[2]S. M. Smith and A. M. Bernstein, Nucl. Phys. A125, 339 (1969).
[3]P. D. Kunz, private communication.
[4]B. F. Bayman and A. Kallio, Phys. Rev. 156, 1121 (1967).
[5]J. B. Ball, R. L. Auble, R. M. Drisko, and P. G. Roos, Phys. Rev. 177, 1699 (1969).
[6]A. G. Blair, J. G. Beery, and E. R. Flynn, Phys. Rev. Lett. 22, 470 (1969).
[7]R. H. Ibarra and B. F. Bayman, Phys. Rev. C 1, 1786 (1970).
[8]R. Jaffe and W. Gerace, Nucl. Phys. A125, 1 (1969).
[9]F. D. Becchetti, Jr., and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).
[10]F. G. Perey, Phys. Rev. 131, 745 (1963).
[11]G. R. Satchler, Nucl. Phys. A92, 273 (1967).
[12]E. R. Flynn, D. D. Armstrong, J. G. Beery, and A. G. Blair, Phys. Rev. 182, 1113 (1969).
[13]E. F. Gibson, B. W. Ridley, J. J. Kraushaar, M. E. Rickey, and R. H. Bassel, Phys. Rev. 155, 1194 (1967).
[14]P. P. Urone, thesis, University of Colorado, 1970 (unpublished); P. P. Urone, L. W. Put, and B. W. Ridley, to be published.
[15]B. W. Ridley, T. W. Conlon, and T. H. Braid, Bull. Amer. Phys. Soc. 13, 117 (1968).
[16]R. N. Glover and A. D. W. Jones, Nucl. Phys. 81, 268 (1966).
[17]B. F. Bayman and N. M. Hintz, Phys. Rev. 172, 1113 (1968).
[18]F. G. Perey and D. Saxon, Phys. Lett. 10, 107 (1964); F. G. Perey and B. Buck, Nucl. Phys. 32, 353 (1963).

POLARIZATION TRANSFER IN THE REACTION $T(d,n)^4He$ AT 0° FROM 3.9 TO 15 MeV†

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Measurements of neutron polarization are reported for the reaction $T(d,n)^4He$ at 0° in which the incident beam is polarized with quantization axis perpendicular to the direction of motion. The beam polarization was described by $p_3 = p_{33} \approx 0.76$, while beam intensities varied from 10 to 40 nA. At $E_d = 15$ MeV the neutron polarization was measured to be $+0.56 \pm 0.036$ with respect to the quantization axis. At 3.9 MeV the polarization was zero, showing the influence of spin-flip interactions from the low-energy $^4S_{3/2}$ resonance. The measurements are related to polarization transfer and efficiency tensor functions for the reaction.

In this note we report on novel measurements of neutron polarization from the reaction $T(d,n)^4He$ in which the initial beam is itself polarized. Experiments of this type in nuclear reaction studies have been infrequent. Seiler et al.[1] made the first such measurements on the $\vec{d}$-T reaction at 170 keV. Robertson et al.[2] have recently made polarization transfer measurements in certain (p,n) reactions at 30 and 50 MeV. In nucleon-nucleon scattering this type of measurement would be classified as a triple-scattering experiment, in which much effort has been expended. The reaction $D(p,n)2p$ has been employed by the Rochester group[3] near 200 MeV for measurements involving the transfer of spin polarization from proton to neutron in the interaction. The first measurements of this kind in free n-p scattering were made at Harvard[4] at 150 MeV.

The present experiment was made possible by the recent initial operation of a high-performance Lamb-shift polarized-ion source[5] on the Los Alamos model FN tandem Van de Graaff accelerator, together with the availability of an efficient liquid-helium neutron polarimeter.[6] Typical target currents varied in the range 10 to 40 nA.[7] The deuteron beam polarization may be described by a mixture ≈76% in the $m_I = +1$ spin state with a remainder that is unpolarized. Stated differently, the beam polarization corresponds to $p_3 = p_{33} \approx 0.76$, where p_3 is the vector polarization and p_{33} is the tensor polarization of the beam, using Goldfarb's[8] notation. The quantization axis, denoted by $\hat{s}$, points in the vertical direction, perpendicular to the incoming momentum.

Gammel, Keaton, and Ohlsen[9] have provided a formalism for the description of polarization observables in the reaction $T(d,n)^4He$, comparable with that of Wolfenstein[10] for the nucleon-nucleon problem. In their notation the outgoing neutron polarization parallel to $\hat{s}$ at 0° is given by

$$\langle\sigma_y\rangle = \tfrac{3}{2}p_3 p_y{}^y(0)/[1+\tfrac{1}{2}p_{33}p_{yy}{}^0(0)]. \quad (1)$$

The y axis labels the direction parallel to $\hat{s}$, the incoming quantization axis. The quantity $p_y{}^y(0)$ represents the vector polarization transfer coefficient, and is analogous to the Wolfenstein D parameter. The square bracket represents the ratio of polarized to unpolarized cross sections, which depends at 0° only on the second-rank efficiency tensor p_{yy}^0. The beam polarization parameters p_3 and p_{33} were defined above. Seiler et al.[1] gave the form of this equation which applies at low energy, i.e., at $E_d \approx 100$ keV, without defining the reaction parameters.

The deuteron beam was accelerated into a 3-cm-long T_2-gas target at 4.8 atm absolute pressure. The neutrons produced at 0° were collimated and subjected to spin precession of approximately ±90° in a solenoid (refer to the insert of Fig. 1 for an elevation view of the experimental geometry). At the distance R_1 the neutrons scattered from 4.8 moles of liquid helium contained in a scintillation counter. The distance R_1 was 139 cm for the first runs and 99 cm for the later runs. The final detectors were plastic fluors each placed at the laboratory angle θ_2 and at a distance $R_2 = 25$ cm. Their dimensions were 5 cm (in $\Delta\theta$) by 17.8 cm (in $\Delta\varphi$) by 7.6 cm thick. The angle θ_2 of n-He scattering was varied from 117° to 125° as the energy was increased. The neutron polarization was determined from measurement of "up-down" asymmetry in n-He scattering, using analyzing power based on the Hoop-Barschall[11] phase shifts. Corrections were made for finite geometry, multiple scattering in the helium, and incomplete precession. Counting rates were favorable; at $E_d = 13$ MeV, for example, the total counting rate was 800/h with 30-nA incident beam. Measurement of the tensor analyzing power $p_{yy}^0(0)$ was accomplished in separate runs by measurement of $I(0)/I_0(0)$, the polarized/unpolarized intensity ratios at 0°, using the helium scintillator for neutron detection.

The zero-degree neutron polarization was measured[12] at incident deuteron energies of 3.9, 7.0, 9.0, 11.4, 13.0, and 15.0 MeV. Table I provides a summary of the measured values of $\langle\sigma_y\rangle$, $I(0)/I_0(0)$, and the derived quantities $p_{yy}^0(0)$ and $p_y^y(0)$. Errors are mainly of statistical origin. The listed beam polarizations $p_3 = p_{33}$ are averages for each energy; they were measured at the ion source by a quenching ratio method.[5] All polarization measurements were repeated at least once, except for the point at 3.9 MeV. The data are portrayed in Fig. 1 where the dashed line shows the (maximum) value of neutron polarization at 0°, $\langle\sigma_y\rangle_{max}$, that would obtain if the incident beam were fully polarized, i.e., for $p_3 = p_{33} = 1$. This curve is about 12% higher, on the average, than the measured values of $\langle\sigma_y\rangle$ given in Table I.

Also shown in Fig. 1 as points with error bars

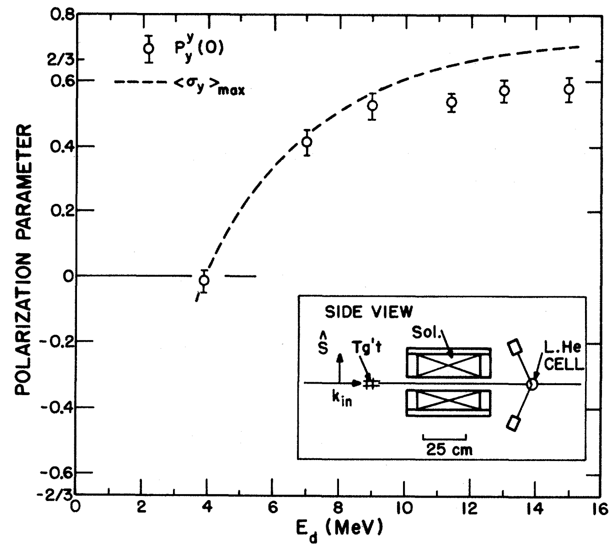

FIG. 1. Polarization parameters versus E_d for the reaction $T(d,n)^4He$ at 0°. The points with error bars represent $p_y^y(0°)$, the vector polarization transfer parameter. The dashed line represents the maximum value of $\langle\sigma_y\rangle$, the y component of outgoing neutron polarization, when the incoming deuteron beam is 100% in the $m_I = 1$ state, with respect to the direction $\hat{s}$. The insert shows an elevation view of the experimental geometry, including the ±90° spin-precession solenoid.

Table I. Summary of polarization measurements in the reaction $T(d,n)^4He$ at 0°. Errors are standard deviations. The ratio of polarized to unpolarized cross section, $I(0)/I_0(0)$, was determined in an independent series of runs and renormalized to the listed values of p_3.

$E_d \pm \Delta E_d/2$ (MeV)	E_n (MeV)	$\langle\sigma_y\rangle$	p_3 (av)	$I(0)/I_0(0)$	$p_{yy}^0(0)$	$p_y^y(0)$
3.9 ±0.25	20.7	−0.014 ±0.034	0.757	1.274 ±0.009	0.724 ±0.024	−0.015 ±0.038
7.0 ±0.15	24.2	0.355 ±0.036	0.759	1.322 ±0.009	0.848 ±0.024	0.412 ±0.042
9.0 ±0.13	26.4	0.470 ±0.033	0.759	1.267 ±0.008	0.704 ±0.021	0.523 ±0.037
11.4 ±0.10	28.9	0.510 ±0.027	0.770	1.206 ±0.008	0.535 ±0.021	0.533 ±0.028
13.0 ±0.09	30.5	0.535 ±0.032	0.758	1.208 ±0.011	0.548 ±0.027	0.568 ±0.034
15.0 ±0.08	32.6	0.565 ±0.036	0.762	1.172 ±0.011	0.452 ±0.029	0.577 ±0.037

are the values of $p_y^y(0)$. This quantity is equal to the deuteron vector polarization which would be produced at 0° in the inverse reaction[9] by a fully polarized incident neutron beam, assuming y components of polarization. From a qualitative picture of the stripping process, one might expect $\langle\sigma_y\rangle = 1$ for an incident beam of 100% $m_I = 1$ deuterons; this would require $p_y^y \to \frac{2}{3}$ and $p_{yy}^0 \to 0$. We note that p_y^y is approaching its limiting value and that p_{yy}^0 is indeed decreasing toward zero as the deuteron energy increases. It would be most interesting to follow this trend to higher energies.

At lower energy p_y^y and $\langle\sigma_y\rangle$ become smaller and cross zero at 3.9 MeV, indicating the influence of a spin-flip process. At very low energy (107 keV) the reaction proceeds primarily through the S-wave $\frac{3}{2}^+$ resonance, which requires neutron spin flip for the component of neutron polarization, $\langle\sigma_y\rangle$, transverse to the outgoing direction of motion. If the reaction proceeds purely through this S-wave resonance, it follows from Ref. 1 or from formulas of Ohlsen[13] that $p_y^y = -\frac{2}{3}$ and that $p_{yy}^0 = \frac{1}{2}$ for the geometry of present interest. The value of $\langle\sigma_y\rangle_{max}$ at 107 keV is $-\frac{4}{5}$ owing to the influence of the cross-section factor. It is clear that at $E_d = 3.9$ MeV the spin behavior of the reaction is strongly influenced by the $\frac{3}{2}$ resonance.

The results reported in this paper also have considerable significance relative to production of polarized neutron beams. The usual method of producing polarized neutrons from 20 to 30 MeV makes use of the reaction $T(d,n)^4He$ at $\theta_L = 30°$, with an unpolarized deuteron beam incident. As E_d increases, the cross-section minimum at 30° decreases steadily, while backgrounds increase greatly. In contrast, the 0° cross section remains constant from $E_d = 7$ to $E_d = 19$ MeV at a value in the neighborhood of 24 mb/sr. At 19 MeV the cross section ratio $I_0(0)/I_0(30)$ is roughly 10. Over the energy range of this experiment further advantage is obtained from a 17 to 32% increase in cross section when the incoming beam is polarized. Also neutron polarization reversal may be obtained by ion-source control, which may be advantageous in many experiments. Thus production of polarized neutrons by polarization transfer will become competitive with the standard method at some point as energy increases.

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[1]F. Seiler, E. Baumgartner, W. Haeberli, P. Huber, and H. R. Striebel, Helv. Phys. Acta 35, 385 (1962).

[2]L. P. Robertson, R. C. Hanna, K. Ramavataram, D. W. Devins, T. A. Hodges, Z. J. Moroz, S. J. Hoey, and D. J. Plummer, Nucl. Phys. A134, 545 (1969).

[3]N. W. Reay, E. H. Thorndike, D. Spalding, and A. R. Thomas, Phys. Rev. 150, 801 (1966); D. Spalding, A. R. Thomas, and E. H. Thorndike, Phys. Rev. 158, 1338 (1967).

[4]P. M. Patel, A. Carroll, N. Strax, and D. Miller, Phys. Rev. Lett. 8, 491 (1962).

[5]G. P. Lawrence, G. G. Ohlsen, and J. L. McKibben, Phys. Lett. 28B, 594 (1969); G. G. Ohlsen, LASL Report No. LA-4451, 1970 (unpublished).

[6]W. B. Broste, J. C. Martin, and J. E. Simmons, to be published.

[7]Subsequently deuteron currents as large as 200 nA at 74% polarization have been accelerated onto a target through an aperture 2.5 mm square.

[8]L. J. B. Goldfarb, Nucl. Phys. 7, 622 (1958).

[9]J. L. Gammel, P. W. Keaton, Jr., and G. G. Ohlsen, LASL Report No. LA-4492-MS, 1970 (unpublished).

[10]L. Wolfenstein, Phys. Rev. 96, 1654 (1954).

[11]B. Hoop and H. H. Barschall, Nucl. Phys. 83, 65 (1966).

[12]Part of these data have been reported in a preliminary fashion: J. E. Simmons, W. B. Broste, G. P. Lawrence, J. L. McKibben, and G. G. Ohlsen, Bull. Amer. Phys. Soc. 14, 1230 (1969).

[13]G. G. Ohlsen, Phys. Rev. 164, 1268 (1967).