Energy and Angular Distribution of Protons from Deuteron Bombardment of Nickel*

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The energy spectrum and angular distribution of protons resulting from 3.03-Mev deuteron bombardment of Ni^{58} and Ni^{60} have been studied by means of a nuclear emulsion technique. Three previously unreported energy levels in Ni^{59} have been found. The angular distribution of the protons indicates that the reaction is primarily due to compound nucleus formation.

I. INTRODUCTION

THE energy of proton groups resulting from deuteron bombardment of nickel has been studied by several investigators[1–3] for the purpose of determining neutron binding energies and the distribution of energy levels in the residual nucleus. The angular distribution of protons resulting from the bombardment of nickel with 14-Mev deuterons has been studied by Gove,[4] who concluded that, for this value of deuteron energy, the (d,p) reaction is primarily due to a stripping process. The present work, using 3.03-Mev deuterons, was undertaken in order to make a further study of energy levels in the nickel isotopes and to determine whether the stripping mechanism still predominates at this value of deuteron energy.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

A deuteron beam of energy 3.07 ± 0.05 Mev was obtained from the University of Iowa Van de Graaff generator. After passing through a suitable collimating system the beam was allowed to enter the target chamber, a schematic diagram of which is shown in Fig. 1. The target consisted of either a thin nickel foil or of a thin nickel deposit on a silver backing. The face of the target was, in all cases, mounted at an angle of 45° with respect to the direction of the deuteron beam. The angular divergence of the beam is less than 1° and the target spot is 2 mm (in the plane of observation) ×1 mm.

Protons emerging from the target are detected in Eastman NTA, 100-micron emulsion nuclear track plates. The plates are tilted so that the protons dip into the emulsion at an angle of 5° with respect to the surface. Protons emerging at angles between 0° and 80°, with respect to the deuteron beam, pass through the target backing (if any) and are detected in the forward plate. Protons emerging at angles between 80° and 160° are detected in the rear plate. Shields of silver and aluminum are inserted between the target and each of the plates. A thickness of silver sufficient to stop elastically scattered deuterons as well as the direct beam is employed. The use of silver for this purpose has been found to give rise to negligible background due to (d,p) reactions in the shield. In addition to the silver shield, it is sometimes found to be advantageous to insert additional shields of aluminum in order to reduce the track length of the protons in the emulsion to a convenient value (20–200 microns) for range measurements with the calibrated eyepiece scale in the microscope. Aluminum is used for this purpose since it gives less scattering of the protons (for a given energy loss) than silver.

After exposure the plates are developed; and scribe marks are placed on the emulsion to divide the surface of the emulsion into regions characteristic of the same angle of emergence of the protons with respect to the deuteron beam. The angular width of these regions would be 3° if the target spot were a point. If the finite size of the target spot is taken into account, the maximum angular width is about 6°. A Spencer monocular microscope with a 4-mm achromatic objective and a 10× eyepiece is used to scan the plates.

III. PROTON ENERGY MEASUREMENTS

Proton energy spectra were obtained at several angles using a target foil of natural nickel of surface density 0.5 mg/cm². The spectrum of protons emerging at an angle of 45° with respect to the deuteron beam is shown in Fig. 2(a). The horizontal scale, giving proton track length in the emulsion, was converted to proton energy using the range-energy relation for NTA emulsions given by Richards *et al.*[5] Corrections for the proton

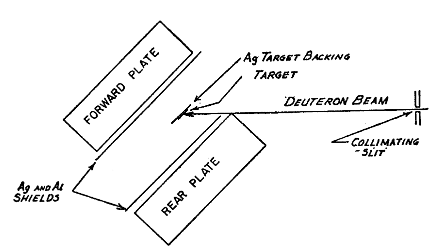

FIG. 1. Diagram of apparatus.

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† Now at the Pennsylvania State University, State College, Pennsylvania.
[1] J. A. Harvey, Phys. Rev. **81**, 353 (1951).
[2] D. C. Hoesterey, Phys. Rev. **87**, 216 (1952); verbal report quoted in Nuclear Science Abstracts **6**, 24B (1952).
[3] McFarland, Bretscher, and Shull, Phys. Rev. **89**, 892 (1953).
[4] H. E. Gove, Phys. Rev. **81**, 364 (1951).
[5] Richards, Johnson, Ajzenberg, and Laubenstein, Phys. Rev. **83**, 994 (1951).

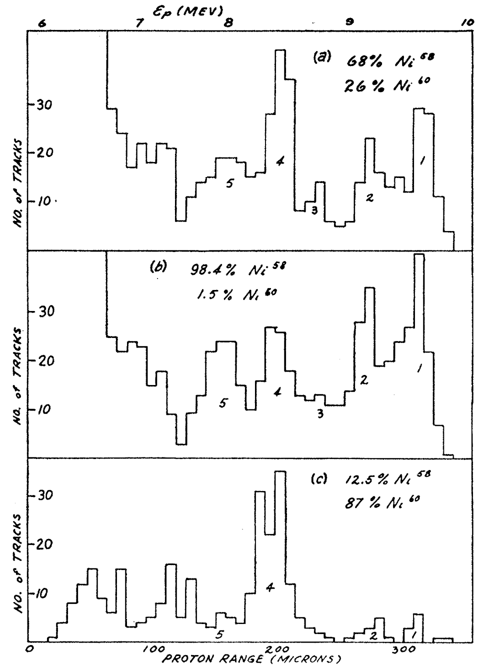

FIG. 2. Proton spectra at 45° angle of proton emission, (a) normal Ni, (b) enriched Ni^{58}, (c) enriched Ni^{60}.

energy loss in the silver and aluminum shields were made using the range-energy relations given by Aron, Hoffman, and Williams.[6]

It is seen from Fig. 2(a) that five groups of protons are reasonably well resolved. All of these groups appear consistently in the data taken at each angle of proton emergence. In order to identify the origin of each of these groups, measurements were made using separated isotopes obtained from the Oak Ridge National Laboratory. Natural nickel contains 68 percent Ni^{58} and 26 percent Ni^{60}; and it has been assumed that all of the proton groups observed here originate in a (d,p) reaction in one of these isotopes. Accordingly measurements were made with a target consisting of 98.4 percent Ni^{58}, 1.5 percent Ni^{60} and a target consisting of 87 percent Ni^{60}, 12.5 percent Ni^{58}. These targets were electrodeposited[7] on a silver backing.

The proton energy spectra obtained using the separated isotopes are shown in Figs. 2(b) and 2(c). The product of (integrated beam current)×(target thickness)×(solid angle observed) is roughly the same in each of Figs. 2(a), 2(b), and 2(c). Background measurements indicate that essentially all tracks observed arise from the nickel targets.

It is seen that all five proton groups are present in the highly enriched Ni^{58} target, and that Group 4 alone appears in strength in the Ni^{60} target. There is also evidence for a group at about 7.5 Mev in the Ni^{60} target which is not apparent in the Ni^{58} target. An analysis of the relative intensities indicates that Groups 1, 2, 3, and 5 are essentially all due to reactions in Ni^{58} and that Group 4 is due to reactions in both Ni^{58} and Ni^{60}. For the ratio of isotopic cross sections for the reactions contributing to Group 4, the value

$$\sigma(Ni^{60}(d,p)Ni^{61})/\sigma(Ni^{58}(d,p)Ni^{59})=1.6$$

is obtained. This implies that the protons in Group 4 observed with the normal nickel target are about 60 percent due to Ni^{58} and 40 percent due to Ni^{60}.

After correcting for the energy loss of the deuterons in the target,[6] the mean deuteron energy is found to be 3.03 Mev. From this and the measured proton energies the Q value (energy released) corresponding to each of the observed proton groups may be computed. The Q values obtained, averaged over all angles for which measurements were made, are given in Table I.

These results may be compared with data observed by several other investigators.

(1) Stelson and Preston[8] have studied the (p,n) reaction in Co^{59}, leading to the ground state of Ni^{59} and to an excited state in Ni^{59}. The result for the excitation energy of the excited state is 0.33±0.05 Mev.

(2) McFarland, Bretscher, and Shull[3] have studied the (d,p) reaction in Ni^{58} using 10.2-Mev deuterons and magnetic analysis of the emerging protons, which should give rather precise energy values. They find proton groups corresponding to Q values of 6.77 Mev, 6.35 Mev, and other groups with Q values below 4 Mev. No groups are reported with Q values between 4 Mev and 6.35 Mev.

(3) Harvey[1] has studied the (d,p) reaction in Ni^{58} using 14-Mev deuterons and range measurement of the emerging protons. His result for the Q value of the ground state in Ni^{59} is 6.78±0.10.

(4) Kinsey and Bartholomew[9] have studied the gamma-ray energy spectrum resulting from thermal-neutron capture in normal nickel. Their results for the six highesten-ergy gamma rays are given in Table II. These values may be converted to the Q value of the corresponding (d,p) reaction if it is assumed that the

TABLE I. Energy released (Q) in the (d,p) reaction in nickel.

Target	Proton group	Q (Mev)
Ni^{58}	1	6.70±0.1
Ni^{58}	2	6.37±0.1
Ni^{58}	3	5.96±0.1
Ni^{58}	4	5.55±0.1
Ni^{60}	4	5.55±0.1
Ni^{58}	5	5.08±0.1

[6] Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-663, May 28, 1951 (unpublished).
[7] The writer is indebted to Professor W. E. Bennett of the Department of Chemistry for advice on the electrodeposition of nickel.

[8] P. H. Stelson and W. M. Preston, Phys. Rev. **86**, 807 (1952).
[9] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).

gamma ray originates in the compound nuclear state in which the neutron is captured. The Q values obtained in this way are also indicated in Table II.

(5) Hoesterey[2] has studied the (d,p) reaction in Ni^{60}, finding a ground state Q value of 6.30 Mev and an excited-state Q value of 5.69 Mev.

(6) Owen, Cook, and Owen[10] have studied the beta decay of Cu^{61} and the resulting gamma-ray spectrum in Ni^{61} to obtain energy levels in Ni^{61} corresponding to the ground state and to excited states at 0.655 Mev, 0.939 Mev, and 1.015 Mev.

All of these data are collected in Fig. 3 in a series of energy level diagrams in terms of the Q value for the (d,p) reaction leading to each level observed. The level diagrams are divided into three columns. The left-hand column contains results for the reaction $Ni^{58}(d,p)Ni^{59}$. The center column contains the (n,γ) data obtained with normal nickel. The right-hand column contains results for the reaction $Ni^{60}(d,p)Ni^{61}$. The data of Stelson and Preston,[8] where energy-level differences rather than Q values were determined, have been normalized to the ground-state Q value obtained by McFarland *et al.*[3] The data of Owen *et al.*,[10] where a similar situation exists, have been normalized to the ground-state Q value obtained by Hoesterey.[2] These normalizations have been indicated by using dotted lines to represent the ground states.

It will be of interest to attempt to identify the precise (n,γ) data of Kinsey and Bartholomew[9] with specific levels in the isotopes.

(1) The first level (A) obtained in the (n,γ) measurements (highest Q value) clearly corresponds to the ground state of Ni^{59}.

(2) The second level (B) in the (n,γ) data differs by 50 kev from the value obtained by McFarland *et al.* for the first excited state of Ni^{59}. Since both of these values are presumably more precise than this discrepancy would imply, it appears that this level should be associated with the ground-state transition in Ni^{61}. The agreement with Hoesterey's value in this case is very good. Furthermore, if the beta-gamma decay data of Owen *et al.* are normalized to this level there is excellent agreement between level E in the (n,γ) data and the

TABLE II. Gamma rays from neutron capture in nickel.[a]

Gamma ray	Gamma-ray energy E (Mev)	Corresponding Q value for (d,p) reactions. $Q=E-2.23$ Mev
A	8.997±0.005	6.77
B	8.532±0.008	6.30
C	8.119±0.010	5.89
D	7.817±0.008	5.59
E	7.528±0.011	5.30
F	7.22 ±0.02	4.99

[a] See reference 9.

[10] Owen, Cook, and Owen, Phys. Rev. **78**, 686 (1950).

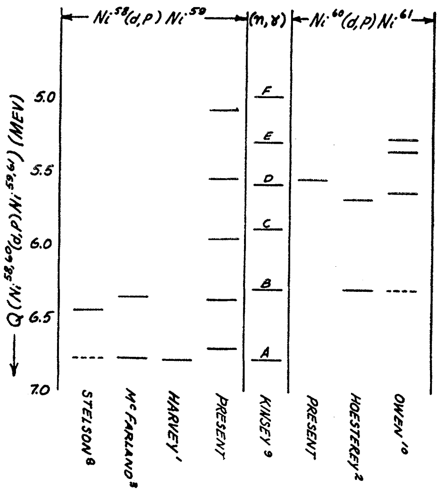

FIG. 3. Energy levels in Ni^{59} and Ni^{61} as observed by various investigators.

third excited state in Ni^{61} obtained by Owen *et al.* There is no indication of any level in Ni^{59} corresponding to level E in the (n,γ) data. Thus levels B and E in the (n,γ) data are assigned to the ground state and third excited state, respectively, in Ni^{61}.

(3) Level C in the (n,γ) data is not near any proposed level in Ni^{61} but is close to the second excited state in Ni^{59} as found in the present work. It is therefore assigned to this state in Ni^{59}.

(4) Level D in the (n,γ) data is not in good agreement with the first excited state in Ni^{61} as obtained by Owen *et al.* or by Hoesterey. It is however in agreement with the third excited state in Ni^{59} as obtained in the present work. Furthermore, it is unlikely from intensity considerations[9] that it can be attributed to any level in Ni^{61}. It is therefore assigned to the third excited state of Ni^{59}.

(5) Level F in the (n,γ) data is within experimental error of the fourth excited state in Ni^{59} as found in the present work, and is tentatively assigned to this state.

Kinsey and Bartholomew[9] have assigned levels A, D, and E to Ni^{59} and level B to Ni^{61}. Our conclusions are in agreement with these assignments with the exception of level E, which we prefer to associate with Ni^{61}.

This section may be concluded by assigning partial energy level diagrams to Ni^{59} and Ni^{61}. These are indicated in Fig. 4. The diagram for Ni^{61} is that proposed by Owen *et al.* In the diagram for Ni^{59}, three new levels have been added by the present work. The (p,n) measurements of Stelson and Preston give faint indications of levels in Ni^{59} at 0.58 and 0.83 Mev. The higher of these is close to the second excited state indicated in Fig. 4. It is, however, difficult to understand why the (d,p) measurements of McFarland *et al.*[3] do not give any indication of the three higher levels in Ni^{59}.

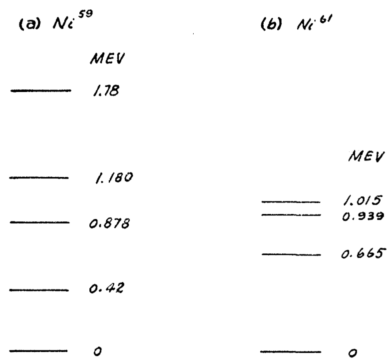

FIG. 4. Proposed partial energy level diagrams for (a) Ni^{59} and (b) Ni^{61}. The diagram for Ni^{61} is that proposed by Owen *et al.* (see reference 10).

IV. ANGULAR DISTRIBUTION OF THE PROTONS

Measurements similar to those shown in Fig. 2 were made at several different angles of proton emission, using a natural nickel target. From these measurements it is possible to obtain the angular distribution of proton groups 1, 2, 4, and 5. These results, some of which have been reported in a previous communication,[11] are shown in Figs. 5 and 6. It is seen that all of the angular distributions are symmetrical about 90°, giving no indication of the peak in the forward direction normally associated with a stripping process.[12] Measurements by Gove,[4] using 14-Mev deuterons, have, on the other hand, indicated a very strong forward maximum in the angular distribution of the protons. The result of one of Gove's measurements is reproduced in Fig. 7.

In the absence of any evidence of the stripping process, it is of interest to consider the predictions of the compound nucleus theory concerning the angular distributions to be expected. A rough estimate of the width and spacing of energy levels in the compound nucleus indicates that the capture of a deuteron will give rise to the simultaneous excitation of a large number of compound nuclear levels. Under these conditions, the statistical theory proposed by Wolfenstein[13] may be expected to apply. The differential cross section predicted by this theory may be expressed in the form

$$\sigma(\theta)=\sum_{l,l',n,J}\frac{C_{s,s',\pi,\pi'}(l,l',n,J)}{F(J)}P_lP_{l'}\cos^{2n}\theta,$$

where θ is the angle of emission of the proton with respect to the deuteron beam; s, s', π, π' are spins and parities of the initial and final nucleus, respectively; l and l' are the orbital angular momentum of the incoming deuteron and the outgoing proton, respectively; n takes on all integral values from zero to infinity; P_l and $P_{l'}$ are the corresponding barrier penetrabilities; and $F(J)$ represents the density of states of angular momentum J in the compound nucleus. The coefficient C is, aside from a constant factor, a known function of all of its arguments and subscripts.[14,15] For a given

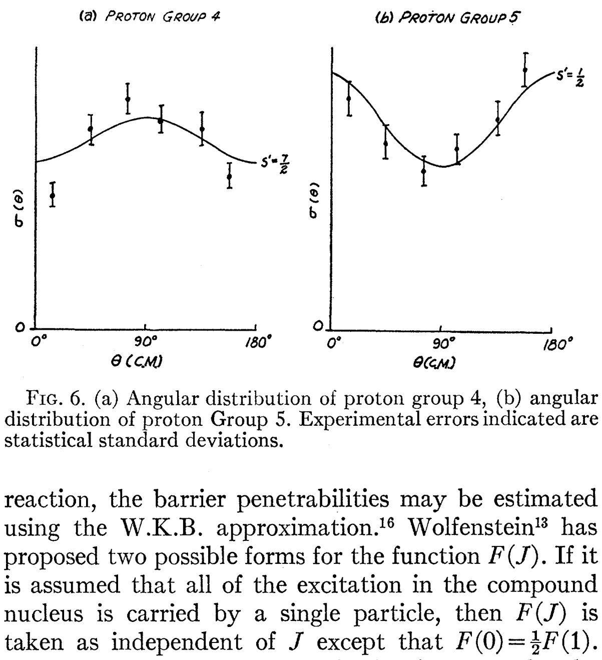

FIG. 6. (a) Angular distribution of proton group 4, (b) angular distribution of proton Group 5. Experimental errors indicated are statistical standard deviations.

reaction, the barrier penetrabilities may be estimated using the W.K.B. approximation.[16] Wolfenstein[13] has proposed two possible forms for the function $F(J)$. If it is assumed that all of the excitation in the compound nucleus is carried by a single particle, then $F(J)$ is taken as independent of J except that $F(0)=\frac{1}{2}F(1)$. If, on the other hand, the excitation is assumed to be distributed among several nucleons, then $F(J)$ is taken as proportional to $2J+1$.

In comparing experimental data from the reactions $Ni^{58}(d,p)Ni^{59}$ and $Ni^{60}(d,p)Ni^{61}$ with the statistical theory, we have employed shell model considerations in order to limit the number of combinations of initial and final spins and parities which must be considered. Both Ni^{58} and Ni^{60}, being even-even nuclei, are assumed to

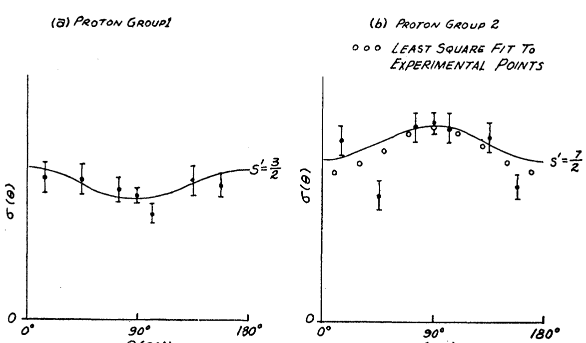

FIG. 5. (a) Angular distribution of proton group 1, (b) angular distribution of proton Group 2. Experimental errors indicated are statistical standard deviations.

[11] William W. Pratt, Phys. Rev. **94**, 1086 (1954).
[12] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[13] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).
[14] The writer is indebted to Dr. D. L. Falkoff for supplying him with a reprint of a paper (see reference 15) which greatly facilitated the evaluation of some of these coefficients.
[15] Falkoff, Colladay, and Sells, Can. J. Phys. **30**, 253 (1952).
[16] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 362.

have zero spin and even parity. For the ground state of either Ni^{59} or Ni^{61}, the shell model[17] implies a spin 3/2 (in units of $\hbar$) and odd parity. Furthermore the lowest three odd-neutron orbitals, outside of the closed $f_{7/2}$ shell, are believed[17] to be $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$, all of which have odd parity. We have therefore calculated angular distributions only for transitions from a 0^+ state to a state of odd parity. Calculations for the transition to states of the type $1/2^-$, $3/2^-$, $5/2^-$, $7/2^-$, and $9/2^-$ have been carried out. The calculations have been performed neglecting the contribution of deuteron orbital angular momenta $\geqslant 3$ and of proton orbital angular momenta $\geqslant 6$. It is estimated that 90 percent of each reaction is due to l values within these limits. In the case of the $0^+ \rightarrow 9/2^-$ transition, certain contributions from protons with $l=5$ were also neglected, leading to an error which is believed to be no greater than 3 percent.

The result of the calculations for the case $E_d=2.94$ Mev, $Q=6.70$ Mev, corresponding to the ground-state transition in Ni^{59}, is presented in Fig. 8.

In Figs. 5 and 6 the experimental results are compared with the predictions of the statistical model. In each case the theoretical curve which can most easily be fitted to the data is shown;[18] and the assumption of single-particle excitation, which appears to give somewhat better agreement than the other assumption,[11] is used.

(1) Proton group 1 [Fig. 5(a)], representing the transition to the ground state of Ni^{59}, is in good agreement with the theoretical curve for a final $3/2^-$ state. This also is the ground state of Ni^{59} implied by the shell model.

(2) Proton group 2 [Fig. 5(b)], representing the transition to the first excited state of Ni^{59}, shows an unduly large spread in the experimental points. However, a least-squares fit of a curve of the form $a+b\cos^2\theta$ is indicated by the open circles, and is in agreement with the theoretical curve for a final $7/2^-$ state.

(3) Proton group 3 is too weak for a measurement of the angular distribution to be attempted.

(4) Proton group 4 [Fig. 6(a)], representing roughly equal contributions from transitions in Ni^{59} and Ni^{60}, is in fair agreement with the theoretical curve for a final $7/2^-$ state.[19] The significance of any such agreement in this case is, of course, open to question in view of the double transition involved.

(5) Proton group 5 [Fig. 6(b)], representing a transition to the fourth excited state in Ni^{59}, is in good agreement with the theoretical curve for a final $1/2^-$ state.

It may be concluded from these results that the

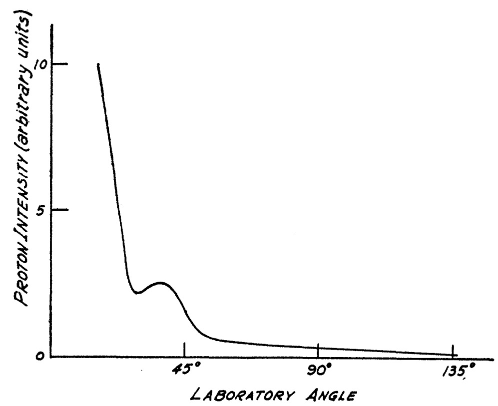

FIG. 7. Angular distribution of long range protons from 14-Mev bombardment of Ni (from reference 4).

reaction in which a compound nucleus is formed predominates over the stripping process in this case, and that the angular distribution of the emerging protons is well represented by Wolfenstein's theory.

In this connection it is of interest to consider the relative effectiveness of compound nucleus formation and stripping in the general case. It has previously been shown[12,20] that, for bombarding energies well above the Coulomb barrier of the target nucleus, the (d,p) reaction appears to proceed mainly by the stripping process. For bombarding energies below the barrier, however, the results which have been obtained to date are not definitive on this point. If it may be assumed, as indicated by the Butler theory,[12] that the angular distribution of protons associated with the stripping process is characterized at all energies by a forward maximum in the cross section which is large compared to the cross section in the backward direction, then the ratio $\sigma(\theta_m)/\sigma(\theta_0)$ may be considered as giving a rough measure of the relative importance of stripping and compound nucleus formation. Here θ_m is the angle in the forward direction corresponding to the maximum value of the cross section, and θ_0 is some angle in the backward direction, where the cross section is usually

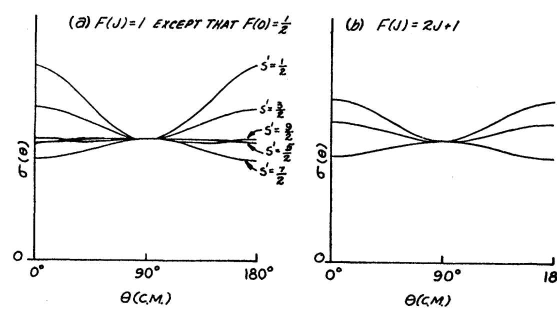

FIG. 8. Angular distribution of protons in a transition from a 0^+ state to an odd-parity state, $Q=6.7$ Mev, deuteron energy$=2.94$ Mev. (a) Single-particle excitation, (b) multiple-particle excitation. All curves are symmetrical about 90°.

[17] P. F. A. Klinkenberg, Revs. Modern Phys. 24, 63 (1952).

[18] Since the theoretical curves are not very sensitive to Q, the fit for other cases may be estimated from Fig. 8.

[19] This group was erroneously attributed entirely to the transition in Ni^{61} in our previous communication (reference 11).

[20] D. C. Peaslee, Phys. Rev. 74, 1001 (1948).

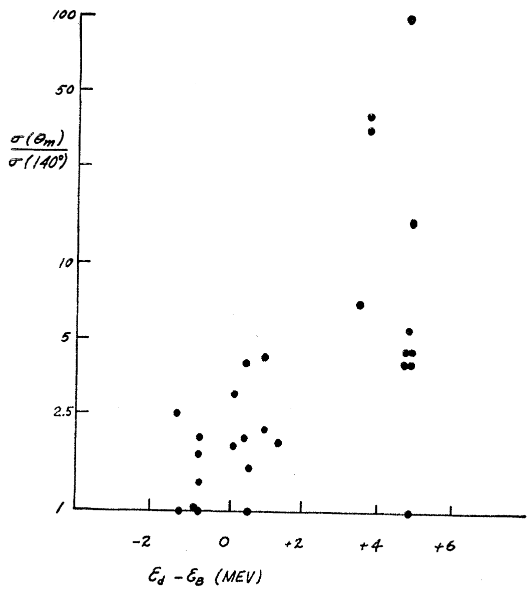

FIG. 9. Ratio of (d,p) cross section in forward direction to that in backward direction as a function of (deuteron energy) — (barrier height).

found to have a relatively small variation with angle. In Fig. 9 this ratio has been plotted as a function of the difference between deuteron bombarding energy (E_d) and Coulomb barrier height (E_B). The data[21–26] from which this figure has been constructed represent transitions in various isotopes leading to various states in the final nucleus.

It is seen that there is a systematic trend for the ratio $\sigma(\theta_m)/\sigma(140°)$ to decrease from a value large compared with unity at bombarding energies above the barrier to a value of the order of unity at bombarding energies below the barrier. This behavior is suggestive of a situation in which stripping predominates for high bombarding energies and compound nucleus formation predominates for low bombarding energies. If this is the correct interpretation of the data, then it is clear that the present results with nickel $(E_B \approx 7$ Mev) represent an extreme case of this effect.

On the other hand, it must be remarked that this interpretation may very well not be correct. Recent theoretical work,[27] in which Coulomb and nuclear interactions of the deuteron and proton with the nucleus have been taken into account, has indicated that the Butler theory may be in considerable error in some cases. In particular, the Coulomb effects appear to result in a broadening of the peak in the angular distribution and in shifting it to larger angles. Since these effects may be expected to increase as the deuteron energy is reduced, it is quite possible that the behavior of the ratio $\sigma(\theta_m)/\sigma(\theta_0)$ indicated in Fig. 9 may be accounted for without resorting to any contribution from compound nuclear formation. Thus, although the data of Fig. 9 are consistent with the suggestion that compound nucleus formation becomes relatively more important for low deuteron energies, they do not furnish a compelling argument that this is the case.

We may conclude this section with a discussion (of a highly speculative nature) of possible spin values for some of the states in Ni^{59} and Ni^{61}. In Fig. 10 the proposed partial energy level diagrams for these nuclei have been reproduced, together with the spin values implied by the angular distribution measurements (the spin $3/2^-$ for the ground states of Ni^{61} and Cu^{61} are taken from the shell model[17]). In addition the gamma rays observed[9] subsequent to thermal neutron capture in Ni^{58} and Ni^{60} have been indicated, as well as the beta rays observed[10] in the positron decay of Cu^{61}.

Most of these observations are seen to be consistent with the spin assignments. The capture of thermal neutrons by the (even-even) nuclei Ni^{58} and Ni^{60} will presumably lead to states in the excited nuclei Ni^{59} and Ni^{61} of spin 1/2 and even parity. Dipole emission of gamma radiation will then be expected to states of spin 1/2 or 3/2, and all of these transitions are indeed observed. The remaining states where spin assignments have been made are all $7/2^-$ states, requiring octupole emission of gamma radiation; in two of these three cases the gamma radiation is not observed. The emission of a positron from the $3/2^-$ state in Cu^{61} to the $3/2^-$ state in Ni^{61} is expected to be allowed, and this is in agreement with experimental observation.[10] The only discrepancies involve the third excited state in Ni^{59} and

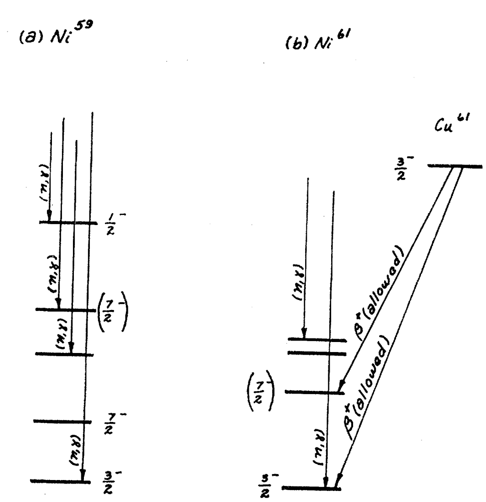

FIG. 10. Possible spin values in (a) Ni^{59} and (b) Ni^{61}.

[21] William E. Nickell, Phys. Rev. **95**, 426 (1954).
[22] W. C. Redman, Phys. Rev. **79**, 6 (1950).
[23] L. D. Wyly, Phys. Rev. **76**, 104 (1949).
[24] N. P. Heydenberg and D. R. Inglis, Phys. Rev. **73**, 230 (1948).
[25] W. M. Gibson and E. E. Thomas, Proc. Roy. Soc. (London) **A210**, 543 (1952).
[26] Burge, Burrows, Gibson, and Rotblat, Proc. Roy. Soc. (London) **A210**, 534 (1952).
[27] W. Tobocman and M. Kalos, Phys. Rev. **95**, 605 (1954); and verbal report.

the first excited state in Ni^{61}, both of which have been tentatively assigned a spin $7/2^-$ on the questionable basis of the angular distribution of proton group 4. The (n,γ) measurements show a strong transition to one of these states and the positron decay from Cu^{61} to the other is believed[10] to be allowed. Both of these observations are in disagreement with the 7/2 spin assignments. Whether these discrepancies can be attributed to the presence of one or more states which have not as yet been observed, to the presence of cascade gamma rays in the (n,γ) measurements, or to some other defect in our analysis, is not known at this time.

V. CROSS SECTIONS

From the known values of integrated deuteron beam current, target thickness, and solid angle subtended by the detecting plates, it is possible to obtain the cross section for the reaction leading to each observed transition. These results are presented in Table III. The absolute values of these cross sections are believed to be accurate to within about a factor of two. The errors in relative value are considerably less than this.

TABLE III. Cross sections for (d,p) reactions in Ni^{58} and Ni^{60} at a mean deuteron energy of 3.03 Mev.

Proton group	Target	$\sigma \times 10^{28}$ (cm²)
1	Ni^{58}	6.6
2	Ni^{58}	8.8
3	Ni^{58}	2
4	Ni^{58}	6.0
	Ni^{60}	9.6
5	Ni^{58}	9.6

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Beta Spectra of Pr^{142}, Tm^{170}, and Rb^{86}†

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The beta spectra and gamma rays of the isotopes Tm^{170}, Pr^{142}, and Rb^{86} have been examined with various types of spectrometers. An intermediate-image beta-ray spectrometer with a 10 percent transmission and a 5.5 percent resolution was used to examine the total and coincidence beta spectra. Total beta spectra were also studied with a thin-lens spectrometer set to about two percent resolution. Gamma rays were also studied with a scintillation spectrometer.

The results of the investigation indicate that the 125-day activity of Tm^{170} has two beta groups with maximum energies of 970±2 kev and 886±9 kev. Their respective intensities are about 78 percent and 22 percent, and their respective log ft values are approximately 9.0 and 9.1. Both beta groups are assigned as first forbidden transitions with $\Delta I = \pm 1$, "yes." The single observed gamma ray of Tm^{170} is assigned as an $E2$ transition with an energy of 84.1±0.4 kev.

The 19.2-hr activity of Pr^{142} has two beta groups with maximum energies of 2166±6 kev and 586±15 kev. The 2166-kev beta group has a log ft value of about 7.8 and the 586-kev beta group has a log ft value of about 7.1. The log$[(W_0^2-1)ft]$ value of the 2166-kev beta group is 10.2. The intensities for the 2166-kev and 586-kev beta groups were found to be, respectively, 90–95 percent and 5–10 percent.

The 2166-kev beta group is assigned as first forbidden with $\Delta I = 2$, "yes" and the 586-kev beta group as first forbidden with $\Delta I = 0$ or ± 1, "yes." The single observed gamma ray, having an energy of 1572±8 kev, is tentatively assigned as an $E2$ or $M1$ transition. The $E2$ and $\Delta I = 0$, "yes" choices are probably correct.

The 19.5-day activity of Rb^{86} has two beta groups with maximum energies of 1770±4 kev and 680±6 kev. Their intensities are about 88 percent and 12 percent, respectively. The log ft value for the 1770-kev beta group is about 8.5 and for the 680-kev beta group 7.8. The log $[(W_0^2-1)ft]$ value for the 1770-kev beta group is 9.7. This beta group is assigned as a first forbidden transition with $\Delta I = 2$, "yes," and the 680-kev beta group is tentatively assigned as first forbidden with $\Delta I = 0$, "yes." The single gamma ray has an energy of 1080±6 kev and is tentatively assigned as an $E2$ transition.

The Kurie plots of the 680-kev beta group of Rb^{86} and the 886-kev beta group of Tm^{170} were examined for deviations from a straight line. Within experimental error no deviation from a straight line was observed.

INTRODUCTION

IN this work an attempt was made to examine primarily the beta decays of Pr^{142}, Tm^{170}, and Rb^{86} using a coincidence technique. An intermediate-image spectrometer[1] which has a transmission of 10 percent at 5.5 percent resolution was used for the coincidence work. For conventional spectra, a thin-lens spectrometer set to two percent resolution and a scintillation spectrometer were also used.

In the intermediate-image spectrometer, the gamma rays were detected by a 5819 photomultiplier and a Lucite-covered NaI(Tl) crystal placed far enough behind the source to prevent distortion of the beta spectra by scattering (6292 phototubes are being used at present for the beta and gamma detectors). The focused beta particles were detected by an anthracene crystal and a

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[1] Nichols, Pohm, Talboy, and Jensen, U. S. Atomic Energy Commission Report No. ISC-345, 1953 (to be published).