NEUTRON POLARIZATION IN THE $T(d, n)He^4$ *REACTION*

N. V. ALEKSEEV, U. R. ARIFKHANOV, N. A. VLASOV, V. V. DAVYDOV, and L. N. SAMOĬLOV

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Polarization of neutrons from the $T(d, n)He^4$ reaction is measured for E_d between 9 and 19 MeV. Scattering by a gas (helium) scintillator connected in coincidence with two neutron counters was employed as the analyzer. To exclude geometric asymmetry effects, the neutron spin was rotated through an angle of 90° in the longitudinal magnetic field of a solenoid. Maximum polarization is observed at an angle $\theta_{1lab} = 30°$, and exceeds 50% in a broad energy range. Resonance effects in the energy dependence of neutron polarization have been detected and are related to the excited states of the He^5 nucleus (16.7 and 20 MeV).

We have previously[1] measured the polarization of neutrons in the reactions $T(p, n)He^3$ and $D(d, n)He^3$ and demonstrated the possibility of obtaining monochromatic neutrons with energies up to 20 MeV and polarizations 20—30%. For many nuclear-physics investigations it is of interest to obtain high-energy polarized neutrons. One of the best sources of such neutrons is the reaction $T(d, n)He^4$. The yield and the angular distributions of the neutrons of this reaction have been sufficiently well studied at deuteron energies up to 14 MeV[2,3]. Measurements of the polarization in the energy interval up to 10 MeV[4,5] have shown that at certain angles the neutrons have a sufficiently high degree of polarization, which increases with increasing deuteron energy. One could assume that neutrons with a high degree of polarization and energies up to 40 MeV would be obtained in the deuteron energy interval attainable in our laboratory, 12—20 MeV. However, it was impossible to predict beforehand the energy and angular dependences of the polarization, all the more since the data for lower energies were not sufficiently detailed. Consequently direct measurements were of undisputed interest and were therefore carried out in the present investigation.

The analyzer used, as in the earlier work[1-6], was scattering by a gaseous helium scintillator connected for coincidence with two neutron counters. The scattering direction was changed from right to left and vice versa by reversing the direction of the current in the coil that rotated the neutron spins through 90°.

Owing to the smallness of the reaction cross section, particularly at the minima of the angular distribution, it was necessary to use a sufficiently thick (100 μ) T + Zr target to obtain a sufficient counting rate. The energy scatter of the deuteron beam, due principally to this cause, was ± 0.8 MeV at $E_d = 19$ MeV and ± 1.0 MeV at $E_d = 12$ MeV. Some points at lower energies were taken with a thinner target, and had a corresponding energy scatter ± 0.5 MeV. The results of the measurements are referred to the average value of the energy. In spite of the large target thickness, the counting rate amounted in most cases to 1—2 counts per minute, and therefore the measurements called for prolonged exposures and could not be carried out with the desired degree of detail. In particular, the energy distribution of the polarization was investigated only at the maximum energy $E_d = 19$ MeV.

We first measured the energy dependence of the polarization at an angle $\theta_{1lab} = 30°$, at which polarization maximum was observed at lower energies[4]. The neutron scattering angle in the analyzer was also maintained constant at $\theta_2 = 123°$. The width of the angle interval of the analyzer was ± 5°.

The deuteron energy was varied from 12 to 20 MeV by adjusting the cyclotron mode. The two points at $E_d < 11$ MeV were obtained by slowing down deuterons with initial energy 12 MeV in platinum foils. The deuteron scattering leads to an uncertainty in the magnitude of the neutron emission angle θ_1. The uncertainty of θ_1 due to scattering in the decelerating foil and the target did not exceed ~ 2°.

Owing to the insufficient certainty in the properties of the analyzer in the neutron energy interval 20—40 MeV, the results obtained are presented directly in the form of the right-left asymmetry observed under these conditions. The dependence of the asymmetry on the energy at $\theta_1 = 30°$ and $\theta_2 = 123°$ is shown in Fig. 1. The numerical characteristics of the conditions are listed in the table.

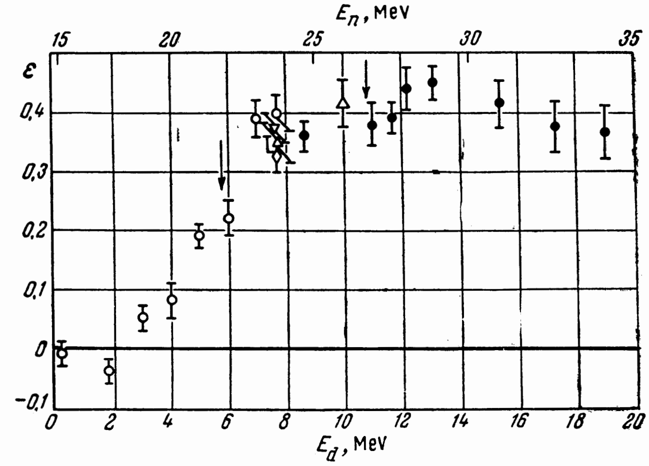

FIG. 1. Dependence of the asymmetry of scattering by He^4 of neutrons from the reaction T(d, n)He^4, on the deuteron energy: o – data of Perkins and Simmons[4]; ▽, △, ◇ – data of Walter et al.[5]; ● – our data. The arrows denote the positions of the resonances.

Figure 1 shows also the results of Perkins and Simmons[4] and four points obtained at the Wisconsin laboratory[5] for lower energies.

The agreement between the results in the adjacent energy interval near 11 MeV is perfectly satisfactory. Some irregularities are observed in the energy dependence of the asymmetry in the energy interval 8—14 MeV. Although the accuracy of the results is insufficient to determine the true shape of the curve, the presence of these irregularities is not subject to any doubt. They are apparently caused by resonances connected with the excited states of He^5 at E* approximately equal to 16.7 and 20 MeV. The resonance corresponding to E* = 20 MeV was observed in experiments on d—T and d—He^3 scattering[7], and also disclosed by the neutron yield in the reactions T(d, n)He^4 (ground state)[3] and T(d, n)He^{4*} (20.1 MeV)[8]. From the aggregate of these results, the resonance position corresponds to a value E_d = 5.8 MeV.

In the present experiments, the resonances could appear in three places: first, in the reaction T(d, n)He^4 (ground state) itself at $E_d \sim 6$ MeV; second and third, in nα scattering at neutron energies E_n equal to 22.1 and 26.4 MeV, which correspond, for observation at an angle θ_{1lab} = 30°, to deuteron energies E_d equal to 6 and 10.7 MeV. Thus, the resonances connected with both levels of He^{5*} can become superimposed at E_d = 6 MeV. In Fig. 1 the positions of both resonances are marked by arrows. The observed variations of the asymmetry pertain precisely to this energy region.

The presence of a resonance complicates the phase-shift analysis of the nα scattering (and apparently also of pα scattering). We can expect the changes in the cross sections and in the polarization of the nα scattering with variation of energy not to be as smooth as predicted by the hitherto published results of the phase-shift analysis at E_n < 20 MeV[9,10]. This is indicated also by the available data[11] on pα-scattering asymmetry at energies E_p equal to 22, 29, and 40 MeV. To refine the analysis it is necessary to carry out more detailed investigations of both the cross sections and the polarization of nα scattering in the neutron energy region 20—208 MeV.

We measured the dependence of the asymmetry on the neutron emission angle θ_1 at the maximum deuteron energy E_d = 19 MeV. The results of these measurements are shown in Fig. 2. It is interesting to note that the maximum asymmetry is observed at an angle θ_1 close to 30°, i.e., practically the same angle at which it was registered earlier at E_d = 5.5 MeV[4]. If the position of the maximum remains constant in the entire energy interval E_d from 5.5 to 19 MeV (a fact still calling for direct experimental verification at intermediate energies), then the curve on Fig. 1 corresponds to nearly maximal neutron polarization in the reaction T(d, n)He^4. Figure 2 shows also the

E_d, MeV	$\theta_{1\,lab}$, deg	E_n, MeV	$\theta_{2\,lab}$, deg	ε, %	$\bar{P}_2$, %	P_1, %
8.7±0.7	30	24.7	123	36.0±2.6	67.2	53.7
11.0±0.6	30	26.9	123	38.0±3.6	69.7	54.5
11.7±1.0	30	27.5	123	39.2±2.3	74.0	53.0
12.2±0.5	30	28.0	123	43.9±3.4	75.0	58.6
13.1±0.9	30	28.8	123	45.3±3.0	76.2	59.5
15.4±0.9	30	30.9	123	41.4±4.2	80.3	51.6
17.3±0.8	30	32.6	123	37.5±4.3	82.5	45.5
19.0±0.8	15	35.9	123	4.1±5.1	84.6	4.8
19.0±0.8	30	34.1	123	36.5±4.4	83.1	44.0
19.0±0.8	45	31.4	123	15.6±3.2	79.6	19.6
19.0±0.8	73	25.2	123	12.6±5.9	68.0	18.5
19.0±0.8	92	21.1	123	—12.2±10.3	58.8	—20.7
19.0±0.8	30	34.1	103	13.4±6.5		
19.0±0.8	30	34.1	135	38.2±6.6		
19.0±0.8	30	34.1	145	36.3±4.8		

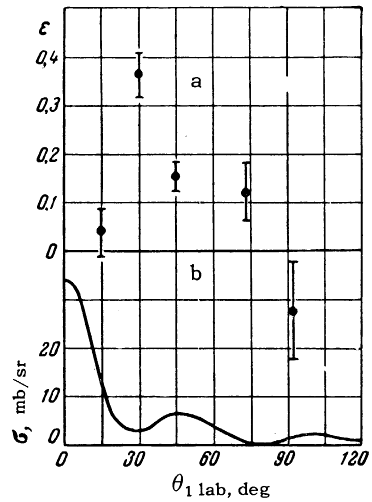

FIG. 2. Angular distribution of asymmetry of scattering of neutrons by He^4 (a) and the cross section of the reaction $T(d, n)He^4$ at $E_d = 19$ MeV (b).

differential cross section of the reaction $T(d, n)He^4$ [12]. The position of the polarization maximum coincides with the minimum of the cross section, and not with the maximum of the derivative of the cross section, as is expected for stripping reactions.

The determination of the absolute value of the polarization is made difficult by the uncertainty in the properties of the helium analyzer in the energy interval E_n from 20 to 40 MeV. The available data pertain principally to $p\alpha$ scattering. The publication of the results of measurements of the asymmetry of scattering of polarized protons with energy 38 MeV[13] has necessitated the revision of the earlier analysis data. Thaler et al.[14] published corrected phase shifts and presented a new picture of $p\alpha$ scattering polarization. However, this picture is not in sufficiently good agreement with the results of the subsequently published British measurements for several values of the energy[11].

A more complete analysis of the experiments at $E_p \approx 38$–40 MeV was made by Suwa and Yokosawa[15], but their results were not extrapolated to other energies.

There are practically no experimental data as yet on $n\alpha$ scattering at $E_n > 20$ MeV. Although one can hope the results on $n\alpha$ and $p\alpha$ scattering to be similar, the degree to which this similarity extends is not clear, so that direct investigations of $n\alpha$ scattering are essential even if the situation with $p\alpha$ scattering becomes clearer. In this connection we have measured the dependence of the asymmetry on the angle θ_2 at $\theta_1 = 30°$. For $E_d = 19$ MeV, the energy of the neutrons emitted at this angle is 34 MeV. We were unable to extend these measurements into the angle region $\theta_2 < 105°$, owing to the strong increase in the background, so that results were obtained only for four values of the angle θ_2: 105, 123, 135, and 143°. These results are shown in Fig. 3. The same figure shows for comparison the curve obtained by interpolating the experimental data on $p\alpha$ scattering asymmetry[11].

The general agreement between the angular

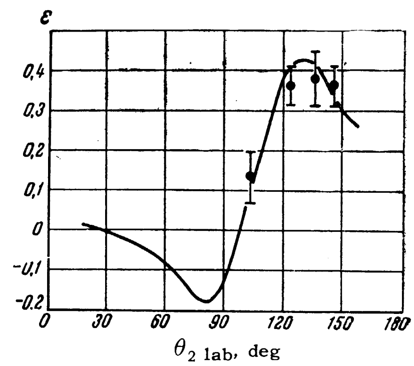

FIG. 3. Angular dependence of the asymmetry of $n\alpha$ scattering at $E_n = 34$ MeV.

dependence of the asymmetry in $n\alpha$ and $p\alpha$ scattering is obvious from Fig. 3. However, there is no good quantitative agreement. To discuss the quantitative difference, neither results are satisfactory as yet. There is no doubt that the maximum of the asymmetry of the $n\alpha$ scattering at $E_n = 34$ MeV occurs at $\theta_2 > 123°$, i.e., it is shifted into a region of larger angles than at lower energy, in accordance with the experimental data and their phase-shift analysis[9,10]. It is obvious that at this energy the angle $\theta_2 = 123°$ is no longer the most suitable one for the helium analyzer, although the asymmetry observed at this angle does not differ very strongly from the maximum asymmetry.

To calculate the absolute value of the neutron polarization in the reaction $T(d, n)He^4$ at an angle $\theta_{1lab} = 30°$, we used the experimental data on polarization in $p\alpha$ scattering[11] and assumed that the polarization is the same in $n\alpha$ scattering. The obtained values of the polarization are listed in the table. Along with the error in the measurements of the value of the asymmetry, these values of the polarization contain an error connected with the insufficient certainty in the properties of the helium analyzer, which can be determined by a subsequent more detailed analysis of $n\alpha$ scattering.

Since the present work has added much to the available data on sources of polarized fast neutrons in the energy region E_n up to 35 MeV, we present in Fig. 4 a summary source diagram, initially

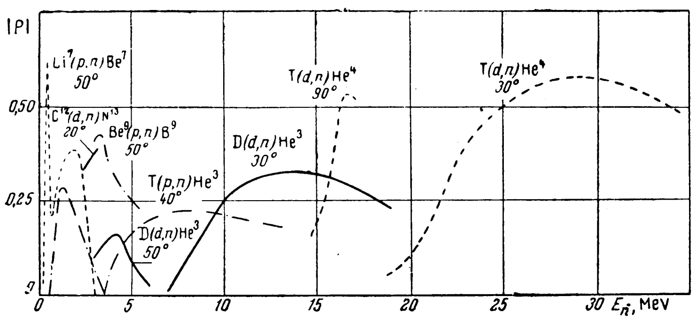

FIG. 4. Polarization of neutrons in different nuclear reactions.

compiled by Haeberli[16] and supplemented with our data.

In conclusion, let us emphasize the main results of the work, which are of interest for investigations with polarized neutrons in the energy region > 20 MeV, and for a theoretical analysis of the reaction $T(d, n)He^4$ and $n\alpha$ scattering.

1. The polarization of neutrons in the reaction $T(d, n)He^4$ (and also of protons in the "mirror" reaction $He^3(d, p)He^4$ [17]) at an angle $\theta_{lab} = 30°$ exceeds 50% in a wide deuteron energy interval, so that we can obtain in these reactions strongly polarized nucleons with energies at least up to 40 MeV. The dependence of the polarization on the energy enables us to assume that with further increase in the energy the nucleons will retain a high level of polarization. The large energy interval between the monoenergetic group of nucleons and the continuous spectrum of the disintegration nucleons simplifies the procedure for separating the monoenergetic group and enables us to use the reaction $T(d, n)He^4$ as a convenient source of polarized neutrons in a broad spectral range. It must be borne in mind, however, that the cross section of the reaction is small and that the intensity of the neutrons in the continuous spectrum is one order of magnitude larger than the intensity of the line. The angle of maximum polarization (near 30°) remains practically unchanged on going from $E_d = 5.5$ MeV to $E_d = 20$ MeV.

2. Resonance effects, previously observed in the reactions $T(d, n)He^4$ (ground state) and $T(d, n)He^{4*}$ (20 MeV) as well as in dT scattering, have been observed in the energy dependence of the neutron polarization in the reaction $T(d, n)He^4$. These resonance effects must be taken into account in the phase-shift analysis of the α-nucleon scattering, and to this end it is necessary to have more detailed experimental data on the scattering of nucleons with energies > 20 MeV from He^4. It is also of interest to make a more detailed study of the polarization of the nucleons in the reactions $T(d, n)He^4$ and $He^3(d, p)He^4$ in the deuteron energy interval 5–15 MeV.

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