported doublets with energies of (1.418, 1.426) MeV and (1.810, 1.826) MeV. There is some indication that a third doublet may lie at (0.846, 0.855) MeV. On the basis of the decay scheme, it is suggested that the levels at 1.810 and 0.475 MeV have spin $\frac{3}{2}$.

\textsuperscript{*}University of Rochester, Rochester, New York.
d. Nuclear-Structure Studies with Direct Reactions (A < 40)

(i) The (d, p) Reaction in the 1p Shell (G. C. Morrison, J. P. Schiffer, R. H. Siemssen, and B. Zeidman). We have obtained angular distributions of the (d, p) reaction at $E_d = 12$ MeV in the angular range $10^\circ - 155^\circ$ for targets of all stable isotopes between $^6\text{Li}$ and $^{14}\text{N}$. The experimental absolute cross sections were analyzed by use of DWBA calculations with average distorting parameters for light nuclei. The spectroscopic factors were found to be in reasonable agreement with those obtained in shell-model calculations, as shown in Fig. 17.

![Fig. 17. Experimental and theoretical reduced transition probabilities in the 1p shell.](image)

By far the worst disagreement was for the $^{12}\text{C}$(d, p)$^{13}\text{C}$ ground state, whose measured spectroscopic factor was 1.9 times the calculated one. No reasonable explanation for this anomaly can be offered. The sensitivity of the results to distorting parameters and to nonlocal, finite-range effects was investigated.

(ii) Mg$^{25}$(He$^3$, d)Al$^{26}$ Reaction (B. Zeidman, G. C. Morrison, R. H. Siemssen, * and A. Weidinger*). The Mg$^{25}$(He$^3$, d)Al$^{26}$ reaction has been used to investigate the levels of the self-conjugate odd-odd nucleus Al$^{26}$. All known states up to 4.1 MeV excitation have been observed. Angular distributions and

*Yale University, New Haven, Connecticut.

1 D. Kurath and S. Cohen (private communication).
spectroscopic factors have been used to set limits on the spins, parities, and wave functions of the observed levels.

(iii) \((\text{He}^3, \alpha)\) and \((\text{He}^3, \text{d})\) Reactions in the sd Shell

(J. L. Yntema and D. Dehnhard). The Mg\(^{26}\) \((\text{He}^3, \alpha)\)Mg\(^{25}\) and Si\(^{30}\) \((\text{He}^3, \alpha)\)Si\(^{29}\) reactions have been studied with the magnetic spectrograph. The Mg\(^{26}\) data have been used principally as an aid in the analysis of the cyclotron data on neutron pickup reactions on this nucleus. The Si\(^{30}\) \((\text{He}^3, \alpha)\)Si\(^{29}\) data have established an accurate position for the isobaric analog of the ground state of Al\(^{29}\) at 8.322 MeV. The location of the isobaric analog to the \(\frac{1}{2}^+\) 1.40-MeV level in Al\(^{29}\) is still somewhat uncertain. It is quite clear that there are a number of \(T=\frac{1}{2}\) levels in Si\(^{29}\) in the region where the isobaric analog state is expected. The data on the \((\text{He}^3, \text{d})\) reaction are being analyzed.

(i) \((\text{He}^3, \text{d})\) Reaction on \(1f2p\)-Shell Nuclei

(B. Zeidman, G. C. Morrison, and R. H. Siemssen). The \((\text{He}^3, \text{d})\) reaction on targets of Ti\(^{46,48,50}\) and Zn\(^{64,66,68,70}\) has been investigated. In addition to the observation and identification of spins and parities of a number of new levels, the effects of the interactions between protons and neutrons in the same single-particle state was observed. In particular, when protons are added to a target, the presence of neutrons in the same orbital results in a reduction in the observed excitation energy. This effect has been used to infer that the number of neutrons in the \(1g9/2\) shell increases abruptly in going from the lighter Zn isotopes to Zn\(^{70}\), as shown in Fig. 18. These results were discussed in an invited paper at the New York meeting of the American Physical Society, January 1967.

(ii) A Study of Low-Lying Levels in Sc\(^{48}\) with the Ca\(^{48}\) \((\text{He}^3, \text{t})\)Sc\(^{48}\) Reaction

(J. R. Erskine, J. A. Nolen, H. Ohnuma, and J. P. Schiffer). The low-lying levels in Sc\(^{48}\) are expected to belong
I. Ce

ASSUME: \( J = 1, J = \frac{3}{2} \) \( J = 3, J = \frac{5}{2} \) \( J = 4, J = \frac{9}{2} \)

Fig. 18. Spectroscopic factors for Zn(\( \text{He}^3, \text{d} \))Ga reactions. The legend indicates the \( \ell \) value for each transition. In extracting spectroscopic factors, all \( \ell = 1 \) transitions are assumed to be \( j = \frac{3}{2} \) transitions. Since some of the \( \ell = 1 \) transitions are, in fact, \( j = \frac{1}{2} \) transitions, the spectroscopic factors for these states should be multiplied by 2 when the spins are determined.

to the \((f_7/2)_p (f_7/2)_n^{-1}\) configuration. Seven states with \( J = 1 - 7 \) are expected within 2 MeV of the ground state, and many of them have been identified. In a recent study with the \( \text{Ti}^{49}(\text{t}, \alpha)\text{Sc}^{48} \) reaction, Schwartz suggested that the missing \( J = 2 \) state may be near 580 keV. However, although we have observed the previously known states at 0, 131, 253, 624, and 1144 keV excitation, we found no new state near 580 keV.

But perhaps a new state found near 1195 keV may be the missing \( 2^+ \) state:

(iii) Investigation of the \( \text{Ca}^{48}(\text{He}^3, \text{p})\text{Sc}^{50} \) Reaction

(H. Ohnuma, J. R. Erskine, J. A. Nolen, Jr., and J. P. Schiffer)

The \( \text{Ca}^{48}(\text{He}^3, \text{p})\text{Sc}^{50} \) reaction was studied at \( E(\text{He}^3) = 12 \) MeV by use of the Argonne tandem Van de Graaff and a broad-range magnetic spectrograph. It was found that \( Q_0 = 7.965 \pm 0.015 \) MeV and that there are excited states at 259, 331, 761, 1857, 2227, 2334, 3087, 3262, and 3289 \( \pm 5 \) keV. From a study of the \( \beta \) decay of \( \text{Ca}^{50} \), Shida et al. have assigned \( J^\pi = 1^+ \) to the 330-keV state. This assignment is difficult to reconcile with the fact that in the present work only four states are observed near the ground state, as expected from the \((f_7/2)_p (p_3/2)_n \) configuration. Our \( Q \) value, taken with that recently measured for \( \text{Ca}^{48}(\text{t}, \text{p})\text{Ca}^{50} \), yields \( Q_\beta = 4.966 \pm 0.020 \) MeV for the ground-state decay. If we assume that the \( \beta \) decay of \( \text{Ca}^{50} \) feeds some levels around
2 MeV instead of the 330-keV state, its log f is about 3.9. This fact suggests the importance of the core-excited configurations in Sc$^{50}$.

(iv) Spin Assignments in the 2p Shell from J Dependence in (d, p) Reactions (L. L. Lee, Jr., and J. P. Schiffer). The empirically established J dependence in (d, p) angular distributions has been used to assign spin values to energy levels in the nuclei Ti$^{47}$, Ti$^{49}$, Ti$^{51}$, Cr$^{51}$, Fe$^{59}$, and Ni$^{65}$ — most of which are populated by $f=1$ (d, p) transitions with large cross sections. The results are in general agreement with available nuclear-structure calculations. The results have been published.

(v) Energy Levels of Fe$^{59}$ from the Fe$^{58}$ (d, p) Reaction (E. D. Klema, L. L. Lee, Jr., and J. P. Schiffer). The angular distributions of the protons from the Fe$^{58}$ (d, p)Fe$^{59}$ reaction to eight states of Fe$^{59}$ have been measured (Fig. 19) with 10-MeV deuterons at the Argonne tandem accelerator. Data were taken at 15°—165°. Absolute cross sections were obtained by comparing elastically-scattered 7-MeV deuterons at 20° with the ground-state protons from the (d, p)
reaction at $E_d = 10$ MeV. Values of the orbital-angular-momentum transfer and spectroscopic factors were obtained by comparing the measured cross sections at the forward peaks with those calculated by means of the JULIE program. Spin assignments were made by use of the empirical rules of Lee and Schiffer. The present work results in the following assignments of

$$E_{\text{exc}} (\ell, J, S):$$

- ground state $(1, \frac{3}{2}^-, 0.45); 0.287$ MeV
- $(1, \frac{1}{2}^-, 0.22); 0.470 (3, \frac{5}{2}^-, 0.54); 0.728 (1, \frac{3}{2}^+, 0.20); 1.026 (3, \frac{7}{2}^-, 0.08); 1.214 (1, \frac{1}{2}^+, 0.81); 1.572 (4, \frac{9}{2}^+, 1.07); 3.59/[2J + 1]$
- spin $\frac{3}{2}^-$ or possibly $\frac{5}{2}^-$.

Fig. 20. Angular distributions and DWBA fits for $\ell=1$ transitions in the Zn isotopes.

(vi) (d, p) Reactions on Zn$^{64,66,68,70}$ (J. P. Schiffer and D. von Ehrenstein). Our experimental angular distributions (Fig. 20) for the (d, p) reaction on Zn$^{64,66,68,70}$, obtained with solid-state detectors and the magnetic spectrograph, permitted us to evaluate the Q values of the reactions and the excitation energies, spins, and parities of a final total of 100 levels—many of which were previously unknown or had different assignments. The decision between $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels was made on the basis of the J-dependence rules.

This investigation was then continued to obtain information about the filling of the neutron shell between the neutron numbers 34 and 40 (the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$ levels). This was done by
Fig. 21. Summed-spectroscopic factors as a function of the center-of-mass energies of single-particle states in the Zn isotopes. The line is calculated from pairing theory. The points enclosed in large circles or parentheses belong to Zn\textsuperscript{67}; they include a correction for the fact that the ground state does not coincide with the Fermi surface.

evaluating the spectroscopic factors which we derived through comparison of our experimental angular distributions and absolute cross sections with DWBA calculations. These spectroscopic factors can be discussed in the light of the theory (Fig. 21). The final paper reporting this experiment has been completed.

(vii) Ga\textsuperscript{69}(d, p)Ga\textsuperscript{70} and Ga\textsuperscript{71}(d, p)Ga\textsuperscript{72} (J. L. Yntema, H. H. Bolotin, and J. Vervier). These reactions have been studied both with the magnetic spectrograph and with the 60-in. scattering chamber. A number of new levels have been found and the analyzed data will be used in conjunction with the neutron-capture \gamma-ray work.

(viii) Absolute Spectroscopic Factors for (d, p) Reactions on Heavy Deformed Nuclei (J. R. Erskine and R. H. Siemssen). Work on absolute spectroscopic factors has continued in an effort to resolve a discrepancy of about a factor of 2 between the theory and experiment in the W\textsuperscript{182}(d, p)W\textsuperscript{183} reaction at \(E_d = 12\) MeV. The discrepancy persisted even after we removed an ambiguity in the deuteron optical potentials, and used a deformed Woods-Saxon well for the bound-state wave function. Applying the current DWBA theory to (d, p) reactions on rare earth nuclei at 12 MeV bombarding energy results in a large discrepancy in absolute spectroscopic factors if measured optical-model parameters are used. The source of the discrepancy is not known; but there is reason to suspect that it might disappear if strong-coupling
effects in the inelastic channels were treated correctly. A report on this study has been published.¹

(ix) A Study of Actinide Nuclei with Charged-Particle Reactions (T. H. Braid, A. M. Friedman,* and J. R. Erskine). Our efforts this past year have been mainly concentrated on U²³⁵ as a typical example of the fourteen odd-A nuclei we have studied. We have identified many rotational bands, based on intrinsic excitations. We have also found an interesting set of states at 700—1000 keV excitation that appear to arise from some vibrational excitation. These states have the unusual properties that they are excited equally well in (d, p) and in (d, t) reactions, and that their cross sections are about as large as the cross sections to the ground-state bands.

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f. Effects in Compound Nuclei

(i) Scattering of Alpha Particles by Medium-Weight Nuclei (P. P. Singh, * J. J. Kroepfl, * D. W. Devins, * A. J. Elwyn, and J. P. Schiffer). The elastic scattering of alpha particles from thin targets of Si²⁸, Si³⁰, Ca⁴⁰, and Ca⁴⁴ have been measured in the angular range 25—165° at energies between 8.0 and 14.0 MeV at the Argonne tandem accelerator. Structure having widths slightly larger than the energy resolution width have been observed in the yield curves at many of the angles. Optical-model and phase-shift analyses of these data are in progress in an attempt to isolate the various properties of such structure. Preliminary measurements of the scattering of alphas from thin targets of Ti⁴⁸ and Ni⁶⁴ have also revealed the

* University of Indiana, Bloomington.
existence of a resonance-like structure in the measured yields at some energies above 14 MeV. Further measurements are planned.


A distinct asymmetry in the line shapes of the 16.62- and 16.92-MeV levels in Be$^8$ has been found with the $^{10}\text{Be}(d, a)^8\text{Be}$ reaction at $E_d = 12$ MeV. A simple two-level resonance formula which includes an interference term has been found to give a good fit to the data. The best-fit parameters give more precise values for level widths and degrees of admixing than had previously been obtained for these two levels. The final report on this work has been published.¹

*University of Notre Dame, West Bend, Indiana.


g. Studies of Isobaric Analog States

(i) Lowest $T=\frac{3}{2}$ States in Al$^{25}$ (D. H. Youngblood, G. C. Morrison, and R. E. Segel). The $T=\frac{3}{2}$ states in Al$^{25}$ have been sought by observing the residual Al$^{25}$ activity¹ produced by the Mg$^{24}(p, \gamma)$ reaction. Two strong narrow resonances were observed at $E_p = 5.864 \pm 0.010$ MeV and $5.936 \pm 0.010$ MeV, as shown in Fig. 22. Both resonances are less than 3 keV wide. The lower corresponds to an excitation energy of 7.92 MeV in Al$^{25}$; an excitation energy of 7.93 MeV for the lowest $T=\frac{3}{2}$ state in Al$^{25}$, determined from the delayed-proton spectrum following the $\beta$ decay of Si$^{25}$, is in good agreement. The separation between the two resonances (69 keV) is somewhat less than the 90-keV splitting of the ground-state doublet.

in Na\(^{25}\). We searched unsuccessfully for the two higher states reported at \(E_{\text{exc}} = 9.17\) and 10.40 MeV. A Ge(Li) detector was used to measure the \(\gamma\) decay from the two observed resonances.

(ii) A Search for Threshold Effects in Coupled Channels

(G. C. Morrison, J. A. Nolen, Jr., J. P. Schiffer, and N. Williams).

If a given nuclear state can be populated by a \((d, p)\) reaction, then the isobaric analog of that state can be populated by the \((d, n)\) reaction on the same target. Normally the \(Q\) value for the \((d, p)\) reaction is positive while that for the corresponding \((d, n)\) reaction is negative. Thus by measuring the yield of the \((d, p)\) reaction as a function of beam energy, it is possible to observe effects in the \((d, p)\) channel which may be induced by the opening of the analogous \((d, n)\) channel. C. F. Moore et al. at the University of Texas observed a pronounced minimum in the Zr\(^{90}\) \((d, p)\) ground-state cross section at the threshold of the \((d, n)\) reaction to its analog state. The similar relation between the \((p, p)\) elastic scattering and \((p, n)\) "quasi-elastic" scattering reactions implies that such coupled-channel effects may also be observed with these reactions. By measuring \((d, p)\) and \((p, p)\) excitation functions on several targets, we have searched for additional examples of this phenomenon. Of the cases studied, only Ca\(^{48}\) \((d, p)\), Ni\(^{64}\) \((p, p)\), and Cu\(^{65}\) \((p, p)\) show fluctuations in the neighborhood of the threshold which are larger than the average fluctuations away from threshold. However, in these examples the threshold effects are much sharper functions of bombarding energy than observed in the Zr\(^{90}\) \((d, p)\) case. The reactions that showed
no effect at the angles studied are Zn\(^{70}\) (p,p), Zn\(^{70}\) (d,p), and Zr\(^{90,91,92,94}\) (p,p). The results for Zn\(^{70}\) (d,p) are shown in Fig. 23.

(iii) Coulomb

Displacement Energies of Ca-Sc Isobaric Pairs (J. A. Nolen, Jr., J. P. Schiffer, N. Williams, and D. von Ehrenstein). A new experimental technique for observing the isobaric analogs of the 0\(^+\) ground states of even-even nuclei by the (He\(^{3}\),p) reaction has been developed and was used to measure Coulomb displacement energies \(\Delta E_c\) in the Ca-Sc isobaric pairs with \(A = 44, 46, 48,\) and 50. The Ca\(^{46}\)(He\(^{3}\),d)Sc\(^{47}\) reaction was used to measure this quantity for \(A = 47\). With this information, \(\Delta E_c\) for all the isobaric pairs from \(A = 41\) to 50 is known for the ground states and for several excited states (Fig. 24). An analysis, in terms of the measured charge distributions of Ca isotopes and utilizing Woods-Saxon wave functions, yields a consistent picture. In one case, \(\Delta E_c\) for the 5.86-MeV 0\(^+\) state in Ca\(^{42}\) seems to exclude the \((2p_3/2)^2_0\) configuration for this state and suggests \((1f_{7/2})^2_0\) coupled to a 0\(^+\) core-excited state of Ca\(^{40}\). Measurements on other nuclei are in progress.

Fig. 23. Excitation functions for the Zn\(^{70}\)(d,p) reaction. The arrows indicate the threshold for populating the corresponding analog state via the (d,n) reaction.
Fig. 24. Coulomb-energy differences $\Delta E_C$ (upper graph) and neutron-well-radius constants $r_n$ (lower) for various Ca-Sc isobaric pairs. Some values of $\Delta E_C$ are for excited states. The values of $r_n$ were derived from the $\Delta E_C$ by the method described in the text. The error bars represent the uncertainties in $\Delta E_C$ and do not reflect uncertainties in the charge distribution or the other parameters nor in the assumptions entering into the calculation. [From Phys. Rev. Letters 18, 1140 (1967).]

(iv) Isobaric Analog States in the Barium Isotopes.

(G. C. Morrison, N. Williams, J. A. Nolen, Jr., and D. von Ehrenstein). Work on the elastic (Fig. 25) and inelastic scattering of protons has been extended to include all the stable isotopes of barium. Isobaric-analog resonances corresponding to f- and p-wave proton capture, which had been observed previously in Ba$^{138}$, Ba$^{136}$, and Ba$^{134}$, are seen also in Ba$^{132}$ and Ba$^{130}$. Both s- and d-wave resonances are also observed in Ba$^{136}$, Ba$^{134}$, Ba$^{132}$, and Ba$^{130}$.

Fig. 25. Proton elastic scattering from the even-mass barium isotopes. The excitation functions show many resonances corresponding to the low-lying levels in the parent analog nuclei.
The positions of the corresponding resonances in different isotopes vary systematically as a function of energy. Absolute Coulomb shifts for all the resonances have been obtained by use of the $Q$ values found from the $(d,p)$ reaction on the same targets [described in Sec. I. Cg(v)]. Except for the difference between La$^{131}$ and Ba$^{131}$, the ground-state Coulomb-energy differences vary closely as $A^{-1/3}$. Total widths $\Gamma$, partial widths $\Gamma_p$, and resonance energies $E_R$ have been derived by use of a program that fits the theoretical curve to the elastic-scattering resonances. Inelastic partial widths $\Gamma_p$, have also been obtained from the excitation functions for inelastic scattering. In particular, it has been observed that neutron particle-hole states based on a particular particle are strongly excited in inelastic scattering at the energy of the corresponding "particle" resonance. With Ba$^{137}$ and Ba$^{135}$ targets, the analogs of such states are observed as elastic-scattering resonances.

(v) $(d,p)$ Stripping Reactions on the Barium Isotopes

(G. C. Morrison, J. A. Nolen, Jr., N. Williams, and D. von Ehrenstein). In order to supplement our study of isobaric analog resonances in the Ba isotopes (preceding section), we investigated the $(d,p)$ reaction on all the stable Ba isotopes with the 12-MeV deuteron beam of the tandem. Protons were detected with a broad-range magnetic spectrograph. Angular distributions (Fig. 26) were obtained typically between $5^\circ$ and $50^\circ$. From the observed proton spectra, we obtained the level schemes of all the odd-$A$ barium isotopes from Ba$^{131}$ to Ba$^{139}$. Several of these levels were previously unknown. DWBA calculations were used to extract $f$ values and absolute spectroscopic factors for levels in different isotopes. The $(d,p)$ spectra of the odd-$A$ target isotopes Ba$^{135}$ and Ba$^{137}$ show strong excitation of the neutron particle-hole states at excitation energies $\gtrsim 4$ MeV in Ba$^{136}$ and Ba$^{138}$. The positions of these states are the same as those observed strongly in the inelastic proton spectra at isobaric analog resonances.
h. Lifetime Measurements

(i) Lifetimes of $d_{3/2}$ Hole States (R. E. Holland and F. J. Lynch). Partial radiative lifetimes for transitions to the ground state have been measured for $d_{3/2}$ hole states in Ca$^{43}$ and Ca$^{41}$. The observed lifetimes are respectively 120 and 60 times the M2 single-particle estimate. Inhibitions of from 100 to 275 were found for similar states in the scandium isotopes. A measurement of the corresponding transition in K$^{39}$ (${3 \over 2}^- \rightarrow {1 \over 2}^+$) gave an upper limit of 18 for the degree of inhibition of the M2 transition.

(ii) Coulomb Excitation of Low-Lying States of Sc$^{45}$ (A. E. Blaugrund, R. E. Holland, and F. J. Lynch). Because of its lifetime ($\tau = 0.47$ sec) and because of its population by pickup reactions with $I = 2$, the first excited state of Sc$^{45}$ at 12.4 keV excitation is thought to be a $3^+_1$ state. Similar states are observed in the other scandium isotopes as well as in calcium and titanium. The first
interpretation of these states described them as resulting from the promotion of a particle from the closed \( d_{3/2} \) shell to the \( f_{7/2} \) shell. An alternative model describes the state as resulting from the coupling of the odd \( f_{7/2} \) particle to the collective \( 3^- \) state of Ca\(^{44} \). The first model predicts that the E3 component in the radiative decay of the state should be small and about equal to the single-particle estimate. The second model would lead one to expect a larger E3 component, on the order of 20 times the single-particle estimate. A measurement of the E3 component by Coulomb excitation of Sc\(^{45} \) with Cl\(^{35} \) particles showed that it is less than 2.7 single-particle units. This is in agreement with a description of the state by the first model. A number of other properties of the first two states of Sc\(^{45} \) were obtained in the course of these measurements.

i. Development of Instrumentation at the Tandem

(i) Automation of the Scattering Chamber (J. L. Yntema).

The large scattering chamber at the Tandem has been assembled and aligned with the beam direction. The angular positions of the four detector arms are remotely controlled and can be changed by a pulser (which can be preset). The radial motion permits the remote adjustment of the distance from the target to the defining aperture in front of the detector in 1-cm steps. The target holder has space for eight targets, and the target to be bombarded can be selected by remote control. An interface between the ASI-210 computer and the control system of the scattering chamber has been constructed so that the computer can change the nine remotely-controlled parameters. Programs for the ASI 210 have been written to permit the computer to issue the appropriate commands. One program provides for the sequencing of a series of runs if the experimenter can predict the required number of incident particles. The other program allows the computer to take
angular distributions in such a way that 75% of the points for a given transition will have at least a preset statistical accuracy. All the components are now completed and the system is ready for testing as soon as sufficient time on the ASI 210 can be scheduled.

(ii) New Split-Pole Magnetic Spectrograph (J. R. Erskine). An Enge split-pole magnetic spectrograph will be installed at the tandem Van de Graaff accelerator. In addition to 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 have a larger solid angle of acceptance, higher resolving power, and a broader range of energy acceptance at a given magnetic field.

The new spectrograph should be in operation by the spring of 1968.

(iii) Data-Handling Programs for the ASI 210 (R. E. Holland). The ASI-210 computer installed at the Tandem now has (or, in some cases, will have) interfaces for controlling the beam shutter, the pulse-height analyzer mode, and the angular positions of the detectors—and for reading the scalers, pulse-height analyzers, and the frequency meter which is related to accelerator energy. In addition, an external memory with 98 304 locations can serve as the memory of a multichannel analyzer as well as storage for data and/or programs.

A data-handling program patterned after the program DIDJERIDO0 has been constructed. The new program consists of a series of subroutines which instruct the new peripheral devices as well as the old ones. These subroutines are linked in a Fortran program to provide data handling. We have put considerable effort into the construction and documentation of these programs in order to make them easily understood and easily changed by the experimenter, even though he is not an experienced programmer. This system of programs is just now being put into use.
(iv) Automatic Plate-Scanning Machine (J. R. Erskine, R. H. Vonderohe, * M. Machálek, and N. Sobel*). An automatic emulsion-scanning machine has been built to process plates that have been exposed in a magnetic spectrograph. This machine has been designed to cope with the large increase in nuclear track plates that will come from the two new split-pole magnetic spectrographs. The machine is now able to scan plates and produce useful data. The system uses a high-resolution electronic scanning tube and a PDP-9 digital computer. The machine is at least 50 times faster than a human scanner.

(v) Investigation to Improve the Contrast Between Tracks and Background in Nuclear Emulsions (J. R. Erskine and M. Machálek). The use of the automatic emulsion-scanning machine for processing plates from the magnetic spectrographs makes it very important to find a technique that gives consistently high contrast between tracks and background in the emulsions. Such factors as types of developer, concentration of developer, time, temperature, influence of various stop baths, fixers, etc. were studied systematically. We discovered the important fact that the use of a certain type of amidol developer at a temperature of 0°C reduced the fog level by a factor of 3 or 4 but only slightly reduced the grain density in the tracks. This reduction in fog level led to the discovery that a considerable amount of fog is produced by the gamma-ray background in the target room. In building the camera of the new split-pole spectrograph, we plan to incorporate special shielding to minimize this problem.

(vi) Thin-Target Vacuum Lock (J. A. Nolen, Jr.). In connection with nuclear scattering experiments at the Tandem, considerable time has been spent in designing and building a vacuum lock to permit targets to be introduced or removed without exposing

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them to the air either before or after the transfer. The system is intended primarily for use with thin evaporated foils of separated stable isotopes. It is particularly useful for such targets as metallic calcium which oxidize or otherwise deteriorate rapidly on exposure to air. It also permits the handling of extremely fragile foils without subjecting them to the stresses of pumping down or letting air into vacuum chambers. With this system, targets can be evaporated onto thin self-supporting carbon backings and then transferred under vacuum to an evacuated storage chamber which holds up to 90 targets. Any of the stored targets can be withdrawn from the storage chamber and used in one of three scattering chambers at the tandem, the 18-in. chamber at the cyclotron, or the 18-in. chamber at the Van de Graaff. Up to four of the targets can be loaded in a scattering chamber at a given time. This system differs from previous ones used at Argonne in that it permits preparation and storage of the targets prior to the experiment, storage of the targets for periods of months or more for use in future experiments, and use of several targets in the scattering chamber simultaneously.

(vii) Construction of the Source of Polarized Ions for the Tandem Van de Graaff (D. C. Hess, C. W. Schmidt, and D. von Ehrenstein). During the past year essential tests have been made on the individual parts of the source, some of them resulting in unexpected improvements. Polarization of the positive ions was successfully tested by means of the T(d, a)n reaction. A second form of ionizer, using a much stronger magnetic field, was built and tested. It gave higher ion currents, although the main purposes of the new design were to decrease the partial loss of polarization that might occur during the ionization process and to improve the vacuum.

Considerable time was spent in designing and testing a charge-exchange unit in which alkali metal vapor was used instead of the foil originally planned. The major advantages of the replacement
are: (1) Better preservation of beam quality (emittance) can be expected. The thinnest foils available place many more atoms in the beam path than are necessary to accomplish the change of charge. These additional atoms may serve to degrade the emittance of the beam and thus to decrease the usable current. With the vapor adder, the number of atoms in the beam path can be optimized by adjusting the temperature. (2) Higher efficiency was observed. We have used NaK (an alloy of sodium and potassium, liquid at room temperature) to supply K vapor without the hazard of handling pure potassium. This adder showed an excellent performance, yielding an 11% efficiency in the conversion of positive to negative ions (as compared with an efficiency of about 1—3% observed with a carbon foil). A strong guide field must be used with the vapor adder to avoid loss of polarization since the atoms spend some time in the neutral state. One possible disadvantage resulting from the use of the vapor adder is that the maximum conversion efficiency occurs at relatively low energies (a few keV) while it was planned to use the carbon foil with a beam energy of about 40 keV. This means that to obtain a beam of adequate stiffness to be efficiently handled (80 keV or more would have been obtained with the foil adder because of the "tandem" effect), it will be necessary to operate many of the source parts perhaps 75 kV below ground potential. To permit this unforeseen change in the mode of operation, the system is being modified.

The polarized source (Fig. 27) has recently been moved into the room built for it at the side of the Tandem vault. In this separate room, assembly and adjustment can continue without radiation hazard while the Tandem is being used for other experiments.
Fig. 27. The polarized-ion source being assembled in its new location next to the vault of the Argonne Tandem. The polarized ions are generated at the right in the background of the picture; the left part shows the half-finished system for spin orientation, beam focusing, and charge exchange.
University Use of the 12-MeV Argonne Tandem

J. P. Schiffer and F. P. Mooring

Since the formal inception of the program in January 1964, the provision of running time on the Tandem has supported the research of scientists from nine universities. However, the number of outside users is now diminishing at a perceptible rate, presumably because so many universities now have accelerators that are better than ours. At the same time, however, the time requirement has increased to >25% of the running time—probably because several theses are nearing completion.

The following experiments by university scientists are currently active at the Tandem.

(i) Multiple Coulomb Excitation and the Reorientation Effect

R. P. Scharenberg, G. Schilling, and J. W. Tippie

Case Institute of Technology, Cleveland, Ohio and Purdue University, Lafayette, Indiana

(ii) Studies of Isobaric-Spin Effects in Nuclear Reactions

C. P. Browne, W. D. Callender, J. R. Duray, and A. A. Rollefson

Notre Dame University, West Bend, Indiana

(iii) Studies of Energy Levels in Light Nuclei with the Magnetic Spectrograph

C. P. Browne, W. D. Callender, J. R. Duray, and A. A. Rollefson

Notre Dame University, West Bend, Indiana

(iv) Elastic and Inelastic Scattering of Alpha Particles by Light and Medium-Mass Nuclei


Indiana University, Bloomington, Indiana

(v) Elastic and Inelastic Scattering of Protons by Light Nuclei

B. A. Watson; J. J. Kroepl, and P. P. Singh

Indiana University, Bloomington, Indiana
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 provides a resolution width of 0.1% or less. In order to utilize the analyzed beam to the maximum extent, a split-pole magnetic spectrograph of the Enge type has been ordered. Delivery is expected by the end of 1967.

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

a. The 60-in. Scattering Chamber at the Cyclotron

(i) Improvement of the Scattering Chamber (J. L. Yntema). Preliminary sketches for redesign of the scattering chamber to permit automated control have been made. The data-handling system is in the process of being converted so that the readout from both the Packard and the Victoreen analyzer will be on computer-compatible magnetic tape.

(ii) Ti(α,α') Reaction (J. L. Yntema and G. R. Satchler\(^*\)). The study of the elastic and inelastic scattering of 43-MeV alpha particles by the titanium isotopes has been completed. The elastic-scattering

\(^*\)Oak Ridge National Laboratory, Oak Ridge, Tennessee.
Fig. 28. Alpha particles inelastically scattered from Ti\textsuperscript{50}, together with the calculated distorted-wave curves. The slight deviation from the calculated curves in the case of the 4.38-MeV data arises from small contributions from nearby levels with opposite parity. The 4.38-MeV level is a known s-hole state in Ti\textsuperscript{50}. The other \( \ell = 3 \) transitions correspond to known d-hole states. However, not all known d-hole states are preferentially excited in the inelastic scattering.

Data on the three even-even isotopes were fitted by several families of parameters for the optical-model potential. Both best-fit parameters and the average parameters were used in an investigation to determine how their use affected the deformation parameters extracted in a comparison with the vibrational model. It was shown that the deformation parameter \( \beta \) is quite insensitive to the choice of parameters for all values of \( \ell \). In the case of Ti\textsuperscript{50}, it is of interest to compare the states excited in the \( V^5\text{I} (d, \text{He}^3) \text{Ti}^5 \) reaction with the states excited in inelastic scattering (Fig. 28). The s-proton hole state is the strongly excited 3\(^-\) state. Some of the d-hole states are rather strongly excited in inelastic scattering, while others are not preferentially excited at all. The excitation of the first 2\(^+\) states and first 4\(^+\) states has been compared with the coupled-equation calculations and with the multiple-excitation and direct-excitation predictions of both the shell model and the vibrational model. The results agree with the shell-model predictions.
Fig. 29. Comparison between the experimental angular distributions from the Si\(^{30}\)(d,t)Si\(^{29}\) reaction and the calculated distorted-wave curves. The state at 3.62 MeV is known to have spin and parity \(\frac{7}{2}^-\) and is fitted with an \(f=3\) calculated curve. There is clearly a measurable admixture of \(f_{7/2}\) particles in the ground-state configuration of Si\(^{30}\). The angular distribution of the isobaric analog to the ground state of Al\(^{29}\) (\(E_x = 8.32\) MeV) is fitted with an \(f=2\) curve. The points at angles smaller than 21° suffer from the Cl\(^{12}\)(d,t)Cl\(^{11}\) reaction due to the carbon in the backing.

(iii) The Si\(^{30}\)(d,t)Si\(^{29}\) and Si\(^{30}\)(He\(^3\),a)Si\(^{29}\) Reactions (D. Dehnhard and J. L. Yntema). The results (Fig. 29) from the neutron pickup reaction indicate that the \(d_{5/2}\) neutron shell is nearly filled and that the remaining neutrons are split about equally between the \(2s_{1/2}\) and \(1d_{3/2}\) shells. A rather weak transition to the known \(\frac{7}{2}^-\) level indicates an admixture of a few percent of \(f\)-wave neutrons in Si\(^{30}\). The weak single-particle neutron-hole component in the 3.027-MeV level and the strong component in the 2.027-MeV level disagree with the conclusions one would draw from the gamma decay of these levels. The isobaric analog of the Al\(^{29}\) ground state was found at 8.32 MeV. The strength of the transition to the isobaric analog state exhausts the available \(d_{5/2}\) strength.

(iv) The Mg\(^{26}\)(He\(^3\),a)Mg\(^{25}\) and Mg\(^{26}\)(d,t)Mg\(^{25}\) Reactions (D. Dehnhard and J. L. Yntema). The transitions to the known \(\frac{7}{2}^+\) and
Fig. 30. Experimental angular distributions of the Mg^{26}(d, t)Mg^{25} reaction, together with the calculated distorted-wave curves. Although most of the fits are quite good, the fit of the transition to the $^{2+}$ level at 1.611 MeV is quite poor. The 3.40-MeV angular distribution should correspond to the sum of a $^{2+}_{3/2}$ and $^{3-}_{1/2}$ angular distribution; but no acceptable fit is obtained. It is to be noted that, contrary to theoretical expectations, the region between 3 and 6 MeV excitation contains no groups with an intensity comparable to that of the ground-state transition.

$^{2+}_{1/2}$ levels have been studied. The larger cross sections for the $^{7}_{2}$ transition in the (He$^3$, a) reaction and the differences in shapes of the angular distributions (Fig. 30) of the transitions to the $^{7}_{2}$ and $^{5}_{2}$ states suggest strongly that the former is excited primarily by a multiple-excitation process, while interference between the simple single-nucleon transfer and multiple excitation may be more important in the latter. For other states, the spectroscopic factors of the two reactions are in excellent relative agreement. The experimental results have been compared with the Nilsson model. It is found that band mixing due to the Coriolis force can explain the rather large absolute strength of the
ground-state transition and the absence of strong transitions to two rotational bands based on Nilsson orbits No. 6 and 7.

(v) The Si$^{30}$ (d,He$^3$)Al$^{29}$ and S$^{32,34}$ (d,He$^3$)P$^{31,33}$ Reactions (R. C. Bearse, D.-H. Youngblood, and J. L. Yntema). The strength of the transition to the ground state of Al$^{29}$ indicates that the d$_{5/2}$ proton shell in Si$^{30}$ is about 90% filled. The transition to the first excited state of Al$^{29}$ at 1.4 MeV has been observed and identified as due to s-wave pickup. All the low-lying states in P$^{31}$ have been observed. This indicates that the d$_{3/2}$ and 2s$_{1/2}$ shells mix strongly. Several new states in P$^{33}$ were found.

(vi) Reactions on Cl$^{35}$ and Cl$^{37}$ (N. G. Puttaswamy and J. L. Yntema). A number of new states in S$^{36}$ and Cl$^{34}$ have been found. Angular distributions have been obtained for the (d,t) and (d,He$^3$) reactions on both nuclei, and distorted-wave calculations are in progress.

(vii) The Ca$^{40}$ (d,a)K$^{38}$ and Ca$^{48}$ (d,a)K$^{46}$ Reactions (N. G. Puttaswamy and J. L. Yntema). Angular distributions for a number of transitions have been obtained for both nuclei. A comparison with previous work at lower energy on Ca$^{40}$ indicates that at higher energy the distorted-wave analysis may prove to be more useful.

(viii) The Mg$^{26}$ (He$^3$,He$^3$)Mg$^{26}$ Reaction (J. L. Yntema and D. Dehnhard). The angular distributions for eight states have been obtained from 20° to 80°. The analysis of the elastic scattering by means of a six-parameter search shows that a satisfactory fit to backward angles is difficult to obtain. In the best fits, the parameters differ drastically from those obtained for less deformed nuclei.

(ix) Nucleon-Transfer Reactions on Mo Isotopes (J. L. Yntema and H. Ohnuma). The single-nucleon-transfer reactions (d,t), (d,He$^3$), and (He$^3$,d) on self-supporting, isotopically enriched targets of Mo have been studied with the deuteron and He$^3$ beams of the ANL cyclotron. Strong transitions were observed to the ground states and to levels at 0.74 and 1.26 MeV in Nb$^{97}$, levels at 0.24, 0.79, and 1.23
MeV in Nb$^{95}$, levels at 0.297, 0.69, and 1.29 MeV in Nb$^{93}$, levels at 0.675, 1.26, 2.20, 2.39, and 2.49 MeV in Mo$^{97}$, levels at 0.78 and 1.03 MeV in Mo$^{95}$, and levels at 0.94, 1.48, 2.42, 2.55, 2.97, 3.08, 3.22, and 3.46 MeV in Mo$^{93}$. Angular distributions have been obtained and will be compared with distorted-wave calculations. Several strongly excited states have been observed in Tc$^{101}$, Tc$^{99}$, Tc$^{97}$, and Tc$^{95}$.

(x) The Ti$^{49}$($d$,He$^3$)Sc$^{48}$ and Ti$^{47}$($d$,He$^3$)Sc$^{46}$ Reactions (J. L. Yntema). The spectroscopic factors for the reaction leading to Sc$^{48}$ have recently been theoretically predicted. The experimental values obtained for the ground state and first and second excited states are in excellent agreement with the theoretical predictions. At higher excitations there appear to be some striking differences with recently published work on the Ti$^{49}$(t,a)Sc$^{48}$ reaction. The present experimental results on Sc$^{46}$ disagree with spin assignments made on the basis of slow-neutron capture gamma-ray work.

(xi) (d,t) and (d,He$^3$) Reactions on the Ca Isotopes (J. L. Yntema). A number of the results from the (d,t) reaction on Ca$^{43}$ disagree with earlier work done elsewhere at lower energies. The results on the Ca$^{42}$(d,t)Ca$^{41}$ reaction show some surprising differences from the theoretical predictions and from the expectations based on the Ca$^{40}$(d,p)Ca$^{41}$ reaction.

b. (He$^3$,a) Reactions in fp-Shell Nuclei

D. D. Borlin and T. H. Braid

The 18-in. scattering chamber and the 33-MeV analyzed He$^3$ beam from the cyclotron have been used to study the (He$^3$,a) reaction in targets of Ca$^{40}$, Ti$^{46,48,50}$, Fe$^{54}$, and Zn$^{64,66,68,70}$. Angular distributions of the alpha-particle groups corresponding to excitations up to 12 MeV in the residual nucleus have been obtained in the angular
range $15^\circ - 40^\circ$, usually in $2\frac{1}{2}^\circ$ steps. The structure of these angular distributions permits the assignment of both orbital-angular-momentum and total-angular-momentum transfer for many levels. From 9 to 23 levels, including some isobaric analog states, have been identified in each residual nucleus. Optical-model analysis of $\text{He}^3$- and $\alpha$-scattering data has yielded parameter sets to be used in DWBA calculations. These DWBA calculations, employing finite-range and nonlocality corrections, have been carried out at the University of Chicago Computation Center. Spectroscopic factors have been extracted for the observed levels, and occupation numbers of the shell-model orbitals exhibit consistent trends, as shown in Fig. 31. The $(\text{He}^3, \alpha)$ reaction at an incident energy of $\sim 30$ MeV has been found to be a unique tool for the observation and identification of $I=3$ and $I=4$ transitions in fp-shell nuclei.

c. Studies of Pickup Reactions

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

As a result of technical improvements and the use of thinner targets, the energy resolution width observed in $(d, \text{He}^3)$
Fig. 32. Hole states in Sc and V isotopes. The experimental and calculated excitation energies of hole states in Sc and V isotopes produced by proton pickup reactions on Ti and Cr isotopes, respectively, are compared.

reactions on 1f2p-shell nuclei has been reduced to 65 keV under standard operating conditions, although target thickness may prevent the resolution width being made smaller than 80 keV for reactions with low cross sections. This improved resolution has been used in the investigation of (d,He3) and (d,a) reactions on Sc45, V51, and isotopes of Cr, Fe, Mn, Co, and Zn. As a result of these measurements, the trends in the excitation energies of the 1d3/2 and 2s1/2 proton hole states have been shown to depend strongly upon neutron number in the target—as seen in Fig. 32. A report of these results was presented in an invited paper at the New York meeting of the American Physical Society, January 1967. Additional data are being obtained on a number of targets, and the problem of complex-particle pickup [such as in (He3',He6), (He4',He6), (d,a), (d, Li6), and (d, Li7) reactions] are now being investigated.

d. Elastic Scattering from Heavy Elements

D. D. Borlin and T. H. Braid

With the magnetically analyzed 22-MeV deuteron beam, 33-MeV He3 beam, and 43-MeV alpha beam from the cyclotron, we have used the 18-in. scattering chamber to observe the elastic scattering of ions from targets of Au197 and U238. Angular distributions of the scattered ions were obtained in the angular range 10°—100°. The
data are being analyzed to find the optical-model parameters that best describe the measurements. Such parameters are needed because of the current Argonne work on heavy-element reactions.

e. Proposed Conversion of the 60-in. Cyclotron


This conversion will improve the performance of the 60-in. cyclotron (now 15 years old) so that it will become a variable-energy machine with maximum particle energies of 60-MeV H^+, 36-MeV D^+, 93-MeV $^3$He$^{2+}$, and 72-MeV $^4$He$^{2+}$. (The present fixed energies are 11.8-MeV H^+, 23.6-MeV D^+, 36-MeV $^3$He$^{2+}$, and 47.2-MeV $^4$He$^{2+}$.)

The 28-in. magnet (Fig. 33, at left), originally a model for the proposed 180-in. HIVEC cyclotron, has been adapted to serve as a model for the 60-in. conversion. It has been found that adequate flutter for 60-MeV protons cannot be attained with four sectors, and a three-sector configuration is now being tested. Data taking has been automated. A satisfactory configuration of the iron shims has been obtained, and the effect of the hill coils is being determined. Measurements of the trim coils will soon be started.

Because the 28-in. model does not have the same shape of yoke as does the 60-in., the magnetic field beyond the boundaries of the poles will not be the same as in the conversion. Consequently, a 12-in. magnet (Fig. 33, at right) with the same yoke shape as the 60-in. has been borrowed from Brookhaven National Laboratory (where a 60-in. machine has recently been converted). This small magnet is being used to measure the fields beyond the pole edges, in order that

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* Chemistry Division.
† Particle Accelerator Division.
‡ Electronics Division.
Fig. 33. The 28-in. (left) and 12-in. (right) model magnets and the field-measuring equipment.

The deflection system can be designed to direct the ions into the existing beam-transport and analyzing system.

The 12-in. model also has been used to find the flux density in the pole bases at the high fields needed for 36-MeV deuterons. The results indicate that the existing power supply for the main coils will be adequate for the conversion.

A computer code has been written to establish equilibrium orbits and to trace paths through the deflector and out to the beam-transport system with the aid of the field data from the two model magnets.

A model dee and tuning system (of the moving short-circuit type) has been constructed to assess operation over the full-scale
range 7.2—22.5 MHz. Its use has fostered several advantageous changes in mechanical design. The broad-band capacitative drive system developed for it will simplify operation and maintenance.

A device has been used to determine the lifetime, under repeated flexure, of the copper straps needed in the tuner, and an evacuated test chamber is being employed to study the appropriateness of several proposed types of contact fingers.

To assay the probability of deleterious charge-exchange during acceleration of heavy ions, the vacuum in the 60-in. cyclotron has been measured as a function of radius, under operating conditions of projectile gas flow. The change was negligible.

Comprehensive studies of the regulation of power supplies for the magnets and the dee oscillator have been made and are continuing, in order to determine a design that will give the best regulation at the least cost. Mechanical design investigations are under way to assess the practicality and cost of hill and trim coils with various types of conductors—e.g., mineral-insulated coaxial cable or insulated bus bar.
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.

a. Levels Populated by Beta Decay

The activations studied were produced at the Argonne 60-in. cyclotron. In the investigation described in Part I. Ea(i), digital coincidence gates were used in conjunction with an 800-channel pulse-height analyzer to record gamma-gamma coincidence spectra. In the study described in Part I. Ea(ii), a versatile two-parameter magnetic-tape system (each parameter occupying 1024 pulse-height channels) was used to record the gamma-gamma coincidence spectra. In each case, each arm of the coincidence system employed a Ge(Li) detector. The exclusive use of these ultra-high-resolution detectors allowed these data to show detail previously unavailable with NaI detectors alone or in combination with only one Ge(Li) detector. The internal-conversion-electron spectra were studied with the Argonne "orange" sector electron spectrometer.

(i) Decay of Cu$^{61}$ and Energy Levels in Ni$^{61}$ (H. H. Bolotin and H. J. Fischbeck). The Ni$^{61}$ nucleus contains five neutrons in excess of the doubly-closed $f_{7/2}$ shell of the $^{56}$Ni$^{28}$ core. This nucleus is therefore felt to be suitable for detailed shell-model calculations which could provide interesting and valuable understanding of the coupling of the shell-model orbitals occupied by the extra-core neutrons.

The 3.3-h positron decay of Cu$^{61}$ was investigated by use of Ge(Li) detectors exclusively, both in singles and coincidence gamma-ray spectroscopic studies. A total of nineteen gamma-ray transitions have been observed between the low-lying excited states of Ni$^{61}$ in the energy region between 67 and 2120 keV; only eight of these had been reported previously. A decay scheme (Fig. 34) deduced on the basis of these data incorporates all of the observed transitions and requires only those Ni$^{61}$ levels that have been excited in nuclear-reaction studies.
Fig. 34. Proposed decay scheme of Cu$^{61}$. All energies are in keV. The $\gamma$-ray intensities in percent per decay are given in parentheses.

These results are in sharp disagreement with previously proposed level schemes. Shell-model calculations are presently being made for comparison with these experimental findings.

(ii) Ga$^{66}$ Levels Populated by the Decay of 2.4-h Ge$^{66}$

(H. H. Bolotin). Two-parameter gamma-gamma coincidence studies employing two Ge(Li) detectors have been made in a continuing effort to understand the level scheme of the odd-odd Ga$^{66}$ nucleus. In addition, the internal-conversion-electron spectrum has been measured with the Argonne six-gap "orange" spectrometer. These data, when combined with other facets of the decay determined in previous phases of this study, are expected to yield a complete and unique decay scheme of this interesting nucleus.
b. Argonne Six-Gap Beta-Ray Spectrometer

G. T. Wood and H. J. Sathoff

During the last year the six-gap (Copenhagen "orange" type) beta-ray spectrometer has been applied to study the conversion electrons from the decay of 18-h Xe\(^{125}\). Xe gas (enriched to 5% Xe\(^{124}\)) was irradiated with neutrons in the Argonne CP-5 reactor and embedded in 100-\(\mu g/cm^2\) nickel foils by use of the Argonne isotope separator. The gamma-ray spectra were studied with Ge(Li) detectors and NaI scintillation counters. The gamma-gamma coincidence spectra were measured with Ge(Li)-Ge(Li) and Ge(Li)-NaI coincidence combinations. About thirty \(\gamma\) rays were reported. Internal-conversion coefficients were reported for many of the transitions and a decay scheme was proposed.

Data acquisition in the spectrometer has now been automated by providing an electronic circuit to repetitively sweep the magnetic field in the spectrometer at a constant rate through the region of interest. The spectra are accumulated in a multichannel analyzer operating in the multiscaler mode. The quality of data is greatly improved over that previously obtained by manual current programming. This is due to greater freedom from magnetic hysteresis effects, improved linearity, better stability, and a smaller correction for the decay of the source.

c. Magnetic Perturbation of the Gamma-Gamma Angular Correlation

G. T. Wood, C. F. Dam, and S. B. Burson

Gamma-gamma angular correlations have been measured for several cascades in the radioactive nuclei Xe\(^{125}\) (18 h), Xe\(^{127}\) (36 d), and Eu\(^{152}\) (13 y) incorporated as dilute impurities in Fe and Ni hosts. The sources were prepared by neutron irradiation at the Savannah River and Argonne CP-5 reactors. The Argonne isotope separator was used to embed the radioactive isotopes in the ferromagnetic hosts. Large
internal magnetic fields exist at the nuclei of the radioactive impurities and are aligned by magnetizing the ferromagnetic host with a small external field. It is intended to study these internal fields by the $\gamma-\gamma$ angular-correlation method and apply the technique to the determination of the magnetic moment of short-lived nuclear states. Although large perturbation effects are observed, the interpretation of the results is complicated by the interaction with the nuclear quadrupole moment and by the uncertainty that all the radioactive impurities reside at "magnetic" lattice sites. These problems are under study in the hope of resolving them.

d. 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.

In the last year several tactics within this general strategy have been tested and a few of the more promising ones picked out for

*Applied Mathematics Division.
testing on a new general-purpose computer (IBM 360-75). By careful optimization of the program, these tests can be done as fast on this computer as on the small special-purpose unit built for this problem; and use of the large computer offers a great gain in flexibility.

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

G. R. Ringo and J. P. Schiffer

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

f. Superconducting Internal-Conversion-Electron Spectrometer

S. B. Burson

The determination of absolute internal-conversion coefficients is a means of assigning quantum-mechanical parameters to the ground states and excited states of nuclei. An instrument (Fig. 35) now being constructed is designed for electron-gamma coincidence measurements either on radioactive sources or on thin targets placed in an external beam of thermal neutrons at the reactor CP-5. The source is viewed simultaneously by two solid-state detectors. A Ge(Li) gamma-ray detector is placed close to the source (approximately 3 cm from it); a Si diode, placed approximately 20 cm from the source, is used to detect the electrons. Both the source and the Si detector are
Fig. 35. Target chamber and Dewar of the conversion-electron spectrometer. The horizontal tube of the target changer (lower photograph) is a vacuum lock to permit changing the target without breaking the vacuum. The neutron beam traverses the chamber via the channel (capped off in the photograph) perpendicular to this tube. Conversion electrons from the target are guided by the field of the superconducting magnet (diagram) to a Si(Li) detector mounted on a cold finger inside the Dewar (upper photograph). These electrons are counted in coincidence with $\gamma$ rays detected in a Ge(Li) detector mounted $\sim$2 in. below the target. The reservoir at the top of the upper photograph maintains the liquid nitrogen at a constant level.
located on the axis of a superconducting magnet whose field guides the electrons from the one to the other. This effectively increases the solid angle for detection of electrons. However, the large source-to-detector distance attenuates the undesirable gamma-ray background by a factor of 50. The magnet, which is housed in a cryostat provided with a through hole 1.5 in. in diameter, is 10 in. long and has a central field of about $22 \times 10^3$ gauss. The electron detector is now operating at a resolution width of 5 keV; the gamma-ray detection system is under construction.
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II. MEDIUM-ENERGY PHYSICS

The program in medium-energy physics consists of two distinct parts. One part consists of physics experiments performed with medium-energy projectiles. The second part is a study of accelerators for the production of particles in the medium-energy range. Currently this effort is devoted to a detailed study of the proposed conversion of the 60-in. fixed-energy cyclotron into a 71-in. variable-energy cyclotron.

a. Muonic \( \mathbf{x} \) Rays


The study of muonic \( \mathbf{x} \) rays has continued at the synchrocyclotron at the Carnegie Institute of Technology, where a Ge(Li) gamma-ray spectrometer is used at the muon channel. Preliminary analysis of the muonic K \( \mathbf{x} \)-ray spectra for the deformed nuclides such as holmium and terbium led to the conclusion that the theory of Wilets and Jacobsohn could be used to describe such spectra with great accuracy. Furthermore, it was possible to conclude that the presence of the muon shifted the energies of the rotational levels of the target nuclides by less than 1 keV and that the shielding by the atomic electrons did not change the energies of the muonic \( \mathbf{x} \) rays by as much as 1 keV. However, more detailed studies of the K and L spectra lead to results that are not quite consistent, within the statistical errors, with the treatment described.

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Fig. 36. Spectra of K x rays from muonic atoms of Eu$^{151}$ and Eu$^{153}$. The spectra clearly show a very large isotope shift as well as the difference between the hyperfine structure associated with a "good" rigid rotor Eu$^{153}$ and a nucleus Eu$^{151}$ that is not represented by such a model. The calculated spectra are based on a Gaussian line-shape (solid curve) and a Lorentzian (dotted curve).

above. Simple shifts in the energies of the rotational levels do not produce better agreement and so far no satisfactory explanation has been found for the differences. Nevertheless, precise values of the intrinsic quadrupole moment $Q_0$ have been obtained.

Samples, highly enriched in Eu$^{151}$, Eu$^{153}$, Gd$^{158}$, and Gd$^{160}$ have been used to study the muonic x-ray spectra from these nuclides. Values of the isotope shifts were, of course, obtained for
II. a, b

each pair; and these shifts were found to be in good agreement with the values obtained from optical hyperfine structure. The spectra of Eu$^{151}$ and Eu$^{153}$ (Fig. 36) are especially interesting since these isotopes lie at the very beginning of the deformed region. In fact, the spectrum for Eu$^{153}$ is typical of a deformed nucleus with a well developed ground-state rotational band. The spectrum for Eu$^{151}$ is very nearly that associated with nuclides displaying only static quadrupole hyperfine structure. However, the situation is not quite that simple and the interpretation of the spectra is complicated by the rather large ground-state magnetic moment and by the lack of a suitable model for this nucleus.

Larger and better Ge(Li) spectrometers with better preamplifiers have been used for the most recent measurements and it is expected that such improvements will continue. One result of this is that many of the earlier measurements will be repeated when it is felt that the refinements in technique warrant it. In particular, measurements of magnetic hyperfine structure will be repeated since most of the earlier work was done with resolution widths about twice those now being obtained (about 5 keV at the double-escape peak of a 6.1-MeV gamma ray) with the present experimental arrangement.

b. Proposed Conversion of the 60-in. Cyclotron

J. J. Livingood, W. J. Ramler, * T. K. Khoe, † R. Benaroya, *
K. W. Johnson, * F. F. Cilyo, ‡ W. Wesolowski, * G. W. Parker, *
T. E. Klippert, * and J. M. Nixon *

This work is reported on p. 74 under RESEARCH AT

THE 60-in. CYCLOTRON.

* Chemistry Division.
† Particle Accelerator Division.
‡ Electronics Division.
III. THEORETICAL PHYSICS

The theoretical group consists of permanent staff and long- and short-term visitors, including several post-doctoral appointees. The greatest theoretical effort goes into studies of nuclear structure and reactions. Research is also carried out in statistical mechanics, in superconductivity theory, and in areas dealing with the mathematical structure of quantum theory.

Activities of the group include several regular seminars. The general theoretical physics seminar enjoys active participation by theorists from other divisions at Argonne and from nearby universities. A nuclear physics seminar is shared with experimental physicists at Argonne and with physicists from the University of Chicago and Northwestern University. These formal programs are supplemented by a variety of informal contacts with the above-mentioned groups, with occasional research collaborations. Members of the Argonne theoretical group also offer occasional courses at neighboring universities, and two men hold joint appointments.

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

The largest single theoretical research project is the automated shell-model program, using the CDC-3600 computer. This project is now producing many valuable results, some of which are reported below. The project has also made valuable fundamental contributions in the area of automated computation. A second major theoretical research program is an investigation of self-consistent nuclear-structure theories. One aspect of this program, a study of the convergence of numerical approximations used in the self-consistent theories, is deeply involved with some of the computational research activity of the shell-model group.
III. a

Theoretical Nuclear Spectroscopy


The system of programs for doing shell-model calculations is now operational under a new highly efficient control program described below. The programs can now extract coefficients of fractional parentage and determine theoretical values for observable quantities such as E2 transition rates and log ft values for beta decay. The programs are still being extensively used for many problems. Some of these are discussed in the following items.

(i) The Shell-Model System (S. Cohen). A new supervisory control program for the shell model has been constructed to increase the efficiency of operation of the system and to allow for more direct access to information produced by the programs. The increase in efficiency is primarily due to the use of the large random-access device now available on the CDC-3600. Calculations now require about half the time previously required. The new versions of the programs will be further optimized and extended.

The operation of the newest version of the shell-model system has been considerably simplified and it is expected that within a few months it will be in a form that can be used by experimentalists with little difficulty. This version will contain a library of experimental data which will be directly available to the programs for comparison with theoretical predictions.

(ii) 1p-Shell Nuclei (S. Cohen and D. Kurath). The 1p-shell wave functions derived in earlier studies have been used in various calculations on problems of current interest.

One problem concerns the relative sign and magnitude of the E2-M1 mixing ratio. This quantity was calculated for several pairs of mirror nuclei whose transitions have been measured in careful experiments. There are difficulties of phase conventions in comparing the calculated quantity with the information extracted from
angular-correlation measurements. However, it was found that the calculations are in agreement with the experimental results.

A similar problem concerns the branching ratios for gamma decay of the $T=\frac{3}{2}$ analog states in $^{13}\text{C}$ and $^{13}\text{N}$. Here there is a possible effect due to isospin mixing in the analog states. This was investigated, but the experimental picture is not yet clear.

The log ft values were calculated for $^{11}\text{Li}$ which was recently found to be particle stable. This will be of assistance in establishing the lifetime and branching ratios for this decay.

(iii) Shell Model of the Nickel Isotopes (S. Cohen, R. D. Lawson, M. H. Macfarlane, S. P. Pandya, and M. Soga). The isotopes of nickel are described by a shell model within the identical-nucleon configurations $(2p_{3/2}' 1f_{5/2}' 2p_{1/2})^n$. A least-squares fit to observed level energies yields an effective interaction which satisfactorily reproduces the level structure of the Ni isotopes from $^{58}\text{Ni}$ to $^{65}\text{Ni}$. This best-fit interaction is shown to indicate repulsive interactions between identical-nucleon shells and to conserve seniority to a useful degree of approximation. The interaction-matrix elements are in fair agreement with those of an approximate reaction matrix computed by Kuo from the free-nucleon interaction of Hamada and Johnston, this agreement being obtained only when core polarization is taken into account. Moments and transitions also show the strong influence of core excitation. Observed quadrupole moments and E2 transition rates are adequately reproduced with an effective neutron charge of between 1.5 e and 2 e; in particular, the observed inhibition of the cross-over ground-state decay of the second $2^+$ $(2_{2}^+)$ states of $^{60}\text{Ni}$ and $^{62}\text{Ni}$ is reproduced with $2_{2}^+$ wave functions for which a 2-phonon vibrational description is clearly incorrect. It is shown that the original model cannot account for the large deviations of observed magnetic moments from the Schmidt values nor for the observed spreading of stripping strength into a given orbit over several states of the residual nucleus.
To account for these, it is necessary to introduce effective transition operators, strongly modified by the influence of neglected configurations.

(iv) Nuclear-Structure Studies of the Early $1d2s$-Shell Nuclei (A. Arima, S. Cohen, R. D. Lawson, and M. H. Macfarlane). If one assumes that the eight protons and eight neutrons of $^{16}$O form an inert core and if one allows the extra-core nucleons to populate only the $1d_{5/2}$ and $2s_{1/2}$ single-particle states, then the spectra of the early $1d2s$-shell nuclei can be characterized in terms of sixteen matrix elements which describe the residual two-body interaction. On the basis of this model one can explain not only the observed spectra of $^{18,19,20}O$, $^{18,19,20}F$, and $^{20}Ne$ but also the observed transition rates and static multipole moments of these nuclei. Of particular interest is the fact that this model can predict the rotational structure of the nucleus $^{20}Ne$. In addition, it is possible to explain the observed E2 transition rates within the ground-state band of $^{20}Ne$ if one endows the neutron with an effective charge of 0.7 e and the proton with an effective charge of 1.7 e. A search for the levels predicted by this model, together with other measurements of the properties of the excited nuclear states (particularly the second or third state of each spin), will do much to determine how well the effects of core excitation can be taken into account if (a) the effective interaction is characterized in terms of its matrix elements and (b) an effective charge is used in the description of the gamma decay of the states.

(v) Pseudonium Revisited (R. D. Lawson and J. M. Soper). Using a model consisting exclusively of neutrons, we previously showed\(^1\) that large amounts of configuration mixing may not appreciably affect nuclear properties. These calculations have been extended to the case in which both neutrons and protons are present. In this case

the exactly-soluble problem was again one that involved two isolated single-particle levels, the $1p_{1/2}$ and $1d_{3/2}$ single-particle states. Neutrons and protons were allowed to fill these two levels, and under the influence of a residual two-body force the exact eigenfunctions of the problem corresponded to strongly mixed configurations. In the wave functions corresponding to the ground state ($J = 0^+$) of the pseudo-nucleus with two neutrons and two protons, the probability of the configuration $(p_{1/2})^4$ was only 32.3%; and for the ground state of the three-neutron two-proton system, the probability of the configuration $d_{3/2}(p_{1/2})^4$ was only 38.2%. Despite the lack of shell closure at $N = Z = 2$, for larger values of $N$ and $Z$ we were able to successfully describe all the properties of the low-lying positive-parity states that resulted from the exact calculation. This description assumed that these states corresponded to valence $d_{3/2}$ nucleons moving outside a doubly-magic $p_{1/2}$ core.

(vi) M2 Transitions in Nuclei (D. Kurath and R. D. Lawson). A survey of experimental data about M2 transitions between low-lying nuclear states shows that the great majority of transitions in nuclei with $A > 30$ are severely inhibited. For heavy nuclei with a permanent deformation, the inhibition can be ascribed to an asymptotic selection rule. Even when a permanent deformation is not present, the effect of this selection rule may persist, and it can lead to M2 transitions whose lifetimes are several hundred times the single-particle estimate. In light nuclei, some transitions are inhibited by an isobaric-spin effect. Theoretical values were obtained for comparison with some recently measured M2 lifetimes in the region around $A = 40$. Both quadrupole deformation and the isobaric-spin effect can contribute to inhibitions in this region. The isobaric-spin effect is sufficient to account for the lifetimes in $^{39}$K and $^{41}$Ca. For nuclei further removed from $^{40}$Ca, the effect of deformation is also necessary. In some simple examples we show that such a trend results from the nature of the particle-hole interaction.
b. Binding Energy of Li\textsuperscript{6}

D. R. Inglis

Shell-model calculations, although much over-simplified, have been remarkably successful in calculating energy-level differences and some other properties of a nucleus. The model can be better understood by investigating the effect of improving the assumptions in various ways. An investigation is being made of the binding energy of Li\textsuperscript{6} as affected by permitting more flexibility than usual in the parameters describing the oscillator functions, so as to introduce both different sizes and different deformations for the odd and even shells, as doubly-excited states are admixed in second-order perturbation theory. The interaction remains nonsingular—a central Gaussian with a soft core. The calculation is intended to explore the extent to which improvement of the first-order approximation through permitting deformations may reduce the magnitude of the higher-order contributions. It should serve as a critique of the validity of a simpler deformed shell model without configuration mixing.

c. The Tensor Virial-Theorem Including Viscous Stress and the Oscillations of a Maclaurin Spheroid

Carl E. Rosenkilde

The present work, which deals with the effect of viscosity, is part of a general investigation of the equilibrium and stability of a rotating charged liquid drop (of interest in connection with the theory of nuclear fission). The tensor virial-theorem was first extended to include viscous stress. This extended virial-theorem then provided the basis for an alternative verification of the conjecture (originally due to Lord Kelvin in 1883) that a slightly viscous, self-gravitating, Maclaurin spheroid would be unstable beyond the classical point of bifurcation. (The present proof is much simpler than the only earlier one, which
was given by Roberts and Stewartson in 1963. A similar conclusion was shown to hold in the case of the rotating charged liquid drop. This result further delimits the extent of the possible stable rotating equilibrium configurations and, moreover, provides a qualitative test for the presence of "viscous like" behavior in the fission of heavy nuclei. The final report on this work has been published.  

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d. 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.

(i) Nuclear Level Density (with P. B. Kahn, SUNY, Stony Brook, N. Y.). Two new results are reported. (a) An accurate and transparent asymptotic formula has been derived for the density of states of a degenerate Fermi system with an arbitrary periodic single-particle spectrum. It is demonstrated that the details of the spectrum produce an additive correction to the excitation energy in the standard formulas. This treatment generalizes, unifies, and simplifies the discussions of related problems by many workers over a period of thirty years.  

(b) The analysis has been extended to include nonperiodic modifications of the periodic level scheme. The modification may be

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a combination of positional shifts and additions and deletions of individual levels. If these alterations occur in the vicinity of the Fermi level, then the resulting formulas are still simple. Positional shifts lead to the usual additive corrections to the excitation energy in the standard formulas. However, the net creation or destruction of levels with respect to the periodic scheme leads, in addition, to a novel multiplicative energy-independent correction of the standard formulas. For example, if a nonrecurring gap in the periodic level scheme occurs near the Fermi energy, the large diminution which it produces in the level density persists indefinitely with increasing excitation energy.2

The above developments in the theory should make it a practical approach to including more details of the nuclear shell model in the semitheoretical description of the measured nuclear level densities. Relatively simple theoretical formulas are obtained by adopting the exact positions of the shell-model levels near the Fermi energy and by postulating a suitable periodic model for the more distant levels.

(ii) Finite-Sample Effects in the Spacing Distributions of Nuclear Levels3 (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. The distribution of a new statistic was calculated on the basis of this ensemble. The agreement between theory and the first 50 levels observed in the reaction U\(^{238}\) + n is entirely satisfactory. On the other hand, there is a definite disagreement between the theory and the published resonance energies measured in the reaction Th\(^{232}\) + n.


(iii) Dependence of Energy-Level Statistics on Approximate Quantum Numbers. It was discovered some years ago that the distribution of the spacing between adjacent energy levels of complex atomic spectra depends on the relative magnitudes of central and spin-orbit forces. At that time we were able to postulate statistical principles that would describe this situation, and the ensuing calculations gave satisfactory agreement with experiment. On the basis of this study it was suggested that the procedure may be inverted, and that the empirical distributions may be used to obtain an indication of the symmetries of the system.

Recently it was suggested, as a result of some high-energy experiments, that time-reversal invariance may not be an exact symmetry of a nucleus. We have postulated an ensemble which expresses this notion quantitatively and have computed the perturbation of the Porter-Thomas distribution of widths for single-channel processes produced by a small part in the Hamiltonian which is odd under time-reversal.\(^4\) It turns out that a relatively small odd part produces a rather large perturbation, and the effect constitutes a sensitive method for investigating the violation of time-reversal invariance in nuclear physics.

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e. Formation Factors in a Decay

A. Kallio

The formation factor in a decay has been calculated for Woods-Saxon single-particle wave functions. The main point of this study was to find out whether the absolute values of the decay rates could be improved by using more realistic Woods-Saxon wave functions instead of the oscillator functions commonly employed. Results for Po\(^ {212} \) (Fig. 37) show that the formation factors are very similar in
the two cases. Therefore, as far as this part of the α-decay theory is concerned, the discrepancies in absolute values remain.

Fig. 37. The dependence of the probability amplitude for finding an α particle inside the nucleus upon the single-particle wave functions used in the case of Po1.2 with the configuration \([\left(2g_9/2^2\right)^0(1h_9/2^2)^0]\). Curve I: Oscillator functions \(\hbar\omega = 7\) MeV. Curves II—V: With Woods-Saxon functions allowing the parameters \(r_0\) and \(a\) to vary within the limits \(1.25 < r_0 < 1.3\), \(0.65 < a < 0.75\).

Fig. 38. The solution of the Bethe-Goldstone equation for relative \(S^3\) motion in \(O^{16}\) for \(\hbar\omega = 12\) MeV and \(\Delta = -125\) MeV. The dotted line is the unperturbed is oscillator function \(\phi\), the dashed line the true solution \(\psi\), and the full line the solution \(\psi_R\) without the Pauli principle (reference equation). The corresponding matrix elements are \(\langle \phi | v | \psi \rangle = -8.05\) MeV and \(\langle \phi | v | \psi_R \rangle = -9.70\) MeV.

f. Studies of Nuclear Matter

(i) Exact Solution of Bethe-Goldstone Equation (A. Kallio).

The Bethe-Goldstone integro-differential equation is solved exactly for a realistic interaction with hard core. The solution (Fig. 38) is constructed with the aid of a sequence of inhomogeneous second-order
differential equations. For the very lightest nuclei (e.g., $\text{He}^4$ and $\text{H}^3$), one can study the convergence of the Goldstone expansion by comparing the result with accurate variational calculations that have been performed with the same interaction. In the preliminary calculations the accuracy of the separation method is studied. In the first order the matrix elements are found to be $10-15\%$ too small. It is also shown that the second-order calculation does not improve the result very much. Self-consistent calculations for light nuclei are in progress. The application of the same method for heavier nuclei and nuclear matter is under study in cooperation with Dr. Ben Day of the Physics Division.

Preliminary calculations with the angle-averaged Pauli operator show that the method is very convenient both for central and tensor forces. In most cases only three iterations are needed, and in all cases studied five iterations give sufficient accuracy.

(ii) The Ground State of Nuclear Matter (F. Coester and James MacKenzie). We investigate the ground state of nuclear matter as a mathematical problem. That is, the problem is not primarily to compute a number that agrees with experiment but to find an approximate solution of the Schrödinger equation for classes of two-body potentials that include realistic potentials. From the Schrödinger equation we derive a coupled set of equations for the correlated parts of the partial $n$-body wave functions. In every case it is necessary to show that the coupling to the amplitudes for $n' > n$ may be neglected. The resulting equations are nonlinear for $n = 2$ and linear for $n > 2$. The general structure of the equations is the same for all potential types under consideration but details differ. In particular, the single-particle spectrum is different, but in every case there is a gap at the Fermi surface. Types of potentials calling for a qualitatively different treatment are (a) strongly repulsive potentials whose range is much
less than the average interparticle distance, (b) strong repulsion plus attraction, and (c) over-all weak potential.

(iii) Review Article on Nuclear Matter (B. Day). A review article entitled "Elements of the Brueckner-Goldstone Theory of Nuclear Matter" has been submitted to Reviews of Modern Physics. Most of the material in the article was presented in five informal talks at Argonne. The important concepts and mathematical techniques of the theory of nuclear matter are examined in detail. It is believed that reading this article will be a useful first step for anyone who wants to begin research on nuclear matter or to apply the same ideas to calculations of finite nuclei.

(iv) Three-Body Correlations in Nuclear Matter (B. Day). In the theory of nuclear matter, the calculation of the energy due to three-body correlations requires the solution of the three-body Bethe-Faddeev equations. These equations describe the simultaneous interaction of three particles, each particle interacting with the others through Brueckner's reaction matrix which plays the role of an effective two-body interaction. An approximate solution to these equations has been developed in the form of a simple polynomial of two-body correlation functions. The approximate solution is sufficiently accurate to be used in detailed numerical calculations. Therefore the calculation of three-body correlations in nuclear matter is now no more complicated than the calculation of two-body correlations, for which simple and accurate methods are known.

(v) Four-Body Correlations in Nuclear Matter (B. Day). Two-body and three-body correlations contribute approximately -35 MeV and -5 MeV, respectively, to the energy per particle of nuclear matter. It has always been assumed that the four-body contribution is less than 1 MeV. An attempt is being made to check this point. All the four-body diagrams have been enumerated, and work is currently under way to
obtain numerical estimates of the contribution of the four-body terms to the energy.

g. Infinite Systems of Classical Particles
Amnon Katz

The ordinary formalism of classical mechanics is limited to the treatment of a finite number of particles because position and momentum variables must be assigned to each particle. In the case of identical classical particles we have overcome this difficulty by creating a formalism which eliminates the position and momentum of individual particles in favor of creation and annihilation operators that create and destroy particles at points in phase space. This opens the way to the treatment of infinite systems with a finite average density. We generalized the definition of thermal equilibrium to infinite systems. The example of noninteracting particles was worked out explicitly.

Infinite systems must be treated before statistical calculations can lead to thermodynamical results. By having the system infinite to begin with, the present approach may serve to eliminate cumbersome and ill-defined procedures of taking the limit of infinite volume.

h. Calculation of Separable Potentials
James J. MacKenzie

Potentials that fit the nucleon-nucleon (N-N) scattering data and that are nonlocal and separable have found widespread application in low-energy nuclear physics. This is due to the great simplification that results in the Schrödinger equation when the interaction is separable. Formulas have been derived for constructing separable potentials directly from the phase shifts and the actual numerical evaluation has been carried out for the first few partial waves of the N-N system. These
potentials have already been used by others in pp bremsstrahlung calculations; investigations of nuclear matter with them are presently in progress.

i. Basis for the Departure from Exponential Decay

M. N. Hack

The derivation of the exponential-decay law in damping theory has always suggested to us a close connection to the corresponding problem of the temporal behavior of the approach to equilibrium in statistical mechanics. In each case one starts from the underlying fundamental dynamical law and determines a regime in which the time evolution of the decay (of an excited state or of a nonequilibrium state, respectively) satisfies approximately an equation of the Pauli or master type. In both cases it is well known that one does not get, from the Schrödinger or Liouville equation, a law of exactly exponential type, but that there are deviations very early and very late in the decay. Arguments have been developed\(^1\) that elucidate the physical reason for the appearance of the deviations from pure exponential decay.

\(^1\) M. N. Hack, Nuovo Cimento 47B, 301 (1967).

j. Study of Hypernuclei and the Interactions of \(\Lambda\) Particles

A. R. Bodmer

(i) Review of Hypernuclear Spectroscopy. A short review entitled "Hypernuclear Spectroscopy" has been completed as the text of an invited talk given at the Second International Conference on High Energy Physics and Nuclear Structure, Weizmann Institute of Science, Rehovoth, Israel, 27 February—3 March 1967. A preliminary version of a more comprehensive review has been completed. These reviews also contain some new material, in particular the two following items.
One-Boson-Exchange Models of the ΛN and ΛΛ Interactions.

Some preliminary results have been obtained for a simple model that includes just σ and K meson exchanges together with a hard core. Further studies of one-boson-exchange models are in progress.

Three-Body ΛNN Forces. Recently there has been renewed interest in these forces since they offer a possible way of reconciling the results of hypernuclear analyses with the Λp scattering data. An interesting effect is that of the two-body ΛN correlations on the ΛNN forces. For hard-core interactions, such correlations suppress the short-range (and most poorly understood) part of the ΛNN forces and enhance the long-range part arising from pion exchange.

(ii) Λ in Nuclear Matter (A. R. Bodmer). This is an interesting many-body problem which is also of considerable importance for hypernuclear physics. Phenomenologically, quite good values of the well depth for a Λ in nuclear matter are now available.

The limiting case of a Λ in nuclear matter has simplifying features as compared with finite hypernuclei but at the same time furnishes a useful touchstone for many questions of importance for finite hypernuclei. Examples of such questions which are being considered are the relative importance of interactions in the relative p states, ΛNN forces, the suppression of the tensor force and of the ΛΣ coupling, and more generally the equivalence of effective central ΛN interactions for the free ΛN case and for hypernuclei.

An important basic problem is to reach good understanding of the nuclear many-body problem of a Λ in nuclear matter, especially of the convergence of the perturbations and the K-matrix expansions. Of particular interest in this connection is the rearrangement energy for a Λ in nuclear matter. This energy results from the distortion of the nuclear matter by the Λ.
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(iii) ΛΛ Hypernuclei and the ΛΛ and ΛN Interactions

(A. R. Bodmer). ΛΛ (or double) hypernuclei are of considerable interest since, presently, they provide the only source of information about the (singlet s-state) ΛΛ interaction. During the past year, Prowse\(^1\) has discovered a second ΛΛ hypernucleus and has uniquely identified it as \(\text{He}_{\Lambda \Lambda}^6\) (i.e., two Λ particles bound to \(\text{He}_4^4\)). The hypernucleus \(\text{He}_{\Lambda \Lambda}^6\) is unique in having six baryons in the s shell and is of particular importance for the ΛΛ interaction because uncertainties due to nuclear structure are rather small as a result of the rigidity of the \(\text{He}_4^4\) core. Thus it is a good approximation to treat \(\text{He}_{\Lambda \Lambda}^6\) as a three-body \((\alpha + 2\Lambda)\) system with the α particle effectively undistorted by the Λ particles.

Extensive calculations for a variety of ΛΛ potentials (in particular, two-pion-exchange and one-boson-exchange potentials) have been made for \(\text{He}_{\Lambda \Lambda}^6\).\(^2\) The three-body variational method\(^3\) previously developed was used. In particular, it is found that for any reasonable hard-core radius no bound ΛΛ state is expected and that for the same potential shape the ΛΛ interaction is somewhat weaker than the singlet s-state ΛN interaction. With a one-boson-exchange potential arising predominantly from the exchange of a σ meson, one finds values of the ΛΛσ coupling constant that are consistent with the values of the NNσ coupling constant obtained from the NN data. This agreement suggests that the σ is a SU(3) singlet universally coupled to the baryons.

The results for the ΛΛ interaction are quite insensitive to uncertainties in the α-particle size but do depend somewhat on the range assumed for the ΛN interaction since this range determines the range of the αΛ potential. This dependence becomes of considerable

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interest in conjunction with knowledge of the binding energy of a heavier \( \Lambda \Lambda \) hypernucleus, since the dependence on the \( \Lambda N \) range is less for this than for \( \text{He}_{\Lambda \Lambda}^6 \). Thus if the earlier event of Danysz et al.\(^4\) is identified as \( \text{Be}_{\Lambda \Lambda}^{10} \), the most probable interpretation, one obtains consistency between the binding energies of \( \text{He}_{\Lambda \Lambda}^6 \) and \( \text{Be}_{\Lambda \Lambda}^{10} \) only for a rather short range of the attractive tail of the \( \Lambda N \) interaction. Such a short range is consistent with theoretical expectations and also with some rather tentative phenomenological evidence. A uniquely identified heavier \( \Lambda \Lambda \) hypernucleus would thus be of considerable interest for the range of the \( \Lambda N \) interaction.


k. 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. The mathematical consequences of the proposed statement have been explored for finite dimensional Hilbert spaces. A paper entitled "Causal Independence" is in preparation.

f. 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 (a) to put the theory of physical conjecturing on a sounder basis and (b) to make it unambiguously applicable to the (realistic) case of infinite-dimensional Hilbert space. Work is continuing.

m. Empirical Foundations of Nonrelativistic (Galilei) Quantum Mechanics

H. Ekstein

The interaction of several Galilei particles is handled in a well-known way by traditional methods. The purpose of the present work is to give a derivation of these methods from prime principles and direct empirical evidence. One may call it an "axiomatization" of nonrelativistic quantum mechanics on an operational basis.

n. Presymmetry

H. Ekstein

Even in the presence of external fields, space-time symmetry implies nontrivial relations between observables at one time, i.e., kinematical relations. Symmetry operations at one time—translations, rotations, and (for Galilei symmetry) velocity shifts—can be performed on observation-producing and on state-producing instruments, regardless of the existence of an external field. Furthermore, it is possible to give an operational definition of every initial state intrinsically, i.e., regardless of the external field. The precise statement of this empirical fact explains, for example, why
a particle in an external field has integral or half-integral eigenvalues of the spin, why a Hamiltonian exists even in the presence of a time-dependent external field, and why (for Galilei symmetry) the canonical commutation relations are still valid, although the full space-time symmetry from which these results can be derived has been destroyed. It is pointed out that the rigorous validity of kinematical relations in spite of strong breaking of the underlying space-time symmetry is analogous to the rigorous validity of equal-time current commutation rules in spite of the breaking of the underlying U(3) symmetry. The final report on this work has been published.¹


Current Algebras

F. Coester and G. Roepstorff

The hadron one-particle states come in nondegenerate multiplets that correspond to irreducible representations of the internal symmetry group. Current algebras establish a relation between the densities of the interaction currents and the generators of the internal symmetry. To establish that relation, it is necessary to consider the infinite-momentum limit of the current densities restricted to one-particle states. The existence of an operator limit has been demonstrated for scalars, vectors, and antisymmetric tensors. The limit vanishes for scalars and, except in special cases, diverges for higher tensors. Kernels of the limit operators have been obtained explicitly as functions of the same invariant form factors that determine the kernels of the original current densities. Commutation relations for the integrated currents are dynamical hypotheses. "Local" commutation relations for the densities at infinite momentum are incompatible with the assumption that the spins are bounded in the one-particle subspace.
IV. EXPERIMENTAL ATOMIC PHYSICS

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.

1. MöSSBAUER MEASUREMENTS

In the last few years, the Mössbauer effect has become a powerful tool for the study of many phenomena in solid-state, chemical, and low-energy nuclear physics. The experiments are aimed in two directions: (a) to yield accurate measurements of previously unobtainable nuclear properties (e.g., the quadrupole moments and magnetic moments of excited nuclear states) and (b) to make accurate determinations of the environment in which a nucleus is immersed (e.g., to determine the charge transfer from an iodine atom as it forms a chemical bond with chlorine). Recent Argonne experiments have been concerned with such diverse nuclear species as K⁴⁰, Fe⁵⁷, Kr₈³, Sn¹¹⁹, Sb¹²¹, I¹²⁷, Xe¹²⁹, Cs¹³³, U²³⁵, and Np²³⁷, and others are being considered.

a. Studies of Cesium-Graphite Compounds

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

Two cesium-graphite compounds have been studied: CsC₈ and CsC₂₄. It is reported in the literature that the cesium in such compounds may be only partially ionized (25%). We have performed Mössbauer experiments on CsC₈ at 4.0 K and in magnetic fields up to 72 kG in an attempt to measure the magnetic moment of the first excited state of Cs¹³³ by utilizing the large hyperfine field which would be produced by the polarization of any unpaired

*Solid State Science Division.
6s electrons left on the cesium atom. The resulting Mössbauer spectra
cast doubt on the possibility that the cesium ion has any unpaired
6s electron spin.

b. Studies with Kr$^{83}$
   S. L. Ruby

During the past year this isotope has been used to study the "particle-in-a-box" behavior of a rare gas atom trapped in an
organic matrix (clathrate). Earlier studies using specific-heat and
infrared measurements had led to anomalous results. The use of
Mössbauer measurements to get at the otherwise unobservable rms
thermal displacement of the krypton atoms from their average positions
has led to a satisfactory solution of this problem in lattice dynamics.

c. Studies with Sb$^{121}$
   S. L. Ruby and G. M. Kalvius*

Argonne is still the only laboratory that has published reports on the use of the Mössbauer effect with Sb$^{121}$. During the
past year, we have found accurate values for the quadrupole moment
and magnetic moment of the first excited state. This in turn allows
the clarification of electrostatic and magnetic fields found in various
environments. The basic chemistry of the isomeric shift has been
clarified (by comparison with tin chemistry) and this experimental
quantity can now be confidently used as an indicator of chemical
states. It will be especially useful in alloy studies now under way.

*Solid State Science Division.
d. Studies in Actinide Elements

S. L. Ruby, G. M. Kalviuš,* M. B. Brodsky,† and D. R. Dunlap*

Results in Np$^{237}$ have come slowly. We are especially interested in getting natural line widths; but to date the best lines have been 10—20 times larger. Despite this hardship, some compounds such as NpF$_4$ have been clarified. Preliminary results on isomer shifts for Np$^{5+}$ and Np$^{6+}$ are now in hand.

Progress with U$^{235}$ is also slow. Here the problem arises from the small amplitude of the effect, coupled with the experimental problems of using an accelerator source. Using 35-MeV O$^{16}$ to Coulomb-excite U$^{235}$ to its first excited state, we were able to obtain fair intensities of the appropriate γ ray, but the amplitude of the observed Mössbauer effect is still too small to use. Work will continue to find out how to improve results in this important isotope.

*S Solid State Science Division.
† Metallurgy Division.

e. Magnetization Near the Curie Point

R. S. Preston

Current theories of critical-point phenomena predict that, in the region just below the Curie temperature $T_c$, the spontaneous magnetization $M$ of a ferromagnet varies with temperature $T$ according to

$$ \frac{M_T}{M_0} = h \left( 1 - \frac{T}{T_c} \right)^\beta \quad (1) $$

Different theories predict different values of $\beta$, with $\beta = \frac{1}{2}$ and $\beta = \frac{1}{3}$ being most fashionable at present. Measured values of $\beta$ for various ferromagnetic materials seem to cluster about these two theoretical values.
The neighborhood of the Curie point in pure iron is a favorable one for study by the Mössbauer effect, since the hyperfine field $H$ is closely proportional to the magnetization $M$. However, there may be some question about the applicability of Eq. (1) to the case of iron. Previous results from this laboratory have shown a rather sharp discontinuity in the isomer shift in iron at $T_C$, which is hard to reconcile with the accepted opinion that this is a phase transition of the second order. If this is not a second-order transition, then Eq. (1) may not be applicable.

A more detailed study of this magnetic transition by the Mössbauer effect was made while the author was at Harwell. The work is being continued at Argonne. According to the first results, $\beta = 0.35$ (significantly larger than $\frac{1}{3}$), and the jump in the isomer shift is even sharper than it appeared to be previously. Existing theories of critical-point phenomena do not seem to provide any explanation for this jump in the isomer shift.

f. Concerning the Parent Ferromagnesian Silicate Reservoir of the Bronzite Chondrite Meteorites

E. L. Sprenkel-Segel and G. J. Perlow

The Mössbauer effect in $^{57}$Fe was used to investigate iron minerals in meteorites. The absorption spectra are composites of the 2-line patterns of olivine $(\text{Mg, Fe})_2\text{SiO}_4$ and pyroxene $(\text{Mg, Fe})\text{SiO}_3$ and the 6-line patterns of troilite (FeS) and kamacite (a nickel-iron alloy with body-centered cubic structure). The ratio of olivine iron to pyroxene iron (calculated from the absorption intensities and the recoilless fractions) was found to be $1.5 \pm 0.2$ for the bronzite chondrites Collescipoli, Ochansk, and Oakley. The ratio of olivine iron to pyroxene iron may be combined with the electron-microprobe analyses of iron and magnesium in the separated minerals to obtain the number of formula
units of pyroxene relative to olivine in the unseparated sample. Previous measurements have shown that thirty-six bronzite chondrites have olivines and pyroxenes of similar compositions and this report indicates that three of the same meteorites have similar proportions of olivine and pyroxene. Thus it appears that at least three (and perhaps all) of the equilibrated bronzite chondrites were derived from a common parent ferromagnesian silicate reservoir. A report on this work is almost complete.

2. ATOMIC-BEAM RESEARCH

W. J. Childs and L. S. Goodman

During the past year continued effort has gone into precision measurements of hyperfine and Zeeman interactions in free atoms. Increasing attention is being paid to the theoretical interpretation of the results so that tests of the theory can be more meaningful.

Papers reporting on detailed measurements in nine atomic levels of two configurations in $V^{51}$ have been published.$^1$,$^2$ It is shown that an extremely high level of agreement exists between the experiment and the effective-operator theory of hyperfine interactions when the theoretical treatment is sufficiently refined. In both multiplets examined in $V^{51}$, for example, once the magnetic-dipole hyperfine-interaction constant $A_J$ had been measured for three levels, it could be predicted theoretically for all other members of the multiplets to within 0.1%. Further theoretical work would appear to be worth while. Similar, although less detailed, studies in $Ni^{61}$ lead to corresponding conclusions.

It is found that the apparent value of the electric-quadrupole moment $Q_{\text{g.s.}}$ of the ground state of a nucleus may differ widely when extracted from hfs data in different atomic levels unless great care is taken in considering even small admixtures of other atomic levels. In Ni$^{61}$, for example, the value obtained for $Q_{\text{g.s.}}$ from the atomic levels $3d^94s^2\,^3D_{2,3}$ is about 4 times the correct value and has the wrong sign if the electric-field gradient at the nucleus is evaluated without taking account of the 9% of $^1D_2$ which the spin-orbit interaction mixes into the $^3D_2$ wave function. The final values found for the nuclear electric-quadrupole moments of V$^{51}$ and Ni$^{61}$ in their ground states are in good agreement with predictions from current nuclear models. The result for V$^{51}$ is, however, in sharp disagreement (both in sign and magnitude) with an earlier determination by a less accurate method.

Work on 3d-shell atoms is continuing; the hyperfine structure of low-lying levels in Co$^{59}$ is currently being investigated.

A good deal of work has also been done on Pt$^{195}$ and Rh$^{103}$. The electronic structure of both atoms is complex and neither the experiments nor analyses are complete.

Considerable progress has been made on the new atomic-beam magnetic-resonance apparatus being constructed to study radioactive transuranic elements. It is anticipated that experiments can be begun in 1967.

3. RADIOFREQUENCY 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 rf 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 electromagnetic fields in resonant cavities.
a. Plasmas in Uniform Electric Fields

A. J. Hatch, M. Hasan, J. Taillet,* and B. A. Tryba

One of our main goals in this work has been to measure the complex admittance of the several plasma modes that occur in (initially) uniform rf electric fields in the 5-decade range of pressure centered about the domain of rf plasmoids, and to correlate the results with theory. During the past year all data-reduction calculations were programmed for machine computation and the final values of admittance were fully corrected for substantial residual effects of leads. A significant feature of the set of such values shown in Fig. 39 is the

Fig. 39. Components of admittance

\[ Y_d = g_d + i b_d \]

describes discharges normalized to susceptance of electrodes without plasma. All values are fully corrected for residual admittances of leads. A highly significant new feature here is the establishment of the central domain (D-J) as one of resonant discharges describable by slab-model theory. Although the multipactoring domain (A-C) and diffusion domain (K-L) are well known, their admittance characteristics have not been studied very extensively.

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existence of a well-defined central domain of resonant discharges (D-J) that includes the rf plasmoids. A brief paper summarizing these results has been accepted for the 8th International Conference on Phenomena in Ionized Gases to be held in Vienna, 27 August—2 September 1967.¹

A new theory of admittance of plasmoids and related resonant discharges based on a free-electron slab model (proposed by J. Taillet) was also developed. In this model the plasmoid, which is actually an oblate spheroid, is represented by a plasma slab having an appropriate thickness. With the help of machine computations, this one-dimensional theory was fitted to the final corrected values of admittance for plasmoids to yield values of the fitting parameters (the electron density and thickness of the plasmoid sheath). These fitted values correspond fairly well to experimental values. The free-electron slab-model theory exhibits a better correlation with the admittance values of plasmoids and resonant discharges than did a

bound-electron theory developed previously. It has the additional important capability of explaining the reversed field in plasmoids (first observed\textsuperscript{2} at Argonne), a phenomenon inherently unexplainable by the bound-electron theory. This capability is illustrated in Fig. 40 which shows the ratio of the reversed field $E_1$ in the plasmoid "slab" to $E_0$ in the nonionized sheath region between the plasmoid and the exciting electrodes. This curve was calculated from the slab-model theory by use of the fitting parameter of electron density as determined above. Negative ratios as large as $\sim 10$ have been confirmed experimentally. A brief paper summarizing this work has also been accepted for the Vienna Conference.\textsuperscript{3}

\begin{itemize}
\end{itemize}

\subsection*{b. Plasmas in Cavity Fields}
A. J. Hatch, S. L. Halverson,\textsuperscript{*} and M. Hasan

The UHF cylindrical-cavity plasma facility was operated extensively at power levels of 300 W and occasionally up to 1000 W, a limit imposed by heating of the air-cooled Pyrex vacuum liner and Viton gaskets. The special provisions for measuring and matching impedance and for shifting the exciting frequency while maintaining the plasma at the desired operating level functioned as intended. Most of these break-in studies were made with the cavity excited in the TM\textsubscript{010} electric-dipole mode at 682 MHz within the pressure range from $2 \times 10^{-3}$ to 10 Torr. Included were measurements of breakdown power, plasma impedance, luminosity, and response of diagnostic modes. A significant result was that in the matched-impedance condition at

*Electronics Division.
300 W the maximum luminosity occurred at a pressure of $10^{-2}$ Torr. This is ~2 decades below the collision-frequency transition pressure (collision frequency = applied radian frequency) where simple resonance theory predicts a maximum power transfer and luminosity.

A paper describing part of the theoretical studies of potential wells for the confinement of plasmas in cylindrical cavity fields has been published.¹


c. Electromagnetic Levitation

A. J. Hatch and W. E. Smith

The interest in this subject is that the stable levitation of nonmagnetic conducting solid or liquid bodies in the vicinity of the nodal point in a quadrupole ac magnetic field is analogous to the stable steady-state confinement of a body of dense plasma in the vicinity of the nodal point of a quadrupole TE magnetic mode in a resonant cavity. The new work is an indirect method of determining the levitational forces on a conducting body of arbitrary shape in a field of arbitrary configuration by measuring the shift $\Delta L$ in the inductance of the levitating circuit. This method was experimentally verified at Argonne. A paper describing this work has been published.¹

4. MASS-SPECTROMETRIC INVESTIGATIONS

The mass-spectrometric investigations employ seven instruments, each designed for one or more 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 photoionization of both simple and 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. The recently completed portable mass spectrometer (MA-28) will be used at various accelerators in studies of the phenomena involved in ion bombardment of polycrystalline and monocrystalline foils and thick targets. 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 main emphasis of these investigations is on providing fundamental information on the thermodynamics and kinetics of chemical reactions, the interaction of radiation with matter, desorption kinetics, the interactions of energetic ions bombarding crystal surfaces, molecular structure, and similar aspects of the properties of matter.

a. Ionization and Fragmentation of Gas Molecules

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

(i) Photoionization Studies of Small Molecules. Photoionization cross sections as a function of photon energy have been measured for the parent ions and most fragment ions from the molecules O₂, H₂O, H₂O₂, H₂S, CH₄, C₂H₄, and argon. The shapes and thresholds of the curves have, in many instances, yielded new information on the ionization process and some new or much more accurate values for such quantities as bond dissociation energies D, electron affinities EA, and ionization potentials IP. Some of the more important of these
quantities determined in this manner are:

\[
\begin{align*}
\text{IP(OH)} & = 12.97 \pm 0.03 \text{ eV}, \\
\text{D(H-OH)} & = 5.05 \pm 0.02 \text{ eV}, \\
\text{IP(HO}_2) & = 11.25 \pm 0.04 \text{ eV}, \\
\text{EA(HS)} & = 2.51 \pm 0.05 \text{ eV}, \\
\text{D(H}_3\text{C-H)} & = 4.450 \pm 0.006 \text{ eV}.
\end{align*}
\]

In the case of argon, the resolution width was 0.04 Å and consequently the autoionization structure was very much better resolved than by previous workers. This structure is being compared with the theory of Fano.

(ii) Photoionization of the Hydrogen Molecule. Photo-ionization studies of the \(\text{H}_2\) (including para-\(\text{H}_2\)), HD, and \(\text{D}_2\) molecules were carried out at 300°K and at 78°K with the unprecedented resolution width of 0.04 Å. The photoionization spectrum is dominated by autoionization of many quasi-discrete states whose rotational components were completely resolved in the case of \(\text{H}_2\) and mostly resolved in the other cases. Many of the autoionizing states near threshold were identified and their relative autoionization probabilities were determined and compared with theory. The results show that present theory is inadequate. The structure near threshold showed conclusively that the previously accepted value of the ionization potential of \(\text{H}_2\) (124 429 ± 12 cm\(^{-1}\)) is too high and that the spectroscopic interpretation on which it was based is incorrect. The present data show that the ionization potential of \(\text{H}_2\) is 124 406 ± 12 cm\(^{-1}\). Certain excited states of \(\text{H}_2\), very near the ionization threshold, were shown to autoionize only in the presence of an electric field, which could be as low as 20 V/cm. However, this behavior varied inexplicably for different electronic states and requires theoretical explanation. At energies near 20 eV the process \(\text{H}_2 + h\nu \rightarrow \text{H}^+ + \text{H}^-\) was studied and shown to occur by predissociation of very highly excited (two-electron) states
of $H_2$. The results of the study demonstrate the need for a much better theoretical understanding of even this most simple of all molecules.

b. Chemi-ionization

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

Photons of energy below the ionization threshold were shown to produce $H_3^+$ ion in hydrogen at a pressure of about $10^{-2}$ mm. Two processes were identified:

1. $H_2^* + H_2 \rightarrow H_3^+ + H + e$,
2. $H^* (2s) + H_2 \rightarrow H_3^+ + e$.

At least six different excited electronic states of $H_2$ contribute significantly to process (1). Process (2) involves the metastable state of the $H$ atom produced both by predissociation of several excited states of $H_2$ and by direct photodissociation. The metastable state was identified by quenching in an electric field. The decrease of the relative cross section of process (2) with increasing kinetic energy of the $H^*$ atom was also determined quantitatively. This is the first time such a measurement has been possible for the process of chemi-ionization—which has been very poorly understood.

In a mixture of argon and hydrogen, a similar reaction was found to produce the $ArH^+$ ion.

c. Ion-Molecule Reactions by Photoionization

W. A. Chupka, J. Berkowitz, M. Russell, K. Refaey, and W. Jivery

Ions were produced by photoionization in known electronic, vibrational, and (in some cases) rotational states; and their reaction with neutral molecules was studied. For several exoergic reactions [such as (1) $H_2^+ + H_2 \rightarrow H_3^+ + H$ and (2) $NH_3^+ + NH_3 \rightarrow NH_4^+ + NH_2$], the reaction cross section was found to decrease monotonically with increasing internal energy of the reactants. On the other hand, for
several endoergic reactions. [e.g., (3) $\text{H}_2^+ + \text{He} \rightarrow \text{HeH}^+ + \text{H}$ and (4) $\text{H}_2^+ + \text{Ne} \rightarrow \text{NeH}^+ + \text{H}]$. The cross section was zero below threshold and increased monotonically toward a limiting value with increasing internal energy of the reactant ion. The data are in accord with predictions of a statistical theory and constitute a totally new type of test for any theory of ion-molecule reactions.

d. Studies of Ion Collisions

J. Berkowitz, W. A. Chupka, K. Refaey, M. Russell, and W. Jivery

Ions produced in known electronic and vibrational states and accelerated to energies between 5 and 500 eV were allowed to collide with neutral molecules and the charged products were studied. For endoergic processes such as $\text{H}_2^+ + \text{He} \rightarrow \text{H}^+ + \text{H} + \text{He}$, the cross section was found to depend strongly on the vibrational energy of the projectile ion. The reactions of $\text{H}_2^+$ and $\text{O}_2^+$ (the latter in an excited electronic state as well) impacting on $\text{H}_2$, $\text{O}_2$, and $\text{He}$ were studied.

The propane ion $\text{C}_3\text{H}_8^+$, produced with very little internal energy, was caused to collide with $\text{H}_2$ and $\text{He}$. The resulting fragmentation as a function of collision energy shows that the impact causes a large fraction of the kinetic energy in the center-of-mass system to be transferred into internal energy of the $\text{C}_3\text{H}_8^+$ ions—which then proceed to decompose in the same manner as excited ions produced directly by photon or electron impact.

e. Study of Fragmentation Processes

H. E. Stanton

The instrumentation for the measurement of the kinetic energy distribution of molecular fragment ions has been improved during the year. The method of interlacing previously mentioned is to be superseded by the use of multiscaler techniques which will permit
rapid kinetic energy sweeps of an unknown distribution and of a known standard distribution—either sequentially or interlaced. Rapid sequential sweeps will produce a much greater signal-to-noise ratio and permit greatly improved accuracy in the investigation of the less abundant fragments; and it should further improve the accuracy for all distributions.

In order to fully utilize the present experimental methods as well as the expected improvements, mathematical studies have been carried forward to improve the analysis of experimental data. It appears to be possible to determine the fundamental kinetic energy distribution of a fragment ion referred to the center of mass of the molecule undergoing reaction. Several promising computer programs and numerical methods have been developed for this purpose.

f. Studies of Ion-Desorption Kinetics with a Pulsed-Molecular-Beam Mass Spectrometer

M. Kaminsky

The mean residence times $\tau_i$ of alkali ions on atomically clean surfaces of polycrystalline tungsten have been studied over a surface temperature range from 1000°K to 1700°K with the Argonne-built pulsed-molecular-beam mass spectrometer (MA-25). The dependence of $\tau_i$ on the surface temperature $T$ is given by Frenkel's equation $\tau_i = \tau_i^0 \exp (E_i/kT)$, where $E_i$ is the desorption energy and the quantity $\tau_i^0$ is inversely proportional to the resonance frequency of the adsorbate coupled to the lattice oscillator. The effect of the incident-beam composition on $\tau_i$ was studied at a surface-coverage degree $\theta < 1 \times 10^{-4}$, using beams from evaporation of alkali metals and alkali chlorides. While the alkali chloride source gave values of $E_i$ approximately 10% smaller than for the metal source, the values of $\tau_i^0$ are considerably larger (e.g., 30 times as large in the case
of desorption of Rb$^+$. The results indicate that $E_i$ is determined predominantly by the image forces with minor contributions from repulsive forces and exchange forces, and that the observed changes in $E_i$ for the different beam compositions are due to chlorine absorption (with the possible formation of a tungsten chloride compound). The observed change in $\tau_i^0$ seems to confirm this view, since earlier results showed that $\tau_i^0$ increases drastically with increasing gas coverage of the surface. To obtain a more direct proof, it is planned to study the mean residence time of Cl$^-$ and Cl$_2^-$ on tungsten. (There is a complete lack of data for the mean residence time of negative ions on metal surfaces.)

The mean residence times $\tau_a$ for neutral alkali atoms are now being measured 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 are being extended to monocrystalline targets.

g. Lattice Effects on the Emission of Secondary Particles from Metal Monocrystals under High-Energy Ion Bombardment

M. Kaminsky

(i) Emission of Charged and Uncharged Heavy Particles. The total sputtering yield $S$ and the total yield $S_{s_0}$ of neutral sputtered particles has been measured for atomically clean surfaces of the (111) planes of aluminum, copper, and silver monocrystals bombarded by 0.4—1.6-MeV mass-analyzed D$^+$ beams at normal incidence. A portable mass spectrometer (MA-27) has been used to determine the species of uncharged and positively charged sputtered particles. From the experimentally determined values of $S$ and $S_{s_0}$, it was possible to determine the total yield $S_{s^+} = S - S_{s_0}$ of positive sputtered particles. Then with the aid of these values of $S_{s^+}$ and the total yield $S_1$ of secondary
positive ions obtained earlier, the yield \( S_R = S_i - S_{s+} \) of backscattered primary ions could be determined. For the energy region studied, it is found that the function \( S_R(E) \) decreases with increasing deuteron energy \( E \) and that \( S_R(\text{Ag}) > S_R(\text{Cu}) > S_R(\text{Al}) \), a result which indicates that the scattering process consists predominantly in a single collision between the incident ion of mass \( m \) and a target atom of mass \( M \) \( [S_R \propto (1 - m/M)] \). This new method of determining \( S_R \) promises to be a valuable tool in studying single-collision processes at higher energies (i.e., in the MeV range).

Our experiments show that the values \( S_i \), \( S_i \), and \( S_{s+} \) have the same dependence on the crystallographic orientation of the target. In particular, \( S[\text{Cu (111)}] > S[\text{Cu (100)}] > S[\text{Cu (110)}] \).

(ii) Secondary Electron Emission. It was observed in earlier experiments that the crystallographic orientation of the target influenced the production of secondary electrons. During the past year, the emphasis has shifted to its influence on the escape mechanism of these electrons. In these continuing experiments at the 2-MeV Van de Graaff, the secondary-electron yield \( \gamma \) was measured for the (100) and (110) planes of Al, Cu, and Ag monocrystals bombarded by protons with energies from 200 keV to 1 MeV under various angles of incidence. In such a set of measurements, the proton energy is kept constant and the proton beam is always incident parallel to a specified crystallographic direction—i.e., the crystal lattice always has the same orientation relative to the incident beam. The angle of incidence \( \alpha \) can then be changed only by using different crystal faces so that different crystallographic planes are exposed to the beam. For a beam incident in the [110] direction, for example, the angle of incidence on a (110) plane is \( \alpha = 0^\circ \) but \( \alpha = 45^\circ \) for a (100). How the crystal orientation affects the escape mechanism can be inferred by comparing the yield \( \gamma \) from the different crystallographic planes. It
is found, for example, that \( \gamma_{[110]}^{(110)}(\alpha = 0^\circ) < \gamma_{[110]}^{(100)}(\alpha = 45^\circ) \)
\( \approx \left( \gamma_{[110]}^{(100)}(\alpha = 0^\circ) \right) \sec \alpha \). Preliminary results indicate a certain degree of anisotropy in the distribution of secondary electrons within the lattice.

h. Anomalous Energy Losses of Energetic Protons in Copper
Monocrystals of Various Crystallographic Orientations
M. Kaminsky

Earlier observations in this experiment showed that the crystallographic orientation affects the yield values of such secondary phenomena as back sputtering, secondary ion emission, and secondary electron emission from metal monocrystals under the impact of light ions in the energy range from 0.2 to 2.0 MeV. The yield data suggested a close relationship between the production of secondary particles and the energy loss of the incident ion within a critical region of the monocrystalline target. While there have been a number of experiments on the energy loss of protons in Si and Ge, there were no such data on the energy loss of such light ions as H\(^+\), D\(^+\), and He\(^+\) in metal monocrystals for the energy region of interest (0.2—2.0 MeV). Therefore, we started by studying how the crystallographic orientation affected the energy loss of energetic protons directed along the (111), (100), and (110) planes of Cu monocrystals, and in strongly and slightly etched, cold-rolled, polycrystalline Cu. In the experiments the incident beam was highly collimated (angular spread of less than 0.01\(^\circ\)) and the angle of incidence was well defined (to better than 0.1\(^\circ\)). Monocrystalline copper foils of different thickness (5—10 microns) were prepared; the variation in the thickness of each foil over a region of 2—3 times the area of the actual target spot was \( \lesssim 5\% \). The proton beam emerging from the crystal foil was finally collimated before being analyzed with a surface-barrier solid-state detector.
IV. 4h

Fig. 41. The energy spectrum of protons emerging from a monocrystalline Cu foil with its (100) plane parallel to the surface. Left: Dependence on the angle between the beam direction and the [100] direction in the copper foil. The protons are incident with an energy $E_p = 1.70$ MeV. The ratio of the number of channeled protons (emerging with an average energy $E_C$) to the number of unchanneled protons (average energy $E_n$) decreases as the angle increases from $0.4^\circ$ to $0.8^\circ$. Right: Dependence on the energy of the incident protons. The angle between beam and [100] direction was $0.4^\circ$ for each of the three proton energies $E_p = 1.75$ MeV (top), 1.50 MeV (center), and 1.25 MeV (bottom).

When the incident proton beam was nearly parallel to one of the low-index directions ([111], [100], or [110]), the energy spectrum of the emergent particles consisted of two well separated peaks, as seen in Fig. 41. The low-energy peak was characteristic for the normal energy loss $E_n$ expected for polycrystalline targets, while the high-energy peak (with energy $E_C$) is probably due to channeled protons. For example, a typical rate of energy loss for 1.5-MeV protons traversing a Cu (111) foil is $\langle dE/dx \rangle_{av} \approx 82$ keV per mg/cm$^2$. 
for the peak at $E_n$ and 43 keV per mg/cm$^2$ for the one at $E_c$. The curves on the left in Fig. 41 show how the intensity of channeled protons decreases relative to that of unchanneled ones as the angle between the beam direction and a given low-index direction (the [100] direction in the figure) increases from 0.4° to 0.8°. The ratio $f$ of the average loss rate for the $E_c$ peak to that for the $E_n$ peak has a value near 0.5 and is practically independent of the energy of the incident proton. This result, which is obtained from data of the type plotted on the right in Fig. 41, supports Bohr’s and Lindhard’s suggestion (the equipartition rule) that on the average very energetic charged particles can lose their energy equally in two processes: (1) close electronic collisions and (2) distant electronic resonant momentum transfers. For the well-channeled protons, process (1) is negligible in comparison with the constant energy loss due to process (2); but both processes contribute equally to the energy loss of the particle in the "normal" peak. Furthermore it is observed that if the $H^+$ beam was incident parallel to the [111], [100], or [110] direction, the value of $(dE/dx)_{av}$ for peak $E_c$ decreased in the order [111] > [100] > [110] and the values of $f$ were in the range $0.48 < f < 0.50$ for the [100] and [110] directions.

Measurements of the energy loss of protons for two differently prepared polycrystalline copper foils of equal thickness (approximately 5.10 microns thick) revealed an interesting result. One of the cold-rolled foils was etched from 10 microns to a thickness of 5.10 microns and was only dipped briefly into an etch solution to remove the surface layer of impurities. It was observed (Fig. 42, left) that over the energy region studied the stopping power for the unetched foil is 14—22 keV per mg/cm$^2$ higher than for the etched foil of equal thickness. Laue diagrams (Fig. 42, right) reveal a considerably higher degree of texture in the unetched foil than in the etched foil. At least part of this observed difference in stopping power may be
Fig. 42. Effects of the grain texture in two cold-rolled polycrystalline copper foils. Target #1 was cold rolled to a thickness of 5.18 microns and then lightly etched to a final thickness of 5.08 microns; target #2 was cold rolled to 10 microns and then etched to 5.08 microns. **Left:** Average stopping powers ($\Delta E/\Delta x$) for protons penetrating through these two polycrystalline foils. Note that the values obtained by other authors cluster along the curves for these two differently prepared targets. **Right:** Laue diagrams of the two foils with which the experimental results at the left were obtained. Note that the pattern for the more strongly etched foil indicates a higher degree of order in the lattice.

attributed to differences in channeling arising from the fact that the cold rolling to produce the thicker and thinner foils may introduce different degrees of preferred orientation in the grains. These findings should be of great interest to those who use copper targets in measurements of nuclear reaction rates.

i. **High-Resolution, Portable Mass Spectrometer**

M. Kaminsky and G. Goodwin

A $90^\circ$ magnetic-sector-field mass spectrometer with a 15-in. radius of curvature has been constructed and assembled during the last year and is now being tested. The all-metal mass spectrometer is differentially pumped in three stages by a combination of mercury diffusion pumps and ion pumps, and pressures less than $1 \times 10^{-9}$ Torr will be reached in the region of the target and ion source. The
spectrometer was built to be portable so that it can be used at various accelerators for studies of high-energy sputtering, ion scattering, and radiation blistering of solids, and of the charge state of energetic ions penetrating through thin monocrystalline foils.

Tests of the field homogeneity (better than 1 part in 1000) and of the field stability (better than 2 parts in 100,000) indicate that the specifications have been exceeded. The entire mass spectrometer has been put into operation successfully and a half-width resolution of 600 has been achieved with a 0.020-in. entrance slit and 0.030-in. exit slit.

j. Production of Thin Monocrystalline Tungsten Filaments with a New Ultrahigh-Vacuum Bell Jar

M. Kaminsky and P. Williams

An ultrahigh-vacuum, all-metal bell-jar system (18-in.-diameter bell) has been built during the last year by Ultek Corporation according to our specifications. The bell-jar system has been installed and we have been able to obtain pressures less than $3 \times 10^{-11}$ Torr. In the first application of the bell jar, monocrystalline tungsten filaments of 0.003-in. diameter have been grown successfully. Such filaments are not commercially available and are needed in our studies of ion-desorption kinetics and of stopping power. The bell jar will also be used in growing thin monocrystalline metal films epitaxially.

k. Heavy-Ion Source for Use with the 2-MeV Van de Graaff

M. Kaminsky and G. Goodwin

A heavy-ion source for the production of positive alkali ions and negative halogen ions (Fig. 43) has been constructed, assembled, and is being tested. The source operates on the principle of surface ionization and electron-impact ionization, and the charged particles
Fig. 43. Heavy-ion source to produce positive or negative ions for use with the 2-MeV Van de Graaff. A. Double oven with independently heated chambers. If both are loaded with the same substance, they can be used in sequence for long-term operation. If they are loaded with different substances, the experimenter can select a beam of either one; or he can form a mixed beam with the partial pressures controlled independently.
B. Nozzle with heater and heat shields. C. Assembly of heated grids (90% transmission). D\textsubscript{1,2}. Extraction electrodes. E\textsubscript{1,2,3}. Einzel lens. F. Collector assembly.

are extracted by an ion-optical system (including an einzel lens). For short periods (several minutes) we have been able to obtain K\textsuperscript{+} ion currents of approximately 250 \(\mu\text{A}\). In order to obtain stable ion currents over longer periods (several hours), several source modifications are being made.

With the aid of the heavier ions, we will be able to vary several of the important collision parameters in the experiments described in Secs. IV.4g and IV.4h above.
IV. Operation of the 2-MeV Van de Graaff Accelerator

Jack R. Wallace

The 2-MeV Van de Graaff accelerator has operated 1516 hours from 1 April 1966 to 31 March 1967. It is operated 40 hours per week.

Major emphasis was placed on operating this accelerator at the lower end of its voltage range with good energy control. A new set of voltage-dividing resistors was made and installed. The voltage-control system has been modified. Other changes at this installation include a new cooling-water system and improvements of the ion source and its components in the high-voltage terminal.

m. Search for Fractionally-Charged Particles

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

The results of our search for quarks, which set limiting concentrations on fractionally-charged stable particles in various natural media such as seawater, air, meteorites, and atmospheric dust, were published in the summer of 1966. Since then new equipment has been designed, constructed, and tested. It should permit us to lower the limits by 2—3 orders of magnitude.

* Chemistry Division.
V. PUBLICATIONS FROM 1 APRIL 1966 THROUGH 31 MARCH 1967

The papers listed here are those whose publication was noted by the reporting unit of the Laboratory in the 1-year period stated above. The dates on the journals therefore often precede this period, and some dated within the period will be listed subsequently. The list of "papers and books," which also includes letters and notes, is classified by topic; the arrangement is approximately that followed in the Table of Contents of this Annual Review. The "reports at meetings" include abstracts, summaries, and full texts in volumes of proceedings; they are listed chronologically.

A. PUBLISHED PAPERS AND BOOKS

1. MEASUREMENT OF THE ELECTRON-NEUTRON INTERACTION BY THE ASYMMETRICAL SCATTERING OF THERMAL NEUTRONS BY NOBLE GASES
   V. E. Krohn and G. R. Ringo

2. PROPERTIES OF PARTIAL RADIATION WIDTHS IN $^{196}$Pt
   H. E. Jackson, J. Julien,* C. Samour,* A. Bloch,* C. Lopata,*
   J. Morgenstern,* H. Mann (Electronics), and G. E. Thomas

3. HIGH-ENERGY $\gamma$ SPECTRA RESULTING FROM NEUTRON CAPTURE IN HAFNIUM ISOTOPES
   A. Namenson, H. E. Jackson, and R. K. Smither
   Phys. Rev. 146, 844-852 (17 June 1966)

4. USE OF CRYSTAL DIFFRACTION WITH A Ge-DIODE DETECTOR FOR HIGH-RESOLUTION GAMMA-RAY SPECTROSCOPY
   R. K. Smither and A. I. Namenson

*Centre d'Etudes Nucléaires de Saclay, Saclay, France.
5. GAMMA-RAY SPECTRUM FROM THERMAL-NEUTRON CAPTURE IN Sm\(^{149}\), AND ASSOCIATED ENERGY LEVELS IN Sm\(^{150}\)
   R. K. Smither
   Phys. Rev. 150, 964-984 (21 October 1966)

6. ANALYSIS OF INTERMEDIATE STRUCTURE IN TERMS OF LEVEL-PARAMETER STATISTICS
   J. E. Monahan and A. J. Elwyn

7. ANALYSIS OF THE INTERMEDIATE STRUCTURE OBSERVED IN THE NEUTRON CROSS SECTION OF \(^{19}\)F
   J. E. Monahan and A. J. Elwyn

8. NEUTRON CROSS SECTIONS OF THE BORON ISOTOPES FOR ENERGIES BETWEEN 10 AND 500 keV
   F. P. Mooring, J. E. Monahan, and C. M. Huddleston
   Nucl. Phys. 82, 16-32 (July 1966)

9. NOTES ON DOPPLER-SHIFT LIFETIME MEASUREMENTS
   A. E. Blaugrund
   Nucl. Phys. 88, 501-512 (1966)

10. EVIDENCE FOR A SINGLE DOMINANT STATE FOR THE E1 GIANT RESONANCE
    Selected Papers in Physics 151: Direct Process in Nuclear Reaction III (Physical Society of Japan, Tokyo, 1966), pp. 187-190

11. GAMMA RAYS FROM B\(^{10}\) + p; DECAY SCHEMES AND EXCITATION FUNCTIONS
    R. E. Segel, P. P. Singh, S. S. Hanna, and M. A. Grace

12. STUDY OF THE K\(^{39}\)(p,\(a\))Ar\(^{36}\) REACTION
    D. von Ehrenstein, L. Meyer-Schützmeister, and R. G. Allas
    Nucl. Phys. 79, 625 (1966)
13. Ca$^{46}$(He$^3$,d)Sc$^{47}$ REACTION
J. J. Schwartz,* W. Parker Alford,* and A. Marinov

14. ISOSPIN SELECTION RULE IN THE $^{12}$Cl(d,a)$^{10}$Be REACTION
L. Meyer-Schützmeister, D. von Ehrenstein, and R. G. Allas
Phys. Rev. 147, 743-752 (22 July 1966)

15. ANOMALY IN THE ENERGY DEPENDENCE OF THE ANGULAR
   DISTRIBUTIONS FOR DEUTERONS SCATTERED FROM Mg$^{24}$
   IN THE ENERGY RANGE FROM 6 TO 13 MeV
C. Mayer-Böricke and R. H. Siemssen
Z. Naturforsch. 21a, 958-963 (July 1966)

16. THE (d,n) REACTION ON Mg$^{24}$ AND Si$^{28}$
   S. G. Buccino (Reactor Physics), D. S. Gemmell, L. L. Lee,
   Jr., J. P. Schiffer, and A. B. Smith (Reactor Physics)
   Nucl. Phys. 86, 353-362 (October 1966)

17. LOWEST T=$\frac{3}{2}$ STATE IN P$^{29}$
   D. H. Youngblood, G. C. Morrison, and R. E. Segel
   Phys. Letters 22, 625-626 (15 September 1966)

18. J DEPENDENCE IN THE (He$^3$,a) REACTION
   L. L. Lee, Jr., C. Mayer-Böricke, and R. H. Siemssen
   Phys. Rev. 147, 797-799 (22 July 1966)

19. ENERGY LEVEL STRUCTURE OF Ca$^{40}$ AS OBSERVED WITH
    THE K$^{39}$(He$^3$,d)Ca$^{40}$ REACTION
    John R. Erskine
    Phys. Rev. 149, 854-862 (23 September 1966)

20. ENERGY LEVELS OF Ca$^{48}$ AND Ca$^{40}$ AS OBSERVED WITH INELASTIC
    SCATTERING OF 11.5-MeV PROTONS
    A. Marinov and J. R. Erskine
    Phys. Rev. 147, 826-828 (22 July 1966)

21. DEPENDENCE OF THE ANGULAR DISTRIBUTION OF THE (d,p)
    REACTION ON THE TOTAL ANGULAR-MOMENTUM TRANSFER. II
    J. P. Schiffer, L. L. Lee, Jr., A. Marinov, and C.
    Mayer-Böricke
    Phys. Rev. 147, 829-835 (22 July 1966)

*University of Rochester, Rochester, New York.
22. SPIN ASSIGNMENTS IN THE 2p SHELL FROM J DEPENDENCE IN (d,p) ANGULAR DISTRIBUTIONS
   L. L. Lee, Jr., and J. P. Schiffer
   Phys. Rev. 154, 1097-1100 (20 February 1967)

23. MEASUREMENT OF THE SPINS OF SOME STATES IN Fe$^{55}$
   D. S. Gemmell, L. L. Lee, Jr., A. Marinov, and J. P. Schiffer
   Phys. Rev. 144, 923-927 (22 April 1966)

24. PARITY MIXING IN Hf$^{180}$
   R. D. Lawson and R. E. Segel

25. W$^{182}$(d,p)W$^{183}$ REACTION AT 7.5 AND 12 MEV: AN INVESTIGATION OF THE STRIPPING PROCESS ON A DEFORMED HEAVY NUCLEUS
   R. H. Siemssen and J. R. Erskine
   Phys. Rev. 146, 911-925 (17 June 1966)

26. DISCREPANCIES IN PROTON-TRANSFER REACTIONS TO STATES WITH DIFFERENT ISOBARIC SPIN
   R. H. Siemssen, G. C. Morrison, B. Zeidman, and H. Fuchs*

27. PROTON REACTION CROSS SECTIONS AND STRENGTH FUNCTIONS
   A. J. Elwyn, A. Marinov, and J. P. Schiffer
   Phys. Rev. 145, 957-962 (20 May 1966)

28. STUDIES OF ELASTIC SCATTERING OF PROTONS AND DEUTERONS BY CALCIUM ISOTOPES
   A. Marinov, L. L. Lee, Jr., and J. P. Schiffer

   C. P. Browne, † W. D. Callender, † and J. R. Erskine

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* Hahn Meitner Institut, Berlin, Germany.

† University of Notre Dame, South Bend, Indiana.
30. ISOBARIC-ANALOG STATES IN Sc$^{49}$
K. W. Jones,* J. P. Schiffer, L. L. Lee, Jr., A. Marinov, and J. L. Lerner (Chemistry)

31. ANOMALOUS ISOTOPE SHIFT OF THE NUCLEAR CHARGE RADIUS
F. G. Perey† and J. P. Schiffer
Phys. Rev. Letters 17, 324-328 (8 August 1966)

32. AN ONLINE COMPUTER SYSTEM IN USE WITH LOW-ENERGY
NUCLEAR PHYSICS EXPERIMENTS
D. S. Gemmell

33. ANGULAR DISTRIBUTIONS FOR INELASTIC DEUTERON SCATTERING FROM SAMARIUM
B. Zeidman, B. Elbek,‡ B. Herskind,‡ and M. C. Olesen‡
Nucl. Phys. 86, 471-480 (October 1966)

34. DECAY OF Co$^{55}$; LEVELS IN Fe$^{55}$
H. J. Fischbeck, F. T. Porter (Chemistry), M. S. Freedman (Chemistry), F. Wagner, Jr. (Chemistry), and H. H. Bolotin
Phys. Rev. 150, 941-955 (21 October 1966)

35. LEVEL STRUCTURE IN Cr$^{52}$ POPULATED IN 5.7-DAY Mn$^{52}$ DECAY
M. S. Freedman (Chemistry), F. Wagner, Jr. (Chemistry), F. T. Porter (Chemistry), and H. H. Bolotin
Phys. Rev. 146, 791-798 (17 June 1966)

36. A NOTE ON THE MEASUREMENT OF THE ENERGIES OF GAMMA RAYS FROM DECAY OF Ga$^{66}$
R. E. Coté, R. Guso (Special Materials & Services), S. Raboy, R. A. Carrigan, Jr., A. Gaigalas, R. B. Sutton, and C. C. Trail§
Nucl. Phys. 77, 239-240 (March 1966)

*Brookhaven National Laboratory, Upton, L. I., New York.
†Oak Ridge National Laboratory, Oak Ridge, Tennessee.
‡Institute for Theoretical Physics, Copenhagen, Denmark.
|Carnegie Institute of Technology, Pittsburgh, Pennsylvania.
§Brooklyn College, New York, N. Y.
37. NUCLEAR RESONANCE FLUORESCENCE IN Kr\textsuperscript{82}
   G. B. Beard
   Phys. Rev. 145, 862-865 (20 May 1966)

38. ANALYSIS OF $\gamma-\gamma$ CASCADES BY POLARIZATION AND DIRECTIONAL CORRELATION: DECAY OF Rh\textsuperscript{101}g
   G. T. Wood, S. Koički, \* and A. Koički\*\*
   Phys. Rev. 150, 956-963 (21 October 1966)

39. AUTOMATED NUCLEAR SHELL-MODEL CALCULATIONS
   S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga\dagger

40. THE REACTION MATRIX AND EFFECTIVE SHELL-MODEL INTERACTIONS FOR THE Ni ISOTOPES
   R. D. Lawson, M. H. Macfarlane, and T. T. S. Kuo$^\ddagger$
   Phys. Letters 22, 168-172 (1 August 1966)

41. CONCEALED CONFIGURATION MIXING AND THE SPECTROSCOPY OF THE PSEUDONIUM NUCLEI
   S. Cohen, R. D. Lawson, and J. M. Soper$^\dagger$

42. SHELL STRUCTURE EFFECTS IN THE LEVEL DENSITY OF A FERMI SYSTEM
   N. Rosenzweig
   Nuovo Cimento 43, 227-235 (11 June 1966)

43. DENSITY OF STATES OF DEGENERATE FERMI SYSTEMS WITH PERIODIC LEVEL SCHEMES
   Peter B. Kahn and Norbert Rosenzweig

44. THE ANGULAR-MOMENTUM DEPENDENCE OF THE NUCLEAR LEVEL DENSITY
   Donald W. Lang
   Nucl. Phys. 77, 545-558 (March 1966)

\daggerTokyo Institute of Technology, Tokyo, Japan.
\ddaggerPalmer Physical Laboratory, Princeton, New Jersey.
45. FREQUENCY OF SPURIOUS "INTERMEDIATE RESONANCES" IN RANDOMLY GENERATED CROSS SECTIONS
   P. P. Singh,‡ P. Hoffman-Pinther,* and D. W. Lang

46. INTRODUCTION TO NUCLEAR MATTER
   Benjamin D. Day
   Argonne National Laboratory Reviews 3(3), 75-79 (July 1966)

47. IMPROVED SOLUTION TO THE BETHE-FADDEEV EQUATIONS
   Ben Day
   Phys. Rev. 151, 826-829 (18 November 1966)

48. PHENOMENOLOGICAL α-α POTENTIALS
   S. Ali† and A. R. Bodmer
   Nucl. Phys. 80, 99 (1966)

49. AN ALPHA-DEUTERON-LAMBDA MODEL OF THE HYPERNUCLEUS
   7
   J. W. Murphy† and A. R. Bodmer.

50. MISSING SU(3) MULTIPLETS AND SU(6)\textsubscript{W} SELECTION RULES
   D. Horn (High-Energy Physics), H. J. Lipkin, and S. Meshkov
   (High-Energy Physics)

51. QUARK MODELS, UNIVERSALITY, SYMMETRY, AND HIGH-ENERGY SCATTERING
   C. A. Levinson,† N. S. Wall,‡ and H. J. Lipkin

52. SPIN-2\textsuperscript{+} MESON DECAYS IN THE QUARK MODEL
   M. Elitzur, H. R. Rubinstein, H. Stern, and H. J. Lipkin

53. INTERNAL SYMMETRIES IN A COUPLED-CHANNEL SOLUBLE MODEL WITH INELASTICITY
   James T. Cushing
   Phys. Rev. 148, 1558-1573 (26 August 1966)

*Indiana University, Bloomington, Indiana.
†The University, Manchester, England.
‡University of Maryland, College Park, Maryland.
|Weizmann Institute of Science, Rehovoth, Israel.
54. **PRESYMMETRY**
   H. Ekstein

55. **THRESHOLD BEHAVIOR OF PARTIAL WAVE AMPLITUDES IN QUANTUM FIELD THEORY**
   Gert Roepstorff and J. L. Uretsky (High-Energy Physics)
   Phys. Rev. 152, 1213-1218 (23 December 1966)

56. **MÖSSBAUER STUDY OF Kr$^8^3$ IN THE COMPOUND KrF$_2$**
   S. Ruby and H. Selig (Chemistry)
   Phys. Rev. 147, 348-354 (8 July 1966)

57. **QUADRUPOLE INTERACTION IN Sb$^{12}$1 BY MÖSSBAUER TECHNIQUES**
   S. L. Ruby, G. M. Kalvius (Solid State Science), R. E. Snyder,* and G. B. Beard*
   Phys. Rev. 148, 176-180 (5 August 1966)

58. **MÖSSBAUER EFFECT IN COMPOUNDS OF $^{127}$I**
   G. J. Perlow and M. R. Perlow

59. **OBSERVATIONS OF THE MÖSSBAUER EFFECT IN Cs$^{133}$**
   A. J. F. Boyle and G. J. Perlow
   Phys. Rev. 149, 165-170 (9 September 1966)

60. **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

61. **MAGNETIC HYPERFINE INTERACTIONS AND ELECTRIC QUADRUPOLE COUPLING IN ALLOYS OF IRON WITH THE ALPHA-MANGANESE STRUCTURE**
   C. W. Kimball (Solid State Science), Walter C. Phillips (Solid State Science), M. V. Nevitt (Metallurgy), and R. S. Preston
   Phys. Rev. 146, 375-378 (10 June 1966)

62. **CRYSTAL STRUCTURES OF V-Fe ALLOYS AS DETERMINED BY THE MÖSSBAUER EFFECT IN Fe$^{5}$7**
   R. S. Preston, D. J. Lam (Metallurgy), M. V. Nevitt (Metallurgy), D. O. Van Ostenburg (Metallurgy), and C. W. Kimball (Solid State Science)
   Phys. Rev. 149, 440-449 (16 September 1966)

*Wayne State University, Detroit, Michigan.
63. MÖSSBAUER ANALYSIS OF METEORITIC IRON MINERALS
   E. L. Sprenkel-Segel and S. S. Hanna*
   in Mössbauer Effect Methodology, Proceedings of the
   2nd Symposium, New York, 25 January 1966, edited
   by I. J. Gruverman (Plenum Press, New York, 1966),
   Vol. 2, pp. 113-126

64. ON THE SCALING OF X-RAY PHOTOGRAPHS
   J. E. Monahan, M. Schiffer (Biological & Medical Research),
   and J. P. Schiffer
   Acta Cryst. 22, 322 (February 1967)

65. HYPERFINE INTERACTIONS AND THE MAGNETIC FIELDS DUE
    TO CORE POLARIZATION IN Fe$^{57}
   W. J. Childs and L. S. Goodman
   Phys. Rev. 148, 74-78 (5 August 1966)

66. SYSTEM FOR SUPPRESSING LARGE, NONSTATISTICAL NOISE
    BURSTS IN DIGITAL AVERAGING
   L. S. Goodman and F. O. Salter (Applied Mathematics)
   Rev. Sci. Instr. 37, 769-771 (June 1966)

67. SUPPRESSION OF MULTIPACTING IN PARTICLE ACCELERATORS
   Albert J. Hatch

68. MOLECULAR COMPOSITION OF SULFUR VAPOR
   J. Berkowitz
   in Elemental Sulfur, edited by Beat Meyer (Interscience

69. EQUILIBRIUM COMPOSITION OF SELENIUM VAPOR; THE
    THERMODYNAMICS OF THE VAPORIZATION OF HgSe, CdSe,
    AND SrSe
   J. Berkowitz and W. A. Chupka

70. PHOTOIONIZATION OF HIGH-TEMPERATURE VAPORS. I. THE
    IODIDES OF SODIUM, MAGNESIUM, AND THALLIUM
   J. Berkowitz and W. A. Chupka

* Stanford University, Stanford, California.
71. ANGULAR DISTRIBUTION OF VALENCE-SHELL PHOTOELECTRONS  
   J. Berkowitz and H. Ehrhardt*  
   Phys. Letters 21, 531-532 (15 June 1966)  

72. KINETIC ENERGIES OF PRODUCTS OF ION-MOLECULE REACTIONS  
   H. E. Stanton and S. Wexler (Chemistry)  

73. MEAN RESIDENCE TIMES OF ALKALI IONS ON POLYCRYSTALLINE  
   WOLFRAM SURFACES AS STUDIED WITH A PULSED-MOLECULAR-  
   BEAM MASS SPECTROMETER  
   Manfred Kaminsky  
   Ann. Physik 18, 53-70 (August 1966)  

74. PROFESSOR DR. ERICH HÜCKEL ZUM SIEBZIGSTEN GEBURTSTAGE  
   AM 9. AUGUST 1966  
   Manfred Kaminsky  
   Ann. Physik 18, 3-5 (August 1966)  

75. EXPERIMENTAL SEARCH FOR STABLE, FRACTIONALLY CHARGED  
   PARTICLES  
   W. A. Chupka, J. P. Schiffer, and C. M. Stevens (Chemistry)  

*Physikalisches Institut der Universität, Freiburg, Br., Germany.
B. PUBLISHED REPORTS AT MEETINGS


1. DISCUSSION: LIGHT SPHERICAL NUCLEI
   Dieter Kurath

2. SINGLE-NUCLEON TRANSFER REACTIONS
   M. H. Macfarlane
   Vol. I, pp. 33-60

3. DISCUSSION: OPTICAL MODEL, DISTORTED-WAVE BORN APPROXIMATION
   J. P. Schiffer
   Vol. II, pp. 455-524


4. PROTON-STRENGTH FUNCTION MEASUREMENTS
   A. J. Elwyn, A. Marinov, and J. P. Schiffer
   p. 496

5. NEUTRON SCATTERING FROM NUCLEI NEAR A = 20
   A. J. Elwyn, J. E. Monahan, R. O. Lane, F. P. Mooring, and A. Langsdorf, Jr.
   p. 288—and repeated on pp. 537-538

6. MEASUREMENT OF RADIATION WIDTHS OF LOW-ENERGY NUCLEAR STATES BY RESONANCE SCATTERING OF THERMAL-NEUTRON-CAPTURE GAMMA RAYS
   H. S. Hans, G. E. Thomas, and L. M. Bollinger
   p. 514

7. PRECISION MEASUREMENTS ON HIGH-ENERGY GAMMA RAYS FROM CAPTURE OF THERMAL NEUTRONS IN Hf$^{177}$, Hf$^{178}$, AND Hf$^{179}$
   H. E. Jackson, A. Namenson, and R. K. Smither
   p. 515
Nuclear Structure Study with Neutrons (cont'd.)

8. SMALL-ANGLE SCATTERING OF NEUTRONS
   J. E. Monahan, A. J. Elwyn, R. O. Lane, A. Langsdorf,
   Jr., and F. P. Mooring
   pp. 558-559

9. NEUTRON CROSS SECTIONS OF THE BORON ISOTOPES
   J. E. Monahan and F. P. Mooring
   pp. 530-531

10. THE DENSITY OF STATES OF A FERMI SYSTEM
    N. Rosenzweig
    pp. 309-310 + discussion on pp. 310-311

11. CAPTURE GAMMA-RAY SPECTRUM OF Cd$^{113}$ (n, $\gamma$)Cd$^{114}$ AND THE ASSOCIATED ENERGY LEVELS IN Cd$^{114}$
    R. K. Smither
    p. 519

12. THE COMBINATION OF A BENT-CRYSTAL DIFFRACTION SPECTROMETER AND A Ge-DIODE DETECTOR FOR HIGH-RESOLUTION GAMMA-RAY SPECTROSCOPY
    R. K. Smither and A. Namenson
    pp. 519-520

13. p-WAVE RESONANCES IN U$^{238}$ AT VERY LOW ENERGY
    G. E. Thomas and L. M. Bollinger
    p. 534


14. POLARIZATION IN THE SMALL-ANGLE SCATTERING OF 0.83-MeV NEUTRONS BY U
    R. O. Lane, A. J. Elwyn, J. E. Monahan, A. Langsdorf,
    Jr., and F. P. Mooring
    pp. 468-469

15. THE POLARIZED ION SOURCE FOR THE ARGONNE TANDEM
    D. von Ehrenstein and D. C. Hess
    pp. 88-90
Zeeman Centennial Conference, Amsterdam, 6—11 September 1965

16. THE ZEEMAN SPLITTING OF THE HYPERFINE LEVELS OF THE 5D GROUND MULTIPLET OF Fe$^{57}$
   L. S. Goodman and W. J. Childs
   Physica 33(1), 283-284 (1967)

Conference on Bases for Nuclear Spin-Parity Assignments, Gatlinburg, Tennessee, 11—13 November 1965

17. (d,p) AND (d,t) STUDIES OF THE STRUCTURE OF Yb ISOTOPES
   Bull. Am. Phys. Soc. 11, 600 (June 1966)

18. J DEPENDENCE IN (α,t) AND (α,He$^3$) REACTIONS ON Mg$^{24}$ AND Mg$^{26}$
   D. Dehnhard
   Bull. Am. Phys. Soc. 11, 599 (June 1966)

19. THE NUCLEAR SHELL MODEL—COMPARISON OF CALCULATIONS AND EXPERIMENTS
   Malcolm H. Macfarlane

20. J DEPENDENCE OF ANGULAR DISTRIBUTIONS
   J. P. Schiffer
   Nuclear Spin-Parity Assignments, pp. 384-405

21. ANALYSIS OF DOUBLY MIXED γ-γ CASCADES BY USE OF POLARIZATION-DIRECTION AND DIRECTIONAL CORRELATIONS: DECAY OF 5-γ Rh$^{101}$
   G. T. Wood, S. Koički, † and A. Koički †
   Nuclear Spin-Parity Assignments, pp. 198-200
   † Bull. Am. Phys. Soc. 11, 595 (June 1966)

* Institute for Theoretical Physics, Copenhagen, Denmark.
† University of Pennsylvania, Philadelphia, Pennsylvania.

Unified presentation of two papers:

22a. X RAYS FROM MUONIC ATOMS WITH SPHERICAL OR NEARLY SPHERICAL NUCLEI

and

22b. STUDIES OF MUONIC ATOMS OF NON-SPHERICAL NUCLEI
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10th Scintillation and Semiconductor Counter Symposium, Washington, D. C., 2—4 March 1966

23. IMPROVED TIMING WITH NaI(Tl)
Frank J. Lynch
IEEE Trans. NS-13(3), 140-147 (June 1966)

APS Topical Conference on Isobaric Spin in Nuclear Physics, Florida State University, Tallahassee, Florida, 17—19 March 1966

24. EXCITATION OF ISOBARIC ANALOG STATES IN MEDIUM-WEIGHT NUCLEI BY THE (He³, α) REACTION

25. EVIDENCE FOR AN ISOBARIC-ANALOG STATE IN Mg²⁵⁷ (7.75 MeV)
D. Dehnhard and J. L. Yntema
Bull. Am. Phys. Soc. 11, 627 (June 1966)

* Carnegie Institute of Technology, Pittsburgh, Pennsylvania.
APS Topical Conference on Isobaric Spin in Nuclear Physics (cont'd.)

26. **THE ISOBARIC-SPIN SPLITTING OF NUCLEAR EXCITATIONS**
Malcolm H. Macfarlane
*Isobaric Spin in Nuclear Physics*, pp. 383-410

27. **A STUDY OF ISOBARIC SPIN PURITY OF ANALOG STATES IN Cu$^{59}$**
G. C. Morrison and J. P. Schiffer
*Isobaric Spin in Nuclear Physics*, pp. 748-756

28. **EXCITATION OF ISOBARIC-ANALOG STATES BY THE (He$^3$,d) REACTION ON Ni ISOTOPIc TARGETS**
G. C. Morrison and J. P. Schiffer

29. **STUDY OF ISOBARIC-ANALOG STATES BY PROTON SCATTERING ON Ba ISOTOPES**
G. C. Morrison and Z. Vager
*Isobaric Spin in Nuclear Physics*, pp. 320-326
+ discussion on pp. 327-332

30. **ISOBARIC-SPIN PURITY IN THE GIANT RESONANCE**
R. E. Segel
*Isobaric Spin in Nuclear Physics*, pp. 194-207
+ discussion on pp. 208-218

31. **EVIDENCE FOR A DEPENDENCE OF SINGLE-PROTON TRANSFER REACTIONS ON ISOBARIC SPIN**
R. H. Siemssen, G. C. Morrison, B. Zeidman, and H. Fuchs*
*Isobaric Spin in Nuclear Physics*, pp. 523-528
+ discussion on p. 529

32. **ISOTOPIC SPIN EFFECTS IN B$^{10}$ + p**
P. P. Singh, R. E. Segel, S. S. Hanna, and M. A. Grace
*Isobaric Spin in Nuclear Physics*, pp. 357-365

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*Hahn-Meitner Institut, Berlin, Germany.*
Twenty-Sixth Annual Conference on Physical Electronics, Massachusetts Institute of Technology, 21—23 March 1966

33. SECONDARY ELECTRON EMISSION FROM ALUMINUM AND COPPER MONOCRYSTALS UNDER HIGH-ENERGY ION IMPACT
M. Kaminsky and P. Eastman
Report on the Conference (Massachusetts Institute of Technology, Cambridge, 1966), pp. 331-332

34. POSITIVE-ION EMISSION FROM METAL MONOCRYSTALS UNDER HIGH-ENERGY DEUTERON BOMBARDMENT
M. Kaminsky and K. Swenson
+ Bull. Am. Phys. Soc. 11, 639 (June 1966)

Conference on Neutron Cross Section Technology, Washington, D.C., 22—24 March 1966

35. NEW APPROACH TO NEUTRON RESONANCE SPECTROSCOPY
L. M. Bollinger
Report on the Conference, edited by P. B. Hemmig


36. SHELL MODEL STUDIES IN NUCLEAR STRUCTURE
R. D. Lawson
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37. THE GIANT DIPOLE RESONANCE IN LIGHT NUCLEI
L. Meyer-Schützmeister
pp. 195-222

38. HIGH-RESOLUTION MEASUREMENTS OF RESONANCE NEUTRON CAPTURE
   A. Bloch,*  H. E. Jackson, and C. Samour*

39. ELASTIC SCATTERING OF He³ AND ALPHA PARTICLES
    FROM Au AND U²³⁸
   D. D. Berlin and T. H. Braid

40. HFS OF THE 3d⁴ 4s ⁶D MULTIPLET IN V⁵¹
    W. J. Childs and L. S. Goodman

41. ENERGY-LEVEL STRUCTURE OF Ca⁴⁰ AS OBSERVED
    WITH THE K³⁹(He³,d)Ca⁴⁰ REACTION
   John R. Erskine

42. POTENTIAL WELLS FOR PLASMAS IN RESONANT CAVITIES
    Albert J. Hatch and M. Hasan

43. ISOMERIC SHIFT MEASUREMENTS IN COMPOUNDS OF Sb¹²¹
    G. M. Kalvius (Solid State Science), S. L. Ruby, R. E.
    Snyder,† and G. B. Beard†

44. ELECTRON EMISSION FROM METAL MONOCRYSTALS
    UNDER HIGH-ENERGY He⁺ BOMBARDMENT
   Manfred Kaminsky

45. DEPENDENCE OF NUCLEAR CROSS-SECTION FLUCTUATIONS ON THE NUMBER OF DEGREES OF FREEDOM
    INFLUENCING THE LEVEL WIDTH
   D. W. Lang and P. P. Singh‡

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* Centre d'Etudes Nucléaires de Saclay, France.
† Wayne State University, Detroit, Michigan.
‡ Indiana University, Bloomington, Indiana.
46. ANALYSIS OF NUCLEAR LEVEL SPACING DISTRIBUTIONS
   J. E. Monahan and N. Rosenzweig

47. EXCITED STATES IN Cu62 FROM THE Ni61(He3, d) REACTION
   G. C. Morrison and J. P. Schiffer

48. AVERAGE PROPERTIES OF COMPLEX ATOMIC SPECTRA
   N. Rosenzweig and B. G. Wybourne (Chemistry)

49. SPURIOUS "INTERMEDIATE RESONANCES" IN RANDOMLY GENERATED CROSS SECTIONS
   P. P. Singh,* P. Hoffman-Pinther,* and D. W. Lang

50. Cd13(d, p)Cd14 ANGULAR DISTRIBUTIONS
   R. K. Smither, A. I. Namenson, and J. R. Erskine

51. COMPOUND-NUCLEUS FORMATION IN THE (α, γ) REACTIONS THROUGH THE GIANT-DIPOLE RESONANCE IN Si28 AND Si30
   Z. Vager, R. E. Segel, P. P. Singh, and L. Meyer-Schützmeister

American Physical Society Meeting, Minneapolis, 20—22 June 1966

52. LIFETIME OF THE THIRD EXCITED STATE IN Ca41
   S. I. Baker, R. H. Siemssen, A. E. Blaugrund, R. E. Segel, and P. P. Singh*

*Indiana University, Bloomington, Indiana.
Recent Progress in Nuclear Physics with Tandems, Heidelberg, Germany, 18–21 July 1966, edited by W. Hering (Max Planck Institute for Nuclear Physics, Heidelberg, 1966)

53. J DEPENDENCE IN DIRECT REACTIONS
   John P. Schiffer
   Session Vb, pp. 1-18

American Physical Society Meeting, Mexico City, 29—31 August 1966

54. PLOTTING THE CURRENT-VOLTAGE RELATION FOR CORONA
   Alexander Langsdorf, Jr.


55. CONTAINMENT OF PLASMAS IN RESONANT-CAVITY FIELDS
   Albert J. Hatch and M. Hasan
   pp. 962-966

American Physical Society Meeting, New York, 30 January—2 February 1967

56. LIFETIME OF THE FIRST EXCITED STATE IN Si29
   S. I. Baker and R. E. Segel

57. GROUND-STATE DECAY OF THE THIRD EXCITED STATE IN 41 Sc
   R. C. Bearse, R. E. Segel, and D. H. Youngblood

58. POLARIZATION MEASUREMENTS ON SLOW NEUTRONS BY MEANS OF A STERN-GERLACH MAGNET
   E. Bieber, V. E. Krohn, and G. R. Ringo

59. GAMMA-RAY TRANSITIONS IN F20
   D. E. Blatchley and G. E. Thomas
60. AVERAGE WIDTHS OF HIGH-ENERGY RADIATIVE TRANSITIONS PRODUCED BY NEUTRON CAPTURE
L. M. Bollinger and G. E. Thomas

61. (He^3, a) REACTION ON Ca^{40} AND EVEN-A Ti ISOTOPES
D. Borlin and T. H. Braid

62. BRANCHING RATIOS OF STATES IN Mg^{25}
R. T. Carpenter* and D. E. Blatchley

63. DYNAMIC QUADRUPOLE EFFECTS IN MUONIC ATOMS OF Ho AND Tb
R. E. Coté, W. V. Prestwich, C. C. Trail,† R. A. Carrigan, Jr.,‡ A. Gaigalas,‡ R. B. Sutton,‡ and S. Raboy

64. (a,t) REACTION ON 1p-SHELL NUCLEI AT 43 MeV
D. Dehnhard and R. H. Siemssen

65. DECAY OF Cu^{61} AND ENERGY LEVELS IN Ni^{61}
H. J. Fischbeck and H. H. Bolotin

66. HYPERFINE-INTERACTION CONSTANTS AND THE NUCLEAR ELECTRIC QUADRUPOLE MOMENT OF Ni^{61}
L. S. Goodman and W. J. Childs

67. TEMPERATURE DEPENDENCE OF THE HYPERFINE FIELD IN NpAl_{2} BY THE MOSSBAUER EFFECT IN Np^{237}
M. Kalvius (Solid State Science), B. Dunlap (Solid State Science), S. Ruby, and M. Brodsky (Metallurgy)

*University of Iowa, Iowa City, Iowa.
†Brooklyn College, New York, N. Y.
‡Carnegie Institute of Technology, Pittsburgh, Pennsylvania.
|State University of New York at Binghamton, N. Y.
68. POLARIZATION AND DIFFERENTIAL CROSS SECTION FOR NEUTRONS SCATTERED FROM $^{10}$B AND $^{11}$B
R. O. Lane, A. J. Elwyn, F. P. Mooring, and A. Langsdorf, Jr.

69. GIANT DIPOLE RESONANCE IN $^{24}$Mg STUDIED BY PROTON CAPTURE IN $^{23}$Na
L. Meyer-Schützmeister, R. E. Segel, and R. C. Bearse

70. MEASUREMENT OF ISOBARIC ANALOG STATES WITH ($He^3$,p) REACTIONS
J. A. Nolen, Jr., J. P. Schiffer, D. von Ehrenstein, and N. Williams

71. INVESTIGATION OF THE $^{48}$Ca($He^3$,p)$^{50}$Sc REACTION
H. Ohnuma, J. R. Erskine, J. A. Nolen, Jr., and J. P. Schiffer

72. DECAY OF THE THIRD EXCITED STATE IN $^{41}$Ca
R. E. Segel, E. F. Kennedy, L. L. Lee, Jr., and J. P. Schiffer

73. STUDY OF THE $^{63}$Cu(n,$\gamma$)$^{64}$Cu AND $^{65}$Cu(n,$\gamma$)$^{66}$Cu REACTIONS
E. B. Shera, H. H. Bolotin, and H. J. Fischbeck

74. TOTAL NEUTRON CROSS SECTION OF LANTHANUM
Hla Shwe, R. E. Coté, and W. V. Prestwich

75. POSSIBLE TWO-PHONON QUADRUPOLE-OCTUPOLE AND THREE-PHONON QUADRUPOLE VIBRATIONAL STATES IN Cd$^{114}$
R. K. Smither

76. DECAY OF Xe$^{125}$
G. T. Wood, H. J. Sathoff, and D. Parks

*Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
American Physical Society Meeting, Chicago, 27—30 March 1967

77. EFFECT OF INCIDENT-BEAM COMPOSITION ON THE MEAN RESIDENCE TIME OF ALKALI IONS ON POLYCRYSTALLINE TUNGSTEN SURFACES
   Manfred Kaminsky

78. MAGNETIC MOMENT IN Sb\textsuperscript{121} FROM MÖSSBAUER MEASUREMENTS
   S. L. Ruby and G. M. Kalvius (Solid State Science)

C. ANL TOPICAL REPORT

1. ENERGY-ANALYZING SYSTEM FOR THE ARGONNE 60-INCH CYCLOTRON
   W. J. Ramler (Chemistry), J. J. Livingood, G. W. Parker
   (Chemistry), J. Aron (Chemistry), and M. C. Oselka (Chemistry)
   Argonne National Laboratory Topical Report ANL-7251
   (October 1966)

D. PHYSICS DIVISION INFORMAL REPORTS

1. THE BRUECKNER-GOLDSTONE THEORY OF NUCLEAR MATTER
   Ben Day
   (June 1966)
2. PROGRESS REPORT ON A STUDY OF PATTERN RECOGNITION USING "DAPHNIS"
   C. Harrison (Applied Mathematics), D. H. Jacobsohn (Applied Mathematics), and G. R. Ringo
   ANL Applied Mathematics Division Technical Memorandum No. 123 (16 June 1966)

3. NOTES ON PROGRAMMING THE ASI COMPUTERS FOR DATA HANDLING
   R. E. Holland

4. THE ISOBARIC-SPIN SPLITTING OF NUCLEAR EXCITATIONS
   Malcolm H. Macfarlane

5. A. ENERGY DEPENDENCE OF CROSS SECTION FOR COLLISION-INDUCED DISSOCIATION AND ENDOOTHERMIC ION-MOLECULE REACTIONS. B. PHOTOIONIZATION OF THE LOWER ALIPHATIC ALCOHOLS AND ETHYLENE
   Kamel M. A. Refaey
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VI. STAFF MEMBERS OF THE PHYSICS DIVISION

The Physics Division staff for the year ending 31 March 1967 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 1966 through 31 March 1967, there were 48 temporary staff members (29 staff members from universities and other laboratories and 19 postdoctoral fellows), 8 graduate students (including 4 doing thesis research), and 26 undergraduates (6 in the Argonne Semester program of the Associated Colleges of the Midwest, 14 co-op technicians, 10 CSUI-ANL Honor Students, and 3 on summer appointments).

RESEARCH AT THE REACTOR CP-5

Permanent Staff

Lowell M. Bollinger,* Ph.D., Cornell University, 1951
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
G. R. Ringo, Ph.D., University of Chicago, 1940
Robert K. Smither, Ph.D., Yale University, 1958
George E. Thomas, Jr., B.A., Illinois Wesleyan University, 1943

*Director of Physics Division.
Temporary Staff

Erhard Bieber, Dr. rer. nat. in Physics, Technische Hochschule, 1965
Donald Blatchley, Ph. D., Indiana University, 1964
David L. Bushnell, Ph. D., Virginia Polytechnic Institute, 1961
(On leave from Northern Illinois University)
Duane J. Buss, Ph. D., University of Notre Dame, 1966
† R. T. Carpenter, Ph. D., Northwestern University, 1962
(On leave from University of Iowa)
† Ram Chaturvedi, Ph. D., University of British Columbia, 1963
(On leave from State University of New York, Cortland)
† Arthur I. Namenson, Ph. D., Columbia University, 1963
William V. Prestwich, Ph. D., McMaster University, 1963
M. Hla Shwe, Ph. D., University of California, Berkeley, 1962
(On leave from Ripon College)

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

† No longer at Argonne as of 31 March 1967.
Temporary Staff

Karl K. Ilgen, Ph.D., Technical University, Stuttgart, Germany, 1966
(On leave from Technical University, Stuttgart, Germany)
Franca T. Kuchnir, Ph.D., University of Illinois, 1965

CHARGED-PARTICLE REACTIONS

Permanent Staff

Thomas H. Braid, Ph.D., Edinburgh University, 1950
John R. Erskine, Ph.D., University of Notre Dame, 1960
Donald S. Gemmell, Ph.D., Australian National University, 1960
Robert E. Holland, Ph.D., University of Iowa, 1950
Frank J. Lynch, B.S., University of Chicago, 1944
Luise Meyer-Schützmeister, Ph.D., Technical University of Berlin, 1943
George C. Morrison, Ph.D., University of Glasgow, 1957
John P. Schiffer, * Ph.D., Yale University, 1954
Ralph E. Segel, Ph.D., Johns Hopkins University, 1955
J. L. Yntema, Ph.D., Free University of Amsterdam, 1952
Benjamin Zeidman, Ph.D., Washington University, 1957

Temporary Staff

† Samuel I. Baker (AMU-ANL Predoctoral Fellow, Illinois Institute of Technology)

Robert C. Bearse, Ph.D., Rice University, 1964

* Associate Director of Physics Division.
† No longer at Argonne as of 31 March 1967.
†A. E. Blaugrund, Ph.D., University of Utrecht, 1960
(On leave from Weizmann Institute of Science)

David D. Borlin (AMU-ANL Predoctoral Fellow, Washington University)
†Dietrich Dehnhard, Ph.D., University of Marburg/Lahn, 1964
†Edward F. Kennedy, Ph.D., University of Notre Dame, 1960
(On leave from College of the Holy Cross, Worcester, Massachusetts)
†Linwood L. Lee, Jr., Ph.D., Yale University, 1955
(On leave from State University of New York, Stony Brook)
†Michael Nagel (RSA, summer, University of Illinois)
J. A. Nolen, Jr., Ph.D., Princeton University, 1965
Hajime Ohnuma, Ph.D., University of Tokyo, 1966
(On leave from University of Tokyo)
N. G. Puttaswamy, Ph.D., Stanford University, 1966
†Rolf H. Siemssen, Ph.D., University of Hamburg, 1963
†J. Curtis Siren (RSA, summer, Stanford University)
Bruce A. Watson (AMU-ANL Predoctoral Fellow, Indiana University).
Norman Williams, Ph.D., Manchester University, 1965
Dave Youngblood, Ph.D., Rice University, 1965

DEVELOPMENT OF EQUIPMENT AND ACCELERATORS

Permanent Staff

David C. Hess, Ph.D., University of Chicago, 1949
John J. Livingood, Ph.D., Princeton University, 1929
Dieter von Ehrenstein, Ph.D., University of Heidelberg, 1960
Jack R. Wallace, B.A., College of Wooster, 1942

†No longer at Argonne as of 31 March 1967.
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

Temporary Staff

†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)
†H. John Sathoff, Ph.D., Ohio State University, 1960
(On leave from Bradley University, Peoria, Illinois)

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

Temporary Staff

†Yau Wa Chan, Ph.D., University of California, Berkeley, 1962
(On leave from Brookhaven National Laboratory)

†No longer at Argonne as of 31 March 1967.
MÖSSBAUER STUDIES

Permanent Staff

Gilbert J. Perlow, Ph. D., University of Chicago, 1940
Richard S. Preston, Ph. D., Yale University, 1954
Stanley Ruby, B. A., Columbia University, 1947

Temporary Staff

L. E. Campbell, Ph. D., Carnegie Institute of Technology, 1966
†Michael A. Grace, Ph. D., Oxford University, 1950
(On leave from Oxford University)
†Charles E. Johnson, Ph. D., Oxford University, 1955
(On leave from A. E. R. E., Harwell, England)
†Edward R. Sanford, Ph. D., Iowa State University, 1959
(On leave from Ohio University, Athens)
Esther L. Segel, Ph. D., University of Rochester, 1959
(On leave from Illinois Institute of Technology)

MUONIC X RAYS

Permanent Staff

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

†No longer at Argonne as of 31 March 1967.
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
Hans Ekstein, Ph. D., University of Berlin, 1934
Melvin Hack, Ph. D., Princeton University, 1956
David R. Inglis, Ph. D., University of Michigan, 1931
Dieter Kurath, Ph. D., University of Chicago, 1951
Robert D. Lawson, Ph. D., Stanford University, 1953
Malcolm H. Macfarlane, Ph. D., University of Rochester, 1959
James E. Monahan, Ph. D., St. Louis University, 1953
Murray Peshkin, Ph. D., Cornell University, 1951
Norbert Rosenzweig, Ph. D., Cornell University, 1951

Temporary Staff

†Akito Arima, Ph. D., University of Tokyo, 1958
   (On leave from University of Tokyo)
†James T. Cushing, Ph. D., State University of Iowa, 1963
Benjamin Day, Ph. D., Cornell University, 1963
†Kenneth Hartt, Ph. D., University of Nebraska, 1963
   (On leave from University of Missouri)
†Peter B. Kahn, Ph. D., Northwestern University, 1960
   (On leave from State University of New York, Stony Brook)
Alpo J. Kallio, Ph. D., University of Helsinki, 1964

*Associate Director of Physics Division.
†No longer at Argonne as of 31 March 1967.
Staff

Amnon Katz, Ph. D., Weizmann Institute of Science, 1961
(On leave from Weizmann Institute of Science)
† Harry J. Lipkin, Ph. D., Princeton University, 1950
(On leave from Weizmann Institute of Science)
† Lionel Lovitch, Ph. D., Cambridge University, England, 1960
(On leave from Columbia University, New York)
James MacKenzie, Ph. D., University of Minnesota, 1966
† Gert Roepstorff, Ph. D., University of Hamburg, 1964
Carl Rosenkilde, Ph. D., University of Chicago, 1966
† John M. Soper, Ph. D., Trinity College of England, 1958
(On leave from A. E. R. E., Harwell, England)
† Donald W. L. Sprung, Ph. D., University of Birmingham, England, 1961
(On leave from McMaster University, Hamilton, Ontario, Canada)

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

Temporary Staff

† Paul S. Eastman (RSA, summer, Michigan State University)
† Kamel M. A. Refaey (RSA, thesis, Illinois Institute of Technology)

† No longer at Argonne as of 31 March 1967.
†Morley E. Russell, Ph.D., University of Michigan, 1959
(On leave from Northern Illinois University)
Peter Williams, Ph.D., King's College, London, 1966

RADIOFREQUENCY PLASMAS

Permanent Staff

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

Temporary Staff

†Mazhar Hasan, Ph.D., Illinois Institute of Technology, 1959
(On leave from Northern Illinois University)
†Barbara Ann Tryba (RSA, summer, University of Illinois)

ADMINISTRATIVE

Permanent Staff

Charles Eggler, B.S., Virginia Polytechnic Institute, 1944
Francis E. Throw, Ph.D., University of Michigan, 1940

†No longer at Argonne as of 31 March 1967.