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Polarization Effects in the Final-State Interaction Region of the *p-d* Breakup Reaction*

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The angular distributions of the vector analyzing power have been measured in the reactions ^{2}H(p,p)np and ^{1}H(d,p)np at 22.7 and 45.4 MeV, respectively, corresponding to the same center-of-mass energy. Significant analyzing powers were found in the production of final-state np pairs with low relative energies, and the angular distributions show a remarkable similarity to those of the corresponding elastic scattering.

We report in this Letter on the first significant polarization effects observed in the final-state interaction (FSI) region of the p-d breakup reaction.

Among the experimental observables in the three-nucleon system, the elastic cross section, inelastic cross section, and elastic analyzing power have been extensively investigated.[1] Inelastic analyzing powers comprise one class of observables which has received very little attention. That is, only a few experiments have been done which even show the presence of polarization effects, and theoretical interpretation and predictions via exact three-body calculations have not, as yet, been made. The three-nucleon calculations, based on the Faddeev equations with separable potentials for the $^1S_0$, $^3S_1$-$^3D_1$, and P-wave components of the nucleon-nucleon interaction,[2,3] have provided predictions of the vector and tensor polarizations which are in good agreement with the experimental data in the elastic channel,[4-6] whereas the S-wave forces alone had been sufficient to give agreement with the differential cross-section data. Similarly, calculations which have been successful in fitting inelastic cross-section data have been restricted to two-nucleon S-wave interactions[7] and, thus, cannot predict analyzing powers for incident polarized protons or deuterons.

Perhaps the first polarization effects seen in the breakup reaction for the production of final-state np pairs with low relative energy were those observed by Arvieux *et al.* in the reaction ^{2}H(p, 2p)n at 10.5 MeV.[8] Their measurements at three angles of the proton analyzing power $A_y(\theta)$ for the transition to the np FSI region showed $A_y(\theta) \leq 0.05$, within the errors of ± 0.02 to ± 0.03. They had noted, for comparison, the similarity of the trend of their measurements to that of the elastic-channel analyzing power at 11.0 MeV. Blyth *et al.*[9] have reported on the determination of the deuteron vector analyzing power at several angles in the reaction $^1H(d, 2p)n$ induced with a beam of 12.2-MeV vector-polarized deuterons. Their reported values are all consistent with zero, within errors of ±0.01 to ±0.03, but it should be noted that in this case the center-of-mass (c.m.) energy was only 4.1 MeV and the elastic-channel analyzing power at the nearby deuteron energy of 11.5 MeV has a maximum value of less than 0.05.[10] Another study was that of Rad *et al.*[11] in a measurement of the polarization of the breakup neutrons at $\theta_{1ab} = 18°$ in the reactions $^1H(d, n)$ and $^2H(p, n)$ at $E_{c.m} = 14.3$ MeV. The observed polarization in the *np* FSI region of the neutron spectra was found to be consistent with zero in the reaction $^2H(p, n)$ and $\simeq -0.025$ in $^1H(d, n)$. Thus, the polarization effects reported in these studies of the breakup reaction have been quite small. It seems that experimental evidence of more substantial effects, such as reported here, are required in order to encourage, or even compel, the addition of the tensor-force and *P*-wave contributions to three-body calculations.

The polarized proton or deuteron beam from the Berkeley 88-in. cyclotron was passed through a gas target in a 36-in.-diam scattering chamber. A description of the experimental arrangement and of the data-acquisition procedure has been given elsewhere.[5]

Our experimental results for the proton analyzing power $A_y(\theta)$ in the reaction $^2H(p,p)d^*$ at $E_p = 22.7$ MeV are shown in Fig. 1, where the errors indicated are purely statistical.[12,13] Here, d^* denotes the final-state *np* pairs with relative energy $E_{np} \leq 1$ MeV, in both singlet and triplet states. For comparison, the smooth curve represents the elastic-scattering analyzing powers measured in the same experiment. As can be seen, $A_y(\theta)$ in the breakup reaction reaches substantial values at angles greater than $\theta_{c.m.} = 70°$, and its angular distribution is quite similar to that of the elastic analyzing power. Figure 2 shows our experimental results for the deuteron vector analyzing power in the reaction $^1H(d,p)d^*$ at $E_d = 45.4$ MeV,[1,13] corresponding to the same c.m. energy as in the reaction $^2H(p,p)d^*$. Again the errors indicated are purely statistical and the solid line is a smooth curve drawn through the elastic-scattering results.[5] Here also the similarity between the inelastic and elastic analyzing powers is quite definite.

This similarity between the angular distribution of the analyzing powers for the elastic and inelastic scattering is rather unexpected in view of the results that were reported by Brückman *et al.*[14] in the analysis of their $^1H(d, pp)n$ cross-section data at the slightly higher energy of $E_d = 52.3$ MeV. In their analysis they used the Watson FSI factorization assumption[15] to determine the separate contributions to the $^1H(d, d^*)p$ cross section from the production of singlet and triplet *np* pairs,

$$(d\sigma/d\Omega)_{d^*} = (d\sigma/d\Omega)_{d^*}{}^s + (d\sigma/d\Omega)_{d^*}{}^t . \qquad (1)$$

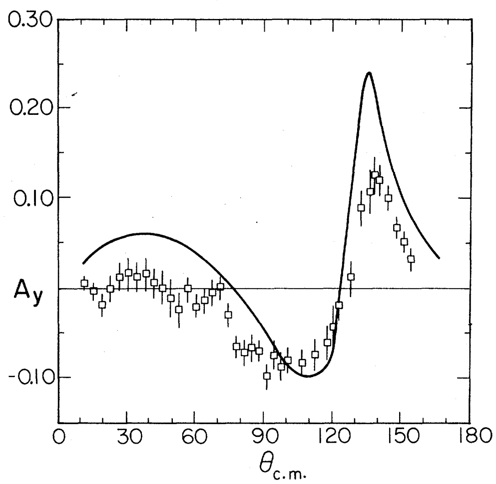

FIG. 1. The proton analyzing power $A_Y(\theta)$ in the reaction $^2H(p,p)d^*$ at $E_p = 22.7$ MeV for the transition to the FSI region with relative energy $E_{np} \leq 1$ MeV. The smooth curve represents the elastic-scattering analyzing powers measured in the same experiment.

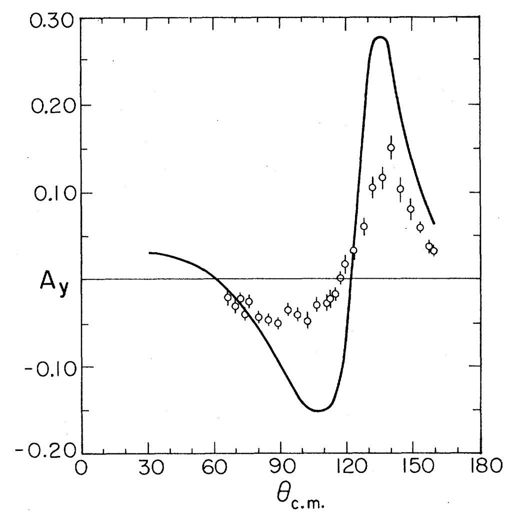

FIG. 2. The deuteron analyzing power $A_Y(\theta)$ in the reaction $^1H(d,d^*)^1H$ at $E_d = 45.4$ MeV for the transition to the FSI region with relative energy $E_{np} \leq 1$ MeV. The smooth curve represents the deuteron elastic-scattering analyzing powers of Ref. 5.

They found that between $\theta_{c.m.} = 85°$ and 150° the production of singlet pairs exceeded that of triplet pairs for $E_{np} \leq 1$ MeV, with the ratio $R = (d\sigma/d\Omega)_{d^*}{}^s/(d\sigma/d\Omega)_{d^*}{}^t$ reaching a value of about 10 near $\theta_{c.m.} = 120°$. The angular dependence of $(d\sigma/d\Omega)_{d^*}{}^t$ was similar in shape to that of the elastic cross section, and their Born-approximation calculation, in which the final-state *np* wave function used was effectively that of a deuteron with binding energy $E_B = 0$, was in excellent agreement with $(d\sigma/d\Omega)_{d^*}{}^t$. However, $(d\sigma/d\Omega)_{d^*}{}^s$ was quite different, with the result that the combined singlet plus triplet cross section showed little resemblance to the elastic angular distribution. The more recent exact three-body calculations of Kluge, Schlüfter, and Ebenhöh,[16] using spin-dependent separable potentials for the relative S state of the two nucleons, substantiate the earlier findings of Brückman *et al.* in the determination of the separate singlet and triplet d^* production cross sections. Furthermore their calculated ratio $|T^s|^2/|T^t|^2 = (d\sigma/d\Omega)_{d^*}{}^s/(d\sigma/d\Omega)_{d^*}{}^t$ for $E_{np} = 0$ is in good agreement with the ratio R deduced by Brückman *et al.* from the analysis of their data. This ratio was shown to be as high as 20 in the backward angular region.

We can, in the same way, express our analyzing-power results as the incoherent sum of the singlet and triplet d^* production contributions:

$$A_y^{d^*} = \frac{A_y{}^s (d\sigma/d\Omega)_{d^*}{}^s + A_y{}^t (d\sigma/d\Omega)_{d^*}{}^t}{(d\sigma/d\Omega)_{d^*}{}^s + (d\sigma/d\Omega)_{d^*}{}^t}, \qquad (2)$$

where $A_y{}^s$ and $A_y{}^t$ are the analyzing powers for production of *np* pairs in the $^1S_0$ and $^3S_1$ states, respectively. If triplet d^* production were the major contribution to the cross section, one could expect the similarity between the elastic and inelastic vector analyzing powers seen in Figs. 1 and 2. However, it is the singlet d^* production which is the major contribution to the cross section in just the backward angular region of maximum analyzing power. In view of the fact that the ratio R is found to be quite large over a considerable region of backward angles, Eq. (2) there reduces to $A_y{}^{d^*} \simeq A_y{}^s$, implying that the angular distribution of the vector analyzing power in the elastic channel is similar to that in the breakup channel with the *np* pair in the singlet state. This condition is quite unexpected, especially in view of the marked dissimilarity between $(d\sigma/d\Omega)_{d^*}{}^s$ and $(d\sigma/d\Omega)_{d^*}{}^t$ for d^* production. Although the exact three-body calculations very nicely reproduce the singlet and triplet d^* production cross sections, there is an obvious need to include the more realistic nucleon-nucleon tensor and P-wave interactions in an effort to explain the analyzing-power results presented here.

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