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Argonne National Laboratory

PHYSICS DIVISION
SUMMARY REPORT

April-December 1964

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ARGONNE NATIONAL LABORATORY
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PHYSICS DIVISION SUMMARY REPORT

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Lowell M. Bollinger, Division Director

Preceding Summary Reports:

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FOREWORD

This issue of the Argonne National Laboratory Physics Division Summary Report brings the record approximately up to date. These short reports on the highlights of the research in the Physics Division during 1964 were originally prepared for the Research Division of the Atomic Energy Commission; only minor changes were made to adapt the material to its present purpose.

Many of the reports cover work still in progress. The results and data therefore must be understood to be preliminary, tentative, and often incomplete.

The issuance of these reports is not intended to constitute publication in any sense of the word. Final results either will be submitted for publication in regular professional journals or, in special cases, will be presented in ANL Topical Reports. Papers published during the period covered by this report are listed in a separate section near the end.

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A NEWLY DISCOVERED PEAK IN THE s-WAVE NEUTRON STRENGTH FUNCTION

R. E. Coté, R. F. Barnes,* H. Diamond,* and P. R. Fields*

Recent measurements on curium have revealed that the s-wave neutron strength function has a peak in the transuranic region of the nuclide chart.

The s-wave neutron strength function has been the subject of numerous experimental and theoretical studies. The early optical-model analysis, based on the "cloudy crystal ball" model of the nucleus, predicted peaks in the strength function near nucleon numbers A = 55 and A = 160. Both of these peaks were confirmed experimentally; but, upon careful examination, neither peak had the simple symmetrical shape predicted by the theory. The complex shape of the maximum near A = 160 was subsequently explained quite well in terms of a more detailed theory that included the effects of nuclear quadrupole deformation.

The use of a spheroidal potential based on the measured quadrupole deformations also leads to the prediction of a strength-function peak in the transuranic region. However, a comprehensive experimental study in this mass region has been severely restricted by the limited availability of samples, since the region is bounded on the low-mass side by very short-lived nuclides and on the high-mass side by the transuranic elements. Nevertheless, in a program extending over several years, we have been studying the neutron resonances of heavy elements as samples of sufficient size become available. Most recently, samples of Cm^{244} and Cm^{246} were studied in transmission measurements

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*Chemistry Division.

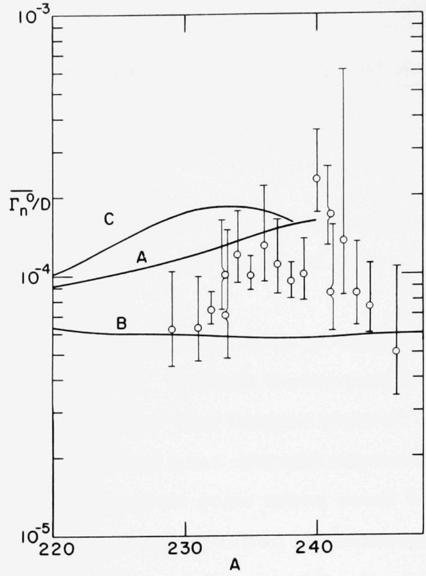

Fig. 1. The strength function $\overline{\Gamma_n^0}/D$ for nuclides with nucleon numbers A between 220 and 248. The curves [from the work of D. M. Chase, L. Wilets, and A. R. Edmonds, Phys. Rev. 110, 1080 (1958)] represent three different theoretical predictions. Curve A is based on a spheroidal potential that provides the best fit to the data near A = 160. Curve B is based on a spherical potential. Curve C corresponds to the same set of parameters as curve A except that the quadrupole deformation is 33% larger for C.

with the Argonne fast chopper.[1] The strength-function values obtained from these data, when combined with all other measured values of the strength function in this mass range, demonstrate the existence of the predicted peak. The experimental data are summarized in Fig. 1, where the recent measurements for the curium isotopes show that a maximum has indeed been passed and that this maximum lies near A = 239.

The experimental establishment of the existence of the predicted peak in the strength function provides additional proof of the essential correctness of the optical-model interpretation. Further study of the peak will make more exacting demands on the theory, since the deformations associated with many of the nuclides in the region have been inferred from experiments of an entirely different nature. (In particular, nuclear octupole as well as quadrupole

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[1] R. E. Coté, R. F. Barnes, and H. Diamond, Phys. Rev. 134, B1281-B1284 (22 June 1964).

deformations have been shown to influence the position of the peak.) These studies must await the construction of more powerful reactors to provide stronger sources of neutrons and larger amounts of transplutonic elements.

With respect to the production of transplutonic elements, the measurements described above (when combined with measurements of the ratio of Cm^{246} to Cm^{244} for different irradiation conditions) lead to the interesting result that the loss of curium because of neutron-induced fission may be reduced by raising the thermal temperature of the neutron flux in which the curium is irradiated.

A VERSATILE NEUTRON TIME-OF-FLIGHT ANALYZER WITH LARGE MEMORY CAPACITY

C. C. Rockwood (EL), L. M. Bollinger, R. E. Coté, and H. E. Jackson

In order to meet the needs arising from the continual improvement in the intensity and precision of the Argonne Fast Chopper and the associated detection system, a new time analyzer of advanced design has been constructed and placed in operation at the reactor CP-5. With this system, extremely large volumes of experimental data can be accumulated over a broad range of neutron flight times with a high degree of flexibility. The analyzer currently is being exploited in measurements of total neutron cross sections of very high statistical accuracy, an order of magnitude better than that of earlier measurements.

Important characteristics of the analyzer include: a total of 4096 channels, control of the channel widths of individual blocks of 256 channels over a range from $\frac{1}{8}$ μsec to 128 μsec, a memory capacity of 262 144 counts per channel, a constant dead time of 5 μsec per event, provision for splitting the memory into two blocks of 2048 channels, and a "verify" mode of operation which makes possible the detection of errors in the readout by comparing it rapidly with the content of the memory. The large number of channels permits simultaneous accumulation of data over almost the full range of neutron energies, especially since the unique "accordion feature" of the channel-width control enables the experimenter to select narrow channels in the region of prime interest to obtain maximum time resolution, while other regions are scanned with wider channels. A high memory capacity per channel provides for the acquisition of very accurate time-of-flight spectra, and is sufficient to permit the observation of transmission dips as small as a few tenths of a percent in a single run. The correction of the experimental spectrum for dead-time effects is kept relatively small by the short dead time of the analyzer, in spite of the high instantaneous counting rates obtained with the new detection system.

Currently, the unit is employed in a study of the small details of the resonance structure of a broad range of nuclei which show promise of giving detailed information on the interaction of p-wave neutrons. With the very high statistical precision now available to the experimenter, it will be possible to gain new information about p-wave resonances, which are of importance to both pure and applied physics.

STUDY 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

A new approach to the measurement of radiation widths of low-energy nuclear states has been explored through study of states in Sr^{88}. Basically, the measurement is similar to resonance-scattering experiments in which a beta ray from radioactive decay provides compensation for the recoil-energy loss of the scattered gamma ray. The essential difference in our measurement is that the compensation is provided by the initial transitions in the cascade of gamma rays resulting from capture of thermal neutrons. The important advantage of the new approach is that it greatly expands the energy range accessible to resonance scattering. Relative to other methods, the resonance scattering of thermal-neutron-capture gamma rays is most advantageous for the study of states in the range from 2 to 5 MeV, a range for which other methods have not yet provided much information.

After capturing a thermal neutron, the target nucleus is excited to an excitation energy equal to the binding energy of the neutron, which is ordinarily of the order of 8 MeV and is as high as 11 MeV for quite a few cases. The nucleus may then decay to the ground state by gamma-ray emission in a few successive steps. In this mode of decay, it is expected that the gamma ray corresponding to the last step will be emitted by a moving nucleus whose speed and direction depend on the energies and directions of the preceding gamma rays. As a result, the emission line corresponding to the final gamma ray is expected to have a width of a few hundred electron volts. The actual shape may, of course, be modified by the resonance absorption in the target and by the slowing down of the emitting nucleus by the other atoms in the target. In any case, under favorable circumstances the emission line may overlap the absorption line if the nuclide used as absorber (or scatterer) is the same as the compound nucleus in the target. Such an overlapping can be effected for levels up to an excitation equal to half the neutron binding energy.

We chose to study the first few excited states of Sr^{88} as a test of the method outlined above. Natural strontium, which contains both Sr^{87} ($\sim$7%) and Sr^{88} (82.5%), was used as a source and was placed near the core of the reactor CP-5. A well collimated beam of thermal-neutron-capture gamma rays from this source was directed into a shielded area outside the reactor. There it was incident on a natural strontium scatterer and the scattered radiation was measured in the backward direction by a 4 $\times$ 4-in. NaI(Tl) detector. Shielding reduced the room background to about 10% of the scattered counts; but the nonresonance scattering contributed more than 90% of the counts in the scattered spectrum. Despite such a preponderance of unwanted counts, it was possible to observe peaks in the scattered spectrum at 1.84 MeV and 3.5 MeV, corresponding to levels at these energies in Sr^{88}.

For the purpose of measuring the partial radiation width Γ_0 corresponding to the transition to the ground state, an absorption experiment was performed. The counts under the resonance peaks were determined with a resonant and a nonresonant absorber in the path of the incident beam. The nonresonant absorber (zirconium in our case) was such that it had the same electronic absorption as the resonant absorber (strontium in our case). The ratio R of the counts with the resonant absorber to those with the nonresonant absorber was determined for various absorber thicknesses and was compared with the theoretical values calculated for various values of Γ_0. The value of Γ_0 which best fitted the experimental points gave the desired result. The values of Γ_0 obtained are

$$\Gamma_0\ (1.84\ \text{MeV}) = 0.003\ \text{eV} \pm 40\%\ ,$$

$$g\Gamma_0\ (3.5\ \text{MeV}) = 0.39\ \text{eV} \pm 25\%\ .$$

The method is now being extended to other nuclei. It is especially suitable for light and medium-weight nuclei.

MAGNETIC MOMENT OF THE 26.8-KEV STATE OF I^{129}

Hendrik de Waard* and Juergen Heberle

In one of the earliest instances in which the Mössbauer effect was used to obtain information about the properties of nuclei, the magnetic moment of the 14-keV state of Fe^{57} was determined by observing the Zeeman splitting of the Mössbauer spectrum. Since then the magnetic moments of several other excited states have been measured by employing the Mössbauer effect. In every one of those experiments, the Zeeman splitting of the nuclear state was produced by the internal magnetic field arising from the ferromagnetic orientation of electron spins in the vicinity of the nucleus. In some cases the internal field was augmented by an external magnetic field produced by a permanent magnet or a conventional electromagnet.

Since this method made use of ferromagnetism, it was limited to nuclei whose atoms could be constituents of ferromagnetic materials. The advent of superconducting magnets, however, offered the possibility of measuring the magnetic moments without having to depend on ferromagnetism. We have now, for the first time, implemented this idea by using a special superconducting magnet to measure the nuclear magnetic moment of the 26.8-keV state of I^{129}. The characteristics of the magnet itself have been described[1] at the Third Conference on the Mössbauer Effect, Cornell University, 1963.

In measuring the Zeeman splitting, it is important to avoid the complications of nuclear electric-quadrupole interactions by using substances with a cubic lattice for both the source and the absorber. Our $Zn^{66}Te^{129}$ source and KI^{129} absorber satisfy this requirement. Since the many lines in the Mössbauer pattern are not

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*On vacation from the University of Groningen, the Netherlands.

[1] J. Heberle, Rev. Mod. Phys. 36, 408 (1964).

well resolved with the available magnetic field, the measurement of the pattern was repeated ten times. All ten sets of data are consistent. A preliminary analysis of the data yields the result $\mu_{exc} = +2.80 \pm 0.18$ for the value of the magnetic moment.

INTERACTION BETWEEN THE NEUTRON MAGNETIC MOMENT AND THE NUCLEAR COULOMB FIELD IN NEUTRON POLARIZATION

J. E. Monahan and A. J. Elwyn

The polarization of neutrons scattered from nuclei through "large" angles can be explained by the inclusion of an effective spin-orbit interaction in an optical-model potential. At small angles of scatter ($\lesssim 5^{\circ}$), on the other hand, the polarization has been shown by Schwinger[1] to be caused principally by the interaction between the magnetic moment of the neutron and the electric field of the nucleus. All of the methods that have been used to estimate the magnitude of this latter effect involve approximations that restrict their validity to small angles. In order to estimate the contributions to the polarization at all angles it is necessary to consider all interactions simultaneously. Recently we have carried out such a calculation. Also, the results of this calculation have been compared with the experimental data[2] (obtained at Argonne) that originally indicated the possibility of an extranuclear contribution to the polarization of $\sim$1.0-MeV neutrons scattered through an angle of 24°. This comparison shows that the electromagnetic interaction can account for a substantial part of the polarization observed at this large angle— even for the case of neutrons scattered from nuclei with moderate charge ($Z \gtrsim 40$).

We consider the polarization of neutrons scattered from a potential of the form $V(r) = V_m(r) + V_e(r)$, where $V_m(r)$ is an optical-model potential, which may include a spin-orbit term, and

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[1] J. Schwinger, Phys. Rev. 73, 407 (1948).

[2] A. J. Elwyn, R. O. Lane, A. Langsdorf, Jr., and J. E. Monahan, Phys. Rev. 133, B80 (1964).

$V_e(r)$ is the potential that describes the interaction between the magnetic moment of the neutron and the electric field of a charge Ze distributed uniformly throughout a sphere of nuclear dimensions. In the present calculation the wave function is treated exactly (numerically) in the region $r \leq r_c$, where r_c is a "cutoff" radius defined such that the nuclear potential is negligible for $r \leq r_c$. In the region $r > r_c$, the wave function is approximated by the first term in an expansion in powers of the electromagnetic potential $V_e(r)$.

Figure 2 compares the results of the present calculation with the data of Elwyn et al.[2] on the polarizations measured for 0.3- to 0.9-MeV neutrons scattered from Zr, Nb, Mo, and Cd. The dashed curves in the figure represent calculations based on a potential equivalent to the nonlocal potential of Perey and Buck plus a spin-orbit potential

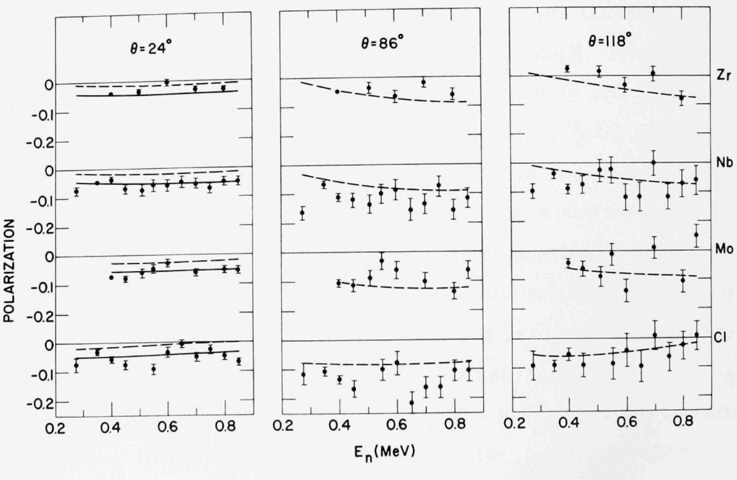

Fig. 2. A comparison of measured and calculated polarizations of neutrons scattered from four nuclei at three angles of scatter as a function of neutron energy. The dashed curves represent optical-model calculations for a potential equivalent to the nonlocal potential of Perey and Buck plus a spin-orbit term of strength predicted by the shell model. The solid curve (at 24°) includes, in addition, the electromagnetic interaction $V_e(r)$. This latter interaction has a negligible effect on the polarization at the larger angle.

of strength predicted by the shell model. These calculations are in good agreement with the values measured at 86° and 118° and at other angles. In contrast, the polarizations observed at 24° are consistently more negative than the calculated values. However, when the electromagnetic potential $V_e(r)$ is included in the total interaction, the agreement between the calculation (solid curve) and the measured values is systematically improved. These results demonstrate that the interaction $V_e(r)$ accounts for a substantial part of the polarization measured at 24°.

The interaction that results from the electric polarizability of the neutron can be included without difficulty in the present calculation. This gives rise to an additional interaction $-\frac{1}{2}\alpha_n \vec{E}^2$, where $\vec{E}$ is the electric field vector and α_n is the electric polarizability of the neutron.

Estimates of the polarizability of the proton, based on measurements of the elastic scattering of photons, give a value of about 10^{-42} cm^3 for this quantity. Theoretically the polarizability of the neutron should be the same order of magnitude. However, these latter estimates neglect effects connected with the internal structure of the nucleons, and the possibility that the polarizability of the neutron is much larger than that of the proton cannot be rigorously excluded.

There has therefore been a considerable effort to determine the value of α_n directly by measuring the small-angle scattering of neutrons on heavy nuclei. The most recent measurement is that of Fossan and Walt[3] who observed the scattering of 0.57-MeV neutrons on U in the angular interval from about 3° to 18°. From their measurements they were able to assign an upper limit of 2×10^{-40} cm^3 for the value of α_n.

The differential cross section for neutrons on U^{238}

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[3] D. B. Fossan and M. Walt, Phys. Rev. Letters 12, 672 (1964).

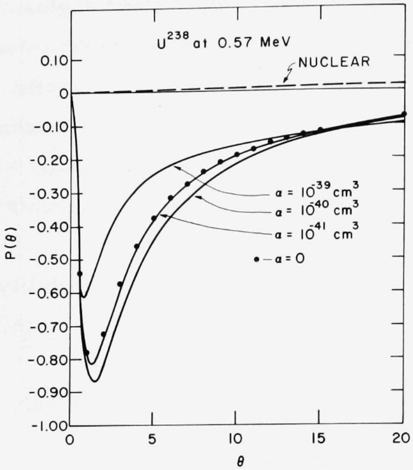

Fig. 3. The calculated differential cross section of neutrons scattered from U^{238} at 0.57 MeV. The nuclear interaction $V_m(r)$ is represented by a nonlocal optical-model potential including a spin-orbit term. The curve labeled "Schwinger only" is the difference between the cross sections calculated with and without the additional potential $V_e(r)$. Similarly, the curves shown for specified values of α represent the scattering from a potential $V_m + V_e - \frac{1}{2}\alpha \vec{E}^2$. The inset shows the difference in the scattering from this potential for the given value of α and from the potential with α set equal to zero.

is shown in Fig. 3 for different values of α_n. These results clearly show the difficulty in the determination of an upper limit smaller than 10^{-40} cm^3. Since the absolute value of the differential cross section depends on the model chosen to represent the nuclear scattering, Fossan and Walt base their upper limit on the slope of the differential cross section as a function of angle for angles below 10°. As shown in Fig. 3, this slope is extremely insensitive to values of α_n less than 10^{-40} cm^3. For $\alpha_n > 10^{-40}$ cm^3, the slope of the differential cross section begins to change more rapidly. This is indicated in the inset of Fig. 3, which shows the contribution from the polarizability for larger values of α_n.

This insensitivity of the differential cross section to values of α_n less than 10^{-40} cm^3 can be traced to the destructive interference between the nuclear scattering and the scattering due to the polarizability. It is possible, therefore, that the corresponding polarization measurements might provide a more sensitive measure of α_n.

Fig. 4. The calculated polarization of neutrons scattered from U^{238} at 0.57 MeV. The dashed curve shows the contribution to the polarization from the spin-orbit term in $V_m(r)$. The remaining curves represent the polarization from the potential $V_m + V_e - \frac{1}{2}\alpha \vec{E}^2$ for various values of α.

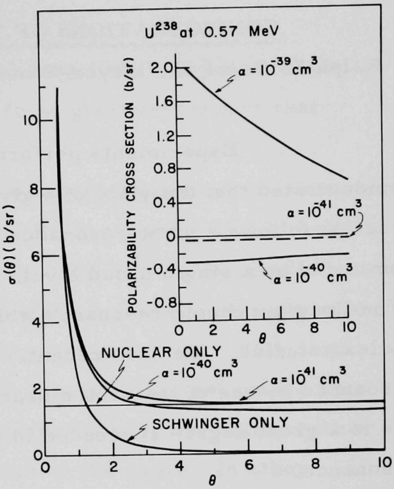

Figure 4 shows the polarization that we calculate for the scattering of 0.57-MeV neutrons from U^{238}. The most obvious result is that polarization measurements in this region of neutron energy and charge number are not sensitive to values of α_n less than about 10^{-41} cm^3. However, assigning α_n a value of about half the upper limit obtained by Fossan and Walt will produce a 10% effect in the polarization in the angular interval from 3^o to 8^o.

CONFIGURATIONS OF THE GIANT RESONANCE

Ralph E. Segel, L. Meyer-Schützmeister, P. P. Singh, and R. Allas

Experiments performed at Argonne and elsewhere have demonstrated that the yield of a given capture gamma ray from a (p, γ) reaction follows a giant-resonance shape, i.e., the yield curve is dominated by a single broad level. This giant resonance has been shown to be the giant dipole resonance which has long been familiar in photonuclear studies. We have recently initiated a program to study the giant resonance by use of the proton beam from the ANL tandem. This program has to a great degree succeeded in establishing the nature of the giant resonance.

The two cases we studied most extensively were the $B^{11}(p, \gamma)C^{12}$ and the $Al^{27}(p, \gamma)Si^{28}$ reactions. In each case the gamma rays to the ground state and first excited state of the daughter nucleus stand out clearly and were studied in detail. For $Al^{27}(p, \gamma)$ we observed a giant resonance built upon the second and third excited states which form a doublet in Si^{28}; but the data on this gamma ray are not good enough to warrant a detailed analysis.

Exhaustive 90^{o} yield curves have been taken for each of these reactions — in 50-keV steps over a 10-MeV interval for $B^{11}(p, \gamma)$ and in 15-keV steps over an 8.5-MeV interval for $Al^{27}(p, \gamma)$. The considerable structure observed in these yield curves indicates that the giant resonance is not a simple state but rather a collection of states. For $B^{11}(p, \gamma)$ the structure is rather mild and appears to represent a few (≈ 10) levels, each several hundred keV wide. On the other hand, the structure in $Al^{27}(p, \gamma)$ is quite violent; in the giant resonance corresponding to each gamma ray there are sharp peaks in the yield about every 100 keV. The peaks in the yields of the two gamma rays usually do not coincide. A statistical analysis of the $Al^{27}(p, \gamma)$ data, along the lines laid down by Ericson, showed that about 1000 individual levels must be present in each of the two $Al^{27}(p,\gamma)$ giant resonances that were analyzed.

Extensive angular-distribution measurements [taken every 50 keV over a 10-MeV interval for $B^{11}(p,\gamma)$ and every 15 keV over several intervals totaling about 2 MeV for $Al^{27}(p,\gamma)$] showed the surprising result that for each (p,γ) giant resonance the gamma-ray angular distribution is practically independent of energy. This result implies that all of the many levels making up the giant resonance must have the same configuration—or at least that part of the configuration that contributes to the (p,γ) reaction must be the same. In other words, all of the levels must represent the same "particle-hole" state or a constant combination of particle-hole states. This result contradicts the published analysis by others who have reported studies of various giant resonances (including those studied here) in which they identified the various structures in a giant resonance with different particle-hole states.

The results obtained at ANL do not deny that a given giant resonance might contain several particle-hole states; in fact, the observed angular distribution sometimes does not appear to fit that of a single state. What does emerge is a giant resonance composed of one or several particle-hole states, this state (or these states) being spread over the collection of individual levels which make up the giant resonance. The fact that the angular distribution stays constant in spite of the strongly fluctuating yield suggests strongly that there are some hitherto unsuspected simplifying features in the mechanism of fragmentation associated with the giant resonance.

STUDIES OF THE GIANT DIPOLE RESONANCE AND ITS ISOBARIC-SPIN MIXTURE

Luise Meyer-Schützmeister, Ralph E. Segel, and Zeev Vager

Although the giant dipole resonance has long been well established by gamma-ray-induced nuclear reactions, superior energy resolution can be achieved by exciting this resonance by energetic protons such as those from the Argonne tandem Van de Graaff. The resulting improvement in detail and accuracy is important for improving the current theories of the giant dipole resonance.

In thorough investigations[1] of the reactions $B^{11}(p, \gamma)C^{12}$, $Al^{27}(p, \gamma)Si^{28}$, and $F^{19}(p, \gamma)Ne^{20}$, the γ-ray yield over the giant dipole resonance showed an entirely different structure for each reaction.

In $B^{11}(p, \gamma)C^{12}$, the yield curve is dominated by a single broad bump (several MeV wide) with little structure imposed on it, while the γ-ray yield of the $Al^{27}(p, \gamma)Si^{28}$ reaction exhibits strong fluctuations indicating that the giant dipole resonance in Si^{28} is composed of many levels whose average width is about 60 keV. Neither of these reactions shows any appreciable correlation between the structures in the yield curves for the two easily observed gamma rays, which lead to the ground state and to the first excited state.

In the reaction $F^{19}(p, \gamma)Ne^{20}$, however, most of the yield of the ground-state transition as well as a great part of the yield of the transition to the first excited state is concentrated in three large well-separated peaks, and the two γ rays in Ne^{20} are strongly correlated (in contrast to those in C^{12} and Si^{28}). It is therefore suggested that the giant resonance in Ne^{20} is composed primarily of a few well

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[1] R. G. Allas, S. S. Hanna, Luise Meyer-Schützmeister, R. E. Segel, P. P. Singh, and Zeev Vager, Phys. Rev. Letters 13, 628 (23 November 1964).

separated resonances, each having comparable probabilities for decay to the ground state and to the first excited state.

Despite the pronounced differences between the structures in the γ-ray yield curves for these three reactions, the angular distribution of the γ rays for each reaction is nearly constant over the giant dipole region — especially in the case of the γ-ray leading to the ground state. This implies that in each of these product nuclides (whether the giant resonance is composed of many levels as in Si^{28} or of only a few as in Ne^{20}) the γ-ray transition to the ground state is due to only one nucleon configuration throughout the giant-resonance region.

In the light of these interesting results, we have recently extended the study of the giant dipole resonance in Si^{28} by means of the reaction $Mg^{24}(\alpha, \gamma)Si^{28}$, again induced by the Argonne 12-MeV tandem generator. The giant dipole resonance in Si^{28} consists of states with isobaric spin T = 1, and both the alpha and the Mg^{24} nucleus have T = 0. An α-capture process followed by an electric-dipole transition should therefore be forbidden by isobaric-spin considerations, while the proton-capture process $Al^{27}(p, \gamma)Si^{28}$ should be allowed. Recent (unfinished) measurements of the γ-ray yield and angular distribution of $Mg^{24}(\alpha, \gamma)Si^{28}$ show definitely that (at least for the γ rays leading to the ground state) the γ rays produced are of electric-dipole character. This means that the reaction occurs via the giant dipole resonance; in fact, the isobaric-spin inhibition reduces its cross section only by a factor of 6 relative to the fully allowed $Al^{27}(p, \gamma)Si^{28}$ process.

Although the α capture has been studied so far over only a fraction of the region of the giant dipole resonance, it shows the significant result that the giant dipole resonance in Si^{28} cannot be a pure T = 1 state. Instead, Coulomb forces enable an originally T = 0 state formed by α capture in Mg^{24} to become a T = 1 state and make an electric-dipole γ-ray transition to the ground state. The transition probability depends, of course, on the presence and overlap of two states with isobaric spin $T = 0$ and $T = 1$; this probability usually is very small. The transitions take place in times of the order of 10^{-20} — 10^{-21} sec. Therefore, the relatively large yield of the $Mg^{24}(\alpha, \gamma)Si^{28}$ reaction going via the giant dipole resonance implies that this resonance is at least partially composed of compound-nuclear states which are sufficiently long lived to enable Coulomb forces to mix the isobaric-spin states.

On the other hand, the analysis of the Ericson fluctuation in the $Al^{27}(p, \gamma)Si^{28}$ reaction appeared to indicate that the proton capture into the giant dipole resonance in Si^{28} proceeds predominantly via direct interaction. The assumption that the Ericson analysis implies a direct-interaction component with a short reaction time (much less than 10^{-21} sec) requires a nearly complete mixture of the isobaric spins $T = 0$ and $T = 1$ in the long-lived part of the giant resonance. But this disagrees with the small isobaric-spin mixture in the well-isolated resonances in Si^{28} at an excitation energy below the region of the giant dipole resonance. It seems more likely, therefore, that the "direct interaction" component derived by the Ericson analysis has a lifetime comparable to the time needed for the Coulomb forces to mix the isobaric spins.

The (α, γ) reaction is now being studied in detail throughout the giant dipole resonance and the results will be carefully compared with the proton-capture process in the hope that this will yield further information on the reaction mechanism responsible for the giant dipole resonance.

ISOBARIC-ANALOGUE STATES IN Cu^{65}

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

The direct excitation of a number of isobaric-spin analogue states has recently been reported by a group at Florida State University[1] for several nuclei in the region $80 \leq A \leq 124$. In a series of measurements with the Argonne tandem Van de Graaff accelerator, we have now confirmed this result by observing a similar excitation of isobaric-analogue states in the lighter nucleus Cu^{65}. These states, which are observed in proton elastic-scattering measurements, are formed by adding a proton directly to a target nucleus T and can be considered as isobaric analogues of the states formed in the nucleus T + n in a (d, p) reaction on the target T. The T + p states are separated from the T + n states by the appropriate Coulomb-energy difference ΔE_c. The proton widths of these states can be compared directly with the neutron widths of the states in Ni^{65} excited in the reaction $Ni^{64}(d, p)Ni^{65}$.

From the calculated Coulomb-energy difference ΔE_c one would expect the state analogous to the Ni^{65} ground state to occur at an excitation energy of about 9.45 MeV, corresponding to an incident-proton energy of about 3.3 MeV. The experimental cross sections for proton scattering from Ni^{64} and for the reaction $Ni^{64}(p, n)$ in the energy range that should reveal this and other analogue states are shown in Fig. 5. One clearly observes five strong resonances whose energy spacings are approximately the same as those of the states in Ni^{65}. Moreover, they are separated from the Ni^{65} states by the expected Coulomb-energy differences.

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[1] D. Robson, J. D. Fox, J. A. Becker, C. F. Moore, P. Richard, D. Long, S. I. Hayakawa, G. Vourvopoulos, and C. E. Watson, Technical Report No. 6, Tandem Accelerator Laboratory, Florida State University, Tallahassee, Florida (unpublished).

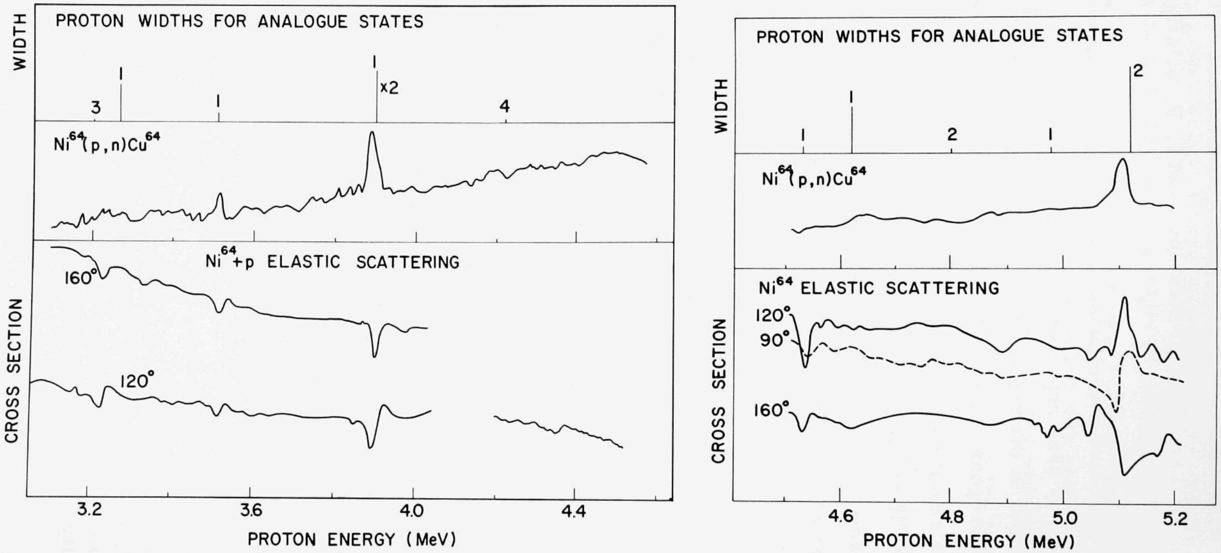

Fig. 5. Excitation function of proton elastic scattering and of the (p, n) reaction on Cu^{65} (a) from 3.3 to 4.6 MeV and (b) from 4.5 to 5.2 MeV. The vertical lines in the top panel of each part, which indicate the expected widths of the analogue states, were calculated from the $Ni^{64}(d, p)Ni^{65}$ data.

The energies of the observed resonances were quantitatively compared with the excitation energies calculated for the Ni^{65} states. The best fit of the observed resonances to the low-lying Ni^{65} states was for $\Delta E_c = 9.246$ MeV. This gave a 35-keV rms deviation between the observed and predicted spacings and is in good agreement with the expected $\Delta E_c = 9.45$ MeV. As in the work at Florida State, ΔE_c was very nearly the same for all states.

The shapes of the resonances observed at the 3 angles studied suggest an assignment of $\ell_p = 1$ for all the states except the one at 5.02 MeV, which appears to have $\ell_p = 2$. All of these assignments are in exact agreement with the ℓ_n assignments from the (d, p) experiments. The intensity with which a resonance is seen in elastic scattering can be used to estimate the ratio of the proton widths to the total widths of the levels. The widths calculated in this way can then be compared with the widths predicted from spectroscopic factors. The agreement is satisfactory.

In summary, the energies of the analogue states in Cu^{65} are remarkably close to the expected values, as calculated from the corresponding states in Ni^{65}; and the narrow widths of the observed resonances show that each analogue state is confined to an exceedingly small range of energy. These experimental results seem to show that the isobaric-analogue states exist in a much more real sense in medium-weight and heavy nuclei than was previously thought to be possible.

NEW ISOTOPE K^{46} PRODUCED WITH THE $Ca^{48}(d,\alpha)K^{46}$ REACTION

A. Marinov and J. R. Erskine

Because of the large neutron excess in Ca^{48}, many hard-to-obtain nuclei can be produced when Ca^{48} is used as a target in charged-particle reactions. The (d,α) reaction on Ca^{48} leads to K^{46}, an isotope which has not been observed previously. The nuclear structure of K^{46} is in itself quite interesting since, on the basis of the nuclear shell model, K^{46} can be described rather simply as a neutron hole and proton hole in the doubly-magic nucleus Ca^{48}.

The $Ca^{48}(d,\alpha)K^{46}$ reaction initiated by a 12-MeV beam of deuterons from the tandem Van de Graaff, was observed with the Argonne broad-range magnetic spectrograph. The ground-state Q value in the $Ca^{48}(d,\alpha)K^{46}$ reaction was measured to be 1.915 ± 0.015 MeV. Excited states were found at 586, 692, 890, and 1949 keV. The uncertainty in these excitation energies was estimated to be ± 10 keV.

In the doubly-magic nucleus Ca^{48}, the last proton and neutron shells are filled with $d_{3/2}$ and $f_{7/2}$ nucleons, respectively. Consequently, the ground-state configuration of K^{46} is expected to be $(d_{3/2})_p^{-1}(f_{7/2})_n^{-1}$. This configuration includes four negative-parity states with spins $J = 2, 3, 4$, and 5. One therefore can assume that the ground state and the three excited states at 0.586, 0.692, and 0.890 MeV belong to this configuration and that each of them has one of the spins mentioned above, while the 1.949-MeV state comes from some higher configuration. The Nordheim strong rule predicts that the ground-state spin from the $(d_{3/2})_p^{-1}(f_{7/2})_n^{-1}$ configuration is $J = 2$. According to the jj coupled shell-model theory, the level structure of K^{46} should be closely related to the level structure of Cl^{38}. Specifically, the jj-coupling theory says that in the absence of configuration interaction, two-hole systems are identical to two-particle systems if both the holes and the particles remain in the same states. The configuration that corresponds to the $(d_{3/2})_p^{-1}(f_{7/2})_n^{-1}$ configuration of K^{46} is the $(d_{3/2})_p(f_{7/2})_n$ configuration of Cl^{38}. On the basis of this theory, Pandya has developed a projection theorem which connects nucleon-nucleon systems with nucleon-hole systems. With this theorem, he has calculated the levels of Cl^{38} from the corresponding levels in K^{40} with $(d_{3/2})_p^{-1}(f_{7/2})_n$ configuration and has obtained very good agreement with the experimental results.

An energy level diagram of Cl^{38}, together with our results on K^{46}, is shown in Fig. 6. It is seen that the K^{46} level diagram has some similarities to the energy levels of Cl^{38}, but the agreement is much worse than the degree of accord found in Pandya's comparison between Cl^{38} and K^{40}. However, neither K^{46} nor Cl^{38} has a level very close to the ground state. Therefore it still seems reasonable to believe that one can relate the ground state of K^{46} to the ground state of Cl^{38} and that both have the same spin, namely $J = 2^-$. This is also in agreement with the result predicted from the Nordheim strong rule.

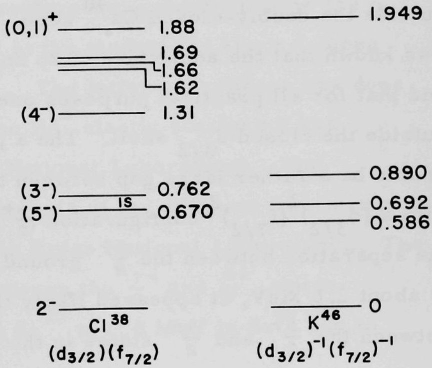

Fig. 6. Energy-level diagram of Cl^{38} and K^{46}.

PROTON CAPTURE REACTIONS AND THE RESIDUAL NUCLEON-NUCLEON INTERACTIONS

J. L. Yntema

Neutron-capture reactions have been used extensively in the last few years to obtain information on the neutron part of the ground-state wave functions of target nuclei as well as the excited states of the final nucleus obtained in the reaction. Comparatively few experiments on proton-capture reactions have been reported. Obviously the proton-capture reaction can provide information on the proton part of the ground-state configuration of the target nucleus. On the other hand, it appeared that it might be of interest to study the change in the location of proton hole states as a function of the number of neutrons in a given element. Such an experiment should provide information on the residual neutron-proton interaction in the nucleus.

The Ti isotopes appeared to be quite suitable for such an investigation. These isotopes contain 2 protons and from 4 to 8 neutrons outside the doubly-closed Ca^{40} core. From previous experiments it was known that the admixture of 2p and $1f_{5/2}$ nucleons is rather small and that for all practical purposes one deals with a $(f_{7/2})^n$ configuration outside the closed $d_{3/2}$ shell. The a priori expectation was that there should be a rather large gap between the ground state and the state with a $(d_{3/2})^3(f_{7/2})^2$ configuration ($\frac{3}{2}^+$ state) in the Sc isotopes. Since the separation between the $\frac{3}{2}^+$ ground state and $\frac{1}{2}^+$ excited state in K^{39} is about 2.6 MeV, it appeared likely that a similar gap should exist between the $\frac{3}{2}^+$ and $\frac{1}{2}^+$ states in the Sc isotopes.

In order to establish the value of the orbital angular momentum of the captured nucleon and the strength (spectroscopic factor) of the transition, it is customary to use the distorted-wave theory. In the case of (d, He^3) reactions, the validity of distorted-wave calculations to extract the relevant information from the experimental data was not established. Therefore it was necessary to use a few known reactions to obtain sufficient phenomenological information for the interpretation of the experimental results and to evaluate the validity of distorted-wave calculations.

The experimental results of the Ti(d, He^3)Sc study made it immediately clear that the separation between the ground states and the excited states with a $(f_{7/2})^2(d_{3/2})^3$ proton configuration was much smaller than expected and changed quite markedly with the neutron number. In particular, the cross section and angular distribution of the Ti^{46}(d, He^3)Sc^{45} reaction indicated that the separation between the $f_{7/2}(d_{3/2})^4$ and $(f_{7/2})^2(d_{3/2})^3$ proton configurations was very small and that a careful analysis with distorted-wave calculations was necessary.

For such calculations it is necessary to have the optical-model-potential parameters for both the entrance and exit channels. The deuteron optical-model-potential parameters were obtained from the elastic scattering of 21.6-MeV deuterons by Ca and the five Ti isotopes. The He^3 optical-model-potential parameters were obtained from the elastic scattering of 12-MeV He^3 ions at the tandem for about a dozen targets, including Ca, Ti^{46}, and Ti^{50}. The latter experiment was done in collaboration with B. Zeidman. The He^3 elastic scattering was analyzed by R. H. Bassel (Oak Ridge National Laboratory). The distorted-wave calculations and the analysis of the deuteron-scattering data were made by G. R. Satchler (Oak Ridge National Laboratory). The results indicate that the separation between the $\frac{7}{2}^-$ and $\frac{3}{2}^+$ states increases from less than 0.05 MeV in Sc^{45} to 0.8 MeV in Sc^{47} and to 2.4 MeV in Sc^{49}.

J. B. French has shown that these results can be used to obtain the two monopole parameters of the $d_{3/2}$-$f_{7/2}$ interaction. The variation of the $s_{1/2}$ hole states is as drastic as the one observed for the

$d_{3/2}$ hole states. However, it is clear from the experimental results that the $s_{1/2}$-$f_{7/2}$ interaction is quite different from the $d_{3/2}$-$f_{7/2}$ interaction.

The $\frac{3}{2}^+$ state predicted by the $Ti^{46}(d, He^3)Sc^{45}$ result has not been observed in (p, p') studies of Sc^{45}. It appeared important to locate this state since it should be an isomeric state. It should decay to the ground state of Sc^{45} by an M2 transition and have a measurable lifetime. The 12-MeV proton beam of the tandem was used to study the $Ti^{48}(p, \alpha)Sc^{45}$ reaction with the magnetic spectrograph in collaboration with J. R. Erskine. A state was found at an energy of 13 ± 2 keV in Sc^{45}. Subsequently Holland, Lynch, and Nystén measured the lifetime of this state with the 3-MeV proton beam from the 4.5-MeV Van de Graaff and found that the lifetime was consistent with the M2 character of the transition.

We have used the parameters obtained by comparing the $Ca^{40}(d, He^3)K^{39}$ experimental results with the distorted-wave calculations to obtain occupation numbers for the ground-state configuration of Zr^{90}. A number of theoretical groups have predicted the admixture of $g_{9/2}$ protons in the ground-state wave functions. We measured this admixture directly by means of the $Zr^{90}(d, He^3)Y^{89}$ reaction. The experimental result was in good agreement with the theoretical predictions. However, the experimental error was rather large since this experiment is at the limit of feasibility with our installation.

(d, n) REACTIONS ON MEDIUM-WEIGHT NUCLEI

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

A program has been initiated to study the structure of medium-weight nuclei by means of the (d, n) reaction. The pulsed beam from the Argonne tandem Van de Graaff and the 10-meter flight path available provide a facility that is unique at the present time.

Over the years a great deal of very useful nuclear-structure information has been obtained from (d, p) reactions on light and medium-weight nuclei. Similar information can be obtained from (d, n) reactions; the analysis is identical except that the proton and neutron interchange roles. However, the difficulties in neutron detection and energy measurement have restricted the study of (d, n) reactions to very light nuclei in which the reactions can be induced by low-energy pulsed-beam accelerators.

The higher energy of the pulsed beam from the Argonne tandem makes heavier nuclei accessible to (d, n) studies. The long flight path available then provides sufficient energy resolution to permit meaningful measurements of angular distributions and proton widths.

The pulsed beam from the Argonne tandem Van de Graaff[1] has a pulse length less than 2 nsec at a frequency of 3.75 Mc/sec with an average deuteron beam current of about 0.05 μA. Fast neutrons from the target being studied are detected in a large liquid scintillator (8 in. in diameter and 4 in. thick) mounted on a 58AVP photomultiplier. The neutron flight time is converted into pulse height and fed to a multichannel pulse-height analyzer. Pulse-shape discrimination is employed to eliminate background pulses due to gamma rays in the scintillator and a high bias level is maintained on the neutron counter so that only

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[1] F. J. Lynch, Argonne National Laboratory Report ANL-6720 (1963), p. 39.

the high-energy neutrons of interest are counted. With these detectors it is possible to get usable counting rates with flight paths of up to 10 meters. These path lengths provide adequate neutron energy resolution and can be used over an angular range from 5° to 135° in the present arrangement.

The first reaction chosen for study is $Fe^{54}(d, n)Co^{55}$. A self-supporting Fe^{54} foil was used as target and the deuteron beam was stopped in a lead backing. The spectrum of neutrons at 14.5° at a deuteron energy of 7.0 MeV is shown in Fig. 7. The peaks identified by asterisks were definitely assigned to the reaction $Fe^{54}(d, n)Co^{55}$; angular distributions for these neutron groups were obtained at angles from 0° to 60°. Comparison with DWBA calculations indicates $\ell_p = 3$ for the ground-state group and $\ell_p = 1$ for those at 2.15 and 2.55 MeV excitation. These preliminary measurements are being extended to a wider range of angles and the detection system is still being improved with better background suppression. Measurements are planned for a wide range of target nuclei with atomic weights in the range $40 \leq A \leq 64$.

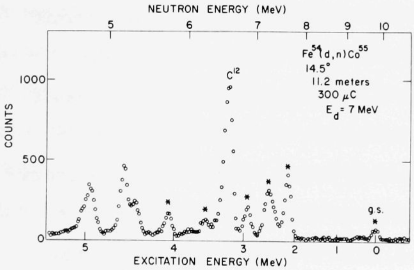

Fig. 7. Spectrum of neutrons from the reaction $Fe^{54}(d, n)Co^{55}$ at 14.5° for a deuteron energy of 7.0 MeV. Peaks indicated by asterisks have been definitely assigned to this reaction.

THE PHYSICS DIVISION ON-LINE COMPUTING SYSTEM, PHYLIS

D. S. Gemmell

The installation of the PHYsics Division On-Line Information System (PHYLIS) was completed during the summer of 1964. PHYLIS is an advanced computing system used for the on-line processing of data obtained in low-energy nuclear physics experiments at both the 4.5-MeV Van de Graaff and the 12-MeV tandem generator. The development of PHYLIS has been a joint responsibility of the Applied Mathematics and the Physics Divisions.

Figure 8 shows a block diagram of the complete system. The central processing unit is an ASI-2100 computer. This is a fast digital machine with a memory of 8192 words and a 21-bit word length. The memory cycle time is 2 μsec. The computer has two buffered input/output channels which can operate simultaneously and independently. Normally, the hardware of the system is distributed into four distinct geographical locations as follows: (1) the central station, which contains the central processor, a digital plotter, a typewriter, a line printer, a card reader/punch, and two magnetic tape units; (2) the tandem Van de Graaff, at which are located a two-parameter pulse-height analyzer, an additional dual ADC unit, a typewriter, a display oscilloscope with a light pen, and three computer interrupt buttons; (3) the 4.5-MeV Van de Graaff, at which are located a typewriter, a card reader/punch, a line printer, and two computer interrupt buttons; and (4) the CDC-3600 computer to which the ASI-2100 is satellited by way of 800-ft twisted-pair cables with receivers and transmitters at each end. The link to the 3600 gives the PHYLIS user direct access to a much higher level of computing power.

Since the external devices of the 2100 are connected to the input/output channels in parallel, any equipment on a particular

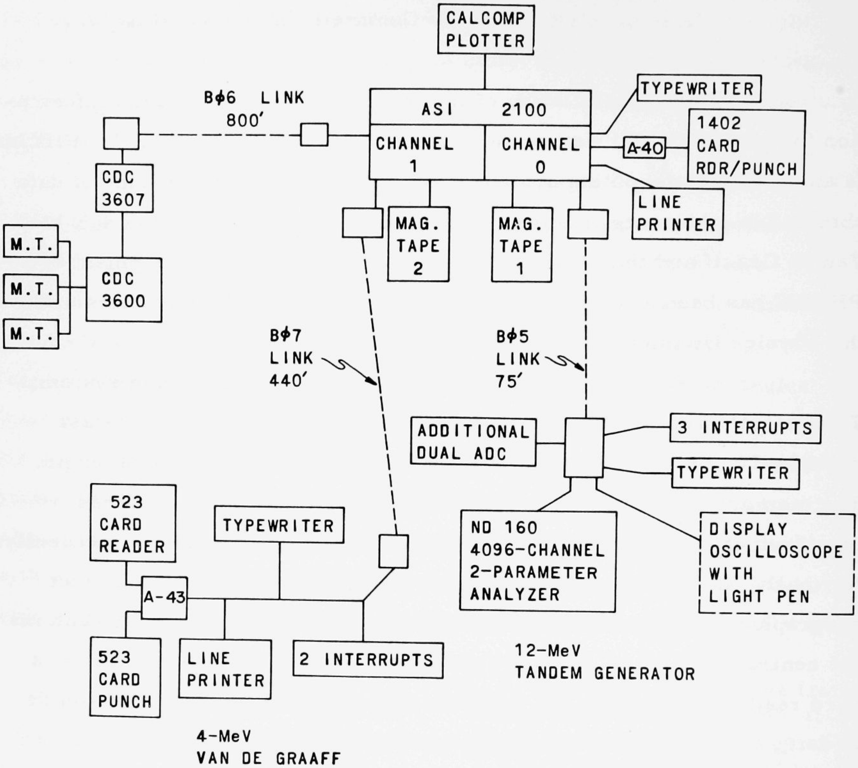

Fig. 8. Block diagram showing how the individual devices making up the PHYLIS system are normally divided among the four experimental areas. Since the two In-Out channels of the ASI-2100 may be operated simultaneously, equipment at two different locations can operate simultaneously. Also, since the devices are connected to the channels in parallel, any equipment on a particular channel can be connected to any other equipment on it; e.g., the printer and 1402 card unit can be moved to the tandem and operated there. Each device depicted has a unique interrupt address which may be either "normal" or "priority." The four instruction addresses associated with the CDC-3600 link (Bϕ-6) are designated "priority" and as such may interrupt any "normal" interrupt routine.

channel can be connected to any other equipment on the same channel; e.g., the oscilloscope, the 1402, and the line printer can all be moved and operated at the data-collection area of the tandem generator if required.

The program-interrupt features in both the ASI-2100 and the CDC-3600 make the system very flexible. For example, an experimenter at the 4.5-MeV machine may interrupt the ASI-2100 (by pushing one of the two interrupt buttons). This interrupt will then force the ASI-2100 into a subroutine which might call in a certain program from magnetic tape. This program, when loaded, may in turn interrupt the CDC-3600. The 3600 could then perform some calculation (e.g., the determination of polarizations and cross sections as a function of angle from data taken in a neutron-scattering experiment). The results would then be transmitted via the 2100 back to the output devices at the Van de Graaff and could then be used immediately to determine what further measurements are necessary.

The ASI-2100 contains a supervisory program which is necessary to control all of the various activities of the system. The resident part of this program occupies about 300 computer words. When the 2100 is not busy, this routine cycles continuously as it waits for an interrupt. When an interrupt occurs from one of the three user locations (console, tandem, or Van de Graaff), control of the computer is given to that location and the user can select the program he needs by typing in a program number. The program selected will then be loaded from the master tape (tape unit No. 1). If the user has a program on cards, he simply uses the typewriter to bring in from the master tape the appropriate card-loading routine. The control routine has been written so that the computer can be completely controlled from either the tandem or the Van de Graaff by means of the interrupt buttons, a typewriter, and a card reader. If an attempt is made to interrupt the

2100 when it is already busy processing another interrupt, a message indicating this is typed out at the appropriate typewriter and the computer then continues to process the first interrupt.

When the CDC-3600 is used on-line by PHYLIS, a number of restrictions are placed on the 3600 programs used. Only two magnetic tape units at the 3600 are made available, one of which contains the PHYLIS program library. A third tape is reserved for saving the program interrupted by PHYLIS. The maximum 3600 time per interrupt has been set at 2 min and the minimum time between interrupts at 15 min. The Applied Mathematics Division has made modifications to SCOPE (the CDC-3600 monitor routine) in order to control these restrictions and to provide for the storing and restoring of the interrupted program. Provided he does not attempt to interrupt at intervals of less than 15 min, the on-line user of PHYLIS can always obtain control of the 3600 within 10 sec. Its great power makes this computer a valuable tool to have available during an experiment since it permits a rapid evaluation of the data while they are being accumulated, even though this evaluation may involve much calculation. The results of the calculation can then be used immediately to modify the course of the experiment.

The link between the ASI-2100 and the pulse-height analyzer has proved to be very useful. This link permits (a) the full 4096-channel memory of the analyzer to be dumped into the ASI-2100, (b) information from the ASI-2100 to be displayed by the analyzer, or (c) the outputs from the ADC's of the analyzer to be stored in the 2100. Since the pulse-height analyzer has a memory of 4096 words, it is capable of performing a 2-parameter analysis limited to 64×64 channels. The ADC's, however, are capable of digitizing pulses to an accuracy of 1 in 1024 (10 bits). To make use of this resolution, the ADC outputs (10 bits each) are fed into the computer and then stored on magnetic tape. These high-resolution data can later be read back into the computer and analyzed.

To store a 1024×1024-channel spectrum, a prohibitively large memory of about one million words would be needed. However, in practice one is usually content to examine either a smaller part of this large matrix or a reduced-resolution version of the whole matrix (e. g., 256 × 256 channels). In any case, a large memory is required for the analysis unless many smaller analyses are to be made consecutively — a laborious and time-consuming operation. In this connection, advantage is taken of the direct link to the CDC-3600 which has a large memory capacity (65 536 words, 48 bits in length). Two-parameter ADC data on magnetic tape No. 2 are read back into the ASI-2100 and transmitted to the CDC-3600. There they are sorted into a 256×256-channel pulse-height distribution stored in one half of the CDC-3600 memory (each word in this half of memory being regarded by the sorting program as split in half so that it represents two channels). When the analysis is complete, the resultant 256×256 matrix is transmitted in sections back to the ASI-2100 where it is stored on magnetic tape No. 1 and is available for further use by the experimenter. The complete operation (including tape-handling times) typically takes about 1 min.

A generalized data-handling program has been written to allow the physicist to choose various data-handling functions and to prescribe the order in which they will be executed. In this way, it has been possible to reduce the processes of accumulating, storing, and analyzing data to simply pushing one or two buttons.

The PHYLIS system has been used extensively by various experimental groups in the past few months. It has been particularly useful in more complicated experiments such as the study of three-body break-up reactions (where three parameters are recorded in high resolution), in the study of short nuclear lifetimes (where two parameters, γ-ray energy and time, are measured), and in the study of charged-particle reactions by means of as many as eight detectors simultaneously.

In addition to its use on-line in experiments, the PHYLIS system has been used extensively off-line in detailed analyses of data and for performing calculations.

LOW-LYING HOLE STATES IN THE ISOTOPES OF SCANDIUM

Studies by Yntema and Satchler[1] of the (d,He^3) reaction on various even-mass isotopes of Ti have revealed states of positive parity surprisingly close to the ground states of the residual Sc nuclei. The strengths of the pickup transitions to these states clearly indicate that they involve the major part of the $1d_{3/2}$ and $2s_{1/2}$ single-hole excitations of the Ti target nuclei. Bansal and French[2] then demonstrated that the binding energies of these levels are consistent to within a few hundred keV with their interpretation as pure single-hole states. The very low excitation energy of the positive-parity levels is thereby explained rather simply.

Now, as Bansal and French emphasized, the general trend of the binding energies is not expected to be very sensitive to impurities in the single-hole wave functions. To measure such impurities it is necessary to consider some quantity more sensitive to the details of the wave function. One such quantity is the lifetime of the lowest $d_{3/2}$-hole states in Sc^{43}, Sc^{45}, and Sc^{47}. Since each of these levels is the first excited state of the appropriate nucleus, the quantity of interest is in each case the rate of the M2 transition from the low-lying $d_{3/2}$-hole state to the $f_{7/2}$ ground state. If now it is assumed that each $\frac{3}{2}^+$ level is a pure $d_{3/2}$ single-hole state and if each $\frac{7}{2}^-$ ground state is assumed to have a wave function consistent with its measured $\ell=3$ strength in the ground-state (d,He^3) transition, it follows at once that the M2 lifetimes should be 4—8 times the single-particle Moszkowski estimate.

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[1] J. L. Yntema and G. R. Satchler, Phys. Rev. 134, B976 (1964).

[2] R. K. Bansal and J. B. French, Phys. Letters 11, 145 (1964).

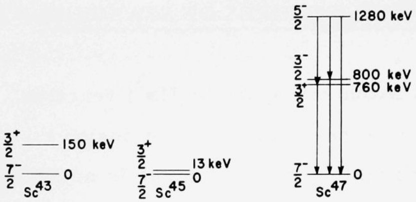

Fig. 9. Level schemes for the scandium isotopes in which the lifetimes of the $d_{3/2}$ hole states have been measured.

EXPERIMENTAL

R. E. Holland, F. J. Lynch, and K.-E. Nystén

Gamma rays from the $d_{3/2}$-hole states of Sc^{45} and Sc^{47} as well as those from a similar state in Sc^{43} have been observed and their lifetimes measured. In these three cases the states being discussed are the first excited states, and the transition to the ground state is an M2 transition ($\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$). Thus the lifetime of the state should be long. These measurements then serve to identify the state and to provide a detailed check on the wave functions.

The relevant levels in these three isotopes are shown in Fig. 9. To excite the $d_{3/2}$ level in Sc^{43}, the reactions $Ca^{40}(\alpha,p)Sc^{43}$ and $Ca^{43}(p,n)Sc^{43}$ were used with thick targets. The beam from the tandem accelerator was pulsed and the lifetime of the state was measured by observing the number of pulses as a function of time after each beam pulse. The observed mean life was 628 ± 10 μsec for each reaction.

From the work of Yntema and Erskine, the $d_{3/2}$ level in Sc^{45} was known to be at 13 ± 1 keV. We observed a gamma ray of 12.8 ± 0.2 keV from 2.7-MeV proton bombardment of a thick metallic scandium target. Again the accelerator (in this case the 4.5-MeV Van de Graaff) was pulsed and the decay of the state was observed. The mean life was 0.44 ± 0.02 sec.

TABLE I. Summary of data on the lifetimes of M2 transitions from $d_{3/2}$-hole states in scandium isotopes.

Isotope	Excitation energy (keV)	Observed mean life	Conversion coefficient	Partial γ-ray mean life τ_γ	Moszkowski estimate τ_M	Ratio τ_γ/τ_M
Sc^{43}	150 ± 3	628 ± 10 μsec	0.045	656 μsec	3.49 μsec	190
Sc^{45}	12.8 ± 0.2	0.44 ± 0.025 sec	330	145 sec	0.6915 sec	210
Sc^{47}	760 ± 20	0.40 ± 0.06 μsec	≈ 0	0.40 μsec	0.98 nsec	410

In Sc^{47}, the initial information was rather confusing. Yntema and Satchler had located the $d_{3/2}$-hole state at about 800 keV, but the only known state near that energy had a very short lifetime and thus could not be the $d_{3/2}$-hole state. Subsequently, it was found that there were two states in Sc^{47} near 800 keV—the $d_{3/2}$-hole state found by Yntema and Satchler and another state of normal parity which is strongly populated in β decay of Ca^{47}. We found that the hole state is also populated in the decay of Ca^{47} (in about 0.05% of the decays) and by using a gamma-gamma coincidence technique, we were able to measure its lifetime. The observed mean life was 0.40 ± 0.06 μsec.

Table I summarizes the data on these three isotopes. In order to obtain the partial lifetime for gamma-ray emission, we used the conversion coefficients given in Table I which were obtained by extrapolating the values calculated by Rose. The theoretical values are the Moszkowski estimates.

THEORETICAL

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

As shown in Table I, the experimental lifetimes of the $d_{3/2}$-hole states are about 200 times the Moszkowski estimate. The possibility of understanding this result without invoking a change in the character of the M2 operator is discussed in this section.

According to the shell model, the low-lying normal-parity levels of the scandium isotopes should be characterized as the various states of one proton and (n - 1) neutrons outside a closed $d_{3/2}$ subshell. Thus a state with angular momentum J should be described by a wave function

$$\psi_M^J = (d_{3/2})^8 (f_{7/2})_J^n . \tag{1}$$

For the odd-A Sc isotopes (n odd) the $d_{3/2}$-hole state would then be written as

$$\psi_{M'}^{J'=3/2} = (d_{3/2})_{3/2}^7 (f_{7/2})_0^{n+1} . \tag{2}$$

The matrix element for the transition between this state and the ground state is then given by

$$ME = \sqrt{\frac{(n+1)(n-2)}{8(n-1)}} \left\langle j^n \; J = 7/2, \; T = \frac{n-2}{2} \right]\!\!\left\} \; j^{n+1} \; J' = 0, \; T' = \frac{n-3}{2} \right\rangle$$

$$\times (ME)_{sp}, \tag{3}$$

where $(ME)_{sp}$ is the single-particle matrix element used in the Moszkowski estimate and $\langle]\!\} \rangle$ is the coefficient of fractional parentage whose square measures the probability that if one nucleon is removed from the ground state of the (n+1)-particle nucleus the remaining nucleons will be in the ground-state configuration of the n-particle system. It is precisely the square of this quantity that is measured in the (d, He^3) experiment. In actual fact the experimental and theoretical uncertainties are such that the square cannot be deduced to better than a factor of two. Using this result, one finds that the lifetime should be 4 to 8 times the Moszkowski estimate; the factor 4 arises if all the transition strength in the (d, He^3) experiment is to the ground state of the odd-A nucleus.

It is, of course, well known that theoretical estimates for gamma lifetimes are very sensitive to admixtures of other configurations. The question is whether a reasonable admixture can produce such a large cancellation in the matrix element. It is obvious that the physical nuclear state will, at the least, be a mixture of the wave function described by Eq. (2) and the state in which the $d_{3/2}$ hole is coupled to the low-lying 2^+ state in the even-even nucleus; i.e., the state is

$$\phi_{M'}^{J'=3/2} = \left[(d_{3/2})^7_{3/2} \times (f_{7/2})^{n+1}_2 \right]^{J'=3/2}_{M'} , \qquad (4)$$

where $[\ \times\ ]^{J'}_{M'}$ stands for the vector coupling of 3/2 and 2 to angular momentum $J' = 3/2$. Determination of the appropriate linear combination in the physical state requires the introduction of a residual two-body interaction between particles and the diagonalization of a 2×2 matrix. Since the n-p interaction needed in shell-model calculations is uncertain, this admixture has been estimated by using wave functions generated from deformed orbitals. For this region, this Elliott generating procedure has already been shown to give normal-parity wave functions which are in excellent agreement with those obtained from a shell-model calculation.[3] The wave function for the $J' = 3/2$ state obtained in this way is

$$\Psi \approx \sqrt{\frac{2}{3}}\, \psi^{J'} + \frac{1}{\sqrt{3}}\, \phi^{J'} \qquad (5)$$

and the resulting lifetime is about 80 times the Moszkowski estimate.

[3] R. D. Lawson, Phys. Rev. 124, 1500 (1962); J. D. McCullen, B. F. Bayman, and L. Zamick, Phys. Rev. 134, B515 (1964).

Therefore it is possible to increase the lifetime of the state to approximately the desired value without changing the structure of the M2 operator and without introducing too large an admixture of other configurations.

UNIVERSITY USE OF THE 12-MEV ARGONNE TANDEM VAN DE GRAAFF

Since the fall of 1963, qualified university scientists have been invited to come to the Argonne National Laboratory to use the 12-MeV tandem accelerator and the associated experimental facilities. This program provides running time on a valuable accelerator to scientists who otherwise would be excluded from what is currently the most active area of nuclear-structure physics. Seven experiments, accepted by a committee representing the universities and Argonne, have been completed or are currently in progress. These are:

1. Multiple Coulomb Excitation and the Reorientation Effect

   R. P. Scharenberg (Case Institute of Technology)

2. Studies of Energy Levels in Light Nuclei with the Magnetic Spectrograph

   C. P. Browne (Notre Dame University)

3. Alpha-Gamma Correlation Studies of the Reaction $C^{12}(O^{16}, \alpha)Mg^{24*}$

   W. W. Eidson, J. G. Cramer, Jr., and R. D. Bent (Indiana University)

4. Magnetic Spectrograph Studies of the Reactions (He^3, α) and (He^3, d)

   W. P. Alford, L. M. Blau, D. Cline, and J. J. Schwartz (University of Rochester)

5. Study of Reaction Cross Sections with Alpha Particles

   L. Haskin (University of Wisconsin)

6. Short Nuclear Lifetimes by Doppler-Shift Techniques

   R. D. Bent and P. P. Singh (Indiana University)

7. Investigation of Ca^{49} Isobaric-Analog States in Sc^{49}

   K. W. Jones (Brookhaven National Laboratory)

SYMPOSIUM ON NUCLEAR SPECTROSCOPY WITH DIRECT REACTIONS 9—11 MARCH 1964

This conference was sponsored and organized by the Argonne National Laboratory and held at the Center for Continuing Education of the University of Chicago. There were some 300 participants; 250 were from outside the Chicago area, and of these about 50 were foreign visitors. A gathering of this size can readily lead to an over-organized conference, wherein each session is crammed with invited papers and successions of 10-minute contributions. Discussion in such conditions is confined to uninvited papers by a few professional conferencemen. These difficulties did not plague the Direct-Reaction symposium. Oral contributed papers were ruthlessly suppressed,[1] leaving ample time for discussion which then turned out to be lively, widely distributed over the audience, and frequently relevant to the points at issue.

There were six sessions, two on each of the three days of the conference. The first session concerned the distorted-wave Born approximation (DWBA) which provides the theoretical framework for most discussions of nuclear direct reactions. The tenor of discussion here was that of description of calculational technique and of exposition of the state of the art of DWBA as currently practiced. The voices of the (fairly numerous) critics of the ad hoc features of current distorted-wave practice and of proponents of alternative ways of describing nuclear direct reactions were to be heard for the most part in the corridors, in the lounges, and at the dinner table. The

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[1] Forty contributed papers were collected in Argonne National Laboratory Report ANL-6848, Nuclear Spectroscopy with Direct Reactions. I. Contributed Papers. This 248-page report was issued to participants at the time they registered for the Symposium.

conference as a whole took DWBA for granted. This of course was an outcome of the choice of topic, which directed attention to the interpretation of nuclear transition matrix elements measured in direct-reaction experiments. The dichotomy so exhibited between "nuclear-structure information" and "reaction mechanism" has been hallowed by custom over the past decade. It has been very useful, in spite of its artificiality, because analyses of direct-reaction transition rates have tended to rely on very general features of the reaction process and thus to demand little from the underlying reaction theories. Perhaps the most important lesson to be drawn from the conference sessions which followed the well-trodden paths of inelastic scattering and single-nucleon stripping was that the questions now being asked are sufficiently exacting to strain the conventional dichotomy past its breaking point. Reaction mechanism and nuclear wave functions must be treated with at the least a comparable degree of sophistication and probably in a unified fashion.

This brings us to a recently-opened avenue of research which was touched upon during the final afternoon session. The underlying physical idea is that it may take only two or three collisions between an incident projectile and target nucleons to produce 'compound-nucleus' phenomena. Thus unified reaction theories are attempting not only to unify the treatment of reaction mechanisms and nuclear wave functions but also to narrow the gap between direct-interaction and compound-nucleus phenomena. The whole subject will obviously be one of the liveliest in nuclear-structure physics during the next few years.

The role of isobaric spin in nuclear reactions has been the subject of numerous illuminating studies during the past three years. Isobaric analogues of the low-lying states of neighboring nuclei are selectively excited in (p, n) and, as compound-nucleus resonances, in (p, p) reactions on nuclei throughout the periodic table. One of the conference sessions was devoted to such matters. Perhaps the most interesting new development reported was an experimental one—the location and clear identification of the higher-T fragments of single-hole excitations in (p, α) reactions. The size of the T splitting and the division of the sum-rule strength between the T fragments seems to be capable of quantitative theoretical interpretation. Whether isobaric spin is a good quantum number for heavy nuclei and whether anyone should care one way or the other are still subjects of controversy. It is clear, however, that isobaric spin is a much better quantum number for all stable and nearly-stable nuclei than would have been believed a few years ago.

To summarize, the Symposium on Nuclear Spectroscopy with Direct Reactions was a success.[2] The impression it gave of nuclear-structure research was that of a subject which, in spite of its antiquity in the short nuclear time scale, is perhaps only now reaching maturity and which is certainly still vibrantly alive and still is raising and answering new questions.

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[2] The 32 papers presented orally were collected in Argonne National Laboratory Report ANL-6878, Nuclear Spectroscopy with Direct Reactions. II. Proceedings. This 530-page volume also includes the discussions of these papers.

THEORETICAL NUCLEAR SPECTROSCOPY

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

The program aimed at the complete automation of shell-model calculations has developed to full maturity since the program was first reported in June 1963. The program has three principal facets: (a) To study the techniques and approximations involved in very large shell-model calculations. (b) To determine the best phenomenological effective interaction directly from experimental data in as many situations as possible. (c) To carry out detailed shell-model calculations of nuclear level structure and transition rates.

A basic set of interlinked FORTRAN programs for carrying out such calculations is now operational on the CDC-3600 computer. The system is constantly being augmented and improved. What is in fact emerging is a large collection of subroutines, each of which performs one of the mathematical operations which arise in computing the properties of a system of interacting fermions in a single-particle basis. Since the number of such distinct mathematical operations which can arise is limited and since each has been programmed in a fashion which makes no reference to the context in which it appears, it is clear that the programming of new calculations involves less and less effort as the system evolves. In this sense the system is more valuable than any of its particular applications.

The following is a brief list of the calculations that have already been carried out and an even briefer sketch of our plans for the immediate future.

(1) The effective interaction in the oxygen isotopes: $(1d_{5/2}, 2s_{1/2})^n$ identical nucleons. Neutrons outside the O^{16} core populate the $1d_{5/2}$ and $2s_{1/2}$ single-particle orbits. The eight possible

T=1 two-body matrix elements are treated as independent parameters and determined by a least-squares fit to observed energy levels of O^{18}, O^{19}, and O^{20}.

(2) Isotopes of oxygen, fluorine, and neon: $(1d_{5/2}, 2s_{1/2})^n$. The isotopes of O, F, and Ne are treated in the fashion described in the preceding paragraph. Since both neutrons and protons are involved, we now have 16 independent two-body energies, eight for T = 0 and eight for T = 1. These are again determined by a least-squares fit to observed excitation energies. The fit is less impressive than for the O isotopes alone, and furthermore the F and Ne data force considerable changes in the T=1 matrix elements. Clearly the effects of configurations (such as $1p_{3/2}{}^{-m}$, $1d_{3/2}{}^{n}$) excluded from our model are least critical in systems of identical nucleons.

(3) Isotopes of Y, Zr, Mo, Nb, and Tc: $(1g_{9/2}, 2p_{1/2})^n$, identical nucleons. A study of exactly the sort described above for the O isotopes has been carried out for the nuclei $_{39}Y^{89}$, $_{40}Zr^{90}$, $_{41}Nb^{91}$, $_{42}Mo^{92}$, and $_{43}Tc^{93}$ in which protons populate the $2p_{1/2}$ and $1g_{9/2}$ levels. An example of the excellence of the theoretical fit to experiment is shown in Table II. An extremely interesting physical result emerges from the study—seniority is a very good quantum number for the $g_{9/2}{}^{n}$ neutron configuration.

(4) The nuclear 1p shell. Work on the effective interaction in the 1p shell is in progress. In particular, the wealth of transition-rate data available here should give some insight into the relative degree of sensitivity with which the interaction parameters depend on transition rates and excitation energies.

(5) The isotopes of Ni: $(1f_{5/2}, 2p_{3/2}, 2p_{1/2})^n$, identical nucleons. In the Ni isotopes we consider neutrons in the $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ orbits and assume a 4-parameter potential form for the effective interaction (central triplet and singlet, two-body spin-orbit,

TABLE II. Experimental and theoretical spins and excitation energies for ${}_{42}Mo^{92}_{50}$.

Nucleus	Experimental data		Theoretical spins and excitation energies (MeV)	
	Spin	Excitation energy	Spin	Our results
	2^+	1.54	2^+	1.47
			0^+	2.30
Mo^{92}	4^+	2.33	4^+	2.32
	5^-	2.57	5^-	2.52
	6^+	2.66	6^+	2.65
	8^+	2.795	8^+	2.80
			4^-	2.86
			2^+	3.02
			4^-	3.05
			3^-	3.28
			4^+	3.39

and tensor). Serious difficulties are encountered here, most of them stemming from the well-known tendency of potential interactions with harmonic-oscillator wave functions to produce very low 0^+ excited states.

(6) Effective interaction potential. It is of interest to determine to what extent the shell-model effective interaction can be parameterized in terms of a simple local potential, with central, two-body spin-orbit, and tensor components. There are two possible procedures here. (a) A least-squares fit to observed energy spectra and transition rates can be carried out with the potential parameters

as independent variables. This has been done for various 1p-shell nuclei, for the isotopes of O and F within the configurations $(1d_{5/2}, 2s_{1/2}, 1d_{3/2})^n$, and, as described above, for the isotopes of Ni. (b) Alternatively, the two-body energies can be determined from the data and a potential can then be obtained by fitting these two-body energies.

This series of studies is as yet incomplete. It is, however, quite clear that to assume a local potential interaction with harmonic-oscillator radial wave functions imposes an unduly severe restriction on the two-body matrix elements. How much of the difficulty here stems from the assumption of a local potential and how much from the inappropriateness of harmonic-oscillator wave functions remains to be seen.

(7) BCS approximations. It has been stressed that approximate ways of handling shell-model calculations are of great importance. One such class of approximations which has been widely applied in the literature is based on the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity. The physical basis for this type of approximation is the goodness of the seniority quantum number for identical nucleons. We have analyzed a special model, involving neutrons in $1d_{5/2}$, $1d_{3/2}$, and $2s_{1/2}$ orbits with various interaction potentials and have compared the exact and approximate excitation energies and transition rates.

(8) Projection of number eigenstates from BCS wave functions. BCS wave functions for nuclear ground states and excited states are superpositions of states corresponding to different eigenvalues of the particle-number operator N. Simple explicit expressions have been obtained for the true-N components of BCS wave functions for the ground state and excited states, and also for the energy matrix elements between those states. These expressions

are being used, first in analyzing the simple model outlined in (7) above, and then in studying isotopes of Sn and Pb.

Further developments in the immediate future will go in two directions: the first is to add new types of programs to the system, the second concerns the nature of the system itself. The approximate methods based on the BCS theory of superconductivity have one important limitation—they are strictly applicable only to systems of identical nucleons. We plan to study approximation methods which are free of this limitation. One such method involves treating neutrons and protons as separate entities; the T=1 part of the interaction is diagonalized first and the separate neutron and proton systems are coupled by the np interaction. The approximation involved is that of separately truncating the complete manifolds of neutron and proton states, the main question being how seriously this separate truncation violates isobaric-spin conservation. Another promising approximation method is that of projecting angular-momentum eigenstates from determinants of deformed-oscillator eigenfunctions. Both methods should be suitable for discussion of Ne^{20} within $(1d_{5/2}, 2s_{1/2}, 1d_{3/2})^n$. Since this problem can also be handled exactly, our first step will be to study the proposed approximation methods in detail for this special case. Finally, the system of programs is continually being improved as a research tool. Ideally such a system should perform all the drudgery involved in a given set of calculations while offering immediate access to any numerical information which we desire to examine. Considerable effort is being invested in studying how on-line display of data on an oscilloscope can be used to further these aims.

EFFECTIVE INTERACTION FOR THE 1p SHELL

S. Cohen and D. Kurath

One of the crucial problems of nuclear structure is to determine the effective interaction between nucleons in the nucleus. All of our information has come from assuming some form for this interaction and comparing calculated results with experimental evidence. This report describes an attempt to investigate the interaction in the region from He^4 to O^{16} without making any assumptions about its form except that it is a 2-body interaction. The information is deduced by fitting observed binding energies and energy differences for nuclei in this region.

The 1p shell is one of the few places in the periodic table where the dominant shell-model configuration is simple and there is enough experimental information to allow one to apply the method used by Bacher and Goudsmit in atomic spectroscopy. In this method, no assumption is made except that the states arise from the $(1p)^n$ configurations. This limits the number of integrals arising from the two-body interaction; and one uses these integrals as parameters to be determined by a comparison of theoretical and experimental energy differences.

There are about 50 pieces of experimental evidence concerning binding energies and energy differences. There are 13 parameters including interaction integrals and 2 single-particle energies. One result of the calculation is that there is no set of parameters which gives a good fit to all the data between He^4 and O^{16}. However, this is probably due to the effect of changing nuclear size since the region between Be^8 and O^{16}, which contains three-quarters of the data, can be fitted very well. As a test of the validity of this picture, the wave functions resulting from the energy fit have been used to calculate observable quantities which depend sensitively on the nature of these 1p-shell states. This includes magnetic dipole moments, M1 transition probabilities, and β-decay rates for pure Gamow-Teller transitions. These calculations show encouraging agreement with observation so that one could very likely fit these quantities exactly without any significant change of parameters.

The integrals of the effective interaction can be compared with what one would expect from the interaction deduced by fitting nucleon-nucleon scattering experiments. Only the signs and rough magnitudes of the interaction components can be compared, but the central-force components of the effective interaction are quite consistent with expectation from the free-nucleon interaction. In order to obtain consistency for the noncentral component, one must include a term proportional to $(\vec{\sigma}_1 \cdot \vec{\ell})(\vec{\sigma}_2 \cdot \vec{\ell})$ which appears in the potential of Hamada and Johnston but not in that of Gammel and Thaler.

SYMPOSIUM ON SYMMETRY AND PARTICLE DYNAMICS

M. Peshkin

Argonne National Laboratory organized and sponsored a Symposium on Symmetries in Particle Dynamics as a part of the autumn meeting of the American Physical Society at Chicago, October 23—24, 1964. The Symposium was originally planned by M. Peshkin as a Topical Conference of the American Physical Society, but was later absorbed into the autumn meeting as a way of helping in the revitalization of that meeting. Nine invited papers dealt with SU_3 symmetry, higher symmetries, symmetry breaking, and experiments which are relevant to the symmetry classifications. Thirteen contributed papers were also read at the three sessions which composed the Symposium. Each of the three Symposium sessions was attended by several hundred persons.

MASS SPECTROMETRIC STUDIES OF VAPOR EJECTED FROM SOLIDS BY FOCUSED LASER BEAMS

J. Berkowitz and W. A. Chupka

The introduction of mass spectrometric detection to the study of vaporization phenomena occurring at high temperatures has accelerated research in this area during the past decade. The Knudsen technique commonly used in this study is limited to temperatures not greatly in excess of 2500°C. Now the advent of high-energy laser beams has provided a new tool to extend the range of vaporization studies to much higher temperatures.

If light from a commercial pulsed ruby laser is focused onto a surface, an energy flux as high as 10^9 watts/cm^2 can be attained. (Very much higher fluxes are obtainable from "Q-switched" lasers.) A study has been undertaken at Argonne, initially using a small laser producing an energy flux of 10^7 watts/cm^2, to determine whether a well-defined "temperature" has been established during the half-millisecond duration of the pulse, and to determine the molecular composition of the vapor ejected from the surface of the solid.

In order to analyze the vapor composition, a magnetic mass spectrometer has been employed. The ejected vapor is collimated into a molecular beam which passes through the ionization chamber of the mass spectrometer and is partially ionized by an electron beam of controlled energy. The resulting ions are then mass analyzed. After the pulses are amplified by an electron multiplier, two methods of ion detection are used. (1) The output is displayed on an oscilloscope triggered by the flash lamp of the laser, and is photographed immediately. (2) The electron pulses from the electron multiplier are accumulated on a capacitor, and the resulting voltage is measured.

In a recent study of graphite by the above methods, species from C_1 to C_{14} were deduced from the mass spectrum, the intensity distribution being as shown in Table III. Also shown for comparison are vapor compositions for 4000°K which were deduced by extrapolation from available data taken at ca. 2500°C. The similarity of the three sets of intensities suggests that the laser-ejected vapor does not deviate greatly from a saturated vapor at ca. 4000°K. If this assumption is confirmed, the laser-produced vapor provides a means for studying species heretofore undetected, such as C_6, C_7, C_8, . . ., C_{14}. The sensitivity of the method has by no means been fully attained.

The phenomena occurring at the intense hot spot of the target are apparently quite complex and may involve plasma formation, superheating, adiabatic expansion with attendant cooling, condensation, supersonic jet formation, etc. However, because of the location at which the vapor is sampled, individual species leaving the hot spot have undergone perhaps 10^2—10^3 collisions before being analyzed. Hence, although there is evidence that the target spot is much hotter, the present studies indicate that in the region of the last molecular collision before sampling, the vapor is saturated (or perhaps super-saturated) at a temperature of ca. 4000°K.

A similar study has been made with a boron target. Here again the B_2:B ratio, when compared with extrapolations of equilibrium data, indicates a saturated vapor at ca. 3500°—4000°K. In this experiment, species as large as B_5, previously undetected, have been obtained.

While it is not certain that accurate thermodynamic data can be obtained by the laser technique, it is obvious that the technique will make possible the identification of the important molecular species existing under the extreme conditions produced and will probably indicate the relative stabilities of these species.

TABLE III. Relative concentrations of vapor species above graphite.

Molecular species	Laser data ($T_{est} \approx 4000^{o}K$)	JANAF[a] ($4000^{o}K$)	Drowart *et al.*[b] extrapolated to $4000^{o}K$
C_1	37.0	23.1	22.2
C_2	31.4	35.6	62.5
C_3	100.0	100.0	100.0
C_4	2.13	3.8	7.8
C_5	7.9	5.7	11.1
C_6	0.413	. . .	. . .
C_7	1.11	. . .	. . .
C_8	0.19	. . .	. . .
C_9	0.11	. . .	. . .
C_{10}	0.32	. . .	. . .
C_{11}	0.15	. . .	. . .
. . .	. . .	. . .	. . .
. . .	. . .	. . .	. . .
. . .	. . .	. . .	. . .
C_{14}	0.042	. . .	. . .

$C_3 = 2.89 \times 10^{-1}$ atm

[a]JANAF Thermochemical Data, issued by the Dow Chemical Company, Midland, Michigan.

[b]J. Drowart, R. P. Burns, G. DeMaria, and M. G. Inghram, J. Chem. Phys. 31, 1131 (1959).

PUBLICATIONS SINCE THE LAST REPORT

PAPERS

RADIATIVE CAPTURE OF PROTONS BY B^{11} AND THE GIANT DIPOLE RESONANCE IN C^{12}

R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel . . . . (Project I-21)

Nucl. Phys. 58, 122-144 (September 1964)

EVIDENCE FOR A SINGLE DOMINANT STATE FOR THE E1 GIANT RESONANCE

R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, R. E. Segel, P. P. Singh, and Z. Vager . . . . (Project I-21)

Phys. Rev. Letters 13, 628-631 (23 November 1964)

ELASTIC SCATTERING OF DEUTERONS BY Ca^{40}

R. H. Bassel,* R. M. Drisko,* G. R. Satchler,* L. L. Lee, Jr., J. P. Schiffer, and B. Zeidman . . . . (Project I-27)

Phys. Rev. 136, B960-B970 (23 November 1964)

NUCLEAR RESONANCE FLUORESCENCE IN Cu^{65}

G. B. Beard . . . . (Project I-9)

Phys. Rev. 135, B577-B580 (10 August 1964)

MASS SPECTROMETRIC STUDY OF VAPOR EJECTED FROM GRAPHITE AND OTHER SOLIDS BY FOCUSED LASER BEAMS

J. Berkowitz and W. A. Chupka . . . . (Project II-27)

J. Chem. Phys. 40, 2735-2736 (1 May 1964)

ISOTOPIC EFFECTS IN THE X-RAY SPECTRUM OF MUONIC ATOMS OF Ca^{40} AND Ca^{44}

J. A. Bjorkland (EL), S. Raboy, C. C. Trail, R. D. Ehrlich,† and R. J. Powers† . . . . (Project I-57)

Phys. Rev. 136, B341-B346 (26 October 1964)

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*Oak Ridge National Laboratory.

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p-WAVE RESONANCES OF Th^{232}
L. M. Bollinger and G. E. Thomas . . . . (Project I-3)
Phys. Letters 8, 45-47 (1 January 1964)

LEVEL STRUCTURE OF Sn^{116} FROM THE DECAY OF 1-h Sb^{116}; AND A DETAILED COMPARISON OF Sn^{116}, Sn^{118}, AND Sn^{120} WITH PAIRING-FORCE CALCULATIONS
H. H. Bolotin . . . . (Project I-9)
Phys. Rev. 136, B1566-B1579 (21 December 1964)

Sn^{116} LEVELS POPULATED BY THE DECAY OF 54-MIN In^{116m}
H. H. Bolotin . . . . (Project I-9)
Phys. Rev. 136, B1557-B1565 (21 December 1964)

ELASTIC SCATTERING OF 21.0-MEV DEUTERONS BY He^4
H. W. Broek and J. L. Yntema . . . . (Project I-22)
Phys. Rev. 135, B678-B679 (10 August 1964)

LEVELS IN $_{75}Re^{188}$ FROM STUDIES OF THE DECAY OF $_{74}W^{188}$ (69.4 DAY), $_{75}Re^{188}$ (18 h), AND $_{75}Re^{188m}$ (18.5 MIN)
S. B. Burson, E. B. Shera, T. Gedayloo, R. G. Helmer, and D. Zei . . . . (Project I-36)
Phys. Rev. 136, B1-B17 (12 October 1964)

ELECTRONIC g FACTORS OF THE p^2 CONFIGURATION IN Ge I AND Sn I
W. J. Childs and L. S. Goodman . . . . (Project I-80)
Phys. Rev. 134, A66-A69 (6 April 1964)

SYSTEMATIC APPROXIMATIONS FOR THE SINGLE-CHANNEL SCATTERING AMPLITUDE
F. Coester . . . . (Project V-20)
Phys. Rev. 133, B1516-B1519 (23 March 1964)

INTERNAL SYMMETRY AND LORENTZ INVARIANCE
F. Coester, M. Hamermesh, and W. D. McGlinn. . . (Project V-31)
Phys. Rev. 135, B451-B452 (27 July 1964)

EFFECTIVE SHELL-MODEL INTERACTION FOR THE ISOTOPES OF OXYGEN
S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga*. . . . . (Project V-9)
Phys. Letters 9, 180-183 (1 April 1964)

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*Tokyo Institute of Technology.

ON THE ACCURACY OF LINEARIZATION APPROXIMATIONS FOR SINGLE-CLOSED-SHELL NUCLEI

S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga* . . . . (Project V-9)

Phys. Letters 9, 243-246 (15 April 1964)

THE EFFECTIVE INTERACTION AND IDENTICAL-NUCLEON SENIORITY FOR NUCLEI NEAR Zr^{90}

S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga* . . . . (Project V-9)

Phys. Letters 10, 195-198 (June 1964)

TOTAL NEUTRON CROSS SECTION OF Cm^{244} . . . . . . (Project I-3)

R. E. Coté, R. F. Barnes (CHM), and H. Diamond (CHM)

Phys. Rev. 134, B1281-B1284 (22 June 1964)

NEUTRON RESONANCES OF SELENIUM

R. E. Coté, L. M. Bollinger, and G. E. Thomas . . . (Project I-3)

Phys. Rev. 136, B703-B710 (9 November 1964)

TOTAL NEUTRON CROSS SECTION OF MANGANESE

R. E. Coté, L. M. Bollinger, and G. E. Thomas . . . (Project I-3)

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EXCITED-STATE SPIN ASSIGNMENTS BASED ON $(n,\gamma\gamma)$ ANGULAR-CORRELATION MEASUREMENTS ON MEDIUM-WEIGHT NUCLEI

R. E. Coté, H. E. Jackson, Jr., L. L. Lee, Jr., and J. P. Schiffer . . . . (Project I-7)

Phys. Rev. 135, B52-B56 (13 July 1964)

MEASUREMENT OF THE GRAVITATIONAL RED SHIFT WITH THE MÖSSBAUER EFFECT . . . . (Project I-19)

T. E. Cranshaw (AERE, Harwell) and J. P. Schiffer

Proc. Phys. Soc. (London) 84, 245-256 (August 1964)

OBSERVABLES IN RELATIVISTIC QUANTUM MECHANICS

W. C. Davidon (Haverford College) and H. Ekstein. . . (Project V-44)

J. Math. Phys. 5, 1588-1594 (November 1964)

MAGNETIC MOMENT OF THE 26.8-KEV STATE OF I^{129} MEASURED WITH THE AID OF SUPERCONDUCTING MAGNETS

H. de Waard and J. Heberle . . . . (Project I-19)

Phys. Rev. 136, B1615-B1617 (21 December 1964)

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EXPERIMENTAL OBSERVATION OF ELECTRIC-QUADRUPOLE HYPERFINE EFFECTS IN MUONIC X-RAY SPECTRA

R. D. Ehrlich,* R. J. Powers,* V. L. Telegdi,* J. A. Bjorkland (EL), S. Raboy, and C. C. Trail . . . . (Project I-57)

Phys. Rev. Letters 13, 550-553 (2 November 1964)

Erratum: Phys. Rev. Letters 13, 650 (23 November 1964)

NEUTRON SCATTERING FROM NUCLEI NEAR A = 20 AT ENERGIES BELOW 2.2 MEV

A. J. Elwyn, J. E. Monahan, R. O. Lane, and A. Langsdorf, Jr. . . . . (Project I-18)

Nucl. Phys. 59, 113-126 (October 1964)

LEVEL STRUCTURE OF Bi^{208} AS OBSERVED AT HIGH RESOLUTION WITH THE $Bi^{209}(d,t)Bi^{208}$ REACTION

J. R. Erskine . . . . (Project I-23)

Phys. Rev. 135, B110-B115 (13 July 1964)

$B^{10}(d,Li^6)Li^6$ REACTION AT DEUTERON ENERGIES FROM 8 TO 13.5 MEV . . . . (Project I-27)

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

Phys. Rev. 134, B110-B112 (13 April 1964)

BESTIMMUNG DER KERNMOMENTE DES Ho^{165} AUS DER HYPERFEINSTRUKTUR DES GRUNDZUSTANDES IM Ho I-SPEKTRUM

L. S. Goodman and K. Schlüpmann (University of Heidelberg) . . . . (Unattached)

Z. Physik 178, 235-243 (1964)

QUANTUM THEORY OF MEASUREMENT: COMMENT ON A PAPER OF SHIMONY

M. N. Hack . . . . (Project V-25)

Am. J. Phys. 32, 890-892 (November 1964)

PSEUDOSCALAR CHARGE DENSITY OF SPIN-$\frac{1}{2}$ PARTICLES. I. EXISTENCE

K. Hiida . . . . (Project V-47)

Phys. Rev. 134, B174-B181 (13 April 1964)

PSEUDOSCALAR CHARGE DENSITY OF SPIN-$\frac{1}{2}$ PARTICLES. II. OBSERVABILITY

K. Hiida . . . . (Project V-47)

Phys. Rev. 134, B860-B863 (25 May 1964)

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*University of Chicago.

LIFETIMES OF $d_{3/2}$ HOLE STATES IN SCANDIUM ISOTOPES
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R. Malmin . . . . (Project I-23)
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PERSONNEL CHANGES IN THE ANL PHYSICS DIVISION

NEW MEMBERS OF THE DIVISION

Resident Research Associate

Dr. Claus U. Mayer-Böricke, Scientist, Max-Planck Institut für Kernphysik, Heidelberg, Germany. Direct reactions. Came to Argonne on 1 May 1964. (Host: J. P. Schiffer.)

Resident Research Associate (Post-Doctoral)

Dr. Dietrich Dehnhard, Physikalisches Institut, Universität Marburg, Marburg/Lahn, Germany. Direct nuclear reactions. Came to Argonne on 1 April 1964. (Host: J. L. Yntema.)

Resident Research Associates (Summer)

Dr. George B. Beard, Associate Professor of Physics, Wayne State University. Nuclear resonant fluorescent scattering of γ rays. Came to Argonne on 1 July 1964. (Host: L. M. Bollinger.)

Dr. Mazhar Hasan, Associate Professor of Physics, Northern Illinois University, DeKalb, Illinois. Theory of high-frequency discharges. Came to Argonne on 5 August 1964. (Host: A. J. Hatch.)

Dr. Kurt Just, Associate Professor, University of Arizona. Theory of gravitation and general relativity. Came to Argonne 13 July 1964. (Host: M. Peshkin.)

Dr. Harry J. Lipkin, Weizmann Institute of Science, Rehovoth, Israel. Symmetries of elementary particles. Returned to Argonne on 29 June 1964. (Host: M. Peshkin.)

Dr. Bert Schroer, University of Pittsburgh. Nonrenormalizable theories. Came to Argonne on 15 April 1964. (Host: M. Peshkin.)

Dr. Michitoshi Soga, Research Associate, Tokyo Institute of Technology. Calculations of nuclear structure. Came to Argonne on 12 May 1964. (Host: M. Peshkin.)

University Users of the ANL Tandem

Dr. William G. Cramer, Jr., Indiana University.
Dr. William Eidson, Indiana University.
Dr. Keith Jones, Brookhaven National Laboratory.
Dr. R. Scharenberg, Case Institute of Technology.
Dr. John J. Schwartz, University of Rochester.

Resident Student Associate (Thesis)

Mr. Kamel M. A. Refaey, graduate student, Illinois Institute of Technology. Working with W. A. Chupka on mass spectroscopy (photoionization, photodissociation and collision-induced dissociation of ions, electron-impact studies, high-temperature chemistry). Came to Argonne on 15 June 1964.

Resident Student Associates (Summer)

Mr. David D. Borlin, graduate student, Washington University, St. Louis. Working with T. H. Braid on experimental nuclear physics. Came to Argonne on 6 July 1964.

Mr. Lewis J. Milton, graduate student, University of Illinois. Working with J. L. Yntema on analysis of spectra to extract angular distributions from deuteron reactions on Ca and Ti. Came to Argonne on 1 July 1964.

Student Aides (ACM)

Mr. Paul S. Eastman, St. Olaf College. Working with J. Heberle on the measurement of the Mössbauer fraction in beta Sn^{119} at 77°K. Came to ANL on 8 September 1964.

Mr. James R. Johnson, St. Olaf College. Working with S. L. Ruby on computer analysis of Mössbauer data. Came to ANL on 1 July 1964.

Mr. James A. Sebben, Ripon College, Wisconsin. Working with S. B. Burson on the determination of nuclear spins from γ-γ angular-correlation measurements. Came to ANL on 8 September 1964.

Co-op Technicians

Mr. Bruce A. Bernott, University of Detroit. Working with J. P. Schiffer on reduction of data on charged-particle reactions. Came to ANL on 17 August 1964.

Mr. Stephen Haley, University of South Florida. Working with R. O. Lane and A. J. Elwyn on computer programming for data analysis in connection with the neutron polarization experiments. Came to ANL on 19 August 1964.

Mr. Leo Koziol, University of Detroit. Working with M. Kaminsky on secondary emission from metal surfaces under high-energy ion bombardment. Came to ANL on 24 August 1964.

Student Aides (Summer)

Mr. Michael Crisp, Bradley University. Working with R. K. Smither on analysis of data from the bent-crystal spectrometer. Came to ANL on 1 July 1964.

Mr. George Dinolt, Lawrence College. Working with J. Heberle on an experimental study of the Mössbauer effect in metallic tin. Came to ANL on 1 July 1964.

Mr. David Patterson, Grinnell College. Working with L. L. Lee and J. P. Schiffer on computer codes for the distorted-wave Born approximation. Came to ANL on 1 July 1964.

Mr. Philip J. Siemens, Massachusetts Institute of Technology. Working with J. R. Erskine on computer programs to be used in the automatic scanning of nuclear-track plates. Came to ANL on 1 July 1964.

Technicians

Mr. Charles W. Schmidt joined the Physics Division on 1 September 1964 to work with D. C. Hess and D. von Ehrenstein.

Mr. James R. Specht joined the Physics Division on 6 July 1964 to work with R. E. Coté.

Secretary

Mrs. Catherine Yack returned to the Physics Division on 1 October 1964 as secretary in B wing.

Clerk

Mrs. Judy Maier joined the Physics Division on 4 May 1964 as receptionist.

PROMOTION

Dr. John P. Schiffer was promoted to Senior Scientist on 23 December 1964.

LEAVES OF ABSENCE

Dr. D. R. Inglis left ANL on 3 April 1964. During April and May he visited and lectured at about a dozen physics departments and institutes in Japan and Formosa. During June and July he lectured as a Visiting Professor at the University of Grenoble, France. He returned to Argonne early in September 1964.

Dr. J. L. Yntema left ANL on 1 August 1964 for a year at the Institute for Nuclear Research, Amsterdam. His work there will be on nucleon capture reactions; inelastic electron scattering. He expects to return to Argonne on 1 September 1965.

DEPARTURES

Dr. Richard G. Allas, resident research associate, has been at Argonne since 14 December 1961. At the tandem, he has studied the (p, α) reactions on K^{39} and K^{41}, and the giant-dipole resonance by means of the (p, γ) reactions on B^{11}, Al^{27}, and F^{19}, and has investigated the isotopic-spin selection rule for the case of $C^{12}(d, \alpha)B^{10}$. At the 4.5-MeV Van de Graaff, he has used the (p, γ), (p, α), and (p, p') reactions on B^{11} to study the properties of energy levels (Project I-21). He terminated at ANL on 8 May 1964 to go to the U.S. Naval Research Laboratory, Washington, D.C.

Mr. John T. Heinrich, technical assistant, has worked with T. H. Braid since 11 March 1958. He terminated on 27 November 1964.

Mr. William C. Johnston, resident student associate (thesis) from Western Michigan University, has been at Argonne since 17 June 1963. He worked with S. B. Burson on angular-correlation experiments. He terminated at ANL on 31 August 1964.

Dr. Karl-Edvard Nystén, resident research associate from the University of Helsinki, Finland, has been at Argonne since 1 July 1963. He worked with R. E. Holland on the study of (p, γ) reactions at the Van de Graaff accelerator. He terminated at ANL on 19 June 1964 to go back to the University of Helsinki.

Dr. Sudhir Pandya, resident research associate from the Physical Research Laboratory, Ahmedabad, India, has been at Argonne since 22 July 1963. He has worked on theoretical nuclear spectroscopy. He terminated at ANL on 11 August 1964 to return to Ahmedabad.

Dr. John K. Perring, resident research associate from A. E. R. E., Harwell, England, has been at Argonne since 9 September 1963. He has worked on the theory of nucleon-nucleon interactions. He terminated at ANL on 28 May 1964 to return to Harwell.

<u>Dr. E. Brooks Shera</u>, resident research associate (post-doctoral) from Western Reserve University has been at Argonne since 14 June 1962. He has worked with S. B. Burson on nuclear spectroscopy of short-lived radionuclides. He terminated at ANL on 10 September 1964 to go to the Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

<u>Dr. P. Paul Singh</u>, resident research associate, has been at Argonne since 2 July 1962. He has worked on the study of the giant dipole resonance through the inverse reaction; study of intermediate structure and fluctuations in nuclear reaction cross sections. He terminated at ANL on 14 September 1964 to go to the Physics Department, Indiana University, Bloomington, Indiana.

<u>Mrs. Barbara Smith</u>, secretary in F wing, has been at Argonne since 11 November 1963. She terminated at ANL on 16 June 1964.

<u>Dr. Carroll C. Trail</u> has been at Argonne since 1954. His work included studies of gamma-ray spectra from capture of neutrons with energies from 0.1 to 10 eV, of gamma rays from fission induced by thermal neutrons, and of muonic x rays from atoms with $7 \leq Z \leq 94$, and the development of an NaI(Tl) gamma-ray spectrometer with anticoincidence annulus. He terminated on 21 August 1964 to become Professor of Physics, Brooklyn College, Brooklyn, New York.

Mrs. JoAnn Wyatt, clerk, has worked in the Physics Division for C. Eggler since 15 June 1961. She terminated on 15 December 1964.

Transfers

Dr. Robert Childers, Dr. K. Itabashi, Dr. A. W. Martin, Dr. W. D. McGlinn, Dr. K. Tanaka, Dr. J. Uretsky, and Dr. K. C. Wali transferred to the High Energy Physics Division on 1 April 1964.

Mr. John J. Vronich, research technician, has worked with the chopper group since 7 July 1959. He transferred to Reactor Operations on 1 July 1964.