Scattering of Neutrons by α Particles*

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Angular distributions of neutrons scattered by α particles were measured at neutron energies between 2 and 23 Mev by observing recoiling α particles in a high-pressure gas scintillator. At the highest bombarding energy the disintegration of α particles by neutrons was also observed. Total cross sections of helium were measured at four neutron energies between 7 and 12 Mev in a simple transmission experiment. The total cross sections agree with values calculated from the analysis of p-α scattering by Dodder and Gammel. The angular distributions agree with these calculations quite well up to a neutron energy of 15 Mev, but not as well at higher energies.

DURING the last few years many measurements of the polarization of neutrons have used helium as a polarization analyzer.[1] This has resulted in a renewed interest in the knowledge of the phase shifts for the scattering of neutrons by α particles, since the analyzing power of helium is calculated from these phase shifts. The present work was carried out in order to obtain data with which proposed n-α phase shifts could be compared.

Since there is some controversy in the literature regarding the reliability of available phase shifts, the current situation will be reviewed briefly. A complete review of the subject of nucleon—α-particle scattering may be found in articles by Hodgson[2] and Burke.[3]

PHASE SHIFTS FOR n-α SCATTERING

The most widely used set of phase shifts for the scattering of neutrons of a few Mev energy by α particles was calculated by Dodder and Gammel[4] and was published by Seagrave.[5] These phase shifts (DGS) were obtained principally from an analysis of experiments on the scattering of 5.8- and 9.5-Mev protons by α particles,[6,7] using single-level dispersion theory. The data could be fitted with s, p, and d waves, but there remained considerable uncertainty regarding the d-wave phase shifts both because of uncertainties in the experimental data and because of the neglect of higher angular momenta.

Phase shifts of the n-α scattering are deduced from the p-α phase shifts by assuming charge symmetry of nuclear forces. The difference in Coulomb energy between He^5 and Li^5 is taken into account, but it is assumed that the reduced widths of states formed by p waves in He^5 and Li^5 are the same. The s-wave phase shifts are calculated by using the same logarithmic derivative of the wave function at the nuclear surface for n-α scattering and for p-α scattering. This is equivalent to assuming that the s-wave wave functions in the interior of the compound nucleus are the same in the two cases.

In view of the higher precision with which the angular distribution of protons scattered by α particles can be measured compared to that for neutron scattering it is to be expected that the phase shifts obtained from p-α scattering are more reliable than those obtained from n-α scattering directly. These phase shifts were extrapolated to a neutron energy of 20 Mev.

More recently Gammel and Thaler[8] have extended the phase-shift analysis for p-α scattering to 40 Mev on the basis of additional data on scattering and polarization (GT phase shifts). This analysis includes f waves which are important above 10 Mev. Gammel and Thaler used an optical-model fit to these phase shifts to extrapolate to other energies. Perkins[9] employed the results of this analysis to deduce phase shifts for n-α scattering (GTP phase shifts). He assumed that the logarithmic derivatives of the wave functions at a radius of 2.9 f for the p-α system describe the n-α system at a center-of-mass energy reduced by 0.8 Mev.

It is well known that there are certain ambiguities in the extraction of phase shifts from experimental data on the scattering of spin-$\frac{1}{2}$ by spin-0 particles. These ambiguities have been studied particularly for the pion-nucleon system.[10]

COMPARISON OF PREVIOUS EXPERIMENTS WITH CALCULATED PHASE SHIFTS

Dodder and Gammel found that the total neutron cross sections calculated from their phase shifts were in good agreement with measurements of Bashkin, Mooring, and Petree.[11] The published experimental data taken with $Li(p,n)$ neutrons had to be corrected for the presence of neutrons leaving Be^7 in the first excited

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[1] Proceedings of the International Symposium on Polarization Phenomena of Nucleons, Helv. Phys. Acta, Suppl. VI (1961).
[2] P. E. Hodgson, Phil. Mag. Suppl. 7, 1 (1958).
[3] P. G. Burke, *Nuclear Forces and the Few-Nucleon Problem* (Pergamon Press, New York, 1960), Vol. II, p. 413.
[4] D. C. Dodder and J. L. Gammel, Phys. Rev. **88**, 520 (1952).
[5] J. D. Seagrave, Phys. Rev. **92**, 1222 (1953).
[6] W. E. Kreger, W. Jentschke, and P. G. Kruger, Phys. Rev. **93**, 837 (1954).
[7] T. M. Putnam, Phys. Rev. **87**, 932 (1952).
[8] J. L. Gammel and R. M. Thaler, Phys. Rev. **109**, 2041 (1958).
[9] R. B. Perkins (private communication).
[10] See, e.g., J. H. Foote, O. Chamberlain, E. H. Rogers, and H. M. Steiner, Phys. Rev. **122**, 959 (1961).
[11] S. Bashkin, F. P. Mooring, and B. Petree, Phys. Rev. **82**, 378 (1951).

state. Later measurements of the (n,α) total cross section between 0.9 and 7.1 Mev carried out at Los Alamos[12] and measurements by Vaughn *et al.*[13] between 0.12 and 6.2 Mev are also in very good agreement with the results of these phase-shift calculations. Measurements done at Los Alamos between 12.3 and 20 Mev agree with the DGS calculations at the lower energies, but a comparison at the higher energies is difficult because of the uncertainty in the d-wave phase shifts at these energies.

The angular distributions for n-α scattering measured by Adair[14] were also in reasonably good agreement with the calculations using the DGS phase shifts. Later measurements by Seagrave[5] at neutron energies of 2.6, 4.5, 5.5, 6.5, and 14.3 Mev likewise agree with the calculations except for the 2.6-Mev point. In order to fit his 2.6-Mev data Seagrave requires a smaller $p_{\frac{1}{2}}$ phase shift than that calculated from the p-α scattering or that required to fit Adair's data. Subsequent measurements by Striebel and Huber[15] at neutron energies between 2.6 and 4.1 Mev agree with Adair's data, but not with Seagrave's results. On the other hand, Demanins *et al.*[16] find at 2.4 and 2.9 Mev $p_{\frac{1}{2}}$ phase shifts which are even smaller than those found by Seagrave.

Levintov, Miller, and Shamshev[17] attempted to get more information about the $p_{\frac{1}{2}}$ phase shift at 2.6 Mev by studying the polarization of neutrons scattered by He^4. They came to the conclusion that their data supported Seagrave's value for the $p_{\frac{1}{2}}$ phase shift. It was pointed out, however, by Pisent and Villi[18] that the measurements of Levintov *et al.* could not be sensitive enough to the value of the $p_{\frac{1}{2}}$ phase shift to enable them to arrive at their conclusion. Haeberli[19] recognized that the conclusion drawn from the polarization measurement was apparently based in part on an error in sign in one of the angular-distribution plots of the polarization.

Bonner *et al.*[20] report an anomaly in the n-α scattering at 22.15 Mev, which they associate with the $d_{\frac{3}{2}}$ state in He^5 which is known from the study of the reaction $D+T\rightarrow He^4+n$. This state may have an appreciable effect on the $d_{\frac{3}{2}}$ phase shift at the higher energies.

One may conclude that most of the measurements below 10 Mev can be fitted with the DGS phase shifts. Up to this energy d-wave phase shifts are so small that their effect cannot be clearly seen in either the total cross section or in the angular distributions. Above this energy d-wave effects will become increasingly important, but more data are needed to study these effects. The d-wave effects are likely to be particularly important in calculations of the polarization in n-α scattering.

The present experiments were undertaken to fill in some gaps in the existing data on total cross sections and angular distributions, and to extend angular distribution measurements to higher energies where the d-wave effects are likely to be more important.

TOTAL CROSS-SECTION MEASUREMENT

The previous total cross-section measurements of helium have a gap between 7 and 12 Mev. It appeared desirable to ascertain whether the total cross section in this energy range agreed with the calculations.

The experimental arrangement was essentially the same as that used in earlier measurements at this laboratory.[21] Neutrons with an energy spread of about 80 kev were produced by bombarding a deuterium gas target with deuterons. The neutrons were detected in a stilbene scintillator with pulse shape discrimination against γ rays.

The detector was placed 80 cm from the source. A high-pressure helium-filled gas cell 2.5 cm in diameter and 30 cm long was placed halfway between the source and detector. The cell had previously been used for the experiments at Lockheed and is described elsewhere.[13] An identical evacuated cell was substituted for the helium-filled cell to determine the transmission of the helium gas which was about 80%. The number of helium nuclei in the cell was determined by weighing.

Statistical uncertainties in the cross-section measurement were about 2.5%. A 2% correction for background and a 0.5% correction for inscattering were applied. The measured cross sections are listed in Table I and are shown in Fig. 1 with the + symbols.[22] In Fig. 1 there are also shown at the lower energies the results obtained by the Lockheed group[13] and at higher energies those of the Los Alamos group.[12] The solid line in Fig. 1 represents the total cross section of helium calculated from the DGS phase shifts. In Table I these calculated cross sections are also listed. It can be seen that the experimental results agree well with the calculated

TABLE I. Total cross section of helium.

Neutron energy (Mev)	Measured cross section (barns)	Cross section from DGS phase shifts (barns)
6.99	1.90 ± 0.05	1.83
8.03	1.66 ± 0.05	1.67
10.07	1.37 ± 0.04	1.41
12.01	1.26 ± 0.03	1.21

[12] Los Alamos Physics and Cryogenic Groups, Nuclear Phys. **12**, 291 (1959).
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[14] R. K. Adair, Phys. Rev. **86**, 155 (1952).
[15] H. R. Striebel and P. Huber, Helv. Phys. Acta **30**, 67 (1957).
[16] F. Demanins, G. Pisent, G. Poiani, and C. Villi, Phys. Rev. **125**, 318 (1962).
[17] I. I. Levintov, A. V. Miller, and V. N. Shamshev, Nuclear Phys. **3**, 221 (1957).
[18] G. Pisent and C. Villi, Nuovo cimento **11**, 300 (1959).
[19] W. Haeberli (private communication).
[20] T. W. Bonner, F. W. Prosser, Jr., and J. Slattery, Phys. Rev. **115**, 398 (1959).
[21] D. B. Fossan, R. L. Walter, W. E. Wilson, and H. H Barschall, Phys. Rev. **123**, 209 (1961).
[22] D. B. Fossan, Bull. Am. Phys. Soc. II **5**, 409 (1960).

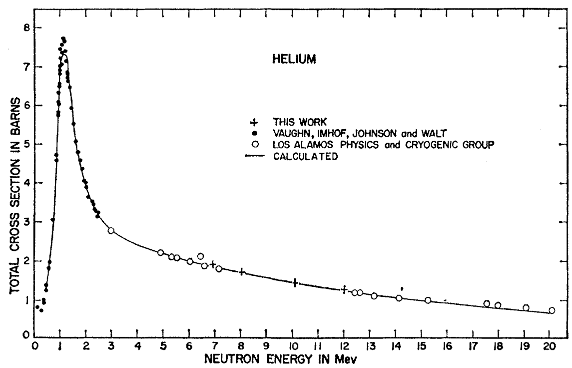

FIG. 1. The total cross section of helium as a function of neutron energy. The present measurements (+) are compared with previous measurements at other energies (references 12 and 13) and with calculations using the DGS phase shifts (references 4 and 5).

curve up to 15 Mev. Above this energy a comparison is difficult because of the uncertainties in the *d*-wave phase shifts.

ANGULAR DISTRIBUTION MEASUREMENTS

Method

The angular distribution of the scattered neutrons was determined from the energy distribution of the recoiling α particles. This energy distribution is proportional to the angular distribution of the scattered neutrons in the zero-momentum system if the angular distribution is expressed in terms of the cosine of the scattering angle.[23] This proportionality holds also relativistically.[24]

Detector

Most previous measurements based on this principle have used ionization chambers or proportional counters. Since the range of the recoiling particles must be small compared to the dimensions of the counter, it is necessary to use high pressure in the counter at the higher neutron energies. Use of high pressures makes it difficult to obtain complete collection of the ions.

In the present experiments a gas scintillator[25] was used which can be operated readily at high pressure. The gas was contained in a thin-walled (1–3 mm) stainless steel cell, 4.5 cm in diameter and 2.9 cm long, closed off at one end by a hemisphere of 2.3-cm radius. The filling consisted of a mixture of helium and xenon. The xenon served both to increase the stopping power of the gas and to increase the light output of the scintillator. The percentage of xenon and the total gas pressure at each energy were chosen to yield the highest stopping power consistent with small energy loss in the gas for electrons and with small multiple scattering effects. In all cases the maximum range of the recoiling α particles was less than 4 mm.

When the recoil energy is measured by collecting ions, it is necessary to ascertain that the efficiency of collecting ions does not depend on the direction of the recoil track as might be the case if columnar recombination occurs. Since there is a correlation between the scattering angle of the neutrons and the direction of the applied electric field, a distortion of the angular distribution might otherwise result. For a gas scintillator this difficulty does not arise. On the other hand, it is well established that the ionization produced by an α particle is directly proportional to the energy of the particle, while the light output of many scintillators is not directly proportional to the particle energy. To study this effect the gas scintillator was irradiated with monoenergetic neutrons of several energies and the maximum pulse height produced by the recoiling α particles was measured. Within the accuracy of the measurements of about 2% this pulse height was a linear function of α-particle energy between 0.4 and 6 Mev. Over the entire α-particle energy range from 0.4 to 14 Mev the counter response was linear to about 3%.

In an ionization detector it is usually possible to arrange the electric field in such a way that tracks of equal energy occurring in different parts of the sensitive volume produce pulses of the same height. This is more difficult to do in a high-pressure gas scintillator because of absorption of light on the reflecting surfaces surrounding the gas volume. The attempts to accomplish as uniform efficiency as possible throughout the volume have been described elsewhere.[25] Nevertheless, the difficulties in accomplishing this are primarily responsible for the pulse-height spread from monoenergetic α particles as it manifests itself in the width of the high-energy cutoff of the pulse-height distribution.

In an ionization detector the pulse-height spread for monoenergetic particles is ordinarily caused by noise in the electronic equipment. It is, therefore, usually the same absolute spread for all energies. For the gas scintillator, on the other hand, the pulse-height spread is a constant fraction of the pulse height for all energies. The spread in pulse height for an α-particle recoil distribution decreases, therefore, for the smaller recoil energies, except when the recoil energy is below about 0.5 Mev where one would expect noise and statistical effects to become appreciable.

Experimental Procedure

In Table II the neutron energies at which measurements were carried out are listed together with the neutron-energy spreads. Causes of this energy spread are straggling of the incident charged particles in the foil separating the gas target from the vacuum system of the accelerator, energy loss of the bombarding particles in the gas target, and the dependence of neutron energy on angle of emission of the neutrons.

[23] H. H. Barschall and M. H. Kanner, Phys. Rev. **58**, 590 (1940).
[24] H. H. Barschall and J. L. Powell, Phys. Rev. **96**, 713 (1954).
[25] R. E. Shamu, Nuclear Instr. and Methods (to be published).

TABLE II. Angular distribution measurements.

Neutron energy (Mev)	Neutron energy spread (Mev)	Neutron source reaction	Helium pressure (atm)	Xenon pressure (atm)	Maximum recoil range (mm)	Total cross section (barns)
2.02	0.06	p+T	6.9	1.1	1.5	4.00
3.02	0.06	p+T	11.1	1.8	1.6	2.76
4.05	0.07	p+T	22.5	4.0	1.2	2.39
5.97	0.09	d+D	46.0	6.1	1.2	2.00
7.96	0.13	d+D	31.6	11.2	1.4	1.68
10.0	0.14	d+D	40.5	14.3	1.6	1.40
12.0	0.15	d+D	40.5	14.3	2.1	1.22
14.7	0.6	d+T	32.8	22.6	2.0	0.99
17.8	0.25	d+T	32.8	22.6	2.7	0.85
20.9	0.13	d+T	32.8	22.6	3.5	0.74
22.3	0.12	d+T	35.3	23.2	3.7	

Neutrons were produced in the reactions shown in the third column. In addition to the monoenergetic neutrons from deuteron-induced reactions, a continuum of neutrons from the breakup of deuterons occurs at high enough bombarding energies. Since it is difficult to take into account the effect of these neutrons, any part of the pulse-height distribution which could be affected by the breakup neutrons will be omitted from the results to be presented. These breakup neutrons restricted the angular range over which the distributions at 10 and 12 Mev could be measured.

The counter was placed in the forward direction for all the measurements except that at 14.7 Mev, where it was at 90° with respect to the bombarding charged particles. The axis of the cylindrical counting volume pointed at the target, the photomultiplier being on the far side of the counter. The distance from the center of the target to the center of the counter was about 19 cm for the measurements up to an energy of 12 Mev; it was 23 cm at 14.7, 20.9, and 22.3 Mev, and 9 cm at 17.8 Mev. Columns 4 and 5 of Table II give the pressures of helium and xenon, respectively, that were used for the gas scintillator filling. In the sixth column the maximum range of recoiling α particles under these conditions is listed. This range is to be compared with the average length of the gas volume of 4.5 cm.

Gas scintillations were viewed by an RCA 6342A photomultiplier. The pulses were amplified, clipped with a delay line, and recorded with a 100-channel analyzer. The linearity of the electronic circuits was checked before and after every angular distribution measurement. Deviations from linearity were always less than 1%. Although the pulses were distributed over most of the 100 channels, the energy resolution of the system does not make such fine subdivisions meaningful. In the results to be presented the counts in three adjacent channels were ordinarily added so that the analyzer was effectively used as a 33-channel analyzer.

No attempt was made in the present experiment to measure the neutron flux, i.e., only relative angular distributions were measured.

Several corrections have to be applied to these pulse-height distributions. Some neutrons are produced in the foil and in the backing, at the two ends of the gas target. Their effect and backgrounds caused by stray beams were subtracted by taking a run with the gas target evacuated. These backgrounds amounted to less than 2%, except at high deuteron bombarding energies and small pulse heights. The largest effect occurred for 12-Mev neutrons, where a 12% background was observed for the smallest recoil energies.

Another background is due to the source neutrons, which may produce disintegrations or recoils in the walls of the counter or in the xenon. This background was measured by filling the counter only with xenon. Since the light output for the same particle energy is different in pure xenon from that for the xenon-helium mixture, pulses from Po α particles were used to adjust the gain of the amplifier so that the pulses from the Po α particles had the same size for both fillings. There was, however, some evidence that pulses caused by electrons were larger relative to α particles in pure xenon than in the xenon–helium mixture, so that this procedure may not be correct for subtracting the background which is probably caused mostly by protons. The background measured in this way was of the order of 2% up to neutron energies of 8 Mev. At higher neutron energies and small recoil energies it increased rapidly, reaching 40% for the smallest recoils from 22.3-Mev neutrons.

Some of the neutrons (about 5%) are scattered out of the incident beam as they pass through the end wall of the gas cell. This effect is only partly compensated by elastic scattering into the cell. Some of the neutrons that are scattered into the cell are degraded and produce recoils of lower energies. To take this effect into account a positive correction had to be applied at the high recoil energies and a negative correction at the low energies. The magnitude of this correction was estimated by slipping over the gas cell a slightly enlarged copy of the steel cell. The correction was largest at 2 Mev where it reached 6% for recoil energies corresponding to 1-Mev neutrons, i.e., for neutrons degraded to an energy near the peak in the n-α total cross section. In most cases the correction was of the order of 3%. It was applied, however, only up to a neutron energy of 8 Mev. Above this neutron energy the effect of the additional steel was so small that it was very difficult to obtain statistically significant results. Even at the lower neutron energies the difference between the number of counts with and without the additional steel showed large statistical fluctuations between adjacent channels. A smoothed number was therefore used to correct the data.

Some of the recoiling α particles hit the window which separates the gas scintillator from the photomultiplier and other recoils hit the cylindrical wall of the cell. For each recoil energy the number of recoils hitting the window or the wall was calculated from the geometry and added to the measured number at that energy. These recoils will produce smaller pulses than they would without wall effect, and the resulting events have to be subtracted from the number of pulses observed

at the lower energies. This subtraction was performed under the assumption that all residual ranges of the recoils hitting the walls were equally probable. The correction for both lost and gained pulses was always highest for the most energetic recoils and amounted in the most unfavorable case (22.3 Mev) to 10%. At each neutron energy the correction at first decreased rapidly with decreasing recoil energy and for the lowest recorded recoil energies it changed sign.

The effect of finite energy resolution of the counting system on the shape of the pulse-height distribution was studied in the following way. A theoretical pulse-height distribution which was calculated from the DGS phase shifts at 10 Mev was modified by smearing out each point with a skew triangular resolution function. This resolution function was an approximation to that observed with the same counter for disintegrations of neon by neutrons.[26] The smeared distribution was then treated as an experimental distribution and the point corresponding to the maximum recoil energy was chosen as described below. This end point differed from that for the theoretical distribution by one channel (one-third the distance between the points plotted in Figs. 2–6). The distributions were then adjusted so that the two end points coincided, corresponding to the way in which the actual experimental data were treated.

The resulting smeared distribution differed from the theoretical distribution by less than 1% up to a c.m. scattering angle $\theta=145°$ ($\cos\theta=-0.8$). A smooth extrapolation of the smeared distribution beyond the point at which it begins to drop off near the maximum pulse height was nearly coincident with the theoretical curve. In addition, the high-energy tail resulting from smearing the theoretical spectrum was very similar to that observed in the angular distribution measurement at 10 Mev.

Since the 10-Mev distribution is more sharply peaked in the backward direction than other measured angular distributions and hence would be expected to show resolution effects most prominently, it was assumed that the finite resolving power of the detector did not distort the pulse-height distribution appreciably for $\theta<145°$ and no correction for finite energy resolution was applied to the data.

The following procedure was followed to decide which channel corresponds to the maximum pulse height which would have been observed, if the counter did not introduce an energy spread. The pulse-height distribution was extrapolated smoothly beyond the point where it began to drop off near the maximum pulse height. A vertical line was drawn at such a pulse height that the number of pulses larger than this pulse height was equal to that below this height between the extrapolated and the observed distribution. The channel corresponding to this line was taken as corresponding to a neutron scattering angle of 180°.

Although only relative angular distributions were measured in the present experiment, it appeared desirable to present the data with an approximate cross-section scale. If the measured relative distributions had extended over all scattering angles, the integral under the distribution would have been equal to the known total cross section, and the differential cross section could readily have been normalized to the total cross section. The actual measurements cover, however, only a limited range of angles and the extrapolation to small scattering angles is quite uncertain. Nevertheless, such

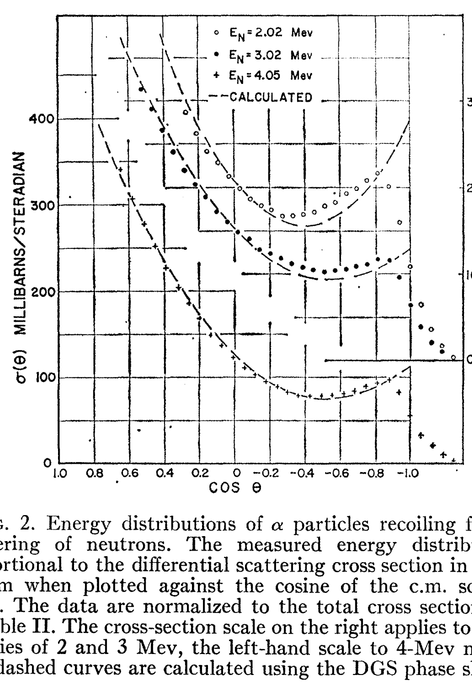

FIG. 2. Energy distributions of α particles recoiling from the scattering of neutrons. The measured energy distribution is proportional to the differential scattering cross section in the c.m. system when plotted against the cosine of the c.m. scattering angle. The data are normalized to the total cross sections listed in Table II. The cross-section scale on the right applies to neutron energies of 2 and 3 Mev, the left-hand scale to 4-Mev neutrons. The dashed curves are calculated using the DGS phase shifts.

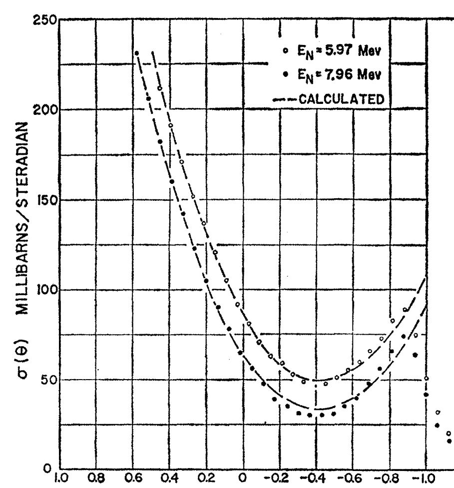

FIG. 3. Differential cross sections in the c.m. system for the scattering of 6- and 8-Mev neutrons by α particles. The dashed curves are calculated using the DGS phase shifts.

[26] R. E. Shamu, Nuclear Phys. (to be published).

an extrapolation was made by fitting parabolas to the measured distributions and extrapolating these parabolas to small scattering angles. This procedure was followed because, except at the highest neutron energies investigated in the present study, primarily s- and p-wave phase shifts are important in the n-α interactions. If only s- and p-waves are responsible for the interaction, the pulse-height distribution is exactly parabolic.[27] It should be emphasized that this method of determining the cross-section scale is subject to considerable uncertainty. The total cross sections to which the angular distributions were normalized are shown in the last column of Table II. At 20.9 Mev the observed distribution differed substantially from a parabolic shape so that the normalization is particularly uncertain. No normalization was attempted at 22.3 Mev, because the total elastic scattering cross section is not well known at this energy and because the distribution could not be fitted with a parabola.

Results

The pulse-height distributions corrected for backgrounds, wall effect, and, at the lower neutron energies, for scattering by the walls of the cell, are shown in Figs. 2–7. Differential scattering cross sections are plotted as a function of the cosine of the scattering angle θ in the c.m. system. Most of the points shown have statistical uncertainties of 0.5 to 2%, except for the measurements at 14.7 and 22.3 Mev, where the statistical uncertainties reach 3% at the minimum in

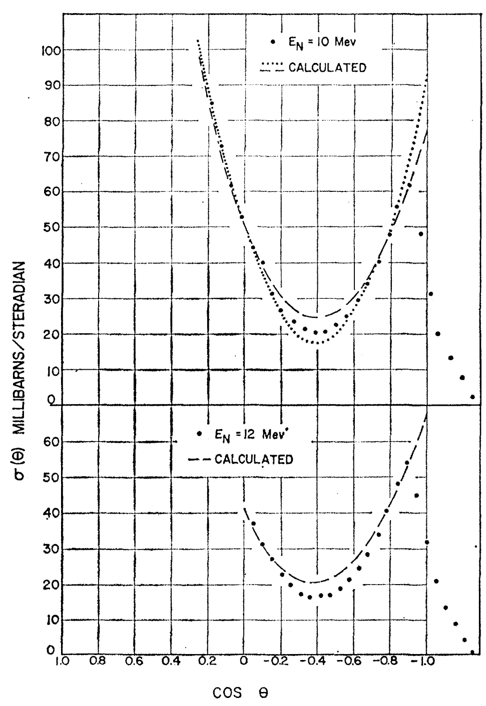

FIG. 4. Differential cross sections in the c.m. system for the scattering of 10- and 12-Mev neutrons by α particles. The dashed curves are calculated using the DGS phase shifts, the dotted curve uses GTP phase shifts (references 8 and 9).

[27] J. A. Wheeler and H. H. Barschall, Phys. Rev. **58**, 682 (1940).

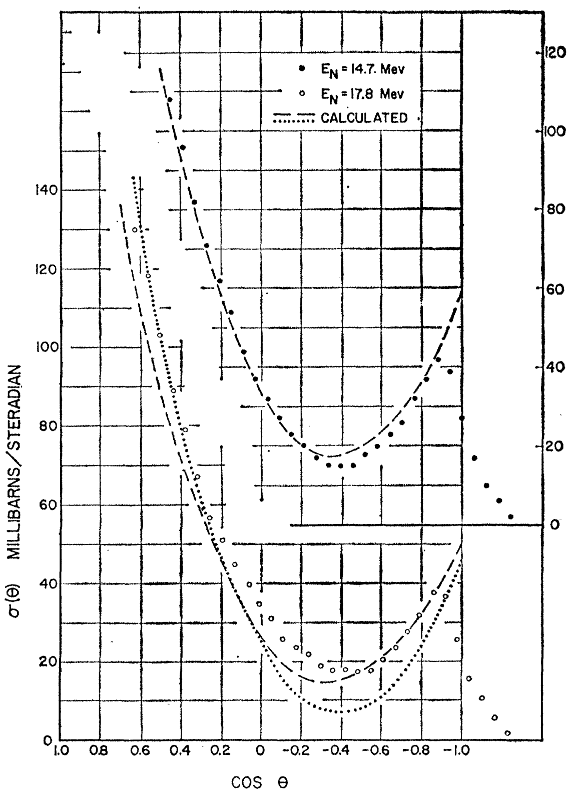

FIG. 5. Differential cross sections for the scattering of neutrons by α particles. The right-hand scale applies to the scattering of 14.7-Mev neutrons, the left-hand scale to the 17.8-Mev neutrons. The dashed curves are calculated using DGS phase shifts, the dotted curve using GTP phase shifts.

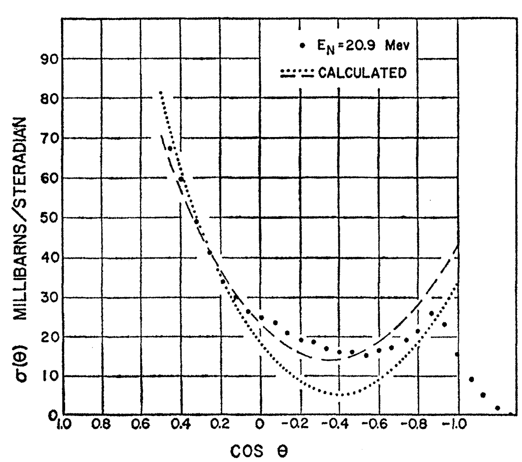

FIG. 6. Angular distribution of 20.9-Mev neutrons scattered by α particles. The dotted curve is calculated using GTP phase shifts, the dashed curve using phase shifts obtained from an extrapolation of the DGS phase shifts.

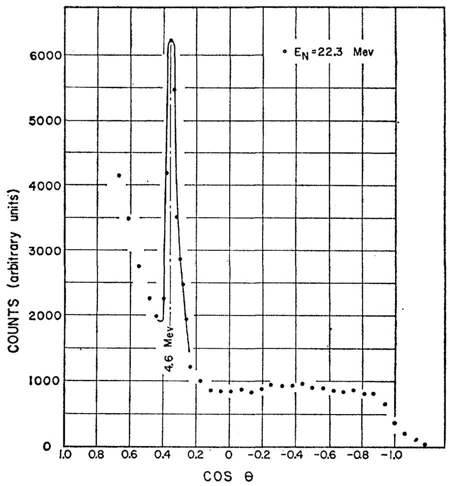

FIG. 7. Pulse-height distribution resulting from the interaction of 22.3-Mev neutrons with α particles. The curve is drawn through the experimental points to show the peak at a pulse height of 4.6 Mev. This peak is due to the reaction $n+\alpha\rightarrow D+T$, the remaining pulses are due to α particle recoils produced by elastic scattering.

the distribution. In all cases the symbols are larger than the statistical errors.

Except for the 22.3-Mev measurement there are shown as dashed lines the differential scattering cross sections calculated from the DGS phase shifts for which the $d_{\frac{5}{2}}$ phase shift is set equal to zero. These phase shifts appear to fit the measurements better than the DGS phase shifts for which the $d_{\frac{5}{2}}$ phase shift is set equal to the $d_{\frac{3}{2}}$ phase shift. At 20.9 Mev the phase shifts were obtained by extrapolating the published curves beyond 20 Mev. The dotted lines shown at 10, 17.8, and 20.9 Mev are angular distributions calculated using the GTP phase shifts.

The smallest scattering angle given, i.e., the smallest recoil energy, is determined at 10 and 12 Mev by the energy of neutrons from deuteron breakup which had to be excluded. At the other energies pulses caused by electrons from γ rays limited the pulse heights which could be attributed reliably to α particles.

At the highest energy the pronounced peak at a charged-particle energy of 4.6 Mev is caused by the reaction $n+He^4\rightarrow D+T-17.6$ Mev. The threshold for this reaction is 22.0 Mev. Although the neutron bombarding energy is only 0.3 Mev above threshold the reaction products have at threshold a velocity in the laboratory system equal to that of the center of mass. At the peak the counts in each channel are shown. The sharpness of the peak compared to the width of the cutoff for the recoils supports the previous statement that the energy spread decreases with decreasing energy. The position of the peak agrees with that calculated from the cutoff of the recoil distribution assuming that the pulse height is a linear function of energy.

Since the cross section for the D+T reaction is known, one could deduce absolute n-α scattering cross sections from the number of disintegrations in the peak using the principle of detailed balancing. Unfortunately, the reaction cross section varies rapidly with energy just above threshold and the neutron energy spread is large and not accurately known, so this method is not reliable at this energy.

The angular distributions are subject to a number of errors. The uncertainty in the normalization has already been mentioned. The measurements are relative angular distributions and little weight should be given to the absolute cross-section scale, particularly at the higher energies. There is also some uncertainty in the scale of abscissas because of the uncertainty in the determination of the pulse height corresponding to scattering through 180°. This uncertainty is estimated to be about 2%.

In addition there are effects which may produce distortions in the distributions. The most serious of these would be a nonlinearity of the system. It is estimated that over the range of a given recoil energy distribution the system including the electronics, was linear to 2%.

The corrections which were applied to the data have considerable uncertainties. Since most of the corrections were small they do not affect the results very much. For the higher neutron energies the corrections are in general larger and introduce, therefore, a greater uncertainty. Particularly the background correction measured without helium in the counter introduces considerable uncertainty, and this uncertainty is probably responsible for the bumps in the distributions at 17.8 and 20.9 Mev observed for $\cos\theta\sim 0$. No correction was applied for neutrons scattered by the floor and other surrounding materials except for the scattering of neutrons by the iron of the gas cell. Because of the short distance between the cell and the target the scattering by materials apart from the cell is expected to be unimportant, and the scattering by the cell itself was found to have a small effect.

The data were not corrected to account for that fraction M of the scattered neutrons which are scattered again before leaving the counter volume. For the gas pressures used in this experiment $M<1.5\%$.

DISCUSSION

The agreement with calculations based on the DGS phase shifts is surprisingly good, particularly up to 15-Mev neutron energy. If one changes the scales by factors which are well within the experimental uncertainty even better agreement between experiment and calculation can be obtained. On the other hand, if one analyzes the data presented in Figs. 2 and 3 in terms of s- and p-wave phase shifts only, one obtains the results shown in Table III. Parabolas based on these phase shifts agree with the data to 3%. Also shown in Table III are the DGS phase shifts. The two sets of

phase shifts differ at the most by 4° (in the s-wave phase shifts). Considering the uncertainties involved in the present experiment, particularly the uncertainty in the absolute cross-section scale, this agreement is very good and supports the validity of DGS phase shifts in this energy range. It should be mentioned that at the lowest energies the agreement between experiments and calculations is not improved by reducing the $p_{\frac{1}{2}}$-phase shift as proposed in references 5, 16, and 17.

At 17.8 and 20.9 Mev an exact agreement between experiment and the calculations based on the DGS phase shifts is not possible because the experimental data are normalized to the experimental total cross section while the calculations from the DGS phase shifts yield too small a total cross section.

At 17.8 and 20.9 Mev the experiments appear to agree better with the results of the calculations using DGS phase shifts than with those using GTP phase shifts, while at 10 Mev the disagreement with the GTP phase shifts is not as bad. One might have expected the opposite trend, i.e., that the GTP phase shifts would fit the data better at the higher energies, since these phase shifts take into account higher angular momenta. On the other hand, the present data are less reliable at the higher energies because of the large background corrections.

The threshold of a competing reaction will have a strong effect on the elastic scattering just below and above threshold.[28] A calculation applicable to the present case has been performed by Baz,[29] but not enough is known yet about the phase shifts to apply this calculation. In addition, the $\frac{3}{2}+$ state in He^5 which occurs just above the threshold greatly complicates the situation. It is, therefore, not to be expected that the measurements at 22.3 Mev can be fitted by simply using a smooth variation of phase shifts with energy.

That the GTP phase shifts do not fit the n-α experiments very well may not be surprising since the GT phase shifts do not fit the p-α scattering and polarization data either in detail as has been pointed out particularly by Brockman.[30] Just as in the case of the p-α scattering, using substantially only s- and p-waves gives at these energies a better fit to the data than the use of the GTP phase shifts which include partial waves of higher angular momenta.

It did not appear profitable to derive phase shifts from the measured angular distributions at the higher energies. Up to 14.7 Mev the distributions can be fitted accurately with parabolas. It is therefore possible to fit the distributions without d and higher waves[27] so that no information about d-waves could be obtained from the present data.

A calculation by Haeberli[19] showed that the data at 17.8 Mev could be fitted equally well by introducing either positive or negative d-wave phase shifts and using different s- and p-wave phase shifts. This may be an example of the well-known ambiguities occurring in phase-shift analyses for spin-$\frac{1}{2}$ particles scattered by spin-0 particles.[10] At present, measurements of the angular distributions of the polarization of neutrons scattered by α particles are in progress at this laboratory. When these results, as well as perhaps improved differential cross sections at the higher energies, are available it may be possible to obtain phase shifts with less ambiguity.

TABLE III. Phase shifts (in degrees) at low energies.

Neutron energy (Mev)	Phase shifts from parabolic fits S	$P_{\frac{1}{2}}$	$P_{\frac{3}{2}}$	DGS phase shifts S	$P_{\frac{1}{2}}$	$P_{\frac{3}{2}}$
2.02	−32	16	117	−35	14	117
3.02	−40	25	123	−43	25	123
4.05	−48	36	121	−50	35	122
5.97	−57	47	115	−61	47	116
7.96	−66	51	108	−70	51	109

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