A New Method for Measuring the Polarization of Medium Energy Neutrons and the Phase Shift Analysis of $n - He^4$ Scattering

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A helium analyzer to measure the polarization of neutrons in the 1-18 mev energy range is described. The efficiency of the analyzer is about 100% in this range, and a typical counting rate is ~ 20 counts/min at a current of 10^5 neutrons/cm^2 sec. The background is practically zero.

The azimuthal asymmetry in the scattering of (D + D) neutrons from He^4 has been measured at neutron energies of 2.4 and 3.4 mev. Analysis of the results agrees with the experimental phase shifts given by Seagrave and disagrees with those of Huber and Baldinger.

1. INTRODUCTION

MOST nucleons produced in nuclear reactions appear to be partially polarized, as is to be expected from the strong spin dependence of nuclear forces. It would be interesting to study these polarizations systematically, both in order to obtain further information on nuclear processes and to find a source of strongly polarized particles.

The presently available data on neutron polarization are sparce and limited to the reactions $D(d, n)$ ($E_d = 600$ kev and Li (p, n) ($E_p = 2.262$ mev). It is hard to do more with the presently available methods, which use C^{12} or O^{16} as analyzers.

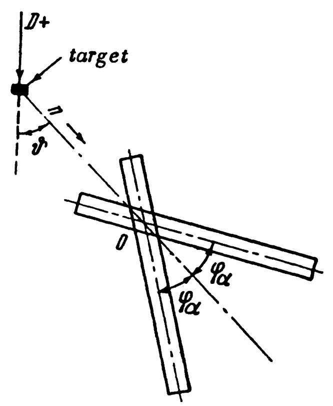

FIG. 1. Schematic drawing of apparatus.

In order to study neutron polarization systematically, an analyzer is needed which will give a large and accurately known polarization over a wide range of incident neutron energies. The levels of C^{13} and O^{17} are widely spaced in the energy range 1-20 mev and have widths of about 100 kev. Hence the polarization of neutrons scattered from C^{12} and O^{16} fluctuates, and an exact phase shift analysis is difficult because there are many levels corresponding to various states. Hence C^{12} or O^{16} are not very suitable for use as analyzers over a wide range of neutron energies and in any case demand a difficult phase shift analysis for each energy region.

A second fundamental disadvantage of these methods is the high neutron background due to neutrons reaching the detector directly from the target without passing through the analyzer. Even with elaborate shielding and collimation, the background is $\sim 80\%$ of the total effect, while the presence of the shielding no doubt complicates measurements on the angular dependence of the polarization.

In the present paper we describe a method for measuring neutron polarization which has an efficiency of ~ 1 at energies between 1 and 20 mev and which is practically free of background*. In addition, we have cleared up some points in the phase shift analysis for the scattering of neutrons by He^4 and measured the polarization of (D + D) neutrons using both thick and thin targets and deuterons of energies 400-1800 kev (cf Ref. 6).

Our analyzer uses He^4 as scatterer. Let us consider the polarization properties of this nucleus in more detail. Since the levels of He^4, if any exist, lie above 25 mev, neutrons incident with energies up to 20 mev can lead only to elastic scattering. Hence at these energies the states of He^5 can to a good approximation be derived from the motion of a neutron in an effective potential due to an unexcited alpha particle. The potential is equivalent to a well of depth $V_{eff} \approx 40$ mev, $r \approx 2 \times 10^{-13}$ cm, the well depth being strongly spin dependent[7]. As is well known, such an interaction gives scattering phase shifts which vary smoothly with energy. On the other hand, the small radius limits the orbital angular momentum of the scattered waves to

* The principle of the method and preliminary results on the phase shifts in n-He^4 scattering are given in Ref. 5.

P states for $E_n \lesssim 10$ mev and to D states for $E_n \lesssim 20$ mev. The phase analysis is simple because there are few phase shifts and they vary slowly with energy*. The strong spin orbit splitting gives a large and smoothly varying polarization, which, for convenient scattering angles, turns out to be about one in the whole energy range 1-20 mev.

The second advantage of He^4 as an analyzer is that we can detect the recoil nuclei rather than the scattered neutrons, thus eliminating background problems.

As detectors we used thin proportional counters filled with helium (Fig. 1). The apparatus was set up to detect He^4 nuclei recoiling at that angle φ_α with the incident beam which gave the largest azimuthal asymmetry in the scattering of polarized neutrons with given energy from He^4. To do this, the counters were placed along the direction φ_α; then the helium pressure and discriminator settings were chosen so that only the nuclei recoiling along the counter axis were detected. The azimuthal asymmetry R was measured by comparing the counting rate I_1 when the counter was in position φ_α with the counting rate I_2 in the position $-\varphi_\alpha$:

$$R = I_1/I_2 = (1 + \overline{P}_x \cdot \overline{P}_{He})/(1 - \overline{P}_x \cdot \overline{P}_{He}).$$

Here $\overline{P}_x$ is the polarization of the incident neutrons, averaged over the volume in which the recoil nuclei were formed (the working volume), while $\overline{P}_{He}$ is the polarization resulting from neutron scattering on He^4, averaged over the scattering angles.

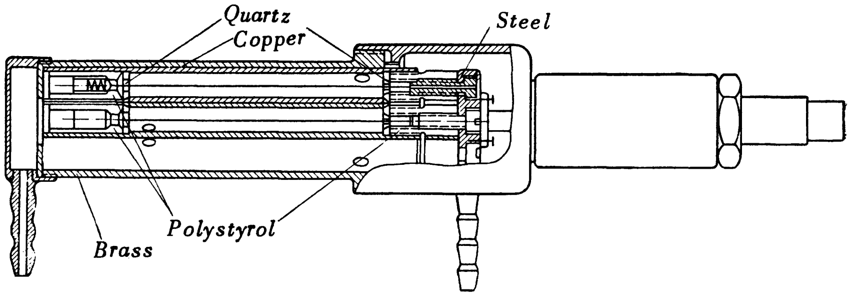

FIG. 2. Construction of the proportional counter.

In order to find P_x, it is necessary to know the phase shifts for n-He^4 scattering. At the present time, two phase shift analyses have been carried out, using the angular distribution of the scattered neutrons. These are the analyses of Huber and Baldinger[11] and Seagrave[8]. They do not agree with each other, especially for $P_{1/2}$. The discrepancy is apparently fundamentally due to the fact that it is difficult to obtain phase splits, arising from spin-dependent forces, using only the differential cross section $\sigma_0(\theta)$ for unpolarized neutrons. This is because the spin-orbit splitting appears in $\sigma_0(\theta)$ as a correction proportional to $\sin^2(\delta_l^+ - \delta_l^-)$. Hence for fixed $(1+l)\delta_l^+ + l\delta_l^-$, $\sigma_0(\theta)$ is often quite insensitive to changes in $(\delta_l^+ - \delta_l^-)$.

On the other hand, the polarization is directly proportional to $\sin(\delta_l^+ - \delta_l^-)$ and hence is sensitive to the magnitude of the spin orbit splitting. Thus even if the incident beam is not very polarized, a measurement of the angular dependence of the axial asymmetry in n-He^4 scattering, using the method described above, can lead to a more exact phase analysis.

We used the (D + D) reaction as a source of polarized neutrons. Since this is not a resonance reaction, it is reasonable to expect that P_n varies smoothly with deuteron energy. This makes the neutrons from the (D + D) reaction especially suitable to use in carrying out a phase shift analysis on n-He^4. It was immaterial that the polarization of the neutrons from the (D + D) reaction was known at only one energy (E_d = 600 kev), since measurements of the azimuthal asymmetry at various scattering angles in n-He^4 allowed us to obtain both the n-He^4 phase shifts and, at the same time, obtain the polarization of the (D + D) neutrons.

2. MEASUREMENTS ON THE AZIMUTHAL ASYMMETRY IN n-He^4 SCATTERING

The detector is shown in Fig. 2. Seven copper

* The results of the analysis can also be compared with the measured phase shifts for elastic proton scattering on He^4[8-10].

tubes, each of inner diameter 7 mm, were soldered together into one block and placed in an airtight container. The tungsten wires in the counters were 0.07 mm in diameter. They were centered through openings in the polystyrene insulators by brass screws. High voltage from a battery was applied simultaneously to all the counters. The quartz washers shielded the working volume from recoil protons produced in the polystyrene insulators. The centering was to 150μ, which limited that part of the uncertainty in the gas multiplication factor which arose from lack of centering to ±1%.

Figure 3 shows a general view of the apparatus. Two groups of counters were used, one on each side of the target. The counter supports could be moved around on a light brass ring whose center was at the target. The counters could be rotated individually on their own supports, their angle of rotation φ_α being read off on a graduated scale. The angle of emission of the neutrons detected was fixed by a scale on the brass ring.

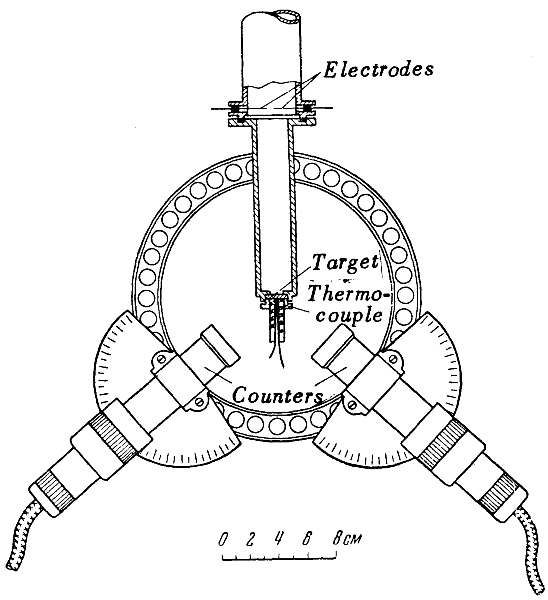

FIG. 3. General view of the experiment.

The geometry of the experiment was such that the position of the neutron source had to be precisely known. To achieve this, electrodes were placed in the tube with the target and connected to a null reading galvanometer. This, together with small correcting magnets, allowed us to determine the position of the ion beam on the target to within 0.2 mm.

Measurements were made using thick and thin zirconium targets saturated with deuterium. The temperature of the target was controlled by a thermocouple and maintained at ~ 200° C. This was to prevent the formation of a carbon film, which can arise from breakdown of adsorbed oil under the action of the beam. A uranium fission chamber 10 cm from the target served as monitor. Less than 1% of the neutrons counted in the chamber were formed outside the target (on the diaphragms, electrodes etc). In all the experiments the helium pressure was chosen so that the recoil He^4 nuclei going down the counter axis had a range of 44 mm. The energy of the recoil nuclei was $E_\alpha = 0.64 E_n \times \cos^2 \varphi_\alpha$ (where E_n is the neutron energy). Data on the slowing down of alpha particles in helium were taken from Ref. 12. The solid angle into which the helium recoil nuclei had to go in order to be counted depended on the discriminator setting and was adjusted to be 10 to 18°, depending on the intensity available.

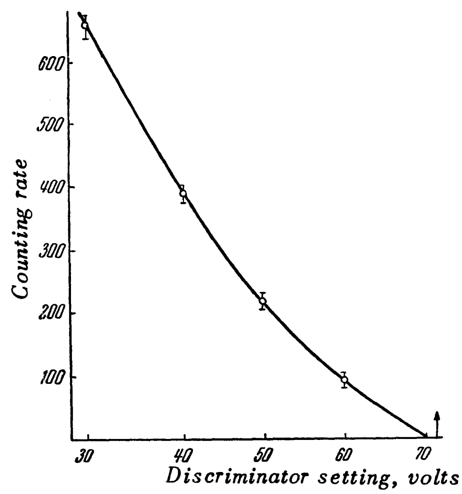

FIG. 4. Spectrum of pulses produced by recoil He^4 nuclei when the counter is in the position $\varphi_\alpha = 0°$. The solid line gives the spectrum calculated from the cross section $\sigma_{n\alpha}(\theta)$ and geometrical factors.

A constant helium current was passed through the counters in order to keep the composition of the gas the same. The current was 30-40 cm^3/min and was controlled by a rheometer at the output of the gas system. In setting the helium pressure, on which the gas multiplication of the counters depends critically, variations in atmospheric pressure were taken into account. Special automatic equipment kept the pressure constant to 0.1%.

Our set up used type DB linear amplifiers feeding five-channel integral discriminators. The scales of the latter were calibrated as follows:

The counters were set to $\varphi_\alpha = 0°$ and the pulse height spectrum taken near its upper boundary. In this case the largest pulses come from head on collisions between neutrons and He^4. Using five discriminator channels the upper limit of the spectrum could be determined to 2% and hence the discriminator scale calibrated in terms of the energy with which the helium nuclei recoiled (Fig. 4)*.

The following points were checked:

1) linearity of the gas multiplication and of the electronics,

2) sensitivity of the apparatus to background neutrons,

3) effect of neutron scattering from the counter walls on the measured asymmetry,

4) dependence of the gas multiplication on helium pressure and current,

5) distortion of the results due to superposition of pulses.

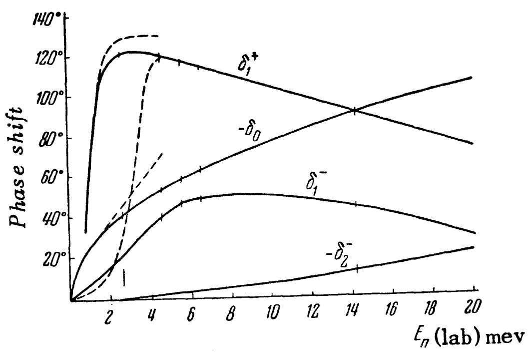

FIG. 5. Energy dependence of the phase shifts in n-He^4 scattering. Dotted curves: from Huber and Baldinger[11]; solid curves: calculated from p-He^4 phase shifts. The experimental points are Seagrave's data[8].

In order to check on the linearity of the amplification, the observed pulse height spectrum was compared with one calculated from data on $\sigma_{n\alpha}(\theta)$ and geometrical considerations. The good agreement between the two spectra (Fig. 4) indicates that departures from linearity are negligible.

The sensitivity of the apparatus to a background of scattered neutrons was estimated by bringing up a heavy (70 kg) lead scatterer close (20 cm) to the counters. No change was observed in the counting rate.

* In the following, discriminator settings are given in units such that one corresponds to the pulse height from head on collisions.

To check on whether neutron scattering from the counter walls was affecting the measured asymmetry, the wall thickness was trebled for one run by adding a lead covering. This led to a slight decrease in counting rate (~ 10%) but had no effect on the measured asymmetry within the statistical error (~ 3%).

The gas amplification depends critically on the pressure of helium and on contaminants. The helium used in the measurements was 99.8% pure. The variation in gas amplification with pressure is 0.017 mm Hg^{-1} (the amplification at 1100 mm Hg being taken to be 1). At speeds $< 10\ cm^3/min$, the gas amplification is particularly sensitive to the helium flow which kept the gas composition constant. At speeds $> 30\ cm^3/min$, the amplification scarcely changed at all with changing helium current.

No distortion due to superposition of pulses was detected at the highest counting rate (1500 pulses/sec) used. The asymmetry measurements were made to 3% at ion currents of 20 and 5 μamp.

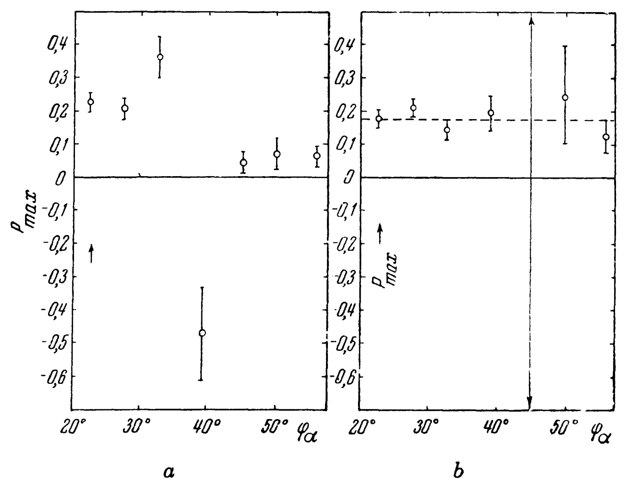

FIG. 6. Values of P_{max} obtained from the experimental data at various counter positions φ_α. a – using the phase shift from Huber and Baldinger[11], b – using Seagrave's phase shift[8].

The sensitivity of the apparatus to neutrons was as follows: at a neutron current of 3×10^5 neutrons/cm^2 sec ($E_n \approx 3.5$ mev) and angle $\varphi_\alpha = 22°$, the discriminator channels set at 0.4, 0.5, 0.6, 0.7 and 0.8 registered about 180, 125, 75, 35 and 17 counts/min respectively.

3. PHASE SHIFT ANALYSIS OF NEUTRON SCATTERING FROM He^4

Since the geometry of the analyzer was rather

"bad", it would have been difficult to carry out a complete phase analysis from the asymmetry measurements. Hence we limited ourselves to investigating two points on the most doubtful phase shift, δ_1^-, and took the other phases δ_0 and δ_1^+ to be sufficiently well known. This choice was made on the basis of the following considerations:
1) The experimental data of Huber and Baldinger[11] and Seagrave[8] on the phases δ_0 and δ_1^+ agree quite well, but disagree strongly on δ_1^- (cf Fig. 5).
2) Charge symmetry implies a definite relation between the phases for n-He^4 and p-He^4. Since the p-He^4 phase shifts have been measured much more accurately than those of n-He^4, analysis of the proton data gives independent information on the n-He^4 phase shifts. Adair[9] and Dodder and Gammel[10] carried out an approximate calculation of the n-He^4 phase shifts from the p-He^4 ones using the method of Wigner and Eisenbud. The results were in satisfactory agreement with experiment (Fig. 5) for the phases δ_0 and δ_1^+. The δ_1^- phase differs appreciably from the δ_1^- obtained by Huber, but, except for one point at 2.61 mev*, agrees with the δ_1^- given by Seagrave.
3) A large peak in the total cross section occurs at around 1 mev neutron energy. This is due to the $P_{3/2}$ level in He^5. Since the $P_{3/2}$ state accounts for about 90% of the total cross section at these energies, Γ and E_{res} can be obtained from the shape of the peak, and from them

$$\delta_1 = \text{arc tg}\,[{}^1/_2\Gamma/(E_{\text{res}} - E_n)].$$

calculated. The δ_1^+ so obtained agrees with that obtained from the analysis of $\sigma(\theta)$ for n-He^4 scattering.

We measured δ_1^- for neutron energies of 2.45 and 3.4 mev. The 3.4 mev point is interesting because according to the data of Huber and Baldinger, δ_1^- passes through $\pi/2$ here, which indicates a $P_{1/2}$ state in He^5.

Energy $E_n = 3.4$ mev.

Neutrons of this energy were emitted at $\theta_n = 49°$ when 800 kev deuterons bombarded the target. The asymmetry in the scattering was measured at 7 angles φ_α. The results are shown in the following table.

TABLE

Counter position	22,5°	27,5°	32,5°	39°	45°	50°	56°
Helium pressure (atm.)	1.340	1.213	1.100	0.935	0.790	0.680	0.540
Discriminator setting	0.75	0.67	0.60	0.49	0.40	0.33	0.25
Solid angle $\Delta\Omega$	10°25′	10°35′	10°40′	11°05′	11°30′	12°00′	12°35′
Measured asymmetry	1.259 ±0.037	1.250 ±0.039	1.105 ±0.033	1.033 ±0.042	0.835 ±0.020	0.807 ±0.032	0.780 ±0.022

Before obtaining $P_{n\alpha}$ and $P_{D(dn)}$ from the data, several corrections have to be made for the poor geometry. The measured asymmetry can be written

$$R = \int \sigma_{DD}\sigma_{n-\alpha}\Delta\Omega r^{-2}(1 + P_x P_{n-\alpha})dv \Big/ \int \sigma_{DD}\sigma_{n-\alpha}\Delta\Omega r^{-2}(1 - P_x P_{n-\alpha})\,dv. \quad (1)$$

where σ_{DD} is the differential cross section of the (D + D) reaction, $\sigma_{n\alpha}$ is the differential scattering cross section, P_x the polarization of the neutrons, $P_{n\alpha}$ the polarization of neutrons scattered from helium, $\Delta\Omega$ the solid angle in which the recoil nuclei were counted and r the distance from the target to an elementary counter volume. We can regard P_x and $P_{n\alpha}$ as known functions of P_{max} and δ_1^-, where P_{max} is the maximal polarization of D(dn) for a given E_d (cf Ref. 13):

$$P_x = P_{\max}\frac{\sin 2\theta}{\sigma(\theta)}K(E_d),$$

$K(E_d)$ is a normalization constant. The connection between P_n and the phase δ_1^- is given by Lepore[14]. Thus formula (1) reduces to an equation with two unknowns:

* The fact that this discrepancy is real was pointed out to us by Sigrein (private communication).

$$R = f(\delta_1^-, P_{max}).$$

For a fixed δ_1^-, and each of the seven measured values of R, P_{max} can be calculated. The calculation was carried out graphically: two values of P_{max} were chosen, one making $f(\delta_1^-, P_{max})$ a little larger than the measured asymmetry R, the other a little smaller. The value of P_{max} corresponding to the measured asymmetry (taking its errors into account) was then found by interpolation. Values of the function $f(\delta_1^-, P_{max})$ were found by numerical integration, the working volume of each counter being subdivided into 20 parts for this purpose.

A proposed value for δ_1^- was checked in the following way:

1) The asymmetry was measured at seven angles φ_α (cf the table above).
2) The maximal polarization P_{max} of neutrons from the (D + D) reaction was calculated for each of the seven angles, and two values of δ_1^-: 30° (Seagrave) and 90° (Huber and Baldinger).
3) The seven values of P_{max} obtained for each value of δ_1^- were compared with each other. Good agreement supported whichever value of δ_1^- had been used.

The results are shown in Fig. 6. Clearly the scatter in the values of P_{max} obtained using $\delta_1^- = 90°$ (Huber and Baldinger) is more than experimental error, while the scatter of those obtained with $\delta_1^- = 30°$ (Seagrave) is within experimental error. The polarization of neutrons from the (D + D) reaction is $P_{max} = 0.17$ in this case.

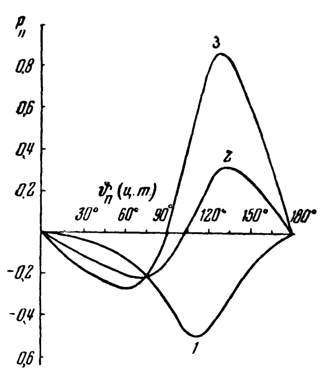

FIG. 7. Polarization of 2.45 mev neutrons scattered from He^4, as calculated for three values of δ_1^-: 1 – 0°, 2 – 10°, 3 – 10°10′ ($\delta_0 = -39°10′$, $\delta_1^+ = 121°10′$)

Energy $E_n = 2.45$ mev

δ_1^- was obtained by comparing the experimental asymmetry in the scattering of neutrons with a known polarization with the asymmetry calculated using various values for δ_1^-. Such a measurement depends critically on the value of δ_1^-. This is shown by Fig. 7, in which polarization is plotted against angle for the scattering of 2.45 mev neutrons from He^4. The calculations were carried out using Seagrave's values for δ_0 and δ_1^+ and for three values of δ_1^-: 0°, 10° and 19° 10′.

2.45 mev neutrons were obtained at an angle $\theta_n = 106°$ (121° in c.m.) with 1800 kev deuterons. At this angle, the polarization of the D + D neutrons is close to maximal. Since, in the D + D reaction, the collision is between two identical particles, $P(\pi - \theta_{c.m.}) = -P(\theta_{c.m.})$. Therefore the polarization of neutrons going "back" at an angle $\theta_{c.m.} = 121°$ can be found directly from the data on the asymmetry in the scattering of neutrons going "forward" at an angle $\theta_{c.m.} = 59°$, since for the latter neutrons we can take the value for δ_1^- given by Seagrave. Indeed, the energy of the neutrons going "forward" is 4.11 mev, i.e., close to where our measurements confirmed Seagrave's analysis. Furthermore, at this energy Seagrave's analysis agrees with the proton one.

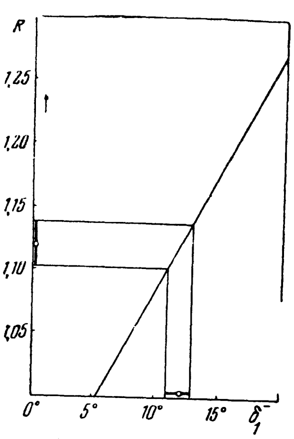

FIG. 8. The expected asymmetry R in the scattering of 2.45 mev neutrons as a function of the phase δ_1^-. The measured value of R, 1.120 ± 0.18, corresponds to $\delta_1^- = 12 \pm 1°$.

The asymmetry in the scattering of neutrons emitted "forward" at $\theta_{n(c.m.)} = 59°$ from a thin

(~ 150 kev) target (for details, see Ref. 6) when bombarded by 1800 kev deuterons was measured and yielded a neutron polarization $P_{max} = 0.170 \pm 0.010$. The asymmetry in the scattering of neutrons emitted "backward" from the same target was measured with the counter rotated to $\varphi_\alpha = 26°$.

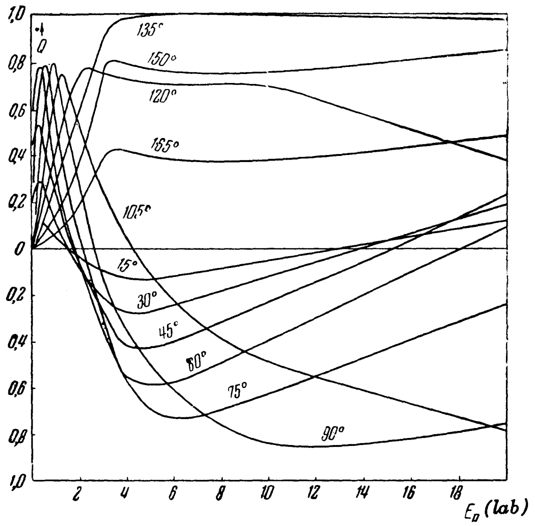

FIG. 9. The polarization of neutrons scattered from He^4 as a function of neutron energy E_n for various scattering angles in the center of mass frame. The curves are calculated from the phase shifts given by Seagrave[8]. The angle at which the He^4 nucleus recoils is $\varphi_\alpha = (\pi - \theta_n)/2$ in the laboratory frame.

With a discriminator setting 0.4 and helium pressure 0.87 atm., the asymmetry turned out to be 1.120 ± 0.018. Figure 8 shows how the expected asymmetry in these measurements depends on the phase δ_1^-. This curve was calculated by the same method used for $E_n = 3.5$ mev. From Fig. 8 we can conclude that the measured asymmetry corresponds to $\delta_1^- = 12 \pm 1°$, i.e., δ_1^- differs considerably from the value obtained from the proton data, but agrees with the experimental data of Seagrave.

Our confirmation of Seagrave's phases clears the way to using helium as a convenient and well calibrated analyzer for polarized neutrons. Figure 9 shows the polarization of neutrons scattered from He^4 as a function of neutron energy and for various scattering angles in the center of mass system.

Our results confirm Seagrave's values for the phase shift δ_1^- at $E_n = 2.61$ mev. The discrepancy between δ_1^- as obtained from the proton data by Dodder and Gammel[10] and the measured value should be attributed to the inadequacy of the Wigner-Eisenbud formalism in this case. The assumption that the logarithmic derivative is linear over such a wide energy range is particularly doubtful.

We should like to thank S. N. Malyshko and E. Z. Tarumov for their help in carrying out the experiment, and to Prof. A. I. Shal'nikov for preparing important parts of the apparatus.

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