Cross section and transverse polarization transfer for the ^{2}H(p,n)2p reaction at 160 MeV

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The cross section and transverse polarization transfer for the ^{2}H(p,n)2p reaction at $E_p=160$ MeV and $\theta=0°$ have been measured with good energy resolution (1 MeV). An asymmetric peak shape characteristic of the $^1S_0$ final-state interaction of the residual two-proton system has been clearly observed. The measured transverse polarization transfer coefficient for this peak is $D_{NN}(0°)=-0.43\pm0.04$. A simple impulse approximation calculation including the $^1S_0$ final-state interaction reproduces the main features of the observed peak shape and polarization transfer. Small discrepancies observed in the peak tail region can be accounted for by including the $^3P_{0,1,2}$ final state interaction.

One of the simplest systems for testing various reaction models is the p-d system. The ^{2}H(p,n)2p reaction at $\theta=0°$ is of particular interest. A narrow peak characteristic of the $^1S_0$ final-state interaction (FSI) of the residual two-proton system[1,2] can be observed at the highest energy end of the neutron spectrum.[3-5] The shape and magnitude of this peak should in principle give information on the $^1S_0$ scattering length of the two-proton system and on the n-p scattering amplitude. In practice, however, owing to the difficulty in measuring a neutron energy spectrum with good energy resolution, no experimental results for energies larger than 50 MeV have been published to date with resolution better than the width of the FSI peak, which is expected to be about 1.7 MeV. It has also been pointed out[6-8] that the transverse polarization transfer coefficient D_{NN} for the FSI peak gives information on the tensor component of the n-p scattering amplitudes. This tensor contribution is usually difficult to isolate from other effects. The polarization transfer at 0° has been measured in several experiments;[9-12] all of these experiments, however, were hampered by rather poor energy resolution (≥ 5 MeV) owing to the experimental techniques required to get reasonable double-scattering yields. The measured values[9-12] of $D_{NN}(0°)$ over the bombarding energy range from $E_p=30$ to 800 MeV disagree with impulse approximation (IA) calculations. Because of poor energy resolution, this disagreement may be caused in part by contributions from final states other than the $^1S_0$ state. This problem is best addressed by new measurements of the cross section and polarization transfer with an energy resolution better than the width of the FSI peak.

In this Brief Report we present a measurement of the neutron energy spectrum and polarization transfer for the ^{2}H(p,n)2p reaction at $E_p=160$ MeV and $\theta=0°$ with a resolution of about 1 MeV. The beam energy was chosen to be high enough for the impulse approximation to be valid, while still maintaining the desired experimental energy resolution. These measurements provide new information on the n-p scattering amplitudes as well as quantitative tests of the impulse approximation and final-state interaction models.

The measurements were carried out at the Indiana University Cyclotron Facility. A proton beam with an energy of 160 MeV and an average polarization of $|p_i|=0.74$ bombarded a deuterated polyethylene (^{12}C^{2}H$_2$) target with a thickness of 195 ± 4 mg/cm^2. A neutron detector polarimeter consisting of six $15\times15\times100$ cm plastic (NE102) scintillators was used to measure the time-of-flight and polarization of neutrons emitted at 0°. The flight path was 91 m and the energy resolution achieved was about 1 MeV for the highest energy neutrons. The neutron polarization p_f was extracted using empirically determined values of the magnitude and energy dependence of the polarimeter analyzing power. The systematic uncertainty in the derived polarization transfer coefficient $D_{NN}(0°)=p_f/p_i$ is dominated by the uncertainty in the polarimeter analyzing power and is estimated to be ±0.02. The experimental technique is

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described in detail in Ref. 13. Approximately 5 h of beam time ($I_p = 50$ nA) were required to make the measurements discussed here.

Spectra obtained from the C^2H_2 target are shown in Fig. 1. The top half of this figure is the laboratory double differential cross section $d^2\sigma/d\Omega\, dE_n$. A large peak with an asymmetric shape is expected for the ^{2}H(p,n)2p reaction owing to the $^1S_0$ final-state interaction and is clearly observed. The carbon content of the target provides a convenient reference transition from which the cross section normalization and experimental energy resolution are obtained. A peak corresponding to the ^{12}C(p,n)^{12}N(g.s.) transition is observed at $E_n = 141.8$ MeV and is assumed to have a c.m. cross section[14] of 6.5 ± 0.5 mb/sr. The measured width (FWHM) of this peak is 0.89 MeV. The lab cross section integrated over a 10 MeV region including the ^{2}H(p,n)2p peak is 30.2 ± 3.0 mb/sr and is consistent with previous measurements.[4,5]

The bottom half of Fig. 1 shows the polarization transfer coefficient $D_{NN}(0°)$. Statistical scatter in the displayed values of D_{NN} was reduced by binning the yield with a 2 MeV width for the FSI peak region and with a 4 MeV width for the tail region. Horizontal bars indicate the bin width and vertical bars represent the statistical uncertainty. The D_{NN} value for the ^{12}C(p,n)^{12}N(g.s.) transition is consistent with previous measurements.[15]

The cross section for the ^{2}H(p,n)2p reaction can be calculated in the impulse approximation[2,16] with the final state interaction (IA + FSI) according to ($\hbar = c = 1$)

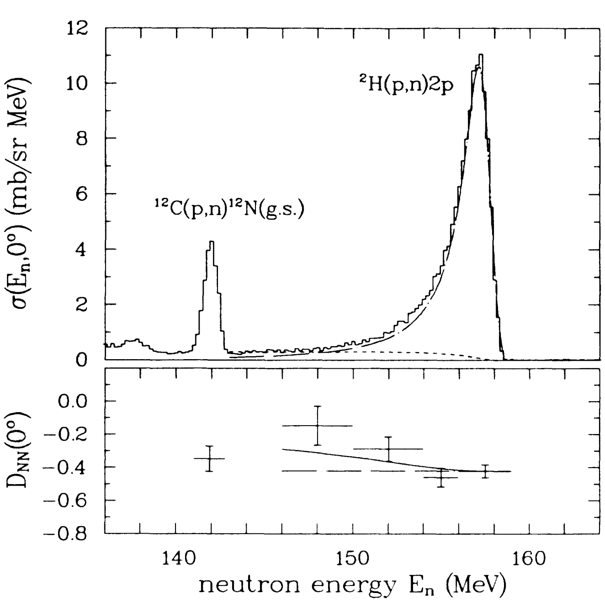

FIG. 1. The laboratory double differential cross section (top) and transverse polarization transfer coefficient D_{NN} (bottom) for the ^{2}H(p,n)2p reaction at $E_p = 160$ MeV and $\theta = 0°$. Horizontal bars in D_{NN} indicate the bin width and vertical bars represent the statistical uncertainty. The dot-dashed curves represent the results of the IA with the $^1S_0$ FSI and the dotted curves with the $^3P_{0,1,2}$ FSI. In the plot of D_{NN} the solid curve represents the sum of the $^1S_0$ and $^3P_{0,1,2}$ contributions. See the text for details.

$$\frac{d^2\sigma}{d\Omega\, dE_n} = \frac{N}{3}\frac{M}{\pi}\frac{k_{2p}k_n}{k_p}\sigma_{np} \times \left| \int \phi^*_{2p}(E_{2p},\mathbf{r})\phi_d(\mathbf{r})e^{i\mathbf{q}\cdot\mathbf{r}/2}d^3r \right|^2 , \quad (1)$$

where M is the nucleon mass and k_{2p}, k_p, and k_n are the relative momenta of the two protons in the final state, of the incident proton in the c.m. system, and of the outgoing neutron in the laboratory system, respectively. The asymptotic momentum transfer is denoted by q. The deuteron wave function $\phi_d(r)$ is of Hulthén type.[17] The final 2p wave function $\phi_{2p}(E_{2p},r)$ is described[2,5] in terms of the scattering length a_{pp} and effective range r_0 for free p-p scattering. N is an arbitrary normalization constant and σ_{np} is the appropriate differential cross section for free n-p scattering.

By assuming a pure $^1S_0$ state for the final two-proton state, which corresponds to defining the transition as $1^+ \to 0^+$, Phillips[6] obtained an expression for $D_{NN}(0°)$ in terms of free n-p scattering amplitudes. More recently, Moss[18] also derived expressions for more general cases on the basis of the IA. For the ^{2}H(p,n)2p $1^+ \to 0^+$ transition *at 0°*

$$D_{NN}(0°) = \frac{-|F|^2}{2|B|^2 + |F|^2} = \frac{-|A' - B' - 8F'|^2}{|A' - B' - 8F'|^2 + 2|A' - B' + 4F'|^2} , \quad (2)$$

where, in the notation of Ref. 18, B and F are related to the spin-dependent central and the tensor parts of the n-p scattering amplitude,[18] and more explicitly in the notation of Ref. 19, A', B', and F' are the central spin-singlet, central spin-triplet, and exchange-tensor amplitudes, respectively, in the n-p scattering matrix.

Numerical calculations have been performed with $a_{pp} = -7.82$ fm and $r_0 = 2.83$ fm.[20] The values for σ_{np}, B, and F were obtained from the recent Arndt phase shift analysis.[21] In this sense there are no free parameters. The calculated results folded with the experimental energy resolution are shown in Fig. 1 as dot-dashed curves. The asymmetric peak shape is well reproduced by the simple IA + FSI calculation. The value $N = 1.16$ was required to reproduce the measured cross section. Considering the normalization uncertainty of the present data ($\pm 10\%$) and that of the N-N cross sections used in the calculations ($\pm 10\%$), this deviation of N from unity is probably not significant.

The IA calculations give $D_{NN} = -0.42$ and are indicated by a dot-dashed line in Fig. 1. Over the energy region considered here the momentum transfer dependence of the IA value is small[7] and has been ignored. This IA value should be compared to the experimental value $D_{NN}(0°) = -0.43 \pm 0.04$ for the ^{2}H(p,n) peak ($E_n = 156-158$ MeV). The excellent agreement for this polarization transfer coefficient further supports the interpretation of this peak in terms of the $^1S_0$ final-state interaction. The value of D_{NN} for a broader 10 MeV region from $E_n = 149$ to 159 MeV is $D_{NN} = -0.40 \pm 0.03$. The present results can also be compared to the D_t parameter[22] for free n-p scattering. This comparison implies treating the target proton as a spectator, so that the angular momentum structure of the reaction is $\frac{1}{2}+\frac{1}{2}\rightarrow\frac{1}{2}+\frac{1}{2}$. The Arndt phase shifts[21] give $D_t(180°)=-0.36\pm0.02$, in poorer agreement with the data. The angular momentum restrictions provided by the $^1S_0$ model therefore appear to be important.

The large negative value of D_{NN} is interesting. For a purely central interaction $B=F$ and Eq. (2) gives $D_{NN}=-\frac{1}{3}$, while for a purely tensor interaction $A'=B'=0$ and $D_{NN}=-\frac{2}{3}$. A departure of $D_{NN}(0°)$ from $-\frac{1}{3}$ can thus be attributed to the presence of a noncentral (tensor) interaction. An empirical average[15] for $\Delta J^{\pi}=1^+$ transitions at 160 MeV is $D_{NN}(0°)=-0.33 \pm0.05$ for $A=6$–90, in sharp contrast with the present value of -0.43 ± 0.04. Full distorted wave impulse approximation (DWIA) calculations for $\Delta J^{\pi}=1^+$ (p,n) transitions in six representative nuclei with $A=6$–208 predict $D_{NN}(0°)=-0.35\pm0.02$ at 160 MeV, in good agreement with the measurements for this mass range. Near $\theta=0°$ the tensor interaction should enter mainly through the knock-on exchange amplitude. While the DWIA direct amplitudes are predominantly functions of the momentum transfer q, the exchange amplitudes are to a good approximation determined by the incident nucleon's momentum k_A in the *N-nucleus* c.m. system, especially near $q=0$.[19] Since k_A varies rapidly for A near unity but is almost constant for $A\geq 12$ we therefore surmise that the differences between the measured $D_{NN}(0°)$ values for ^{2}H and the heavier nuclei can be directly related to an anticipated momentum dependence of the tensor exchange amplitude.

In the tail region ($E_n=145$–155 MeV) of the ^{2}H(p,n) spectrum, the agreement between the IA + FSI calculation and the measured cross section is not perfect, although the difference is very small. The peak shape is insensitive to r_0, but an almost perfect fit to the data may be obtained by changing a_{pp} from 7.8 to 7.0 fm. This corresponds to explaining the difference entirely in terms of the $^1S_0$ state. A consequence of such a limited model is that D_{NN} should be approximately constant as a function of energy loss, contrary to the observed trend (Fig. 1). The small cross section enhancement in the tail region is therefore probably meaningful and could be explained better by adding a contribution from a FSI other than $^1S_0$. It is clear that such a conclusion could not be easily drawn without the D_{NN} data.

The present analysis can be extended to include P states of the residual two-proton system. These states should be important at higher excitation (lower E_n) energy. Calculations for $^3P_{0,1,2}$ final states have been carried out in a manner similar to that used for the $^1S_0$ state. Scattering lengths and effective ranges were obtained from Ref. 23. Possible contributions from the D-wave component of the deuteron ground state have been ignored.

The D_{NN} value for the $^3P_{0,1,2}$ contribution is obtained in the following way. The possible transitions are combinations of $\Delta L=1$, $\Delta S=0,1$, and $\Delta J=0,1,2$, where ΔL, ΔS, and ΔJ are the transferred orbital, spin, and total angular momentum. For $\Delta S=1$ transitions the central and tensor nucleon-nucleon amplitudes in the simplest impulse approximation give $D_{NN}=-1.0$, 0.0, and -0.47, for $\Delta J=0$, 1, and 2, respectively, and $D_{NN}=1.0$ for $\Delta S=0$ transitions.[18] We have also assumed a relative weighting of $(\Delta S=1)/(\Delta S=0)=8.43$ from the empirical ratio of spin-dependent to spin-independent isovector effective interaction strengths.[24] The final ^3P value of $D_{NN}=-0.21$ is obtained by adding the various ΔJ contributions with $2\Delta J+1$ statistical factors.

The calculated ^3P contribution with $N=1.16$ is shown in Fig. 1 as a dotted curve. The strength is distributed over the highly excited region because of momentum transfer requirements and thus adds to the cross section primarily in the tail region. The summed $^1S_0$ and $^3P_{0,1,2}$ contributions now provide a good description of the observed cross section. Inclusion of the ^3P states in this manner significantly improves the description of the polarization transfer data as well.

In summary, the cross section and transverse polarization transfer for the ^{2}H(p,n)2p reaction have been measured at $E_p=160$ MeV and 0° with an energy resolution of 1 MeV. The main features of the spectrum can be explained by an impulse approximation (IA) calculation with a $^1S_0$ final-state interaction (FSI). Deviations from the predictions of this simple calculation in the low-energy tail of the ^{2}H(p,n) peak may be due to a $^3P_{0,1,2}$ FSI, although we have neglected multiple-scattering effects and contributions from the deuteron D state. Nevertheless, we have shown that good energy resolution and polarization transfer data play a crucial role in the interpretation of the spectrum for this reaction. On a practical note, the relatively large polarization transfer and cross section make this reaction a reasonable candidate for a secondary polarized neutron standard for calibration of neutron polarimeters in the IUCF energy range.

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