Neutron-Helium Interaction. I. Scattering of Polarized Neutrons at 1.01 and 2.44 MeV*

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(Received 31 August 1967; revised manuscript received 2 January 1968)

Precision angular distributions of the asymmetry in the scattering of 1.015- and 2.44-MeV polarized neutrons from helium were determined. The reactions $Li^7(p,n)Be^7$ and $C^{12}(d,n)N^{13}$ served as neutron sources, and target thicknesses of 46 and 175 keV, respectively, were used. Analyzing angles ranged from 30° to 140°, in 10° increments. A spin-precession solenoid was employed and the helium was contained in a high-pressure scintillation cell. It is demonstrated that asymmetry data alone are sufficient to accurately determine the scattering phase shifts at 2.44 MeV. Here the phase-shift values were found to be 142.1°, 21.2°, and 121.6° for the δ_0, δ_1^1, and δ_1^3 phase shifts, respectively. *d* waves were not found to be necessary. Assuming hard-sphere scattering, the *s*-wave phase shift gives a radius of 2.42 F, which is consistent with the values recently obtained by others from both *n*-He and *p*-He scattering data. Since at 1.015 MeV, equally good fits to the present data could be obtained with vaules of δ_0 differing by as much as 15°, the hard-sphere formula was used in conjunction with the scattering radius determined at 2.44 MeV to fix the *s*-wave phase shift at 155.5°. The fit to the data then required that $\delta_1^1=4.4°$ and $\delta_1^3=61.2°$. The presently determined *s*-wave phase shifts are larger than the commonly accepted ones due to Dodder, Gammel, and Seagrave (DGS). At both energies the δ_1^3 was in excellent agreement with DGS, although δ_1^1 is about 1.6° below DGS at 1.015 MeV, and 2.8° above at 2.44 MeV.

I. INTRODUCTION

IN the last decade the development of techniques for neutron polarization measurement has been rapid, resulting in increasingly more accurate experiments. The quantity of interest, the polarization, is measured by neutron elastic scattering from light nuclei for which the resonance parameters are believed to be well known; for example, He^4, C^{12}, O^{16}, and Mg^{24}. At the present time, the preferred analyzer is He^4, since the analyzing power is large and does not change rapidly with energy. In addition, helium scintillation cells permit coincidence requirements to be employed in the polarization measurements for background reduction. Because of the emphasis on He, there has been a renewed interest in the determination of the *n*-He scattering phase shifts, since the analyzing power of He is determined from these quantities. Doubt still exists concerning the reliability of presently available phase shifts for low-energy scattering, so a program was initiated in order that precise data might be available for testing existing phase-shift sets and ultimately to provide a new phase-shift set.

The present paper concerns a determination of the phase shifts at 1.01 and 2.44 MeV by means of a polarization measurement. The succeeding paper[1] reports on cross-section measurements for *n*-He scattering which cover the range from 0.2 to 7.0 MeV. Since most of the past determinations of the phase shifts have been derived from cross-section data, it was felt apropos to leave the discussion of much of the earlier work for the succeeding paper. However, it is necessary to introduce some of the analyses with which the present results are to be compared and to review the previous polarization measurements. Recently, Hoop and Barschall[2] (hereafter referred to as HB) gave tables of phase shifts for energies from 0.5 to 30.0 MeV. Their values below 7 MeV differ little from those obtained in 1952 by Dodder and Gammel,[3] and reported by Seagrave[4] (hereafter referred to as DGS). When one considers that the origin of the DGS phase shifts was early *p*-He cross-section data,[3] it is truly surprising that the DGS phase shifts describe *n*-He scattering as well as they do. At the time the present polarization experiment was undertaken, it was believed that no experiment had tested the DGS phase shifts well enough to permit reliable use of He in neutron polarization experiments. The real stimulation for the project was, in fact, the neutron triple-scattering program underway at our laboratory.[5] These experiments utilize He as the third scatterer and the information derived depends on accurate knowledge of the *n*-He phase shifts around 2 MeV.

An earlier *n*-He polarization measurement at 3.4 MeV, reported by Levintov *et al.*,[6] was not accurate enough to test the phase shifts.[7,8] An experiment by

* Work supported in part by the U. S. Atomic Energy Commission.

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[5] F. O. Purser, J. R. Sawers, and R. L. Walter, in *Proceedings of the 2nd International Symposium on Polarization Phenomena of Nucleons, Karlsruhe, 1965*, edited by P. Huber and H. Schopper (Birkhäuser Verlag, Basel, Switzerland, 1966), p. 311.

[6] I. I. Levintov, A. V. Miller, and V. N. Shamshev, Nucl. Phys. **3**, 221 (1957); Zh. Eksperim. i Teor. Fiz. **32**, 274 (1957) [English transl.: Soviet Phys.—JETP **5**, 258 (1957)].

[7] G. Pisent and C. Villi, Nuovo Cimento **11**, 300 (1959).

[8] W. Haeberli, *Fast Neutron Physics*, edited by J. L. Fowler and J. B. Marion (Interscience Publishers, Inc., New York, 1963), Part II, Chap. V.G.

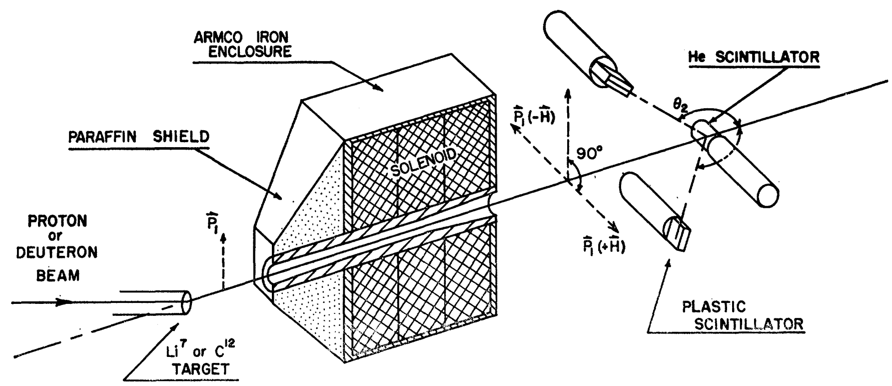

FIG. 1. A schematic view of the polarimeter.

May *et al.*[9] which determined the shape of the polarization distribution at five energies from 2.0 to 23.7 MeV gave results which were consistent with DGS predictions at the lowest energies. However, the results were not sufficiently accurate to actually yield phase-shift values. It was hoped that a polarization experiment similar to that of May *et al.*, but done with much greater accuracy, could be used in connection with available cross-section data to provide sufficient knowledge of the phase shifts at low energies. This expectation was not fully achieved since the cross-section information was later found to be insufficiently accurate. Therefore, except for preliminary reports,[10,11] the publication of the polarization work was witheld until better cross-section data were available to complement the work. The latter measurements were recently completed and are reported in the following paper.[1] The phase shifts derived from both sets of experimental data are presented separately, though, in order to provide two independent sets of values, partly because if there is a weakness in the assumptions in one paper the other can stand alone. Another purpose for presenting the phase-shift analysis in this paper is to illustrate the usefulness of an asymmetry distribution, even though the incident beam polarization is unknown.

The experiment described in this paper is one of the most accurate polarization measurements to date. Because of this and because of the ultimate significance of the results, a sizeable portion of the paper will be devoted to the details of the measurement and care of the data handling.

II. EXPERIMENTAL APPARATUS

A. General

A brief general summary of the apparatus and technique will be given first. The experimental arrangement is illustrated in Fig. 1. Polarized neutrons which emerged at a reaction angle θ_1 had their spins precessed 90° by a magnetic field produced with a solenoid. (Unless stated to the contrary, the values of the angles are given in the laboratory system.) After passing through the solenoid the neutrons were incident on a high-pressure helium scintillation cell. Those neutrons which scattered through the desired analyzing angle θ_2 were detected by a pair of plastic scintillators. Coincidence and pulse-height requirements had to be met before a count was considered acceptable.

B. Neutron Production

Polarized neutrons were produced using either the reaction $Li^7(p,n)Be^7$ or $C^{12}(d,n)N^{13}$. The protons or deuterons were accelerated by the Duke University 4-MeV Van de Graaff accelerator. Machine voltages were measured using a precision digital voltmeter to read the signal from a generating voltmeter, the technique having been described by Hollandsworth *et al.*[12] Taking into account the uncertainty in calibration energy and in the target thickness, the average beam energy was known to ± 7 keV.

The neutron producing targets were chosen on the basis of large polarizations, large cross sections, ability to withstand large beam currents, and a polarization which was nearly constant with energy and angle. The $Li^7(p,n)$ and $C^{12}(d,n)$ reaction met these requirements and were used to provide 1.01- and 2.44-MeV neutron beams, respectively. Andress *et al.*[13] reviewed polarization measurements at low energies for the $Li^7(p,n)$ reaction. For $E_p \approx 2.9$ MeV and $\theta \approx 50°$ (which gives $E_n \approx 1.0$ MeV), the polarization [14] of neutrons $P_1 \approx 0.3$. In addition to the 1.0-MeV neutron group, there is a second group about 0.4 MeV lower in energy from the Li^7+p reaction. As discussed later, the lower-energy group did not interfere with the final extracted data. Two Li^7 targets were used in the course of the experi-

[9] T. H. May, R. L. Walter, and H. H. Barschall, Nucl. Phys. **45**, 17 (1963).

[10] J. R. Sawers, Jr., R. L. Walter, G. L. Morgan, and L. A. Schaller, Bull. Am. Phys. Soc. **11**, 304 (1966).

[11] J. R. Sawers, Jr., thesis, Duke University, 1966 (unpublished).

[12] C. E. Hollandsworth, S. G. Buccino, and P. R. Bevington, Nucl. Instr. Methods **28**, 353 (1964).

[13] W. D. Andress, Jr., F. O. Purser, J. R. Sawers, Jr., and R. L. Walter, Nucl. Phys. **70**, 313 (1965).

[14] In this paper, all values of the polarization are consistent with the Basel sign convention.

ment. Both were measured to be 46 keV thick at the (p,n) threshold, as determined by the rise-curve method. To 2.9-MeV protons, this corresponds to a thickness of 33 keV. Taking into account the angular spread accepted by the He cell, the total neutron energy spread was 50 keV. The targets were metallic Li evaporated onto 0.25-mm Ta backings.

The $C^{12}(d,n)$ reaction has been discussed by Sawers *et al.*[15] and Meier *et al.*[16] for $E_d \approx 2.8$ MeV and $\theta \approx 25°$ (which gives $E_n \approx 2.4$ MeV). Here P_1 is known to be around -0.4. Below $E_d = 3.0$ MeV this reaction is monoenergetic. To reduce counting time, targets were chosen to be as thick as was consistent with an accurate measurement of the helium analyzing power. Since around 2.4 MeV the n-He cross section and polarization do not change sizeably with energy, a relatively thick target of 175 keV (to 2.9-MeV deuterons) was used. The target was made by depositing carbon onto a 0.25-mm Ta backing. The thickness was determined by carefully comparing neutron yields with those from a thin carbon foil of known thickness.[17]

The Van de Graaff voltage of 2.82 MeV was chosen because here (i) there is a region in the $C^{12}(d,n)N^{13}$ cross section where the neutron production is relatively constant across the whole of the target thickness, and (ii) the polarization was optimum and nearly constant across the energy range in question. This choice of energy and angle is reasonable, as the polarization peaks at this energy for $\theta_1 = 25°$ and fortunately the differential section also peaks at this angle.

To better determine the energy dependence of $P_1(25°)$, the asymmetry was measured to an accuracy of ± 0.007 with a 60-keV target at three energies across the energy range spanned by the 175-keV target. Scattering from He through 120° was employed. The measured asymmetries were -0.360, -0.382, and -0.367 for $E_d = 2.76$, 2.82, and 2.88 MeV, respectively. (These asymmetry values have not been corrected for small systematic effects which are not critical to the test at hand.) A slight peaking outside of statistics was observed, but because the analyzing power and cross section of helium are nearly constant in this energy range, in the final analysis, it was possible to neglect this suggested peaking in the source polarization.

C. Solenoid

In order to minimize the instrumental asymmetries, a solenoid was used to precess the neutron spins through 90°. Since the reaction plane was horizontal, the analyzing plane was therefore vertical. Data could be recorded with the spin precessed alternately in the clockwise and counter-clockwise direction. Measuring asymmetries using this method has been discussed previously.[18] The main advantages are elimination of the need for highly accurate determinations of the detector efficiency, angles, and beam monitoring. The disadvantages are all related to problems with the fringing field of the solenoid. First, the major effect, the change in gain of the phototubes, was made negligible by enclosing the solenoid in a soft-iron flux-return box and by encasing the phototubes and light pipes in magnetic shielding.

Secondly, it is known that some depolarization of a neutron beam will occur as it passes through a solenoidal magnetic field due to the effect of the radial component of the field.[19] But, since the amount of depolarization is a constant fraction of the polarization, this effect merely decreases the effective value of P_1. In the initial treatment of the angular distribution $P_1P_2(\theta)$ from which the phase shifts are derived, P_1 is treated as an unknown quantity. Consequently, the depolarization due to this effect is only of secondary importance to the prime consideration in this work. However, a byproduct of this present experiment is an accurate determination of P_1 whose true value is dependent on the amount of depolarization. An estimate of the size of the magnetic depolarization is discussed in Sec. VIII in connection with extracted values of P_1.

D. Polarimeter

A typical arrangement of the polarimeter is shown in Fig. 1. The plastic detectors were shielded from the neutron-producing target by approximately 70 cm of paraffin, iron, copper, water, and polyethylene. Through use of a tapered polyethylene collimator inserted into the center of the paraffin shadow cone and the solenoid, a narrow neutron beam of half-angle 1.3° was selected at an angle θ_1. The helium scintillator was about 1 m from the target. The polarimeter was designed so that the plastic scintillators could be placed at any scattering angle θ_2 from 0° to 140°, in 10° increments. In the present experiment data were taken between 30° and 140°. At angles less than 30° the energy of the recoil α particles was not sufficient to produce a pulse which could clearly be distinguished from phototube noise. The mean analyzing angles θ_2 were measured to within 0.3° by optical methods.

The helium scintillation cell was somewhat similar to the one described by Shamu.[20] The present cell was turned from a block of stainless steel and, in the region of neutron irradiation, had a wall thickness of 0.22 cm. The interior of the cell was polished and coated with a thin evaporated layer of aluminum over which a layer of MgO was deposited. The viewing end of the helium cell was closed with a glass disk. A thin layer of diphenyl-

[15] J. R. Sawers, Jr., F. O. Purser, Jr., and R. L. Walter, Phys. Rev. **141**, 825 (1966).

[16] M. M. Meier, L. A. Schaller, and R. L. Walter, Phys. Rev. **150**, 821 (1966).

[17] Other comments regarding target considerations are included in Ref. 11.

[18] See, e.g., Ref. 8.

[19] J. Atkinson and J. E. Sherwood, Nucl. Instr. Methods **34**, 137 (1965).

[20] R. E. Shamu, Nucl. Instr. Methods **14**, 297 (1962).

stilbene was evaporated onto the MgO coating and onto the glass window to serve as a wavelength shifter. The cell was filled with 120 atm of helium and 5 atm of xenon, which served to increase the light output. The pressure of the xenon was lower than values typically used in order to reduce the γ-ray sensitivity of the helium cell. Morgan and Walter[21] have shown that the helium-cell output pulse height is proportional to the recoil energy of the struck α particle. The energy resolution (full width at half-maximum) of the present helium cell was about 9% for pulses from a 5-MeV α source inside the cell. From the recoil distribution one estimates[21] the resolution under neutron bombardment to be about 28 and 19% for 180° neutron scattering, i.e., $E_{\mathrm{He}}=(16/25)E_n$ for $E_n=1.0$ and 2.4 MeV, respectively.

The scattered neutrons were detected with two plastic phosphors whose dimensions were $5.1\times2.5\times5.1$ cm^3 and which were placed 19 cm from the center of the helium cell. To avoid excessive γ-ray sensitivity, a 0.5-cm-thick layer of lead also covered the sides and face of the scintillators. For the 1.0-MeV measurement, the detector biases were set so that those pulses resulting from recoil protons of energy less than 200 keV were not detected. The discriminator level at 2.4 MeV corresponded to about 240 keV.

E. Electronics

The asymmetry values were based on thorough analyses of gated He-recoil spectra. To obtain these spectra, a linear signal from the He scintillator was put into quadrants of a multichannel analyzer. A gate for each quadrant was obtained from a coincidence between the pulses from the He scintillator and either the "up" or the "down" plastic phosphor. (See, for example, Ref. 16, regarding this technique which is now fairly standard.) Typical recoil spectra are exhibited and discussed in Sec. V. It was important in the present experiment to ensure that no events of interest were eliminated in the coincidence circuitry. To be on the safe side, the coincidence resolving time was usually operated around $2\tau\approx20$ nsec. For measurements at the lower energy, where it was sometimes required to observe proton and He recoils down to about 100 keV, this resolving time was increased to about 30 nsec, so that acceptance of the desired events was guaranteed. Because of flight time and favorable rise-time differences, 20 nsec was also sufficient to separate many of the γ-ray coincidences from the neutron coincidences. In order to monitor the neutron flux and the operation of the electronics, scalers recorded counting rates at various points in the circuit.

III. DATA ACQUISITION

The data for each angle at 1.0 MeV were acquired in three or more separate measurements, each composed of about nine foreground sets and three chance-background sets. Each set was limited to less than 15 min and comprised of a run with the spin rotated through 90° in both directions. To minimize errors which can result, for example, from variations in target thickness and long-term electronic drift, the analyzing angle θ_2 was changed between the separate measurements. Chance backgrounds were obtained by accumulating spectra with a 70-nsec delay inserted in the helium fast circuitry. The "room background," i.e., the effect of room-scattered neutrons which gave true coincidence events, was measured by plugging the solenoid and observing coincidence spectra under these conditions. Data for the 2.4-MeV angular distribution were taken in a similar manner but fewer independent determinations were made at each angle, principally because the higher incident polarization reduced the need for a large number of counts. The total number of foreground-less-background counts accumulated at each angle average 100 000 and 45 000 at 1.01 and 2.44 MeV, respectively.

IV. PERTINENT THEORETICAL FORMULAS

Prior to discussing the handling and interpretation of the data, it is necessary to discuss some relations employed. The ultimate comparison of the new results with older data is made using elastic-scattering phase shifts. At our energies, only s and p waves contribute to n-He scattering. Thus, only three parameters are necessary to describe the scattering at each energy, δ_0, $\delta_1{}^1$, and $\delta_1{}^3$, which represent the phase shift for the scattering of the s wave, and p waves with total angular momentum equal to $\frac{1}{2}$ and $\frac{3}{2}$, respectively. The formulas for the total cross section σ^T and the differential cross section for unpolarized neutrons $\sigma(\theta)$ are given in numerous texts. For partial waves the relations are relatively simple. The expression in terms of phase shifts for the "right-left" asymmetry produced by scattering a polarized beam is complicated, even when only three phase shifts are involved. The required formulas are given, for example, in Ref. 8. In the case of elastic scattering, the asymmetry is equal to the polarization $P(\theta)$ in the outgoing beam produced by scattering unpolarized particles from the same target. In this paper $\epsilon(\theta)$ will be reserved to describe the experimentally observed asymmetry. When a beam of polarization P_1 is scattered, then the observed asymmetry $\epsilon(\theta)=P_1P_2(\theta)$, where $P_2(\theta)$ is the same as $P(\theta)$ above. If $P_2(\theta)$ is known, P_1 can be determined from a measurement of $\epsilon(\theta)$. Hence, $P_2(\theta)$ is called "analyzing power," the nomenclature used herein.

So far, there has not been an absolute measurement of P_1 for *any* neutron source with an accuracy which is sufficient to aid in further understanding the n-He problem at low energies. However, even if P_1 is unknown, at discrete energies the distribution of $P_2(\theta)$ can be determined to within a scale factor from a

[21] G. L. Morgan and R. L. Walter, Nucl. Instr. Methods **58**, 277 (1968).

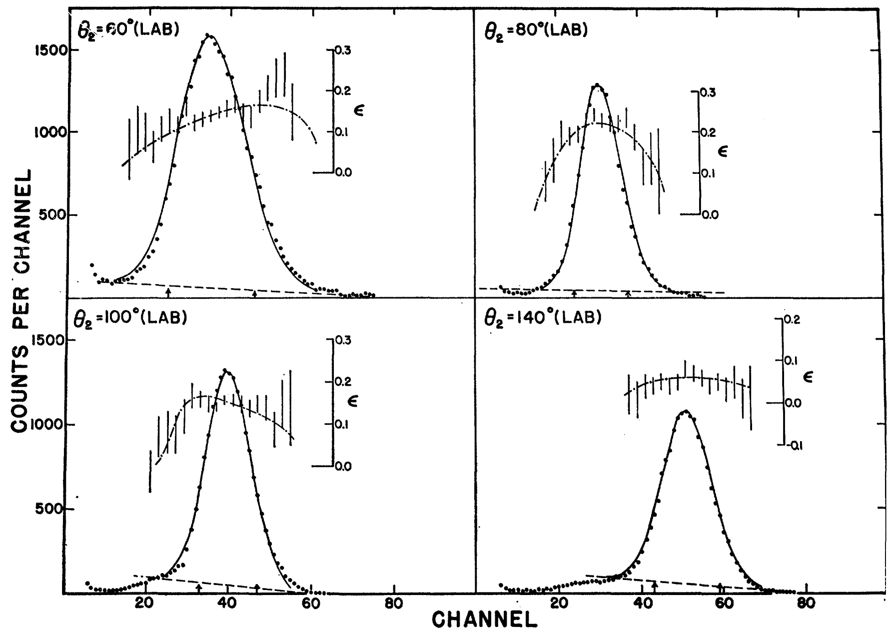

FIG. 2. Helium recoil spectra gated by coincidences between the helium-scintillator and the plastic-phosphor pulses. The fits to the data (●) are represented by the solid line. The incident neutron energy was 1.015 MeV.

measurement of an angular distribution of $\epsilon(\theta)$. This is the approach used in the present experiment.

Brown *et al.*[22] have shown that the energy dependence of δ_0 in p-He scattering up to 3.2 MeV is well represented by merely assuming that it is produced by scattering from a hard sphere of radius $R_0=2.48$ F. There is evidence that the n-He scattering behaves in the same way. Hoop and Barschall[2] used a hard-sphere radius of $R=2.40$ F to calculate their low-energy s-wave phase shift. In the present analysis, the hard-sphere scattering relation

$$\delta_0=\pi-kR_0$$

(where k is the neutron wave number) was used to obtain δ_0 at 1.01 MeV from the value of δ_0 extracted from the data at 2.44 MeV.

The triple-scattering relations of Wolfenstein[23] have been employed in the calculations for the multiple-scattering corrections to the measured asymmetry. Use of these relations was required because the scattering intensity in a particular direction, e.g., right or left, depends upon the neutron spin orientation prior to the scattering. Usually this consideration has been omitted because either the accuracy of the data didn't warrant such a formidable calculation or because the number of scatters was small enough so that essentially no multiple scattering existed. In our case, the magnitude of the effect caused by the rotation of the spin vector was unknown and so the triple-scattering R parameter[23] was included in the multiple-scattering code. This parameter was calculated directly from phase shifts. (The existing DGS phase shifts were sufficiently accurate for this calculation.) It was not necessary to include the D parameter[23] since there is no depolarization in scattering from a spin-zero target. Because the computation gets extremely involved if one includes more than two scatterings, the correction for just two were obtained initially. For such a situation, the asymmetry is insensitive to the size of the A parameter.

V. ANALYSIS OF SPECTRA

A. General

Typical gated recoil spectra are plotted in Figs. 2 and 3 for 1.01 and 2.44 MeV, respectively. In order to have confidence in the data and to obtain accurate numbers for the asymmetry calculation, it was necessary to be able to interpret these spectra. Most of the following calculations were designed for this purpose.

B. Program for Asymmetry Calculations

An elaborate program, "Monte Carlo Calculation of Asymmetry in Neutron Scattering" (MOCCASINS), was written for asymmetry calculations for single and for double scattering from spin-zero nuclei when the phase shifts for the scattering are approximately known. A complete description of the code is given in Ref. 11. Because of its completeness and length, only a brief outline of the code will be given here. Its purpose is to calculate the probabilities for neutron scattering from helium into each of the plastic scintillators located at θ_2 on opposite sides of the helium cell. In addition, the probability of leaving a given amount of total recoil

[22] L. Brown, W. Haeberli, and W. Trachslin, Nucl. Phys. **A90**, 339 (1967).
[23] L. Wolfenstein, Ann. Rev. Nucl. Sci. **6**, 43 (1956); Phys. Rev. **96**, 1654 (1954).

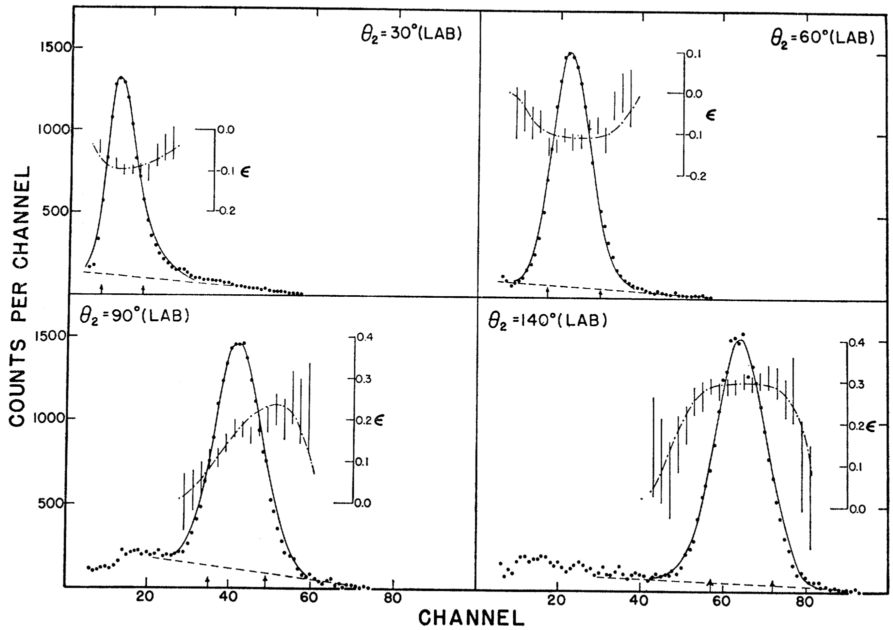

FIG. 3. Helium recoil spectra gated by coincidences between the helium-scintillator and the plastic-phosphor pulses. The fits to the data (●) are represented by the solid line. The incident energy was 2.44 MeV.

energy in the helium for a particular detector position is calculated. This information, presented in the form of a histogram, allows comparison of the calculated coincidence-peak shape with the experimental one. Prior to comparison, a Gaussian distribution whose width was compatible with the energy resolution of the helium scintillator was folded into the histogram with a second program. Also obtained was a Gaussian "smeared" asymmetry function for each detector position, which was compared with the experimentally determined one.

A few of the pertinent features and assumptions are the following: (1) The calculation was a Monte Carlo type which included multiple scattering in the helium gas, the geometry of the helium cell, and the plastic scintillator, the plastic scintillator bias level and the n-p and n-C^{12} cross sections, and as mentioned previously, the triple-scattering R parameter. (2) Only up to two scatterings were considered initially. (From the results, the contributions of additionally scattered events were estimated to be negligible.) (3) For computational reasons the helium volume was taken to be spherical. This is not a bad assumption since the cell was actually hemispherical on one end and the neutrons were collimated to a cylindrical beam normal to the axis of symmetry of the cell. (4) Since the DGS n-He phase shifts were expected to be close to the true phase shifts, the DGS set was used in the calculation. The approximation was certainly suitable for the spectral analysis. In the final determination of the distribution of $P_2(\theta)$, for each angle the size of the deviations from the DGS P_2, as determined by MOCCASINS, was employed to adjust the experimentally obtained asymmetries. By studying the distributions $P_2(\theta)$ obtained after applying corrections to the experimental data, it was clear that the DGS set is close enough to reality to also predict these corrections with sufficient accuracy.

C. Spectral Shapes

The data points shown in Figs. 2 and 3 represent the total of the counts per channel of four recorded spectra (two spectra for each 90° precession condition). The solid curve represents the Gaussian "smeared" histogram output of the Monte Carlo code. The height and peak location were adjusted by eye. Further adjustment of the parameters might have improved the agreement between the points and the calculated curves, but it was believed that the fits shown already were sufficiently good to demonstrate that the experimental spectra could be interpreted. (The tails of the solid curves exhibit the largest deviation from the points. These are the regions of the curve which are most sensitive to the differences between the actual irradiated He volume and the approximated spherical geometry. As mentioned below, only the central portion of the peaks was used in the final analysis.) The dashed curves under the peaks represent estimates of a "nonsubtracting background." In all cases, this background, which is discussed later, was taken to be linear and unpolarized. In some of the spectra, the data in the channels below the peak fall under the dashed lines. This was caused in part by a discrimination bias (on the helium pulses) which was not sharp when the counting rates were excessive.

Data from the four spectra at each angle were broken up into three-channel blocks and an asymmetry was calculated for each block. The relation used for this was

$$\epsilon = P_1 P_2 = (1-r)/(1+r),$$

TABLE I. Asymmetries, corrections, and polarizations for $E_n=1.015$ MeV.

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	ϵ	B	MS	$\delta P(\theta,\varphi)$	$\delta P(\bar{E})$	ϵ_{corr}	$\Delta\epsilon$	P_2	$\pm\Delta P_2$
30.0	37.2	0.027	0.0016		0.0016	0.0006	0.031	0.005	0.102	±0.016
40.0	49.3	0.051	0.0013	0.0001	0.0022	0.0007	0.055	0.004	0.182	±0.014
50.0	61.1	0.095	0.0012	0.0002	0.0046	0.0010	0.102	0.003	0.334	±0.010
60.0	72.6	0.147	0.0048	0.0005	0.0079	0.0016	0.162	0.004	0.533	±0.013
70.0	83.7	0.206	0.0073	0.0011	0.0097	0.0022	0.226	0.004	0.744	±0.014
80.0	94.4	0.225	0.0044	0.0014	0.0058	0.0009	0.238	0.005	0.782	±0.015
90.0	104.6	0.195	0.0038	0.0010	−0.0002		0.199	0.004	0.656	±0.014
100.0	114.4	0.166	0.0032	0.0005	−0.0023		0.167	0.004	0.549	±0.013
110.0	123.7	0.128	0.0040	0.0004	−0.0026	−0.0007	0.129	0.005	0.424	±0.015
120.0	132.6	0.101	0.0023	0.0002	−0.0025	−0.0012	0.100	0.005	0.328	±0.013
130.0	141.1	0.074	0.0029	0.0002	−0.0022	−0.0005	0.074	0.004	0.244	±0.012
140.0	149.3	0.056	0.0021	0.0001	−0.0016	−0.0004	0.056	0.004	0.185	±0.012

where

$$r=[U(+)D(-)/D(+)U(-)]^{1/2}. \quad (1)$$

Here, the notation U and D represents the up and down counting rates and the + and − represent the clockwise and counter-clockwise 90° precessions. This relation, which also is used to obtain the asymmetry for the total peak counting rates, has been discussed elsewhere.[8] Use of this relation makes the data insensitive to a number of instrumental problems, such as absolute efficiencies, various electronic drifts, and fluctuations in beam position and target thickness. The bars in Figs. 2 and 3 represent the block asymmetries, the total length of the bar being twice the statistical standard deviation. The ordinate to the right of each set of bars gives the scale for the asymmetries. In all cases, the three-channel asymmetries approach zero in the region of the tails where the counts are largely due to the unpolarized, linear background. The corresponding three-channel asymmetries obtained from MOCCASINS, incorporating a linear unpolarized background, are represented by the dot-dash curves. The structure, for example at 2.44 MeV for 90°, is produced by the changing value of $P(\theta)$ across the angular spread in the He-cell, plastic-scintillator detection system. The general agreement is considered proof that the data can be properly interpreted and analyzed in this fashion.

To minimize the uncertainties in the background, only the central portions of the peaks were used to obtain the numbers for Eq. (1) to arrive at the final asymmetry values listed later. The arrows along the abscissas in Figs. 2 and 3 indicate the bounds used. At 2.4 MeV, the bounds correspond to about 50% of peak height and at 1.01 MeV, 35% of peak height.

D. Backgrounds

The chance coincidence and room backgrounds have been subtracted from the data exhibited in Figs. 2 and 3. Counts arising from chance coincidences amounted to less than 3% of the total. Background from room-scattered neutrons generally contributed less than 2%, but rose to 9% at 1.01 MeV for 30°. From the nature of these backgrounds, one expects them to be unpolarized. Since this was statistically consistent with our measurements, they were taken to be unpolarized in the analysis.

An attempt to find the cause of the "linear" non-subtracting background was made using the on-line computer facility[24] operating in a two-dimensional analyzer mode. The helium pulses were supplied to one input and to the other pulses corresponding to the time separation between two events in the helium cell and a plastic scintillator. These tests showed that the interactions of γ rays were sufficiently well resolved from the neutron interaction that only a portion of the non-subtracting background could be accounted for in this fashion. Other sources could have been neutrons degraded in energy by inelastic scattering in the target region, collimator, or Fe cell[25] which contained the He. The latter was estimated using a modified version of MOCCASINS and was found to contribute less than 0.1% to the peak, most of the contribution appearing in lower channels. Neutrons which have been elastically scattered[25] from Fe through small angles ($\theta<45°$) contribute about 1% of the counts in the peak. Those which scatter from Fe through larger angles, e.g., backscattering, can produce counts above or below the peak, depending on the scattering angles involved. MOCCASINS estimated that these contributions were less than the 1% peak contribution above. These calculated percentages were found to be consistent with results obtained in a crude test which enhanced the Fe effect by encasing the helium cell in 1 to 2 cm of additional Fe.

In the 1.01-MeV measurement, the neutrons from the $Li^7(p,n)Be^7$ (432 keV) reaction are produced with about 15% of the intensity of those leading to the

[24] N. R. Roberson, D. R. Tilley, and M. B. Lewis, Bull. Am. Phys. Soc. **10**, 55 (1965).

[25] The paper by L. A. Schaller, R. L. Walter, and F. O. Purser [in *Proceedings of the 2nd International Symposium on Polarization Phenomena of Nucleons, Karlsruhe, 1965*, edited by P. Huber and H. Schopper (Birkhäuser Verlag, Basel, Switzerland, 1966), p. 309] discusses depolarization effects in elastic and inelastic scattering from Fe. The latter process was observed to completely depolarize a beam, the former effect to produce no depolarization, as expected.

TABLE II. Asymmetries, corrections, and polarizations for $E_n = 2.44$ MeV.

θ_{lab} (deg)	ϵ	B	MS	$\delta P(\theta,\phi)$	ϵ_{corr}	$\Delta\epsilon$	P_2	$\pm\Delta P_2$
30	0.090	0.0129		0.0027	0.106	0.005	−0.2306	±0.010
40	0.107	0.0156	0.0001	0.0033	0.126	0.006	−0.2745	±0.013
50	0.126	0.0123	0.0001	0.0035	0.142	0.005	−0.3100	±0.011
60	0.108	0.0081	0.0001	0.0029	0.119	0.005	−0.2600	±0.011
70	0.059	0.0055	0.0001		0.064	0.005	−0.1404	±0.011
80	−0.036	−0.0035		−0.0043	−0.044	0.007	0.0965	±0.014
90	−0.159	−0.0163	−0.0007	−0.0118	−0.188	0.007	0.4107	±0.014
100	−0.291	−0.0227	−0.0022	−0.0136	−0.329	0.008	0.7183	±0.017
110	−0.357	−0.0268	−0.0031	−0.0101	−0.397	0.009	0.8668	±0.019
120	−0.377	−0.0217	−0.0036	−0.0056	−0.407	0.008	0.8895	±0.017
130	−0.343	−0.0164	−0.0029	−0.0025	−0.365	0.008	0.7967	±0.016
140	−0.285	−0.0121	−0.0021	+0.0015	−0.298	0.007	0.6509	±0.014

ground state.[26] The lower energy group, whose energy is 0.57 MeV, is known to be unpolarized.[27] These neutrons were not apparent in the recoil spectra because the σ^T for the He(n,n) reaction was down appreciably and the plastic scintillator discriminators passed only a small fraction of the counts. As a result, just a fraction of the tails of the nonsubtracting background can come from these neutrons.

The portion of the nonsubtracting background below the peak was unpolarized within statistics. To be consistent with its most probable origins, it was assumed that the background tail was also unpolarized in the peak region. The dot-dashed asymmetry curves in Figs. 2 and 3 are MOCCASINS predictions based on this assumption and their agreement with the data bears out the reasonableness of this assumption.

For the region of the peak between the arrows shown in Fig. 3, the relative size of the background averaged 9% at 2.44 MeV. This magnitude could not be fully explained on the basis of the interactions and measurements discussed above. The dot-dash asymmetry curves, however, are in agreement with the size of the constructed linear backgrounds.

At 1.01 MeV, the background averaged only 3%, but as exhibited in Fig. 2 there were extra conditions used to draw the dashed curves. At some angles it was difficult to choose a level through which to draw a linear background curve, because the He-cell discriminator distorted the background spectrum. Requirements in such instances were that the background fraction should vary only slightly with θ_2 and that there should be reasonable consistency with the calculated (dot-dash) asymmetry curve. An error of ±25% was placed on the magnitude of the nonsubtracting background estimates.

E. Possible False Asymmetries

The advantages of using the present experimental method for asymmetry determinations have been outlined above. However, some tests to detect instrumental asymmetries which may have been introduced by the apparatus were conducted. The main concern is the effect of the fringe field on any of the detectors when the magnetic field in the solenoid is reversed. Measurements indicated that the largest error in ϵ could have been 0.0005±0.0003, occuring at the largest scattering angles at 1.01 MeV. This was ultimately neglected since it was an order of magnitude less than the final uncertainty.

Concern was also given to the Pb shields on the sides of the plastic detectors. Their presence produces inscattering into the plastic and has the effect of widening the angular acceptance. It was estimated that 2% of the coincidence counts originate from such multiple events. Calculations carried out at both energies and all angles indicated that the upper bound for a correction to account for this effect in the worst instance was 0.002 in the value of the polarization. Due to the small size of this correction, no alteration to the data was made.

In brief, no false asymmetries were found which existed to such an extent that the results could be affected.

F. Asymmetry Results

Listed in Tables I and II are the final results. The asymmetry ϵ is the experimental value extracted from the region of the peak between the arrows in Figs. 2 and 3. Corrections for the chance and room background already have been included in the values. The additive quantities B and MS are, respectively, the correction for the nonsubtracting background and the multiple scattering. The MS numbers are the difference between the corrections calculated with and without the double-scattering option in MOCCASINS.[28] The geometrical averaging effect was computed with the single-scattering option of MOCCASINS. The values $\delta P(\theta,\varphi)$ represent the calculated geometrical corrections. A correction $\delta P(\bar{E})$

[26] P. R. Bevington, W. W. Rolland, and H. W. Lewis, Phys. Rev. **121**, 871 (1961).

[27] G. L. Morgan, C. E. Hollandsworth, and R. L. Walter, in *Proceedings of the 2nd International Symposium on Polarization Phenomena of Nucleons, Karlsruhe, 1965*, edited by P. Huber and H. Schopper (Birkhäuser Verlag, Basel, Switzerland, 1966), p. 523.

[28] For the multiple-scattering calculation, it is necessary to assign a value of P_1 to the incident beam. Values very close to the final extracted ones had been employed.

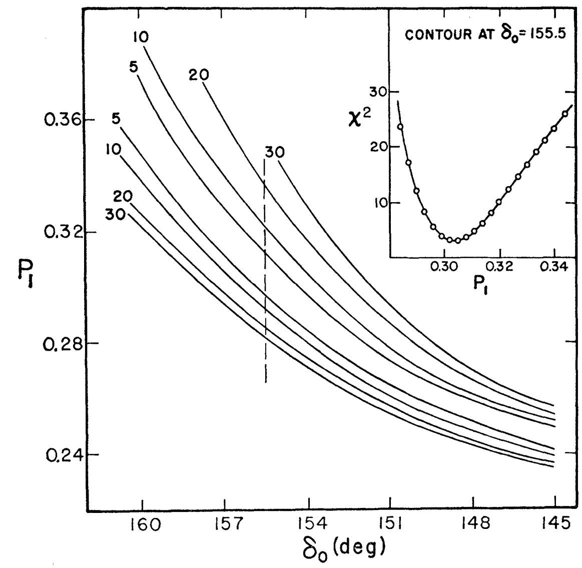

FIG. 4. Contour plot of χ^2 at 1.015 MeV for a range of values of P_1 and δ_0. The value of equal χ^2 contour lines is indicated. The p phase shifts were the free parameters in the search at each grid point.

for the neutron energy spread was required at 1.01 MeV since the energy dependence of the n-He differential cross section was not negligible. When all the corrections are made to ϵ, one gets ϵ_{corr} which is tabulated. The standard deviation $\Delta\epsilon$ of the asymmetry includes the statistical uncertainties, the previously mentioned uncertainty assigned to the nonsubtracting background, and reasonable estimates of the uncertainties associated with the applied correction of Table I. Also listed in Tables I and II are values for P_2 obtained from the corrected asymmetries, using the best estimate for P_1 as discussed in the next section. In Tables I and II, some of the listed numbers are reported to an accuracy which is not significant to the final result. This was done intentionally to indicate the sign and size of the correction.

VI. PHASE-SHIFT ANALYSIS

A phase-shift program designed to search the multidimensional surface in χ^2 was used to fit the data. The search program was modeled after one written by Moss and Haeberli[29] and minimized the quantity

$$\chi^2=\sum_j\left[\frac{P_{\text{expt}}(\theta_j)-P_{\text{calc}}(\theta_j)}{\Delta P(\theta_j)}\right]^2+\left[\frac{\sigma_{\text{expt}}^T-\sigma_{\text{calc}}^T}{\Delta\sigma^T}\right]^2,$$

where $P_{\text{expt}}(\theta_j)$ is the experimental value of the polarization for the angle θ_j and $\Delta P(\theta_j)$ represents the associated experimental error. Likewise, σ_{expt}^T represents the experimental total cross section with uncertainty $\Delta\sigma^T$. The symbols with the subscript "calc" are the corresponding quantities calculated from the phase shifts, the numbers which are varied in the search. As pointed out in the Introduction, no significant differential-cross-section data was available at the time these data were analyzed for phase shifts. Since some possibly vulnerable assumptions were necessary to obtain the differential-cross-section values in the work by Morgan and Walter reported in the following paper, we prefer to present independent phase-shift analyses of each set of data. That is to say, if weaknesses invalidate the cross-section experiment, the phase shifts extracted from only the polarization data will be quite valuable. Only P and σ^T were searched upon and only s and p waves were included since the higher partial waves don't contribute to the low-energy scattering.[2] In the search program, one may restrict any phase shift to a fixed value. The program also permitted stepping a scale factor for the polarization function $P(\theta)$, which was useful in our case since the product $P_1P(\theta)$ was the measured quantity and the true value of P_1 was unknown.

The search was centered around the DGS phase shifts. Brown *et al.*[22] made a test using a grid of values in their p-He analysis and demonstrated that there is only a single valley in the χ^2 surface consistent with their polarization data. We assume that this is true in the n-He case also because of the similarity to p-He scattering.

Results of a study in which δ_0 and P_1 were changed in a stepwise fashion and δ_1^1 and δ_1^3 were searched are exhibited by way of a χ^2 contour plot in Figs. 4 and 5. In such a search routine, one hopes for a minimal χ^2 at the base of a conical valley, as is the case for the 2.44-MeV computation, where a well-defined bottom was found at $P_1=-0.458$ and $\delta_0=142.1°$. Unfortunately, this was not the case at 1.01 MeV. Here, the valley degenerated into a long, narrow trough. From Fig. 4 one can see that equally good fits can be obtained for values of δ_0 ranging from 160° to 145°. For this reason, it was obvious that some other criterion must be placed on either the value of δ_0 or P_1 in order that a

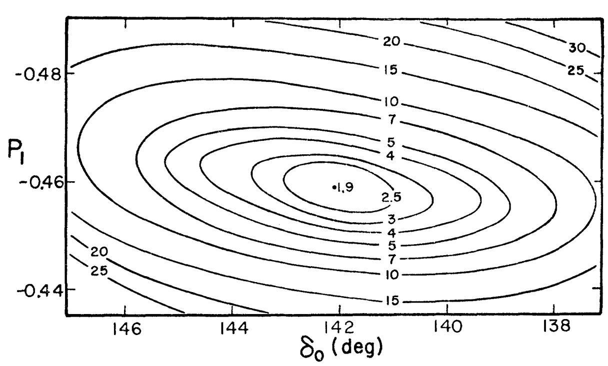

FIG. 5. Contour plot of χ^2 at 2.44 MeV for a range of values of $P1$ and δ_0. The value of equal χ^2 contour lines is indicated. The p phase shifts were the free parameters in the search at each grid point.

[29] S. J. Moss and W. Haeberli, Nucl. Phys. **72**, 417 (1965).

TABLE III. Phase shifts for n-He scattering.

Energy (MeV)	δ_0 (deg)	$\Delta\delta_0$ (deg)	δ_1^1 (deg)	$\Delta\delta_1^1$ (deg)	δ_1^3 (deg)	$\Delta\delta_1^3$ (deg)	Set
1.015	154.9		6.1		60.0		DGS
	155.9		6.1		63.0		HB
	155.5	±1.5	4.4	±1.0	61.2	±4.5	Present work
2.00	145.0		14.0		117.0		DGS
	146.0		15.0		118.0		HB
	145.8		15.4		119.0		Present analysis
2.44	141.3		18.4		121.4		DGS
	142.5		19.2		120.8		HB
	142.1	±2.4	21.2	±0.5	121.6	±0.5	Present work

unique set of phase shifts might be obtained at 1.01 MeV.

In Table III, the phase shifts extracted from the 2.44-MeV χ^2 plot are listed. As a result of the complex manner in which the phase shifts determined the polarization, it is difficult to estimate the uncertainty in these values. In the table, the $\Delta\delta$ listed for 2.44 MeV represents the approximate change in δ when χ^2 reached twice its minimum. Because of the way in which the splitting of the p phase shifts affects the polarization, there is some correlation between the magnitudes of the p phase shifts which is not represented by the errors shown. (See Ref. 11 for the values of the p phase shifts at the χ^2 minimum as a function of δ_0.) One should not confuse our $\Delta\delta$ with the usual standard deviation. However, this value can be used as a measure of the sensitivity of this experiment for determining phase shifts.

Since no sufficiently accurate values of P_1 are available, it was required that δ_0 must be preset in some fashion for the 1.015-MeV analysis. One method is to require that σ^T calculated from the phase shifts match the experimental value of about 7.0 b reported by Vaughn *et al.*[30] For our purposes, the large uncertainty in their results is inadequate. Another method for fixing δ_0 is to rely on the hard-sphere approximation for obtaining δ_0 at 1.01 MeV from the value of δ_0 at 2.44 MeV. The latter phase shift (142.1°±2.4°) yields a hard-sphere radius $R_0=2.42\pm0.13$ F, which in turn sets δ_0 (1.01 MeV) at 155.5±1.5°. This value of R_0 is in agreement with the value of 2.5 F found by Brown *et al.*[22] for the p-He interaction. The uncertainty $\Delta\delta$ listed in Table III for the 1.01-MeV p-wave phase shifts represents approximately the change in δ at the $\chi_{\min}^2$ when δ_0 took on the ±1.5° change. That artificial error represents the sensitivity of the analysis to the difference in δ_0 values. The ±7-keV uncertainty in neutron energy contributes very little to the uncertainty of δ_0 and δ_1^1. To δ_1^3 this causes an effect of $(d\delta_1^3/dE)\approx0.15°/\text{keV}$, which is small compared to the uncertainty produced by the uncertainty in R_0.

The low values of the χ^2 obtained for best fits indicate that the data points agree with the curves considerably better than one would expect from a purely statistical standpoint. The uncertainties in the data points include a large contribution from the nonsubtracting background; this was particularly true at 2.4 MeV. As the nonsubtracting background enters systematically and increases the error bars, it may explain the small values of χ^2 for the final fits to the data.

The $\theta_2=104°$ (c.m.) point at 1.0 MeV was omitted from the fit by statistical requirements. It was obvious in fitting the 1.0-MeV data that the polarization at this angle could not be satisfactorily fitted. Since this point was more than three standard deviations from the predicted value obtained using the other points alone, Chauvenet's criterion[31] justifies the omission of this point from consideration in determining the final fit.

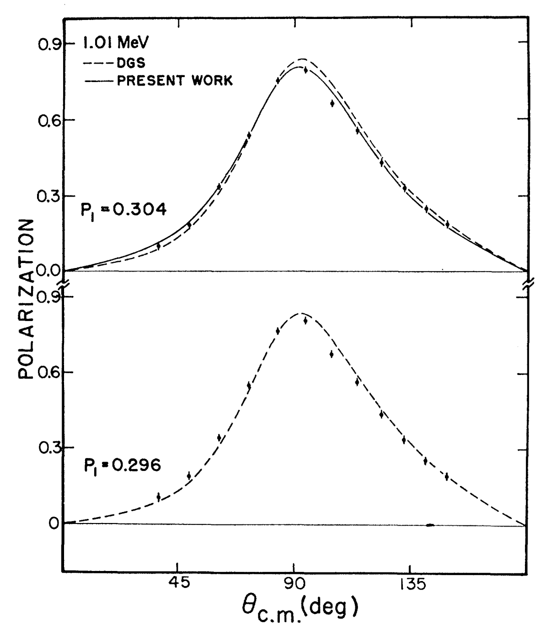

FIG. 6. Experimental values of P_2 at 2.44 MeV derived from the asymmetries assuming $P_1=0.304$ and 0.296 for the upper and lower parts, respectively. The solid curve is the calculated curve using phase shifts from the present work, the dashed curves using the DGS phase shifts.

[30] F. J. Vaughn, W. L. Imhof, R. G. Johnson, and M. Walt, Phys. Rev. **118**, 683 (1960).

[31] See, e.g., Yardley Beers, *Introduction to the Theory of Error* (Addison-Wesley Publishing Co., Cambridge, Mass., 1953).

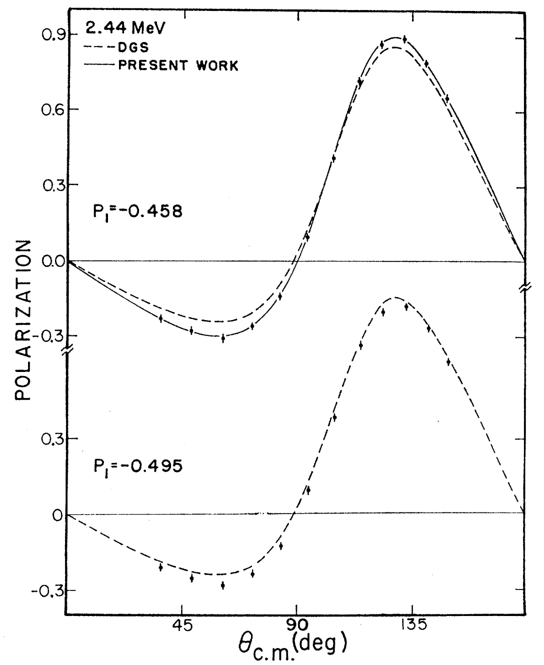

FIG. 7. Experimental values of P_2 at 2.44 MeV derived from the asymmetries assuming $P_1=-0.458$ and -0.495 for the upper and lower parts, respectively. The solid curve is the calculated curve using phase shifts from the present work, the dashed curves using the DGS phase shifts.

For comparison, values of phase shifts gotten by drawing a reasonable curve through the discrete HB and DGS δ's are also given in Table III. In view of the fact that the phase shifts of HB are only given to the nearest degree and those of DGS only every MeV, the agreement is quite close.

Values of $P_{\text{expt}}(\theta)$ determined in the present experiment, assuming P_1 for optimum fit, are shown in Figs. 6 and 7. Solid lines represent the values of P_{expt} calculated from the present phase shifts in Table III. Dashed lines are used to represent the values predicted by DGS. The lower portion of each figure shows the data with P_1 adjusted for optimum fit to DGS. The values for P_1 are shown. Present phase shifts provide a much more satisfactory fit to the data than DGS. For both energies the HB prediction provided a fit of poorer quality than DGS.

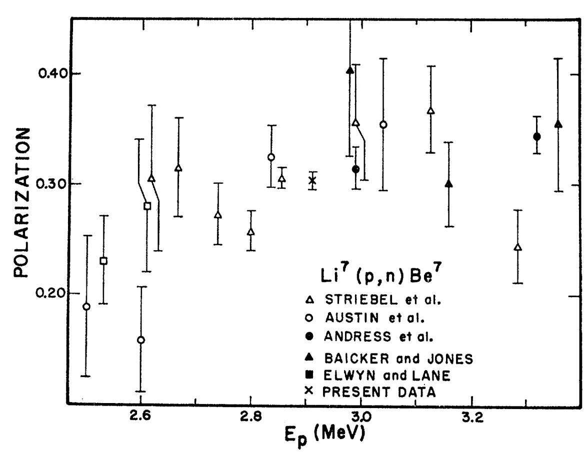

FIG. 8. Plot of the polarization produced in the $Li^7(p,n)$ reaction for emission angles near 50°. The previous experimenters listed have been referred to in Ref. 13. The value obtained in the present work is indicated by (×).

TABLE IV. Polarization data of May, Walter, and Barschall.

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	ϵ	ϵ_{corr}	$\Delta\epsilon$	P_2	$\pm\Delta P_2$
30	37.2	−0.030	−0.0317	0.011	−0.141	±0.050
40	49.3	−0.034	−0.0359	0.011	−0.159	±0.050
50	61.1	−0.018	−0.0194	0.012	−0.086	±0.055
60	72.6	−0.016	−0.0181	0.011	−0.081	±0.050
70	83.7	0.003	0.0031	0.011	0.014	±0.050
80	94.4	0.057	0.0591	0.013	0.262	±0.059
90	104.6	0.122	0.1281	0.013	0.568	±0.059
100	114.4	0.146	0.1531	0.014	0.679	±0.064
110	123.7	0.182	0.1886	0.014	0.836	±0.064
120	132.6	0.182	0.1868	0.015	0.828	±0.068

An extreme test was tried to determine the sensitivity of the phase shifts to the assumption that the nonsubtracting background was unpolarized, as is presumed in the above calculations. The test was to take the background to have the same polarization as the incident neutron beam, i.e., basically to ignore the existence of the background tail. The difference between the sets of δ's so derived and the sets in Table III averaged 0.1° at 1.01 MeV and 1.0° at 2.44 MeV, where both the background and P_1 were larger. Although the assumption in this check was unrealistic (as evidenced by the asymmetry curves in Figs. 2 and 3), it did show that the δ's listed are not sensitive to this background within reasonable limits on its polarization.

VII. PREVIOUS EXPERIMENTAL INFORMATION

The best test of the δ's seems to be the cross-section measurement in the following paper.[1] All the previous measurements[32] of differential and total cross sections are not accurate enough to distinguish between the various proposed sets of δ's in Table III. The other data at low energies are the polarization measurements of May *et al.*[9] In order to compare their published asymmetry data with predicted fits, we corrected the 2.00-MeV data for geometrical and multiple-scattering effects in a fashion similar to the corrections in the present work. The new values are listed in Table IV. The listed quantities are defined earlier in regard to Tables I and II.

The phase-shift fit program was used to search the corrected May *et al.* data for minimum χ^2 in order to

[32] See, e.g., S. M. Austin, H. H. Barschall, and R. E. Shamu, Phys. Rev. **126**, 1532 (1962).

extract a set of phase shifts. These data by themselves exhibit such large uncertainties that no unique fit could be defined. In order to sharpen the valley, the hard-sphere value for δ_0 was used. The values for P_2 are listed in Table IV for a $P_1=0.226$ for which the minimum in χ^2 was found. The phase shifts obtained are listed in Table III alongside of the DGS and HB sets. Although the May *et al.*[9] data do not allow a completely independent determination of the phase shifts, the set extracted does favor HB over DGS. (In fact, the set is nearly identical to the phase shifts proposed in the succeeding paper.)

VIII. INCIDENT POLARIZATION P_1

The present work, in addition to determining the phase shifts, provided a highly accurate determination of the polarization P_1 of the incident neutron beam. This was done by calculating χ^2 as a function of P_1, allowing all δ's to vary with the exception of the δ_0 at 1.01 MeV. The resulting χ^2 curves showed a well-defined minimum. If one assigns a liberal error by permitting χ^2 to move to $\pm 3\chi_{\min}^2$, one gets the values for P_1 of 0.304 ± 0.008 and -0.458 ± 0.011 for the neutron polarization from the $Li^7(p,n)$ reaction for $E_p=2.91$ MeV at 50° (33-keV-thick target) and the $C^{12}(d,n)$ reaction for $E_d=2.82$ at 25° (175-keV-thick target). These values are represented by the crosses in Figs. 8 and 9, where comparison is made with earlier measurements at nearby energies and angles.

All the known corrections have been applied to obtain the above values except the "magnetic depolarization" which is associated with the inhomogeneous magnetic field of the solenoid. This effect has been discussed by Atkinson and Sherwood[19] and their published curves and tables were employed to estimate the effect for the Duke solenoid. Extrapolation of their results gave an expected value of the fractional depolarization of 0.3% of the polarization. This would result in an increase in P_1 for the Li^7 neutrons of about 0.0009 and for the C^{12} neutrons, 0.0014. Because of the way the approximations were made in the extrapolation, these estimates are upper limits. Due to the small size of the corrections, it was not worthwhile to pursue more accurate calculations.

The values of P_1 are also based on the assumption that the nonsubtracting background was assumed to be unpolarized. If there was some polarized component in

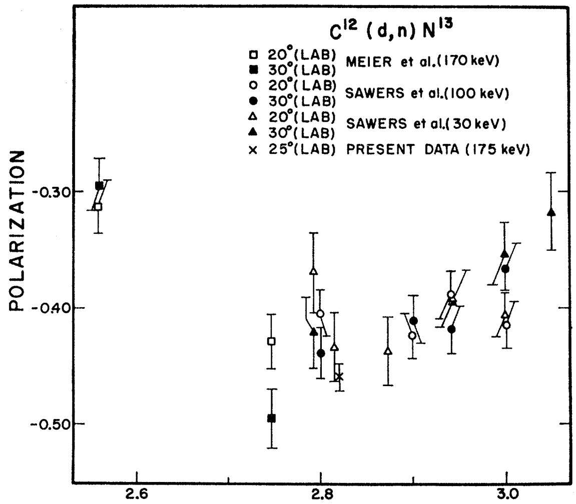

FIG. 9. Plot of the polarization produced in the $C^{12}(d,n)$ reaction for emission angles near 30°. Earlier data are from Refs. 15 and 16. The value obtained in the present work is indicated by (×).

this background, because of its possible causes, it would enter in such a way as to reduce the magnitude of P_1 slightly from the values given. However, as mentioned before, we feel strongly that this background was essentially unpolarized.

In fitting the 2.0-MeV data of May *et al.*[9] a value of $P_1=0.226$ gave the $\chi_{\min}^2$ for the $T(p,n)He^3$ reaction for $E_p=3.0$ MeV at $\theta=33°$.

IX. SUMMARY

Phase shifts have been derived for n-He scattering at 1.015 and 2.44 MeV. The values were somewhat inconsistent with previously existing sets and indicated the need for additional data on the n-He interaction at low energies. Further work and discussion on the n-He system is presented in the succeeding paper.[1]

ACKNOWLEDGMENTS

The authors would like to acknowledge the many fruitful discussions with Dr. F. O. Purser and the assistance of R. S. Thomason in taking the data. The aid and discussions offered by numerous other members of the nuclear physics group is greatly appreciated.