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Measurement of the $^1H(\vec{d},\vec{n})pp$ transverse polarization transfer coefficient at 42.8 MeV

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The transverse polarization transfer coefficient $K_y^{y'}$ has been measured for the reaction $^1H(\vec{d},\vec{n})pp$ at 0° for $E_d=42.8$ MeV as a function of breakup neutron energy. For the high-energy neutrons ($E_n>28$ MeV) the average value for $K_y^{y'}$ is close to 0.6, in conformity with the prediction of a simple stripping or spectator model for polarization transfer in deuteron stripping reactions. Good agreement is found with available Faddeev calculations.

[NUCLEAR REACTIONS $^1H(\vec{d},\vec{n})pp$, $E_d=42.8$ MeV; measured $K_y^{y'}$ for $\theta_{lab}=0°$; stripping model; Faddeev calculations.]

I. INTRODUCTION

During the past decade, considerable effort has been spent on the measurement[1,2] and calculation[3] of low energy three-body observables, especially for the N-d elastic channel. Calculations have been made with more and more realistic N-N forces, and predictions are in fairly good quantitative agreement with available elastic N-d scattering data below 30 MeV.[1,2] Calculations for the elastic channel have revealed that polarization observables are more sensitive to the details of the N-N force than are the cross sections; the need for a simultaneous fit to polarization as well as differential cross section data puts important constraints on the N-N forces used, which presumably can be satisfied only by extending the calculations to higher partial waves and incorporating tensor components in the N-N forces considered. This has been done in some of the more sophisticated theoretical calculations of N-d breakup,[4–6] which have been designed to calculate polarization observables as well as the cross sections. The breakup reaction is expected to be more sensitive to the combination of off-energy-shell effects and three-body forces than is N-d elastic scattering, and more sophisticated N-d breakup polarization measurements should provide more stringent tests[7] of these calculations.

Some years ago we began a many-faceted investigation of the breakup neutrons at center-of-mass energy $E^*=14$ MeV using, alternatively, 21.4 MeV protons and 42.8 MeV deuterons to initiate the reactions while observing the breakup neutrons at both 0° and 18°. In this way, four different kinematic regions in the c.m. system could be explored. The results of a measurement of the polarization transfer parameter $K_y^{y'}$ for the $^2H(\vec{p},\vec{n})pp$ reaction at 18° have already been published.[8] In the present paper, the results of a measurement of $K_y^{y'}$ for the breakup neutrons from the $^1H(\vec{d},\vec{n})pp$ reaction as a function of neutron energy at $\theta_{lab}=0°$ for $E_d=42.8$ MeV are reported.

II. EXPERIMENTAL DETAILS

The techniques used in the measurement and analysis are similar to those described extensively in an earlier paper,[9] and hence will be summarized here only briefly. The deuteron beam from an atomic-beam polarized ion source was injected axially into the cyclotron, accelerated, magnetically analyzed, and transported to the target area, where it passed through a high-pressure liquid-nitrogen-cooled hydrogen gas target (thickness ~1.0 MeV). The mean beam energy in the target was 42.8 MeV. Beyond the target, the deuteron beam was magnetically deflected into a heavily-shielded Faraday cup, while the neutrons were collimated at 0°. The beam polarization was vertical and could be reversed at the source in alternate runs so as to eliminate false asymmetries. It was monitored continuously by measuring the asymmetry in d-^{4}He elastic scattering in a gas polarimeter located upstream of the target area, using a known value for the d-^{4}He analyzing power.[10] The average vector polarization of the beam was $p_y \simeq 55\%$.

The polarization $p_n(E_n)$ of the continuum of breakup neutrons at 0° was determined in a liquid-helium polarimeter[9] placed beyond the steel collimator at a flight path of 4.5 m from the target. The scattering angles of the polarimeter side detectors (NE102 scintillators) were set symmetrically to the left and right at 80° and 120° so as to get independent measurements where the analyzing power $A_y(\theta,E)$ for n-He elastic scattering is opposite in sign. From the measured asymmetry $\epsilon(\theta,E_n)$ the neutron polarization is given by the well-known relationship

$$p_n(E_n)=\epsilon(\theta,E_n)/A_y(\theta,E_n) \; ,$$

and from $p_n(E_n)$ the parameter $K_y^{y'}(0°,E_n)$ is given by the relationship

$$K_y^{y'}(0°,E_n)=\tfrac{2}{3}p_n(E_n)/p_y \; .$$

As in earlier experiments, four-parameter tagged data were written event by event onto magnetic tape for later off-line analysis. The four parameters recorded were the following: the pulse height produced by the scintillation in the liquid-helium scatterer, the pulse height observed from the neutron detector at 80° or 120°, the time-of-flight from hydrogen target to helium cell, and the time-of-flight between helium cell and neutron detector. The tag identified the neutron detector involved. The data were taken in cycles of four runs, the beam polarization for successive runs being switched in the pattern ↑ ↓ ↓ ↑ so as to minimize asymmetries caused by slow drifts in the apparatus. Background runs with the hydrogen gas emptied from the production target were taken (in the same pattern) in order to determine the contribution from the target windows.

III. ANALYSIS

After background subtraction, application of corrections for time-walk and kinematic shifts, and suitable use of software gates,[9] the data were assembled into eight energy spectra, one for each state of beam polarization for each of the four n-He scattering angles. The bin width of the energy spectra was set at 1 MeV, consistent with the energy loss of the incident deuteron beam in the hydrogen target. The asymmetries were calculated for each energy bin using the "ratio method" (Ref. 11), in which the asymmetry is given by

$$\epsilon(\theta,E_n)=(r-1)/(r+1) \; ,$$

where r is the quantity

$$[(L\uparrow \cdot R\downarrow)/(L\downarrow \cdot R\uparrow)]^{1/2}$$

and the symbol $L\uparrow$, for example, represents the yield in the left neutron detector when the beam polarization is in the "up" orientation, and the remaining symbols have corresponding meanings. The ratio method has the advantage of minimizing the effect of differences in solid angle and efficiency between left and right detectors, differences in normalization between spin-up and spin-down runs, and fluctuations in beam position on the target.

The analyzing power A_y of the liquid-helium polarimeter as a function of neutron energy was determined by a phase-shift calculation. In the energy region below 20 MeV, the phase shifts of Stammbach and Walter[12] were used, in the 23 to 30 MeV region those of Hoop and Barschall[13] were used, and at higher energies, those given by a program[14] developed in this laboratory were used. Corrections for plural scattering and finite geometry were calculated using a revised form[14] of the code PMS1.[15]

IV. RESULTS AND DISCUSSION

The resulting values of $K_y^{y'}(0°)$ are shown in Fig. 1. For each point, the vertical bar represents the statistical error and the horizontal bar shows the energy bin used. Hoop and Barschall gave no estimate of error for their phase shifts, and Stammbach and Walter only quoted estimated uncertainties for a few representative cases. Since a reliable estimate of the uncertainties in the A_y used is lacking, no estimate of the associated error in $K_y^{y'}(0°)$ has been included. Thus, the error bars shown for the final values of $K_y^{y'}(0°)$ reflect only the statistical uncertainty of the measured asymmetries.

A. Stripping model

The large values of $K_y^{y'}(E_n)$ for $E_n \geq 28$ MeV are consistent with a simple deuteron stripping model,[16] in which the reaction is assumed to be peripheral, with the neutrons and protons of the incoming beam deuterons being separated without perturbing their spins. This implies that the polarization of the outgoing neutrons is the same as the average polarization of the neutrons in the deuteron beam. When the D-state probability P_D of the deuteron is taken into account, the average neutron polarization within a deuteron beam in a pure $m=+1$ state is given by $(1-\frac{3}{2}P_D)$.[16] Similarly, within a deuteron beam in a pure $m=-1$ state the average neutron polarization is $(-1+\frac{3}{2}P_D)$, while within a pure $m=0$ deuteron beam the average neutron polarization is zero. For a deuteron beam of pure vector polarization p_y, the fraction F_0 of deuterons in the $m=0$ substate is $\frac{1}{3}$, and p_y is given by the difference (F_+-F_-) between the fraction F_+ in the $m=+1$ substate and the fraction F_- in the $m=-1$ substate, so that $p_y=F_+-F_-$ and $F_++F_-=\frac{2}{3}$. The polarization of the neutrons within such a deuteron beam is

$$p_n=F_+(1-\tfrac{3}{2}P_D)-F_-(1-\tfrac{3}{2}P_D)=p_y(1-\tfrac{3}{2}P_D) \; .$$

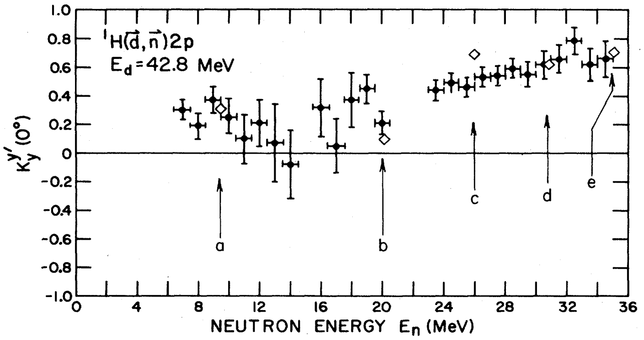

FIG. 1. Measured values of $K_y^{y'}(0°)$ vs breakup neutron energy for the ^{1}H($\vec{d},\vec{n}$)pp reaction at E_d=42.8 MeV. No values were determined for energies between 21 and 23 MeV because of the uncertainties in the n-^{4}He analyzing power due to the $2D_{3/2}$ resonance in that region. A point near 15 MeV has been deleted because the presence of a γ-ray peak there caused a large background subtraction and correspondingly large statistical uncertainty in the value. The open diamonds show the results of Faddeev calculations for selected kinematic conditions: (a) n-col; (b) np FSI; (c) SCRE; (d) p-col; and (e) pp FSI.

It can be shown[17] that for a $(\vec{d},\vec{n})$ reaction initiated by deuterons polarized along the y axis (normal to the reaction plane), the outgoing neutron polarization is

$$P_n(\theta)=\frac{P(\theta)+\frac{3}{2}p_yK_y^{y'}(\theta)+\frac{1}{2}p_{yy}K_{yy}^{y'}(\theta)}{1+\frac{3}{2}p_yA_y(\theta)+\frac{1}{2}p_{yy}A_{yy}(\theta)} ,$$

where $A_y(\theta)$ is the analyzing power and $P(\theta)$ is the polarization for the (d,n) reaction. For a deuteron beam of pure vector polarization, $p_{yy}=0$, and for a scattering angle of 0°, $P=A_y=0$, so that

$$K_y^{y'}=\frac{2}{3}\frac{p_n}{p_y}=\frac{2}{3}(1-\frac{3}{2}P_D)=\frac{2}{3}-P_D .$$

If a 6% D-state probability is assumed, this leads to the prediction that $K_y^{y'}(0°)=0.607$. The prediction is the same, of course, for $K_y^{y'}(0°)$ for $(\vec{d},\vec{p})$ reactions.

It is expected that deviations from this prediction should be found at lower energies.[18] A summary of available data on $K_y^{y'}(0°)$ for $(\vec{d},\vec{n})$ and $(\vec{d},\vec{p})$ reactions with a variety of targets[19] has shown that there are such deviations but that at energies above ~ 12 MeV all available results are in agreement with the spectator model prediction.

A somewhat less simplified stripping model[20] which incorporates both polarization transfer and tensor analyzing power results obtained with both vector and tensor polarized deuteron beams yields $K_y^{y'}(0°)=0.615$. This prediction differs slightly from that (0.607) of the simpler model and is in even better agreement with the available $(\vec{d},\vec{p})$ and $(\vec{d},\vec{n})$ polarization transfer results.

The data of the present experiment provide an additional opportunity for the testing of these predictions. For the low energy portion of the neutron spectrum, which is associated with hard collisions involving large momentum transfer, the prediction would not be expected to hold, but it would be expected to have some validity for the high-energy portion of the spectrum, which is associated with peripheral collisions and small momentum transfer. It is apparent from visual inspection of Fig. 1 that these expectations are verified. Quantitatively, the weighted average of the $K_y^{y'}(0°)$ values for neutrons in the region 25 to 35 MeV is 0.63 ± 0.04, which is in good agreement with both of the model predictions.

B. Faddeev calculations

It is also possible to compare the results with some Faddeev calculations of $K_y^{y'}$ for the $^1\mathrm{H}(\vec{d},\vec{n})\mathrm{pp}$ reaction at a nearby energy. The calculations were performed using the Doleschall code[21] on a CDC7600 computer at Los Alamos National Laboratory. This code solves the Alt-Grassberger-Sandhas (AGS) form[22] of the Faddeev equations and uses separable N-N interactions which reproduce the N-N phase parameters[23,24] up to several hundred MeV. The N-N force used has been described in Ref. 6. It is an improved interaction over one that had been used earlier to compare with analyzing power measurements in a kinematically incomplete $^1\mathrm{H}(\vec{d},\mathrm{p})\mathrm{pn}$ experiment[25] at $E_\mathrm{d}=16$ MeV. The tensor force used is the four-term force ($4T4R$) of Ref. 6. The three-body T matrices generated from this N-N force have been obtained previously for a deuteron bombarding energy of 45.4 MeV. This is certainly close enough to the energy of the present experiment to allow the making of a meaningful comparison, and therefore these existing T matrices have been used. No Coulomb corrections have been made.

Except in special cases (two of which will be found here), the Doleschall code does not calculate results directly comparable with kinematically incomplete experiments, such as the present one. The calculation of $K_y^{y'}$ has been done, however, for several final-state geometries which are commonly studied in kinematically complete three-nucleon breakup reactions. The 0° neutron energies from these reactions span the range of neutron energies of the present experiment. These geometries are the following: (1) the p-p final-state interaction (pp FSI) in which the two protons move off together in the opposite direction to the neutron ($E_\mathrm{n}=35.0$ MeV); (2) the proton colinearity condition (p-col) in which one of the protons is at rest in the c.m. system ($E_\mathrm{n}=30.7$ MeV); (3) the symmetric, constant-relative-energy (SCRE) configuration characterized by equal relative energies between all pairs of particles ($E_\mathrm{n}=25.9$ MeV); (4) the n-p final-state interaction (np FSI) in which the neutron and one proton move off together in a direction opposite to that of the other proton ($E_\mathrm{n}=20.3$ MeV); and (5) the neutron colinearity condition (n-col) in which the neutron is at rest in the c.m. system ($E_\mathrm{n}=9.5$ MeV).

The $K_y^{y'}$ results for these five final-state geometries are shown as open diamonds in Fig. 1. Two of these results are unique, in that no other configuration contributes at that neutron energy; these are the pp FSI and n-col points. The pp FSI arises from one simple configuration in which, in the c.m. system, the neutron moves in the same direction as did the incident deuteron, and the two protons move in the opposite direction with zero relative energy. The n-col result, however, arises from a continuum of configurations in which, in the c.m. system, the line defined by the neutron at rest and the two oppositely moving protons makes an angle γ with the beam direction. The code calculates $K_y^{y'}(\gamma)$ and $\sigma(\gamma)$, where σ is the c.m. differential cross section. The $K_y^{y'}$ prediction was obtained by calculating

$$\int K_y^{y'}(\gamma)\sigma(\gamma)\sin\gamma\, d\gamma \Big/ \int \sigma(\gamma)\sin\gamma\, d\gamma .$$

It is seen from Fig. 1 that both of the unique results agree quite well with the data. The disagreement shown by the SCRE calculation implies that such a configuration cannot be the dominant reaction for $E_\mathrm{n}=25.9$ MeV. The agreement of the p-col and np FSI calculations with the data is consistent with their being the dominant reactions at the corresponding E_n values, but by no means proves it. It would not be surprising, however, if the np FSI geometry were to be a major contribution at $E_\mathrm{n}=20.3$ MeV, since the FSI reaction mechanism generally occurs with a large cross section.

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[1] W. Grüebler, in Proceedings of the Ninth International Conference on the Few Body Problem, University of Oregon, 1980, edited by M. J. Moravcsik and F. S. Levin [Nucl. Phys. A353, 31c (1981)].

[2] G. G. Ohlsen, in *Proceedings of the Eighth International Conference on Few Body Systems and Nuclear Forces,* edited by H. Zingl, M. Haftel, and H. Zankel (Springer, Berlin, 1978); H. E. Conzett, in *Proceedings of the VII International Conference on Few Body Problems in Nuclear and Particle Physics, Delhi, 1976,* edited by A. N. Mitra (North-Holland, Amsterdam, 1976), p. 611; these survey papers and Ref. 1 contain extensive references to an earlier work.

[3] J. A. Tjon, in Proceedings of the Ninth International Conference on Few Body Problems, University of Orgeon, 1980, edited by M. J. Moravcsik and F. S. Levin [Nucl. Phys. A353, 47c, (1981)]. A. C. Phillips, Rep. Prog. Phys. 40, 905 (1977); Y. E. Kim and A. Tubis, Annu. Rev. Nucl. Sci. 24, 68 (1974); these survey papers contain extensive references to an earlier work.

[4] J. Bruinsma and R. Van Wageningen, Nucl. Phys. A282, 1 (1977).

[5] J. H. Stuivenberg and R. Van Wageningen, Nucl. Phys. A304, 141 (1978).

[6] P. Doleschall, W. Grüebler, V. König, P. A. Schmelzbach, F. Sperisen, and B. Jenny, Nucl. Phys. A380, 72 (1982).

[7] D. P. Saylor and F. N. Rad, Phys. Rev. C 8, 507 (1973).

[8] R. G. Graves, M. Jain, H. D. Knox, E. P. Chamberlin, and L. C. Northcliffe, Phys. Rev. Lett. 35, 917 (1975).

[9] F. N. Rad, R. G. Graves, D. P. Saylor, M. L. Evans, E. P. Chamberlin, J. W. Watson, and L. C. Northcliffe, Nucl. Instrum. Methods 190, 459 (1981).

[10] H. E. Conzett, W. Dahme, Ch. Leemann, J. A. MacDonald, and J. P. Meulders, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions, Zurich, 1975,* edited by W. Grüebler and V. König (Birkhaüser, Basel, 1976), p. 566; H. E. Conzett (private communication).

[11] M. K. Craddock, R. C. Hanna, L. P. Robertson, and B. N. Davies, Phys. Lett. 5, 335 (1963).

[12] Th. Stammbach and R. L. Walter, Nucl. Phys. A180, 225 (1972).

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

[14] J. C. Hiebert (unpublished).

[15] T. G. Miller, F. P. Gibson, and G. W. Morrison, Nucl. Instrum. Methods 80, 325 (1970).

[16] J. E. Simmons, W. B. Broste, G. P. Lawrence, J. L. McKibben, and G. G. Ohlsen, Phys. Rev. Lett. 27, 113 (1971).

[17] G. G. Ohlsen, Rep. Prog. Phys. 35, 717 (1972); the expression for p_n is easily obtained from Eqs. 8.8 of this reference.

[18] P. W. Lisowski, R. C. Byrd, G. Mack, W. Tornow, R. L. Walter, T. B. Clegg, and F. D. Santos, Phys. Rev. C 24, 1852 (1981).

[19] L. C. Northcliffe, W. D. Cornelius, R. L. York, and J. C. Hiebert, in *Polarization Phenomena in Nuclear Physics—1980 (Fifth International Symposium, Santa Fe),* Proceedings of the Fifth International Symposium on Polarization Phenomena in Nuclear Physics, AIP Conf. Proc. No. 69, edited by G. G. Ohlsen, R. E. Brown, N. Jarmie, M. W. McNaughton, and G. M. Hale (AIP, New York, 1981), p. 1335.

[20] L. C. Northcliffe, W. D. Cornelius, R. L. York, and J. C. Hiebert (unpublished).

[21] P. Doleschall, Nucl. Phys. A201, 264 (1973); A220, 491 (1974).

[22] E. O. Alt, P. Grassberger, and W. Sandhas, Nucl. Phys. B2, 167 (1967).

[23] M. H. MacGregor, R. A. Arndt, and R. M. Wright, Phys. Rev. 182, 1714 (1969).

[24] R. A. Arndt, R. H. Hackman, and L. D. Roper, Phys. Rev. C 15, 1002 (1977).

[25] F. D. Correll, G. G. Ohlsen, R. E. Brown, R. A. Hardekopf, N. Jarmie, and P. Doleschall, Phys. Rev. C 23, 960 (1981).