terms of an interference between single dipole and quadrupole isoscalar resonances. But it may be unreasonable to expect the collectivity, in a nucleus as light as ^{13}C, to be represented by single broad resonances. The isoscalar and isovector quadrupole strengths are very likely spread broadly and unevenly enough, in excitation energy, to produce considerable fluctuation in the sign of the interference term.

On the basis of the foregoing discussion one would expect forward enhancement in (n,γ) as well as in (p,γ) reactions in the region of the isovector quadrupole resonance, which presumably lies about half again as high as the GDR. In this higher energy region, especially for heavier nuclei, the model of two broad interfering resonances might be expected to be reasonably valid. There is, in fact, some evidence[5] for the expected forward enhancement in the reaction $^{208}\mathrm{Pb}(p,\gamma)$ and in preliminary studies[17] with neutrons of targets heavier than those of Table I. Hopefully it will be possible to continue to improve the precision of the (n,γ) measurements in this energy region, since neutrons appear to provide a unique tool for characterizing higher-lying collective excitations of nuclei.

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Measurement of the $^2\mathrm{H}(p,n)pp$ Transverse Polarization Transfer Coefficient at 20.4 MeV*

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The transverse polarization transfer coefficient, $K_y^{y'}$, has been measured for the reaction $^2\mathrm{H}(p,n)pp$ at 18° for $E_p = 20.4$ MeV as a function of neutron energy. Although predictions based on a three-body separable-potential model with S-wave N-N interactions are in reasonable agreement with the data, the need for a three-body theory with more realistic N-N forces is indicated.

Recently there has been extensive interest in the calculation and measurement of medium-energy three-body polarization observables, particularly for elastic N-d scattering.[1-3] Calculations based on increasingly realistic N-N forces now give predictions which are in fairly good quantitative agreement with all elastic N-d scattering data below 30 MeV.[1,3] In such calculations the need to fit polarization data as well as differential cross sections has proved to be an important constraint which can be satisfied only by including higher partial waves and the tensor interaction in the N-N forces used. By contrast, the most sophisticated calculations of N-d breakup have been designed only to fit the cross-section data.[3] Both experimental data[4-8] and theoretical calculations[9-11] on spin observables in N-d breakup are scarce. The only spin observables in N-d breakup for which published data are available are the zero-degree ^{2}H(p, n) polarization transfer[5,6] (for the highest-energy neutrons only), the ^{2}H(p, $2p$)n asymmetry,[7] and the ^{2}H(p, n)pp neutron polarization.[8] More sophisticated N-d breakup polarization measurements would provide more stringent tests for present theories of N-d breakup as well as valuable information for the development of three-body breakup calculations using more realistic N-N forces. Here we report measurements of the transverse polarization transfer coefficient $K_y^{y'}(E_n)$ (analogous to the Wolfenstein D_t parameter) for the reaction ^{2}H(p, n)pp at $E_p = 20.4$ MeV and $\theta_n = 18°$ and compare them with the predictions of a three-body separable-potential model.[12] These measurements complement previous measurements of the polarization parameter[8] and differential cross section[13] for the same reaction at the same angle and at about the same incident proton energy.

The experiment was performed at the medium-energy neutron facility briefly described earlier[8] using a 21.8-MeV polarized-proton beam[14] from the Texas A & M cyclotron. The beam was magnetically analyzed and transported to the target area where it passed through a high-pressure (~15 atm) liquid-nitrogen-cooled deuterium-gas target. The mean beam energy in the target was 20.4 MeV and the average beam current was 49 nA. Beyond the target the beam was magnetically deflected into a heavily shielded Faraday cup. The beam polarization is vertical and can be reversed at the source. It was monitored continuously by measuring the asymmetry of elastic p-^{4}He scattering in a ^{4}He gas polarimeter located just ahead of the target. The average beam polarization p_y as determined from the analyzing power given by p-^{4}He phase shifts of Bacher *et al.* was $(70.4 \pm 3.1)\%$. The error includes a systematic error due to fluctuations of the polarization with time.

The breakup neutrons from the reaction passed through a collimator channel at angle $\theta_n = 18°$ formed by two transverse-field magnets which were used to precess the neutron spins. The neutrons then were scattered from a liquid-helium sample in a polarimeter located 4.50 m from the target and were detected by one of four NE102 scintillators located at angles $\psi = \pm 78°$ and $\psi = \pm 125°$ to the collimator axis. Both reaction planes were horizontal. Data were obtained with incident proton polarization either up $(+p_y)$ or down $(-p_y)$ and with the precession magnet fields either parallel (giving a net neutron spin-precession angle α which depends on E_n) or antiparallel (giving $\alpha = 0$). If the subscripts a and p indicate antiparallel and parallel precession mode and the superscripts + and − indicate "up" and "down" proton polarization, respectively, then the four possible running modes are $\binom{+}{a}$, $\binom{-}{a}$, $\binom{+}{p}$, and $\binom{-}{p}$. Runs were made in the sequence $\binom{+}{p}$ $\binom{-}{p}$ $\binom{-}{a}$ $\binom{+}{a}$ $\binom{+}{a}$ $\binom{-}{a}$ $\binom{-}{p}$ $\binom{+}{p}$ so as to minimize errors due to long-term drifts in any part of the apparatus. Further details of the experimental arrangement and data-acquisition procedure have been given earlier.[16,17]

The general formalism for polarization-transfer experiments has been presented by Ohlsen.[18] In terms of this formalism, the number of neutrons scattered into one of the NE102 scintillators in the liquid-helium polarimeter (N_p^+, N_p^-, N_a^+, or N_a^-) is given by[19]

$$N_{a(p)}^{+(-)} = N_0[1 \pm p_y A_y \pm (P_{y'} \pm p_y K_y^{y'}) A_{y'} \cos\alpha], \quad (1)$$

where N_0 is proportional to the number of neutrons recoiling into angle θ_n (= 18°) in the reaction ^{2}H(p, n)pp with unpolarized protons, $P_{y'} = |\vec{P}_{y'}|$ is the neutron polarization produced in that reaction with unpolarized protons, A_y is the analyzing power of the reaction ^{2}H(p, n)pp, $A_{y'}$ is the ^{4}He(n, n)^{4}He analyzing power, and $\cos\alpha$ is given in terms of the vertical unit vector $\hat{j}'$ and the precessed neutron polarization $\vec{p}_{y'} \cdot \hat{j}'$ by $\cos\alpha = \vec{p}_{y'} \cdot \hat{j}'/p_{y'}$. In the formulas for N_a^+ and N_a^-, $\cos\alpha = 1$. The transverse polarization transfer coefficient $K_y^{y'}$ is given by[20]

$$K_y^{y'} = \vec{p}_{y'} \cdot \hat{j}'/\pm p_y + (\vec{p}_{y'} \cdot \hat{j}')A_y - P_{y'}/\pm p_y. \quad (2)$$

Note that in Eqs. (1) all quantities except p_y are functions of the neutron energy E_n while $N_{a(p)}^{+(-)}$ and $A_{y'}$ also are functions of ψ. The ± sign before the parentheses in Eqs. (1) is taken as + for left-scattered and as − for right-scattered neutrons, and the ± sign before p_y in both Eqs. (1) and (2) is taken as + for up polarization and − for down polarization of the incident proton beam.

The four independent Eqs. (1) can be solved for

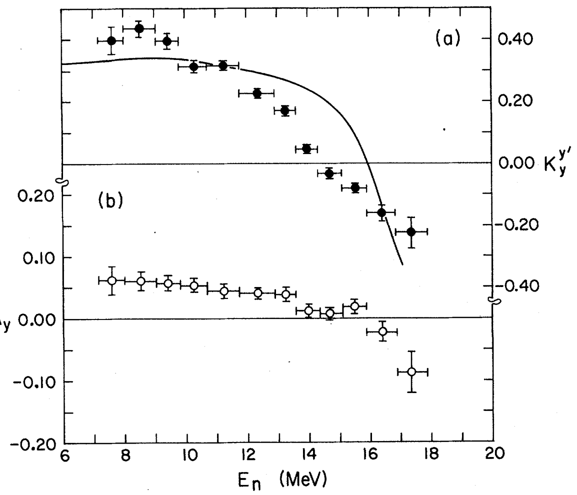

FIG. 1. Spin observables for the ^{2}H(p,n)pp reaction at $\theta_n = 18°$ for $E_p = 20.4$ MeV. (a) Measured transverse polarization transfer coefficient $K_y^{y'}$ (closed circles) and the prediction (solid line) given by a three-body separable-potential model; (b) measured analyzing power A_y (open circles).

the four unknowns (N_0, A_y, $P_{y'}$, and $K_y^{y'}$) by forming ratios of various combinations of the measured $N_{a(p)}^{+(-)}$ values. The resulting values of $K_y^{y'}$ and A_y are shown in Fig. 1. The values for $P_{y'}$ are not shown but are consistent with our previous measurement of $P_{y'}$ using an unpolarized beam.[8] For each point in Fig. 1 the vertical bar represents the statistical error and the horizontal bar shows the energy bin used. The data have been corrected for multiple-scattering and finite-geometry effects using the method described by Broste.[21] The $A_{y'}$ values were calculated using the phase shifts of Stammbach and Walter.[22]

Previous attempts to calculate the transverse polarization transfer coefficient for the reaction ^{2}H(p,n)pp have used the impulse approximation (IA). Phillips[11] first calculated $K_y^{y'}$ for the highest-energy neutrons emitted at zero degrees. His results, based on the nucleon-nucleon potentials then available, showed $K_y^{y'}$ (0°) ranging from -0.49 at 40 MeV to -0.58 at 156 MeV. Dass and Queen[10] have done more complete IA calculations of $K_y^{y'}$ (0°) as a function of both incident-proton and final-neutron energy including final-state interactions and multiple-scattering corrections. At 30 MeV their results show $K_y^{y'}$ (0°) decreasing smoothly with neutron energy from ≈ -0.28 to ≈ -0.05. Ramavataram and Ho-Kim[9] have calculated $K_y^{y'}$ as a function of angle for the highest-energy neutrons for $E_p = 24-100$ MeV. At $E_p = 24$ MeV they found $K_y^{y'}(0°) = -0.24$ using the energy-dependent phase shifts (AM1) of Arndt and MacGregor[23] and $K_y^{y'}$ (0°) $= -0.13$ using the Arndt-MacGregor energy-independent phase shifts (AM2).

Our present measurement of $K_y^{y'}$ (18°) $= -0.22 \pm 0.05$ for the highest-energy neutrons is in agreement with the prediction of Ramavataram and Ho-Kim[9] for $K_y^{y'}$ (0°) at 24 MeV using AM1 phase shifts, although their value should be lowered somewhat to account for our lower energy and larger angle. While the IA predictions may seem to be reliable for the highest-energy neutrons, their sensitivity to the nucleon-nucleon phase shifts used should be noted. For the low-neutron-energy region, however, the IA calculations are not expected to be reliable[10] and, in fact, the measured $K_y^{y'}$ values are qualitatively different from the IA prediction.[10]

Recently Jain and Doolen[12] have developed a three-body code which has been successful in fitting p-d breakup differential cross sections in both kinematically complete[12] and incomplete[13] experiments. Based on an exact solution of the three-particle Faddeev equations for separable spin-dependent S-wave nucleon-nucleon potentials, their code calculates the three independent scattering amplitudes, q, d_1, and d_2 for p-d breakup.[24] The predictions given by this code are in excellent agreement with our previous cross-section measurements.[13] Using their amplitudes and the zero-order M matrix and equation for polarization transfer of Saylor and Rad,[25] we have calculated $K_y^{y'}$ as a function of neutron energy. The results are shown as a solid line in Fig. 1(a).

Although the $K_y^{y'}$ predictions given by the three-body code are in better qualitative agreement with the trend of the measured $K_y^{y'}$ values than are the IA predictions, the agreement is only qualitative and there are significant discrepancies between the calculated and measured values in the region of intermediate neutron energy where $K_y^{y'}$ changes sign. The inadequacy of the calculation is due in part to the fact that the M matrix used includes only two-body S waves. One consequence of this restriction to the two-body S-wave interaction is that the theory cannot reproduce the A_y values shown in Fig. 1(b) since it can only give zero for $P_{y'}$ and A_y. As a result, terms in Eq. (2) involving $P_{y'}$ and A_y vanish, and the prediction for $K_y^{y'}$ assumes a zero-order value: the ratio of the outgoing neutron polarization to the incoming proton polarization.[26] The discrepancy between the theoretical and experimental $K_y^{y'}$ values must involve more than the effect of nonzero terms containing $P_{y'}$ and A_y, however, because the discrepancy is greatest at $E_n \sim 14$ MeV where A_y and $P_{y'}$ are very small. Higher partial waves must be responsible for this discrepancy as well as for the nonzero A_y and $P_{y'}$ values. The present results clearly indicate the need for a theoretical model of three-body breakup which uses more realistic N-N forces.

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