NEUTRON POLARIZATION IN THE REACTIONS $T(p, n)He^3$ *AND* $D(d, n)He^3$

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Submitted to JETP editor May 28, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) 45, 1416-1424 (November, 1963)

Asymmetry of $n\alpha$ scattering through an angle $\theta_n = 123 \pm 5°$ is measured for neutrons from the reactions $T(p, n)He^3$ for E_p ranging from 12 to 17 MeV and $D(d, n)He^3$ for E_d between 12 and 20 MeV. The analyzer employed was a helium gas chamber—scintillator in coincidence with two neutron counters. In order to exclude geometric asymmetry effects, the neutron spin was rotated 90° in a magnetic field. In the $T(p, n)He^3$ reaction an asymmetry of 20 per cent was observed at an angle $\theta_{lab} \approx 45°$ for all energies investigated. In the $D(d, n)He^3$ reaction the asymmetry at $\theta_{lab} = 30°$ reached (32.5 ± 6.0) per cent at $E_d = 14$ MeV and decreased slowly with further increase of energy. The directions of neutron polarization in the two reactions were opposite.

1. INTRODUCTION

NEUTRON polarization studies are valuable for investigations of the spin dependence of nuclear forces, for the determination of the quantum characteristics of nuclei in different states, and for an understanding of the mechanism of some nuclear reactions. Recent experiments have shown that nuclear reactions with unpolarized beams and targets result as a rule in polarized nucleons. This means that spin-orbit nuclear forces play an appreciable role in nuclear collisions.

For a quantitative description of the spin-orbit nuclear forces it is necessary to investigate in detail the scattering of polarized nucleons or the polarization of unpolarized nucleons upon scattering. Methods for research with polarized nucleons have developed rapidly in recent years. The results obtained so far pertain principally to proton scattering by nuclei[1], since simpler methods are needed for experiments with protons. At the same time, Coulomb interaction with the nuclei makes the observation and interpretation of polarization difficult.

Research with polarized neutrons is much cleaner and more universal, although the methods required are much more complicated. Polarized fast neutrons were observed first in the reactions $D(d, n)He^3$ and $Li^7(p, n)Be^7$ [2-5]. These sources were used by Barschall[6] and in a few other experiments[7] to study the scattering of polarized neutrons with energy $E_n < 4$ MeV by many nuclei, in order to determine the parameters of the spin-orbit nuclear potential. However, the theoretical analysis of these results[8-10] was found to be difficult, for at such low neutron energies an appreciable role is assumed by elastic scattering via a compound nucleus, which distorts the potential scattering effect describable with the aid of the optical model of the nucleus.

This adds to the importance of searches for sources of high-energy polarized neutrons. These searches are still under way principally along the line of examining the sources most widely used in many laboratories. Polarization of 8—9 MeV neutrons obtained from the $T(p, n)He^3$ reaction was observed in our laboratory in 1959[11]. More detailed investigations of neutron polarization in this reaction, with protons up to 12 MeV, were made recently in Wisconsin[12] and have confirmed the earlier results. At approximately the same time, the $D(d, n)He^3$ and $T(d, n)He^4$ reactions were investigated with deuteron energies E_d up to 11 MeV[13] and 7.7 MeV[14], respectively. Reviews of the present status of polarized-neutron research were presented by Barschall[15] and Haeberli[16] at a conference in Houston.

The main purpose of the present paper was to measure the polarization of neutrons in the $T(p, n)He^3$ and $D(d, n)He^3$ reactions at energies not covered by the earlier experiments, and to search for sources of polarized neutrons with energy > 10 MeV.

2. MEASUREMENT CONDITIONS

The procedure used in the measurement has by now become almost universal. Polarization is analyzed by using gaseous helium to scatter the neutrons. The scattered neutrons are registered by plastic scintillators connected for coincidence with the helium scintillator-scatterer that registers the recoil α particles. Thus, the analyzer consists of a helium chamber and two neutron counters, and registers simultaneously the intensity of neutron scattering 'to the right' and 'to the left.' The spectrum of the helium-chamber pulses coinciding with the counter pulses is representative of the spectrum of the investigated neutrons. In all our experiments we kept the scattering angle constant at $\theta_2 = 123°$. According to available data, this angle corresponds to maximum right-left asymmetry of N_α scattering over a wide energy interval.

A solenoid was installed between the cyclotron target and the analyzer to turn the neutron spin 90°. The right-left asymmetry of scattering is measured by reversing the current in the solenoid, so that false effects due to geometrical asymmetry are eliminated. The procedure was described in greater detail in [17].

The charged-particle beams were obtained from the cyclotron of the Atomic Energy Institute. The cyclotron has been improved and converted for operation with variable energy, with the upper proton energy limit raised to 17 MeV[18]. The particle energy was determined from the current in the deflecting magnet on the basis of prior calibration against the time of flight and range in aluminum. For a narrow target the energy is determined accurate to approximately 0.3 per cent. Under the conditions of the present experiment, the energy uncertainty depended on the target width and reached 100 keV. The particle flux to the target was measured accurate to approximately 1 per cent with the aid of an integrator.

For the $T(p, n)He^3$ reaction we used a solid T + Zr target 14.3 mg/cm^2 thick on a tungsten substrate. The target diameter was 20 mm. The background was measured by placing in the beam a zirconium target of the same thickness. A gas target 50 mm thick was used for the $D(d, n)He^3$ reaction, at a deuterium pressure of 4.4 atmospheres. The iron-foil entrance and exit windows were 20 mm in diameter and 11 mg/cm^2 thick. In this case the beam passing through the target was deflected 50 cm away from the target and made to strike the lead walls of a beam-current meter (Faraday cylinder). The background from such a 'shot through' target was due only to the reactions in the windows, the analyzer being screened from the substrate. The background measurements were made with the same target but without the deuterium. The energy losses in the target and in the windows were taken into account in determining the energy of the bombarding particles.

The helium scattering chamber was placed at different angles θ_1 to the cyclotron beam, 2—2.8 m away from the target. Most measurements were made with a cylindrical chamber 88 mm in diameter and 120 mm high, filled with a mixture of He + Xe (3%) to a pressure of approximately 80 atmospheres. The plastic scintillators, 70 mm in diameter and 100 mm high, were placed in a vertical plane at 123° to the axis of the neutron beam incident on the helium chamber. The distance between the centers of each counter and the chamber was 40 cm.

The coincidences of the pulses for each of the two counters with the pulse from the helium chambers triggered a 256-channel ÉLA-2 analyzer, with which the spectra of the chamber were registered. One of the counters triggered channels 1—128 and the other channels 129—256. Thus, two spectra of chamber pulses were registered simultaneously, each corresponding to the pulses coinciding with one of the counters.

3. RESULTS

Figure 1 shows the results of one of the measurements. The polarized neutrons produce a spectral line whose intensities varies when the current in the coil is reversed. The intensity of the line increases in one of the counters and decreases in the other, since the counters are on opposite sides

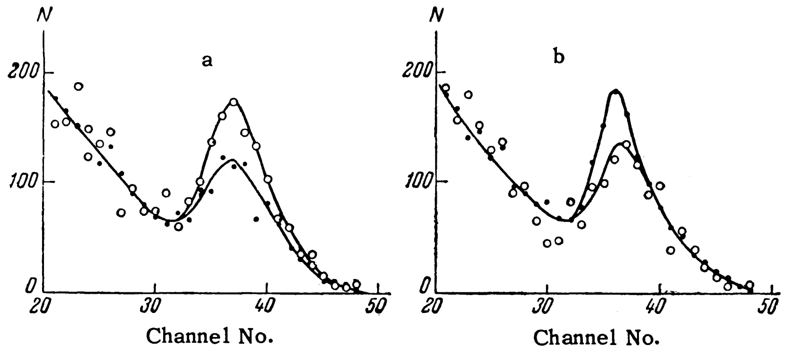

FIG. 1: Spectra of recoil α particles for coincidences between the helium-chamber pulses and the pulses from the two neutron counters, for opposite directions of the magnetic field of the coil: a—lower counter, b—upper counter; ●—current in the solenoid to the left, o—current to the right.

of the reaction symmetry plane, and when one registers scattering 'to the right' the other registers scattering "to the left," and vice versa with the solenoid field reversed. The decreasing part of the spectrum to the left of the line is the background due to the target windows and the substrate, and also the random-coincidence background.

The line intensity was determined from the total number of counts in the channels with number > n, with account of the background and of the random coincidences. The data were reduced with the spectrum cutoff at three different values of n, from the left edge of the line to its maximum. The asymmetry values obtained for different n agree within the limits of statistical accuracy. The final statistical error of the results was determined from the number of counts constituting the total line intensity. The asymmetry was determined by comparing the counts from each counter for opposite coil current directions.

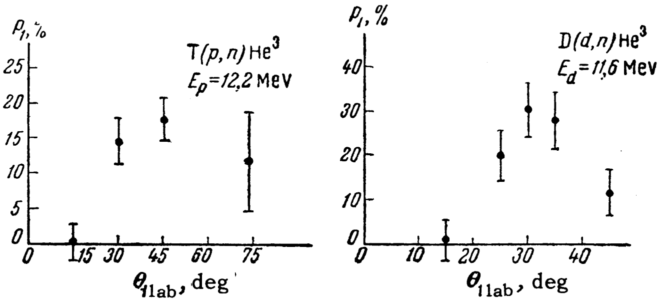

FIG. 2. Angular distributions of neutron polarization.

Figure 2 shows the angular distribution of the right-left asymmetry, observed in the $T(p, n)He^3$ reaction at a proton energy 12.2 MeV. The maximum asymmetry was observed at approximately 40°. The sign of the asymmetry corresponds to negative polarization. Analogous results were obtained for $E_p = 14.5$ and 16.5 MeV. The angular distribution of the polarization does not change noticeably when the energy is increased to 17 MeV. The magnitude of the polarization was calculated under the assumption that the asymmetry of the $n\alpha$ scattering follows the curves given in [19]. The effective values assumed for the asymmetry $\overline{P}_2$ are indicated in the table, with allowance for the angular resolution.

Figure 3 shows the dependence of the polarization obtained in this manner on the proton energy. The second scale gives the energy of the corresponding neutrons. The same figure shows the results obtained earlier at lower proton energies [12]. They pertain to somewhat different values of the angle θ_1, and the slight scatter of the results

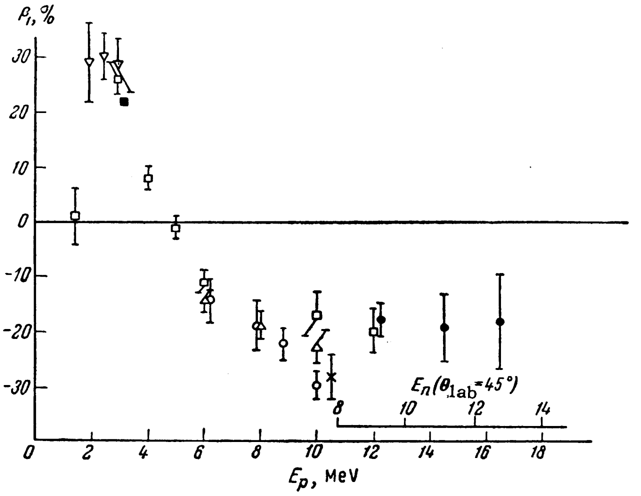

FIG. 3. Energy dependence of neutron polarization in the $T(p,n)He^3$ reaction: □ – data of[12], $\theta_{cms} = 45°$; ∇ – data of S. E. Darden (private communication), $\theta_{1ab} = 30°$; ■ – [20], $\theta_{1ab} = 33°$; △ – [12]; $\theta_{1ab} = 40°$; ○ – [11], $\theta_{1ab} = 40°$; × – [17], $\theta_{1ab} = 40°$; ● – present work, $\theta_{1ab} = 45°$.

in the neighboring energy region can be partially attributed to this. However, all the points give a polarization close to maximal and illustrate its energy dependence. The preceding measurements disclosed a continuous increase of the polarization with increase in E_p from 4 to 12 MeV. The present measurements show that further increase in the energy is not accompanied by an increase in polarization, which remains at a level of ~20 per cent or even decreases slowly.

The polarization of the neutrons in the $D(d, n)He^3$ reaction was investigated in many experiments at low deuteron energy up to 2 MeV[21, 22]. At large energies, up to 11 MeV, the most complete data are found in the paper by Dubbeldam and Walter[13], which cites earlier investigations their principal results. In the energy region $E_d < 5$ MeV, the results of Dubbeldam and Walter[13] do not agree with the earlier results of Baicker and Jones[23]. Measurements were made recently at 9 and 12 MeV by Trostin and Smotryaev[24], who also obtained polarizations noticeably different from those obtained at Wisconsin[13]. Thus, the polarization data are contradictory for $E_d \leq 12$ MeV and there are none for $E_d > 12$ MeV.

In the present investigation we extended the measurements to $E_d = 19.2$ MeV. The angular distribution of the asymmetry has been measured at 11.6 MeV. The results of these measurements are shown in Fig. 2. For $E_d = 19.2$ MeV, measurements were made for only two angles, 30 and 20°. They show that the maximum of the asymmetry does not shift noticeably to the small-angle region, as might be expected from general considerations. However, the question of the angle corresponding to the maximum polarization at E_d = 19.2 MeV has not been solved. The character of the angular distribution at E_d = 11.6 MeV does not differ noticeably from the results obtained at lower energies. The asymmetry at an angle close to 30° (in the laboratory system) is apparently close to maximal in the energy interval from 4—5 to 19 MeV. The sign of the asymmetry corresponds to positive polarization (according to the Basel convention) and consequently is opposite that of the polarization observed in the T(p, n)He^3 reaction. To calculate the polarization from the observed asymmetry, the same data[19] on the asymmetry in nα scattering were used, with analogous corrections for the angular resolution of the analyzer.

The dependence of the polarization on the deuteron energy is shown in Fig. 4. For $E_d \leq 12$ MeV, the results were obtained in previous investigations[13,21,22], while the data for $E_d > 12$ MeV were obtained in the present work. For $E_d \approx 12$ MeV, our results agree satisfactorily with those of Dubbeldam and Walter[13]. The tendency noted in earlier experiments for the polarization to increase at $E_d > 12$ MeV was not confirmed. At E_d = 14 MeV, the polarization reached ~30 per cent and remained practically constant to 19 MeV. The same figure shows the energy scale of the neutrons emitted at 30°, corresponding to maximum polarization.

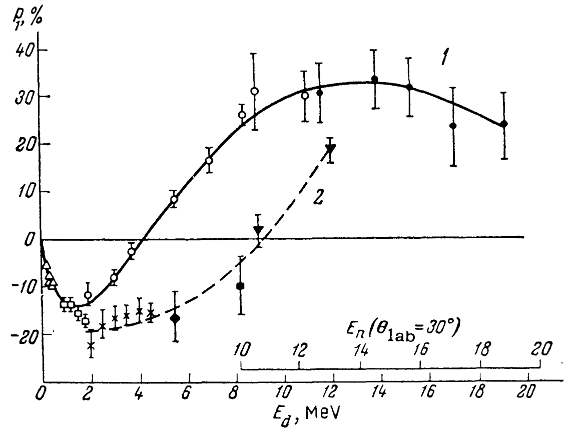

FIG. 4. Energy dependence of the polarization of neutrons from the reaction D(d,n)He^3: △ – data of[22], θ_{1ab} = 47°; □ – [21], θ_{1ab} = 49°; × – [23], θ_{1ab} = 40°, ◆ – [25], θ_{1ab} = 40°; ■ – [26], θ_{cms} = 47°; ▼ – [24], θ_{1ab} = 30°; ○ – [13,20], θ_{cms} = 45°; ● – present work, θ_{1ab} = 30°.

4. DISCUSSION OF RESULTS

The direct result of the present measurements is the scattering asymmetry of neutrons obtained in the reactions T(p, n)He^3 and D(d, n)He^3 and scattered by He^4 nuclei at 123 ± 5°. The table lists the observed asymmetry, the reaction angles θ_1, and also the neutron energies E_n to which these values pertain. The last column indicates the polarization, calculated under the assumption that the asymmetry of nα scattering follows the diagram obtained in [19]. This diagram is based on a phase-shift analysis of pα and nα scattering, made by Dodder and Gammel[27] for the nucleon energy interval up to 20 MeV. The results of this analysis were reported by Seagrave[28] and are known as the Dodder-Gammel-Seagrave phase shifts (DGS). It is in [29] noted that the angular asymmetry of nα scattering of polarized neutrons with energy 20.7 MeV differs from the DGS diagram and agrees better with the analysis of Gammel and Thaler[30], made later for the energy

Reaction	E_p, E_d, MeV	θ_1 lab, deg	θ_1 cms deg	E_n, MeV	ε, %	$\overline{P}_2$	$\overline{P}_1$, %
T(p, n)He^3	12.2	15	24	11.2	—0.3±2.6	0.98	—0.3±2.6
	12.2	30	47	10.4	—14.4±3.3	0.98	—14.5±3.3
	12.2	45	70	9.3	—17.7±3.1	0.98	—17.8±3.1
	12.2	73	107	6.8	—11.7±7.0	0.99	—11.8±7.0
	14.5	15	24	13.4	—4.7±3.5	0.98	—4.8±3.6
	14.5	30	47	12.5	—19.5±5.2	0.98	—19.8±5.3
	14.5	45	70	11.1	—19.0±6.0	0.98	—19.4±6.1
	16.5	15	24	15.4	—10.1±6.3	0.98	—10.4±6.5
	16.5	30	47	14.3	—17.1±4.5	0.98	—17.4±4.6
	16.5	44.5	71	12.8	—18.0±8.5	0.98	—18.3±8.6
	16.5	73	107	9.4	—20.0±21.0	0.99	—20.2±21.4
D(d, n)He^3	11.6	15	22	14.1	1.0±4.5	0.97	1.0±4.5
	11.6	25	36	13.2	19.6±5.7	0.98	20.1±5.8
	11.6	30	43	12.8	29.7±6.1	0.98	30.4±6.2
	11.6	35	50	12.2	27.3±6.5	0.98	27.9±6.6
	11.6	45	64	10.9	11.4±5.1	0.98	11.6±5.2
	13.9	30	44	14.7	32.5±5.9	0.97	33.5±6.1
	15.3	30	44	15.8	30.7±5.9	0.97	31.7±6.1
	17.1	30	44	17.2	22.5±8.1	0.97	23.3±8.4
	19.2	20	30	20.4	10.6±5.4	0.96	11.1±5.7
	19.2	30	44.5	18.9	22.5±6.7	0.96	23.4±7.0

interval up to 40 MeV. Recently Barschall et al[3t] measured the $n\alpha$ scattering cross sections at energies E_n up to 20 MeV in order to check on the phase shift analysis. It was found that better agreement with experiment is obtained by the DGS set of phase shifts, which are assumed to be less reliable for $E_n > 15$ MeV. A noticeable disparity with the results of Gammel and Thaler is seen also in the results, reported by Barschall, of the measurement of the asymmetry of scattering by He^4 nuclei of polarized 23.7 MeV neutrons[20] and the results obtained by Hwang et al[32] on the asymmetry of scattering of 38 MeV polarized protons.

Thus, the question of the phase shift analysis of $n\alpha$ scattering has not yet been sufficiently clarified, and the available asymmetry predictions need direct experimental verification. This has not been done yet, so that the polarization values presented here can be regarded as the lower limits to be further refined.

As regards the polarization of neutrons in the $D(d, n)He^3$ reaction with $E_d \leq 12$ MeV, the existing data are decisively contradictory, as noted in the paper by Haeberli[16]. Our results pertain to $E_d \geq 11.6$ MeV. At $E_d = 11.6$ MeV they are in satisfactory agreement with the Wisconsin data[13] obtained by the same method. Therefore the dependence of the polarization on E_d, represented by curve 1 of Fig. 4, seems to us to be the more reliable one.

Both the $T(p, n)He^3$ and $D(d, n)He^3$ reactions investigated in the present work give identical end results $He^3 + n$, and it is therefore of interest to compare their differential cross sections and polarizations. The maximum neutron polarization in both reactions corresponds to an approximately the same angle $\theta_{cms} = 45°$ over a wide energy interval. Figure 5 shows the dependence of the

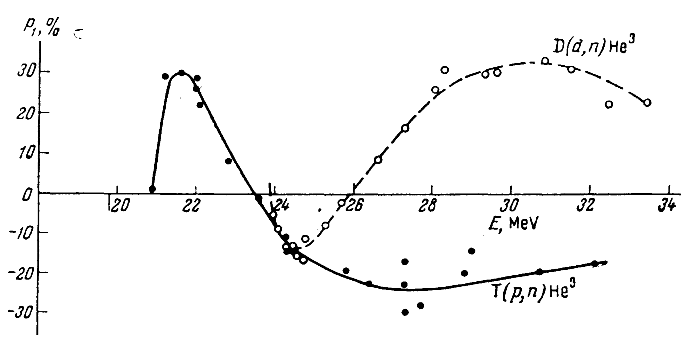

FIG. 5. Polarization of neutrons in $T(p,n)He^3$ and $D(d,n)He^3$ reactions in the region of the forward maximum, given in a scale of equal excitation energy E of the intermediate nucleus He^4.

polarization at $\theta_{cms} = 45°$ on the energy, referred to the same energy of the He^4 immediate state. The neutron polarizations of the two reactions are of opposite sign in a wide energy range. It is obvious that this difference in the sign of polarization can be attributed only to the difference in the input channels of the two reactions.

Both the $T(p, n)He^3$ and $D(d, n)He^3$ reactions are very widely used laboratory sources of monochromatic neutrons. The results of the present work show that they can be used to obtain neutrons with any energy up to 20 MeV, and with a polarization of 20–30°. A shortcoming of both reactions is the formation of continuous-spectrum neutrons at an energy exceeding the thresholds of the three-particle reactions, i.e., at $E_p > 8.34$ MeV in the former reaction and $E_d > 4.45$ MeV in the latter. The intensity of the continuous spectra in the reaction $D(d, n)He^3$ increases with energy, and for $E_d \approx 20$ MeV it is 4–5 times larger than the intensity of the monochromatic line[33,34]. The reaction $T(p, n)He^3$ has been investigated in detail at $E_p \leq 12$ MeV[35,36]. The continuous-spectrum neutrons have not yet been registered, since their study has not yet been undertaken. But this does not mean that their number is small. Therefore for investigations with monochromatic polarized neutrons it is necessary to use in both reactions apparatus that excludes the effects of the continuous-spectrum neutrons.

The authors are grateful to S. P. Kalinin and N. I. Venikov for interest in the work and to the crew of the Cyclotron Laboratory under their direction, who made the completion of the present investigation possible.

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Translated by J. G. Adashko
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