T(*d*,*n*)He[4] Reaction as a Source of Polarized Neutrons*

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The polarization of neutrons from the source reaction T(*d*,*n*)He[4] has been measured at laboratory angles of 30° and 90° over the range of deuteron energy E_d, from 0.1 to 7.7 Mev. In addition, at $E_d=5$ Mev an angular distribution of the polarization was measured. The polarization, which is small at low energies, at $E_d=7.7$ Mev attains values of $+0.64$ and -0.52 at 30° and 90°, respectively. The Basel sign convention is used. The polarization was analyzed by means of a liquid helium scintillator used in coincidence with a plastic scintillator.

THE T(*d*,*n*)He[4] reaction is a primary source of neutrons with energies in the range 12 to 30 Mev. The neutron yield is known[1] for deuteron energies up to 11.5 Mev which corresponds to a neutron energy of 29 Mev in the forward direction. This paper will give experimental results for deuteron energies up to 7.7 Mev which show that these neutrons are highly polarized at certain angles. From the work of Levintov, Miller, and Shamshev[2] at relatively low deuteron energy ($E_d=1.8$ Mev) it is known that the magnitude of the neutron polarization may take values of 0.12 at certain angles. At deuteron energies near 7 Mev the value of the polarization is found to be many times larger.

The experimental geometry will be described briefly as follows. Deuterons from the large Los Alamos Van de Graaff enter a 1 cm long target of tritium gas maintained at a pressure of 60 psi absolute. The neutrons emitted at angle θ_1 (lab system) impinge on a liquid helium scintillator[3] at a distance $R_1=27.3$ in. Neutrons scattered from the helium at an analyzing angle θ_2 (lab system) are detected in a plastic scintillator at a distance $R_2=7$ in. from the helium vessel. Scattering events are recorded as fast coincidences between the helium and plastic scintillations. The helium vessel is a cylinder of 2.8 in. inside diameter by 3 in. high with vertical axis, while the plastic scintillator is a cylinder 2 in. in diameter by 2 in. long with horizontal axis. Brass cones 12 in. long are used to shield the plastic scintillators from the direct neutron flux.

The polarization of the neutrons from the reaction is called $P_1(\theta_1)$ and is reckoned positive in the direction of the normal to the plane of the scattering, $(\mathbf{k}_d\times\mathbf{k}_n)/|\mathbf{k}_d\times\mathbf{k}_n|$. The vectors $\mathbf{k}_d$ and $\mathbf{k}_n$ represent the momenta of the incoming deuterons and outgoing neutrons, respectively. The value of P_1 is measured by a left-right asymmetry measurement[4] in the scattering from helium, $e=(L-R)/(L+R)=-P_1(\theta_1)P_2(\theta_2)$. The minus sign comes in owing to the fact that $\mathbf{k}_d\times\mathbf{k}_n$ points downward for the conditions of this experiment. The quantity $P_2(\theta_2)$ is the polarization function (or analyzing power) in the helium scattering. The left and right scattering intensities were obtained by counter rotation. For θ_2 a value of 120° was used for all cases reported here. The zero of θ_2 was determined by the attenuation of 1.2 Mev neutrons through the liquid helium volume and by geometrical measurements. The value of θ_2 is estimated to be accurate to $\pm0.4°$.

The results of the polarization measurements together with other pertinent quantities are given in Table I. The measured asymmetry e can be regarded as a lower limit on the magnitude of P_1, since $|P_2|\leqslant 1$. The errors quoted for the measured values of e are standard deviations, including statistical and recognized

TABLE I. Polarization of neutrons from the T(*d*,*n*) reaction and related parameters.

E_d (Mev)	θ_1 (deg)	E_n (Mev)	e	Δe	P_2	$\bar{P}_2$[b]	P_1[c]
0.1[a]	30	15.0	+0.01	0.02	0.82	0.82	−0.01
1.80±0.13	30	17.5	+0.04	0.02	0.80	0.78	−0.05
1.80±0.13	90	14.7	+0.13	0.02	0.83	0.82	−0.16
3.00±0.09	30	18.9	−0.05	0.02	0.77	0.76	+0.06
3.00±0.09	90	15.2	+0.17	0.02	0.82	0.81	−0.21
4.00±0.07	30	20.0	−0.08	0.03	0.75	0.75	+0.11
4.00±0.07	90	15.6	+0.27	0.03	0.82	0.81	−0.33
5.00±0.06	15	21.7	−0.09	0.02	0.71	0.71	+0.12
5.00±0.06	30	21.1	−0.19	0.02	0.73	0.73	+0.26
5.00±0.06	45	20.0	−0.11	0.02	0.75	0.75	+0.15
5.00±0.06	60	18.8	+0.10	0.02	0.78	0.77	−0.13
5.00±0.06	75	17.4	+0.34	0.03	0.80	0.79	−0.43
5.00±0.06	90	16.0	+0.35	0.03	0.82	0.80	−0.43
5.00±0.06	105	14.8	+0.30	0.03	0.83	0.82	−0.37
5.00±0.06	120	13.7	+0.26	0.02	0.83	0.82	−0.32
6.00±0.05	30	22.1	−0.22	0.03	0.70	0.70	+0.31
6.00±0.05	90	16.4	+0.43	0.03	0.81	0.80	−0.54
7.00±0.04	30	23.1	−0.39	0.03	0.67	0.66	+0.59
7.00±0.04	90	16.8	+0.41	0.03	0.80	0.79	−0.51
7.70±0.04	30	23.7	−0.40	0.03	0.65	0.63	+0.64
7.70±0.04	90	17.1	+0.41	0.03	0.80	0.79	−0.52

[a] Taken at an energy corresponding to the peak of a yield curve for low-energy deuterons entering the gas target.
[b] Average of P_2 over the experimental geometrical resolution function.
[c] $P_1=-(e/\bar{P}_2)$.

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[1] M. D. Goldberg and J. M. LeBlanc, Phys. Rev. **122**, 164 (1961); S. J. Bame, Jr. and J. E. Perry, Jr., *ibid.* **107**, 1616 (1957); J. E. Brolley, Jr. and J. L. Fowler in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1960).

[2] I. I. Levintov, A. V. Miller, and V. N. Shamshev, J. Exptl. Theoret. Phys. (USSR) **34**, 1030 (1958) [translation: Soviet Phys.—JETP **7**, 712 (1958)].

[3] R. B. Perkins and J. E. Simmons, Bull. Am. Phys. Soc. **6**, 368 (1961); a more complete report on the liquid helium scintillation polarimeter is being prepared for publication.

[4] The sign conventions and definitions of L. Wolfenstein will be used as given in Ann. Rev. Nuclear Sci. **6**, 43 (1956).

systematic errors. Corrections amounting to 0.02 maximum have been subtracted from the experimental values of e due to lack of concentricity of the axis of the helium vessel with the axis of rotation of θ_2, and to flux anisotropy effects. Corrections arising from multiple scattering of the neutrons in the liquid helium have not been included in the calculation of e or its errors. Insertion of this effect in the analysis could increase the magnitude of e by as much as 10%.

The last three columns of Table I are concerned with obtaining an estimate of P_1. Suitable phase-shift analyses for n-He^4 scattering in this energy range do not exist owing to lack of data. Therefore, the nuclear phase shifts for proton-helium scattering given by Gammel and Thaler[5] were used to calculate P_2 as listed in Table I. Interpolations for the various incident neutron energies were made graphically. Averages of $P_2(\theta_2)$ over the angular resolution of the analyzing geometry, yielded values of $\bar{P}_2$, which have been used to calculate P_1 listed in the last column. No error has been assigned to P_1 because of the unknown applicability of the p-He^4 phase shifts to the present data.

Figure 1 shows an angular distribution $P_1(\theta_1)$ at $E_d=5$ Mev. The filled-in symbols represent lower limits for the polarization, $P_1=-e$. The errors indicated are those associated with e. The open symbols are the values of P_1 listed in the last column of Table I. The polarization shows a positive maximum at 30° and a negative maximum at 90°; these angles were chosen for subsequent excitation function studies.

Figure 2 gives the values of P_1 as a function of E_d for energies up to 7.7 Mev at the angles $\theta_1=30°$(circles) and 90°(squares). The open and filled-in symbols have the same significance as in Fig. 1. At $E_d=0.1$ Mev,

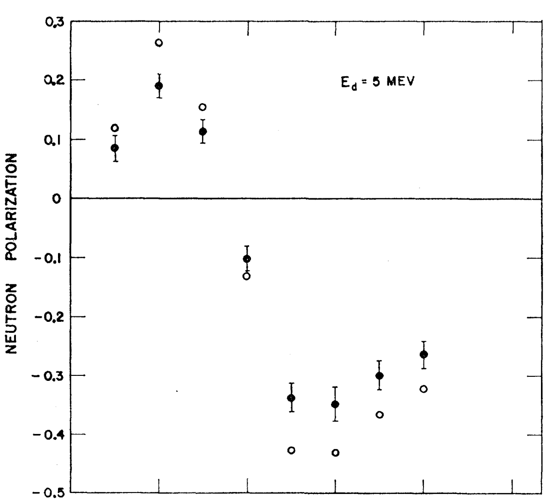

FIG. 1. Neutron polarization P_1 as function of θ_1, the laboratory neutron emission angle, at $E_d=5$ Mev. Filled-in circles represent minimum values, $P_1=-e$; open circles are values, $P_1=-e/P_2$, for P_2 calculated from the p-He^4 phase shifts of reference 5.

[5] J. L. Gammel and R. M. Thaler, Phys. Rev. **109**, 2041 (1958).

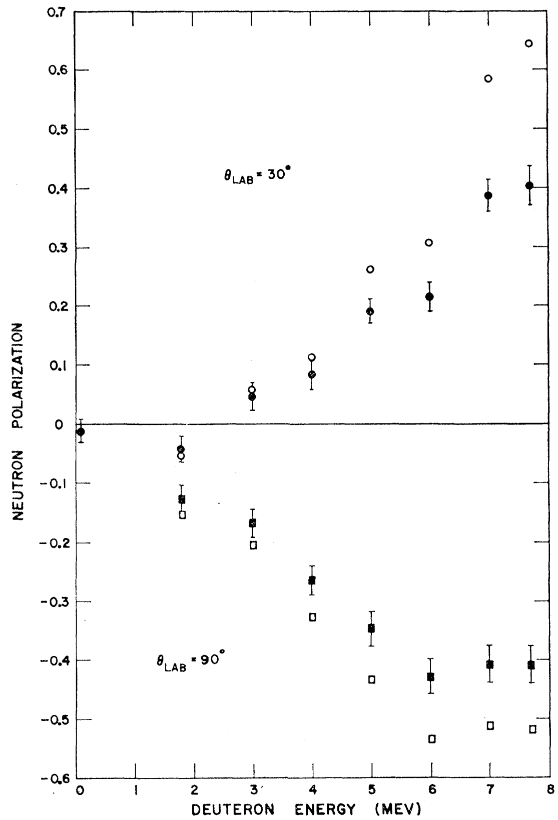

FIG. 2. Neutron polarization P_1 as function of E_d. Circles represent values at $\theta_1=30°$(lab) and squares are values for $\theta_1=90°$(lab). The filled-in and open symbols have the same significance as in Fig. 1.

the results are consistent with zero polarization at $\theta_1=30°$, which agrees with the work of Pasma.[6] At $E_d=1.8$ Mev and $\theta_1=90°$, the results may be compared with the measurements of reference 2, where a value of $P_1=10\%\pm3\%$ is quoted. This number is said to represent a lower bound for the polarization. If it is assumed that the sign convention of reference 2 is the opposite of the one used here, then there is essentially no discrepancy with our value of $P_1=-0.16$. It is observed that the polarization at $\theta_1=30°$ changes sign between 2 and 3 Mev and steadily increases to a value of $P_1=+0.64$ at 7.7 Mev. At $\theta_1=90°$ the values of P_1 remain negative and attain larger absolute values at lower energies than do the values of P_1 at 30°. The recent work of Brown and Haeberli[7] on the mirror reaction, $He^3(d,p)He^4$, gives values of proton polarization larger than the values given here for neutron polarization, but of the same sign.

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[6] P. J. Pasma, Nuclear Phys. **6**, 141 (1958).
[7] R. I. Brown and W. Haeberli, Bull. Am. Phys. Soc. **6**, 307 (1961).