Differential Cross Sections of Some (α,p) Reactions*†

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Using 30.4-Mev alpha particles, proton differential cross sections have been obtained for the following transitions, corresponding to discrete states of the residual nuclei: $B^{10}(\alpha,p)C^{13}{}_{\text{gnd}}$; $Na^{23}(\alpha,p)Mg^{26}{}_{\text{gnd, 1.83 Mev}}$; $Al^{27}(\alpha,p)Si^{30}{}_{\text{gnd, 2.24 Mev}}$; and $P^{31}(\alpha,p)S^{34}{}_{\text{gnd}}$. A proton energy spectrum corresponding to the first 12 Mev of excitation of the residual nucleus was obtained for the case involving the Al^{27} target. The differential cross sections are interpreted with the aid of predictions of the Butler direct-interaction (surface) theory. It is concluded that this theory is probably a more useful tool in interpreting the results obtained than is the compound nucleus theory. Some deviations from the predictions of the surface direct-interaction calculations are discussed.

I. INTRODUCTION

IN reactions involving alpha particles of only a few tens of Mev one might expect compound-nucleus processes to dominate.[1] This expectation is based on the necessary conditions for such reactions: (a) strong absorption of the incident particle in the target nucleus, and (b) a sharing of the incident alpha-particle energy so that the average excitation energy per nucleon is sufficiently low that the system must remain in an intermediate state for some length of time.

The first point seems to be satisfied in 30-Mev alpha-particle reactions as indicated by the short mean free path for absorption as deduced from optical model analyses of alpha-particle elastic scattering.[2,3] Short in this sense means that the mean free path (1 to 2×10^{-13} cm) is significantly less than the nuclear matter radius (3 to 6×10^{-13} cm) as deduced from electron elastic scattering experiments and their analysis.[4] However, it should be pointed out that the condition of strong absorption means only that the particles are removed from the incident beam in the region of the nuclear surface. Thus, if the subsequent reaction does not occur through the formation of the compound nucleus, it will have to proceed through some sort of surface interaction.

Relative to the second condition necessary for the formation of the compound nucleus, we would like to point out that for the reactions to be described here the ratio of the average separation energy per nucleon to the average excitation energy in the compound system[1] is of the order of 10. Under these conditions one might therefore not expect compound nuclear processes to be too prevalent.

On the other hand, the necessity for any non-compound interaction to take place at the surface suggests the applicability of the direct-interaction theories developed by Butler and his co-workers.[5,6] This theory has been further developed and applied to a variety of reactions such as inelastic scattering of alpha particles,[7] inelastic scattering of protons,[8] and, of course, (d,p) and (d,n) reactions.[9,10]

The usual formulation of these theories has been in terms of reactions involving discrete states of the residual nucleus. At lower energies such alpha-particle experiments have been performed and analyzed in terms of direct interaction theory although there are indications of compound nucleus behavior.[11–13] At 40-Mev alpha-particle energy Eisberg, Igo, and Wegner[14] studied the spectra of protons from copper and gold targets. While there was no resolution of proton group corresponding to discrete levels in the residual nucleus, the results suggested that the direct-interaction mechanism may become less important with increasing excitation energy in the residual nucleus, This is, of course, related to condition (b) above.

To avoid the ambiguities inherent in extending the direct-interaction theories to more than one level,[15] we have investigated several alpha-particle reactions which lead to discrete states of the residual nucleus and have attempted to analyze our data on the basis of the direct surface interaction theory of Butler.[6] Since the discrete states we studied were those cor-

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† Based in part on a thesis submitted by C. E. Hunting to the faculty of the Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
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[1] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).
[2] G. Igo and R. Thaler, Phys. Rev. **106**, 126 (1957).
[3] W. B. Cheston and A. E. Glassgold, Phys. Rev. **106**, 1215 (1957).
[4] R. Hofstadter, Revs. Modern Phys. **28**, 214 (1956).
[5] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).
[6] S. T. Butler, Phys. Rev. **106**, 276 (1957).
[7] H. J. Watters, Phys. Rev. **103**, 1764 (1956).
[8] C. A. Levinson and M. K. Banerjee, Ann. Phys. **3**, 67 (1958).
[9] R. Sherr, in *Proceedings of the University of Pittsburgh Conference on Nuclear Structure, June 6–8, 1957*, edited by S. Meshkov (University of Pittsburgh and Office of Ordnance Research, U. S. Army, 1957).
[10] G. E. Owen and L. Madansky, Atomic Energy Commission Report NYO-2001, July, 1957 (unpublished).
[11] G. F. Pieper and N. P. Heydenburg, Bull. Am. Phys. Soc. Ser. II, **2**, 182 (1957); Phys. Rev. **111**, 264 (1958).
[12] P. von Herrmann and G. P. Pieper, Phys. Rev. **105**, 1556 (1957).
[13] Von A. Papkow, Z. Naturforsch. **11A**, 776 (1956).
[14] Eisberg, Igo, and Wegner, Phys. Rev. **100**, 1309 (1955).
[15] T. Tamura and D. C. Choudhury, Phys. Rev. **113**, 552 (1959).

responding to no, or little, excitation energy of the residual nucleus we may, in fact, as indicated by Eisberg, Igo, and Wegner,[14] be centering our attention on just those small fractions of the interactions involving direct reactions.

II. EXPERIMENTAL METHODS

To produce and focus the alpha particles used in this investigation, the M.I.T. cyclotron and emergent-beam apparatus were used.[7,16] Doubly ionized helium ions were accelerated to approximately 30.4 Mev and and focused onto a spot $\frac{5}{16}$ in. high by about $\frac{1}{4}$ in. wide on the thin targets.

With this equipment the accuracy with which the beam direction relative to the scattering chamber could be measured reproducibly was limited to about ±0.5 deg. This was limited by the collimating system and slight fluctuations of the beam direction. The angular resolution of the detectors was equivalent to that of a cone of radius about 1.3 degrees, and the data to be reported have not had this resolution unfolded.

For detecting particles from the target, a NaI(Tl) scintillation counter was used (Fig. 1). The method of separating the high-energy protons from scattered alpha particles and other heavy charged particles was very simple, making use of the long range in matter of the high-energy proton groups. Because of this long range, it was possible to palce a lucite absorber between the target and scintillator such that all alpha particles were stopped in the absorber, other charged-particle groups were degraded in energy well below the high-energy proton groups, and the proton groups suffered little energy loss or energy straggling. This counter was used with conventional electronic equipment and a twenty-channel pulse-height analyzer similar to the Atomic Instrument Company's Model 520.

Another scintillation counter was used to monitor the beam on the target. Particles from the target penetrated a thin Mylar window on the scattering chamber above the plane of the movable counter and were detected by the CsI(Tl) crystal of the monitor counter. The pulses were amplified in the conventional manner and fed to an integral discriminator, which was set just below the high pulse-height group. Due to the small amount of absorber in front of the detector and the 23-deg scattering angle, the pulses in this detector corresponded largely to elastically scattered alpha particles.

The beam energy quoted above was measured using the range-energy relationship for protons in aluminum[17] and the fact that NaI(Tl) crystals respond linearly to proton energy loss in the crystal.[18] Using protons from elastic alpha particle-hydrogen scattering, measurements were made of the fraction of proton energy lost in a 359-mg cm^{-2} aluminum absorber. From kinetics and differential range measurements,[17] the alpha-particle beam energy was found to be 30.4±0.7 Mev. This value is in agreement with the result of an estimate using the cyclotron resonance condition and previous measurements of the cyclotron's deuteron beam energy.[19]

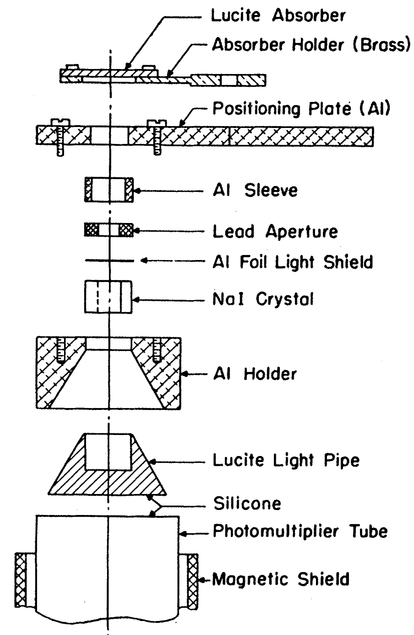

FIG. 1. Assembly diagram for the variable-angle counter. The end of the mu-magnetic shield extended beyond the end of the RCA-6199 photomultiplier tube.

All targets were $1\frac{1}{8}$-in. square films or foils. For the aluminum target, 1.9-mg cm^{-2} commercial foil was used. The B^{10} target employed the separated isotope,[20] which was repurified and evaporated in vacuum as boric acid onto one side of 0.25 Mylar sheet. Na^{23} and P^{31} targets were prepared in the bell jar above the scattering chamber described above—the Na^{23} target by sputtering of the metal onto one side of a thin layer of Formvar, and the P^{31} target by sublimation of commercial red phosphorous onto thin nickel foil. In each case the target thickness introduced an energy spread in the groups of interest which was small compared to the energy difference between the group and the energy groups in the observed spectra.

For identification of the levels involved in these reactions, the energy of the proton groups was compared to the energy of protons from (α,p) reactions on C^{12} [21]

[16] J. W. Haffner, Phys. Rev. **103**, 1398 (1956).

[17] Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-663, 1949 (unpublished).

[18] F. S. Eby and W. K. Jentschke, Phys. Rev. **96**, 911 (1954).

[19] N. S. Wall, Phys. Rev. **76**, 664 (1954).

[20] Obtained from the Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[21] For results on the ground-state transition of $C^{12}(\alpha,p)N^{15}$ see the following: R. Sherr and M. Rickey, Bull. Am. Phys. Soc. **2**, 29 (1957); M. Rickey, University of Washington, Cyclotron Progress Report, 1957 (unpublished); reference 5 above; C. E. Hunting and N. S. Wall, Bull. Am. Phys. Soc. **2**, 181 (1957).

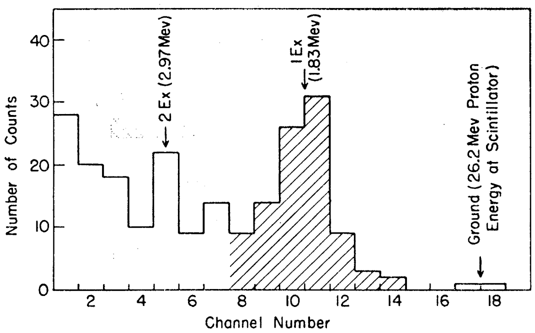

FIG. 2. Proton energy spectrum at 46.8 deg (lab system) from reactions induced in the sodium target by 30.5-Mev alpha particles, as displayed on the 20-channel analyzer. The shaded peak is due to the $Na^{23}(\alpha,p)Mg^{26}$ transition to the 1.83-Mev (first excited) level of Mg^{26}. Also indicated are the expected positious of peaks corresponding to the ground state ($Q=1.849$ Mev) and 2.97-Mev state of Mg^{26} in this reaction. The arrows indicate expected pulse heights relative to the observed position of the ground-state peak, which was about 0.8 channel above its expected position.

and Al^{27}. One of the more poorly resolved energy spectra is shown in Fig. 2.

Each angular distribution was measured on at least two separate days, with reproducibility consistent with counting statistics (the principal error). The counter zero-angle position was obtained by taking angular distributions involving carbon and aluminum targets on both sides of the beam direction.

In order to obtain an absolute differential cross section, comparison was made with the known differential cross section of elastically scattered alpha particles from Au.[22] The thickness of each target was estimated either by direct measurement or by use of another known differential cross section—that of proton elastic scattering at small angles.[23] (For the B^{10} case, unknown oxygen content of the target made measurement of the corresponding absolute differential cross section unfeasible.)

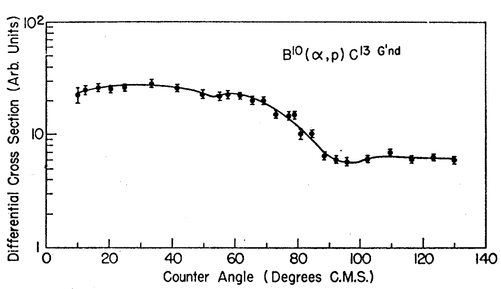

FIG. 3. Ground-state proton differential cross section from $B^{10}(\alpha,p)C^{13}$. In the angular range 130 to 150 deg an experimental upper limit to the differential cross section is 7 arbitrary units. In the angular range 20.8 to 41.4 deg electronic pile-up resulting from recoil hydrogen nuclei prevented accurate results. From the rough data obtained, however, it is estimated that the differential cross section in that range remains within 30% (probable error) of the value at 41.4 deg.

[22] L. W. Swenson (private communication); Swenson, Schindewolf, and Wall, Nuclear Phys. 6, 203 (1958).

[23] W. F. Waldorf, S. M. thesis, Massachusetts Institute of Technology, August, 1956 (unpublished); W. F. Waldorf and N. S. Wall, Phys. Rev. 107, 1602 (1957).

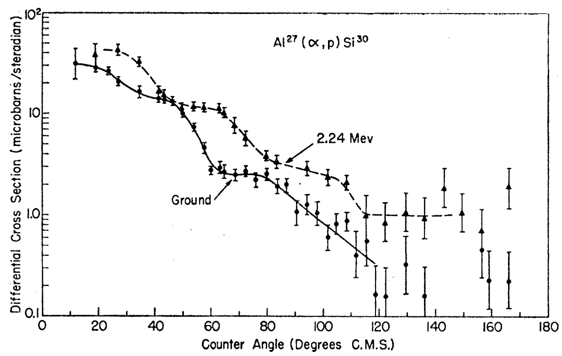

FIG. 4. Proton differential cross sections for $Al^{27}(\alpha,p)Si^{30}$ transitions corresponding to the ground and 2.24-Mev levels of Si^{30}. Results obtained with an angular resolution of ± 1 deg confirmed the "plateau" near 67 deg.

Obviously, the absolute differential cross section measurements reported here are not highly precise. Rather, they are intended as approximate measurements for comparison with each other and with theoretical interpretations. The estimated errors quoted for the normalizations indicate the inaccuracy of the compounded estimates involved.

III. RESULTS

The observed angular distributions for (α,p) transitions induced by 30.4-Mev alpha particles and corresponding to discrete states in the residual nuclei are shown in Figs. 3–7. The reproducibility of the several measurements on each target was always consistent with the indicated errors, which were due to counting statistics and uncertainty in separation of proton groups. The estimated errors in the absolute differential cross sections are as follows: aluminum target, $\pm 30\%$; phosphorus target, $(_{-70\%}^{+200\%})$; sodium target, $(_{-50\%}^{+100\%})$. Tabulated data for all the results are given by Hunting.[24]

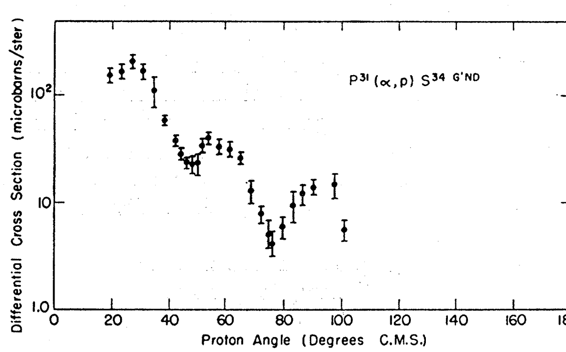

FIG. 5. Ground-state proton differential cross section for $P^{31}(\alpha,p)S^{34}$. An experimental upper limit to the differential cross section in the range 100.8 to 165.6 deg is 1.5 times the differential cross section at 97.2 deg.

[24] C. E. Hunting, Ph.D. thesis, Massachusetts Institute of Technology, January, 1958 (unpublished).

For the case involving the aluminum target, the monisotopic target and the Q values for α-induced reactions were such that it was possible to obtain (α,p) proton spectra for an extended range of excitation energies of the residual nucleus. The results at a laboratory angle of 40 deg are shown in Fig. 8.

IV. DISCUSSION

In the Introduction we indicated the fact that the criteria for compound nucleus formation were but marginally met. To indicate the fact that our attention may be centered on a very small fraction of the total α-particle-induced reactions we point out that the integral of the observed differential cross section for the ground-state reaction on Al^{27} is only the order of 10^{-4} of the total reaction cross section, πR^2, expected on the assumption that Al^{27} is "black" to 30-Mev alpha particles. The relatively small number of transitions leading to the ground state is also indicated by Fig. 8.

The strong forward peaking observed in all of our experimental results on the low-lying levels of the residual nuclei does, however, strongly suggest a direct interaction mechanism.[5] We therefore have analyzed our data on the basis of the direct interaction theory

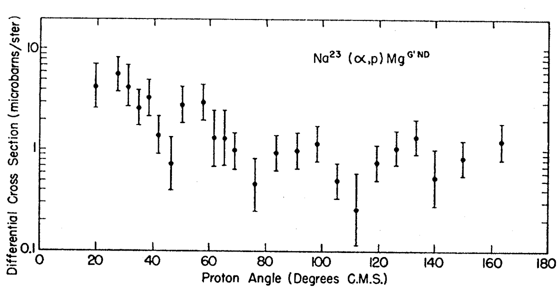

FIG. 6. Ground-state proton differential cross section for $Na^{23}(\alpha,p)Mg^{26}$. Since this differential cross section and that corresponding to the 1.83-Mev level of Mg^{26} (Fig. 7) were determined during the same runs, their relative magnitude is independent of any calibration (cf. Fig. 2). No explanation is offered for the order-of-magnitude difference.

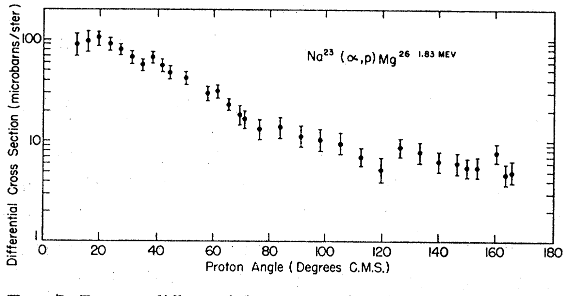

FIG. 7. Proton differential cross section for the $Na^{23}(\alpha,p)Mg^{26}$ transition corresponding to the 1.83-Mev level of Mg^{26}. In the angular range 105.3 to 165.8 deg an experimental upper limit to the differential cross section is the 98.2 deg differential cross section.

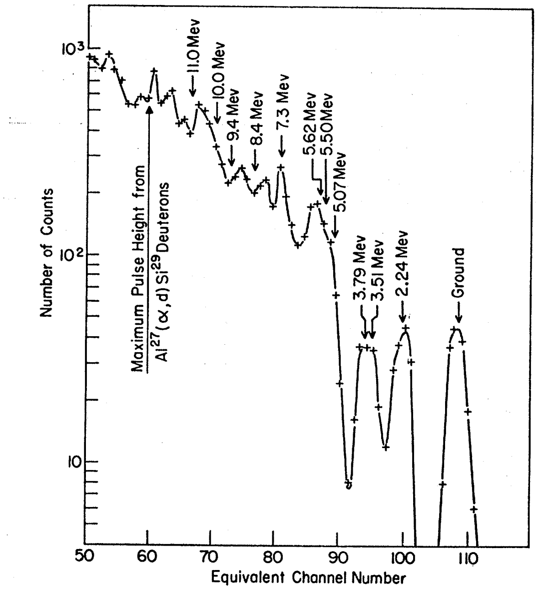

FIG. 8. Pulse-height spectrum at a laboratory angle of 40 deg from reactions induced in the aluminum target by 30.5-Mev alpha particles, as compiled from several monitored 20-channel analyzer spectra. The absorber used was 7-mil gold, which reduced the energy of protons corresponding to the ground-state transition of $Al^{27}(\alpha,p)Si^{30}$ ($Q=2.389$ Mev) from 31.0 Mev to about 28.1 Mev. The expected positions of peaks corresponding to excited states of Si^{30} in the above reaction are indicated, as well as the expected maximum pulse height from the $Al^{27}(\alpha,d)Si^{29}$ reaction. New information on the level structure of the Si^{30} nucleus may not be deduced from this diagram because of inaccuracy in the energy scale to the left of the peak for the 3.79-Mev level.

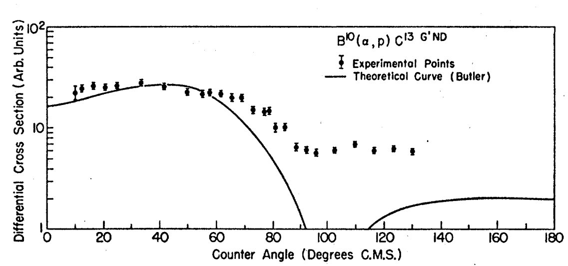

FIG. 9. Theoretical fit to the ground-state differential cross section of $B^{10}(\alpha,p)C^{13}$ using Eq. (57) of reference 5 with $l=3$ (uniquely) and $R=3.3\times10^{-13}$ cm. The location of the maxima and minima, as listed in Table I, actually suggest a slightly larger radius.

of Butler.[5,6] In particular, the simplified calculation of reference 6, as embodied in Eq. (57) of that paper,[25] is compared with our results in Figs. 9 and 10 and those

[25] In order to evaluate the various momentum transfers occurring in Eq. (57) of reference 6, we have assumed that the process proceeds through the "direct ejection" mechanism which neglects any interaction except that with the proton struck by the alpha particle. If, instead, one were to assume that the observed proton comes from the incident alpha-particle, the predicted curves would be slightly different. This point is discussed at some length by N. Austern, in *Fast Neutron Physics*, edited by J. L. Fowler (to be published), and is indicative of the ambiguity of using only angular distribution measurements to define a reaction mechanism.[11]

TABLE I. Comparison of the positions of maxima and minima of experimental proton differential cross sections from (α,p) reactions with the predictions of Eq. (57) of Austern *et al.*[a] The observed transition corresponds to the ground state of the residual nucleus in each case.

Target nucleus	Maximum or minimum	Proton angle (degrees c.m. system) Experiment	Theory
P^{31}	Max	27°	27°
	Min	48°	46°
	Max	~55°	60°
	Min	~76°	77°
	Max	~94°	91°
Al^{27}	Min	···	19°
	Max	~41°	39°
	Min	···	60°
	Max	~72°	74°
B^{10}	Max	~30°	~ 40°
	Min	~95°	~105°

[a] See reference 5.

of Hunting and Wall.[26] Tables I and II characterize the agreement between theory and experiment, as measured by the criteria of the location of maxima and minima and of reasonable deduced nuclear sizes.

The above three detailed comparisons with the predictions of a simplified calculation based on the surface direct interaction theory can be characterized by saying that in general the calculation gives reasonable agreement, but that there are some points of marked disagreement. Specifically these are (a) the marked filling in of the regions between the secondary maxima and (b) a much higher degree of forward peaking particularly in the Al^{27} case. (By forward peaking is meant the ratio of the average differential cross section forward of 90 deg c.m. system to that back of 90 deg, in the observed angular range.)

The first of these disagreements may be due to the finite absorption mean free path mentioned above,[2,3] the nonsphericity of the target nuclei, or distortion of the plane waves involved in Butler's calculation.[6] The absorption mean free path and nonsphericity arguments may be of particular importance in the cases under consideration because of the large momentum transfers involved, the momentum transfer-radius product being the critical parameter.[5,27] Regarding the nonsphericity argument it is interesting to note that the case involving the P^{31} target gave the best agreement with prediction, while the P^{31} nucleus is expected to be more spherical than some of the other target nuclei employed in this investigation.[24]

Recently Butler, Austern, and Pearson[28] have shown in a somewhat simplified calculation, employing a semiclassical treatment of the direct interaction, that absorption of either the incident or emergent particle will in general produce just the effects we have observed. In particular, they show that for strong absorption of the incident alpha particle the maxima of the angular distributions have essentially the same location as the simple quantum mechanical theory predicts and that the minima are filled in. However, it should be noted that their calculations show a decrease of the forward

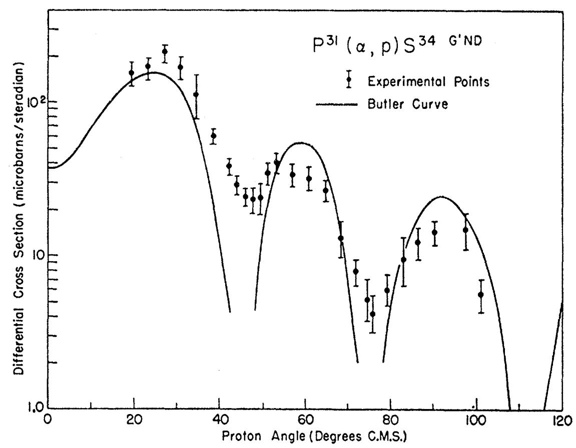

FIG. 10. Theoretical fit to the ground-state differential cross sections of $P^{31}(\alpha,p)S^{34}$ using Eq. (57) of reference 5 with $l=0$ (uniquely) and $R=5.5\times10^{-13}$ cm.

peaking with decreasing mean free path, whereas our experiments show that in the cases where the observed angular distributions are most washed out the forward peaking in a maximum. On the other hand, this may be too detailed a conclusion to draw from an approximate calculation such as theirs. A detailed calculation similiar to that of Levinson and Banerjee[8] may be necessary to clarify this point.

Relative to the forward peaking in the Al^{27} case, it should be noted that in Butler's calculation of direct interaction differential sections[6] the forward peaking reflects characteristic nucleon momenta in the nuclei involved. Although this interpretation may be overemphasized in reference 26, it is nonetheless interesting that the particular form factor used there yields

TABLE II. Comparison of interaction radii for the system target nucleus-alpha particle. Column (2) lists the target for the (α,p) ground-state transition fitted in the figure or reference named in column (1). The theoretical curves use Eq. (57) of Austern *et al.*[a] with the R value listed in column (3) (in units of 10^{-13} cm). Column (4) states the value of R expected from the alpha-particle elastic scattering analysis given by Waldorf and Wall[b]: $1.35A^{\frac{1}{3}}+1.3$ (in units of 10^{-13} cm).

(1) Figure	(2) Target	(3) R from fit	(4) R expected
9	B^{10}	3.3	4.2
[c]	Al^{27}	5.0	5.3
10	P^{31}	5.5	5.5

[a] See reference 5.
[b] See reference 23.
[c] See reference 26.

[26] C. E. Hunting and N. S. Wall, Phys. Rev. 108, 901 (1957).

[27] For the Al^{27} case at least, a change in the radius parameter of only 1×10^{-13} cm is sufficient to interchange the expected angular positions of maxima and minima of the differential cross section.

[28] Butler, Austern, and Pearson, Phys. Rev. 112, 1227 (1958).

reasonable values for the characteristic momenta[29] in the Al^{27} reaction. Our other data have not been analyzed in this manner.

ACKNOWLEDGMENTS

For valuable discussions regarding the results obtained in this work, the authors are indebted to Professor R. Sherr and Professor S. T. Butler. It is a pleasure to acknowledge the assistance of C. W. Darden, III, regarding the 20-channel anlayzer used. For the loan of the B^{10} target used in this work, thanks are due to K. S. Lee. The varied assistance and encouragement of P. R. Klein, L. W. Swenson, and A. Tubis are gratefully appreciated. For able and efficient maintenance of the cyclotron and the external beam equipment sincere thanks are extended to E. F. White, F. J. Fay, and the late A. Numella.

[29] A. Wattenberg *et al.*, Phys. Rev. **104**, 1710 (1956).

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Scattering of 2- to 4-Mev Polarized Neutrons by Carbon*

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The right-left asymmetry in elastic scattering of partially polarized neutrons by carbon has been observed for 45° (c.m.) scattering angle and for neutrons in the 2- to 4-Mev energy range. The $C^{12}(n,n)$ polarization, inferred from the measured asymmetries, has a direction and energy dependence in agreement with phase-shift analyses obtained previously by others. The magnitude of the polarization is slightly larger than predicted.

THE differential cross section for elastic scattering of medium-energy neutrons by C^{12} has been measured by several groups of workers.[1,2] These results together with total cross-section measurements have resulted in the assignment of definite parameters for the three C^{13} levels responsible for the first three resonances. Specifically, these occur at neutron bombarding energies of 2.076, 2.95, and 3.67 Mev, the corresponding C^{13} level parameters being $D_{\frac{5}{2}}$ with a 7-kev width, $D_{\frac{3}{2}}$ with a 90-kev width, and $D_{\frac{3}{2}}$ with a 1.69-Mev width.

For incident neutrons in the 2- to 4-Mev region, interference between the scattered S-wave amplitude and the D-wave amplitude, deriving from these levels, give rise to appreciable polarization of the scattered neutrons. The details of the $C^{12}+n$ elastic interaction are embodied in the phase-shift analysis of the differential cross-section measurements. The predicted neutron polarizations differ somewhat for sets of phase shifts extracted by different groups of workers. The polarization has been observed[2,3] but no systematic measurement of its dependence upon incident neutron energy has been reported.

The present work involves such a measurement for 2- to 4-Mev neutrons scattered at 45° (c.m.), where the polarization is greatest. The polarization, $P_c(E)$, was deduced from measurement of the right-left asymmetry in the scattering of neutrons of known polarization P_n and energy E, using the relation

$$P_c(E)P_n=(R-L)/(R+L),$$

where R and L represent neutron intensities scattered at 45° (c.m.) to the right and left, and

$$\mathbf{P}_n=P_n\frac{\mathbf{k}_d\times\mathbf{k}_n}{|\mathbf{k}_d\times\mathbf{k}_n|},$$

$$\mathbf{P}_c=P_c\frac{\mathbf{k}_n\times\mathbf{k}_n'}{|\mathbf{k}_n\times\mathbf{k}_n'|}.$$

The neutron source was the $D(d,n)He^3$ reaction for which the most dependable measurements of the emitted neutron polarization are those employing $He^4(n,n)$ for polarization analysis.[4] In the above expressions k_d, k_n, and k_n' are the momenta of the incident deuteron, emitted neutron, and scattered neutron. We have relied on these measurements of P_n as summarized by Pasma[4] in interpretation of the results reported herein.

EXPERIMENTAL METHOD

Polarized neutrons from the bombardment of thin heavy-ice targets by monoenergetic deuterons were selected by a collimator similar to that described previously.[3] Target thickness was determined by two

* Supported by the U. S. Atomic Energy Commission and the Office of Ordnance Research, U. S. Army.
† United States Rubber Company Fellow.
[1] Wills, Bair, Cohn, and Willard, Phys. Rev. **109**, 891 (1958). References to previous work are given here.
[2] Meier, Schemer, and Trumpy, Helv. Phys. Acta. **27**, 577 (1954).
[3] McCormac, Steuer, Bond, and Hereford, Phys. Rev. **104**, 718 (1956); Phys. Rev. **108**, 116 (1957).
[4] Levintov, Miller, and Shamshev, Nuclear Phys. **3**, 221 (1957); Levintov, Miller, Tarumov, and Shamshev, Nuclear Phys. **3**, 237 (1957); P. J. Pasma, Nuclear Phys. **6**, 141 (1958).