Vector Analyzing Power in d-p Scattering at 45.4 MeV and the Nucleon-Nucleon Interaction*

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The deuteron vector analyzing power in deuteron-proton elastic scattering has been measured at $E_d = 45.4$ MeV. Our results, when compared with recent three-body calculations, suggest the possibility of deducing information on the n-p phase-shift parameters which has not been available from n-p scattering itself.

During the past few years, three-body calculations[1-5] have achieved notable success in fitting measured polarization observables[6-13] in elastic nucleon-deuteron scattering. These calculations, which use the Faddeev equations with separable nucleon-nucleon potentials, have been made with more and more complicated N-N interactions. The simple S-wave force had been sufficient to give agreement only with the differential-cross-section data.[14,15] The increasingly accurate and extensive polarization data, including nucleon and deuteron vector analyzing powers and deuteron tensor analyzing powers,[16] have played a significant role in this theoretical refinement. It now seems possible to derive from such data, via the three-body calculations, information on the N-N interaction which, as yet, has not been available from N-N scattering experiments. The most recent calculations of Doleschall[5] show a surprisingly strong dependence of the nucleon and deuteron vector polarizations on variations of the input ${}^3S_1$-${}^3D_1$ N-N tensor interaction. We report here measurements[17] of the deuteron vector analyzing power, iT_{11}, in d-p elastic scattering at $E_d = 45.4$ MeV, which can be compared directly with the calculated vector polarization at the equivalent nucleon energy $E_N = 22.7$ MeV.

Although it has been known[1-3,12] that the vector polarizations in N-d scattering are essentially due to the N-N P-wave interactions, there have been conflicting conclusions concerning the contribution to these polarizations from the tensor force. Pieper[4] reported only slight changes with the addition of the tensor force, and he suggested[18] that changes in the ${}^3S_1$-${}^3D_1$ potential would have little effect on the nucleon polarizations. This conjecture was based on Sloan and Aarons's[1] result, which demonstrated that none of the N-d polarizations were very sensitive to changes in the ${}^3S_1$-${}^3D_1$ potential. However, that calculation did not include the P-wave interactions, and so the calculated vector polarizations were unrealistically small. Doleschall's first calculation[3] showed a substantial change in the vector polarizations with the addition of the tensor force to the S- and P-wave interactions, and his most recent calculation[5] shows that the vector polarizations are quite sensitive to the details of the ${}^3S_1$-${}^3D_1$ potential. It is just this sensitivity that offers the promise of providing information on the ${}^3S_1$-${}^3D_1$ n-p mixing parameter ϵ_1, and the ${}^1P_1$ phase shift, which are poorly determined from phase-shift analyses of n-p scattering data below 80 MeV.[19] Although Doleschall does not address this question, it seems clear that variations of ϵ_1 and the ${}^1P_1$ phase shift, in a search for improved fits to the vector polarization data, could result in a better determination of these parameters than has been possible from n-p scattering data.

The polarized deuteron beam from the Berkeley 88-in. cyclotron passed through a hydrogen-gas target in a 36-in.-diam scattering chamber. The 7.5-cm-diam gas cell with a 5-μm Havar-foil window was operated at pressures of 11.55 and 15.02 lb/in.^{2}. The vector polarization of the beam was 83% of the maximum possible value $P_y = (2/\sqrt{3})it_{11} = \frac{2}{3}$ with zero tensor components. Left-right asymmetry data were taken simultaneously at angles separated by 20°, by using pairs of ΔE-E silicon detector telescopes. This allowed the simultaneous detection of forward-scattered deuterons and recoil protons from backward-scattered deuterons. In order to eliminate instrumental asymmetries, alternate runs were taken with the spin vector of the beam oriented up and down with respect to the scattering plane. The angular resolution, defined by tantalum collimators, was 0.71 and 1.31° (full width at half-maximum) for the forward and backward telescopes, respectively. Two monitor counters were placed left and right of the beam axis at a scattering angle of $\theta \simeq 23°$ and azimuthal angles $\varphi \simeq 70$ and 110°. This enabled a relative cross-section measurement to be made which was used in a finite-geometry correction to the vector analyzing power. A helium-gas cell along with a pair of ΔE-E counter tele-

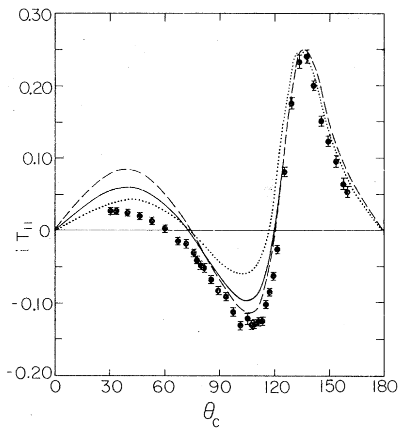

FIG. 1. The deuteron vector analyzing power, $iT_{11}(\theta)$, in d-p elastic scattering at $E_d = 45.4$ MeV. The curves are calculated results from Ref. 5 with different N-N interactions. Dotted line, set C (S and P waves) + $T4D$ tensor potential; dashed line, set $C + T4M$; solid line, set $C + T4M + {}^3D_2$.

scopes at equal left and right scattering angles were positioned in a smaller scattering chamber downstream from the main scattering chamber and provided a continuous monitoring of the beam polarization. The analyzing power of the d-^{4}He interaction at this energy had been previously measured in detail.[20]

Our experimental results are shown in Fig. 1, where the relative errors include the statistical error and a contribution of ± 0.004 which was determined from measured asymmetries with the beam polarization set to zero. In addition, there is a $\pm 3\%$ normalization uncertainty from that of the d-^{4}He analyzing power. Also shown in Fig. 1 are Doleschall's calculated results.[5] In this calculation he used an improved set of p-wave potentials which provide much better agreement with the two-nucleon p-wave phase shifts[19] for the lower energies which contribute in the three-nucleon calculation. Additionally, rank-2 tensor interactions were constructed in an attempt to reproduce simultaneously the $^3S_1$, $^3D_1$ phase shifts, the mixing parameter ϵ_i, and the deuteron properties. It was not possible to find a single rank-2 tensor force which satisfied all of these criteria, so two such sets were used. One, the $T4D$ force, reproduced the low-energy (≤ 100 MeV) $^3D_1$ phase shifts but gave larger values of ϵ_i than have been deduced from n-p scattering.[21] The other, the $T4M$ force, reproduced the low-energy ϵ_1 behavior but not that of the $^3D_1$ phase shifts. As shown in Fig. 1, the $T4M$-force calculation is good agreement with our data backward of $\theta_c \simeq 80°$, but the agreement deteriorates at the forward angles. Even though the calculations are for n-d scattering they can be compared with our data since charge symmetry of the nuclear interaction provides equality of the n-d and p-d polarizations in the absence of Coulomb effects. Such effects have been demonstrated to be small near $E_N = 22$ MeV, in that the nucleon analyzing powers in n-d [22] and p-d [10] scattering are equal within the experimental error. In a further effort to improve the agreement between experiment and theory for the proton analyzing-power data,[10] Doleschall also included a $^3D_2$ interaction. Computational limitations precluded the addition of a complete set of D-wave interactions. The results of that calculation with the $T4M$ interaction, the $T4M + {}^3D_2$ result, are also shown in Fig. 1. Some improvement toward agreement is seen at the forward angles at the expense of a slightly poorer fit in the region $\theta_c = 85$ to $115°$. A very similar comparison between experiment and theory was found for the proton analyzing-power data.[5]

The three-nucleon calculations represent major progress in predicting the polarization observables in N-d elastic scattering below 50 MeV. Small discrepancies remain with the vector polarizations in the forward-angle region, which is just the region of greatest sensitivity to details of the $^3S_1$-$^3D_1$ tensor interaction. Clearly, it would be most useful to do the calculation with a tensor force which simultaneously reproduces the N-N $^3D_1$ phase shift and the mixing parameter ϵ_1, for example, the rank-4 potential recently constructed by Pieper.[23]

Binstock and Bryan[19] have shown that the presently available n-p data [σ_{tot}, $d\sigma/d\Omega$, and $P(\theta)$] near 50 MeV leave ϵ_1 undetermined between -10 and $+3°$. They also examined the sensitivity of other experimental observables to ϵ_1, and they found that the neutron-to-proton polarization-transfer coefficient D_t combines fairly high sensitivity with reasonable experimental feasibility. A measurement of D_t to an absolute accuracy of $\pm 1\%$ could determine ϵ_1 to about $\pm 1°$. However, it should be possible in the three-nucleon calculation to fix $\delta(^3D_1)$ at the values determined from the n-p analyses and then to vary ϵ_1 in a search for improved fits to the p-d vector analyzing-power data. It seems quite possible that this procedure could provide a better determination of the low-energy values of ϵ_1 than is feasible via the much more difficult n-p measurement of D_t. If this should prove to be so, one would, indeed, have deduced from the three-nucleon problem specific information about the two-nucleon interaction that has not yet been attainable.

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What Can We Learn from Three-Body Reactions?

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Deuteron-breakup calculations are performed by using phase-equivalent potentials that differ off shell with and without the constraint of a fixed triton binding energy. This approach is compared with the previous work of Brayshaw. We examine various regions of phase space and energy between 14 and 65 MeV. Our results show that new off-shell information can be obtained from deuteron-breakup studies in the final-state region of phase space.

Nuclear reactions involving three nucleons have been extensively studied in the last few years. One motivation has been the possibility of learning new information about short-range two-particle interactions, in particular, the off-shell behavior of the nuclear force. Several authors have suggested regions of phase space in which this information may be readily obtainable. They generally agree that the $L=0$ part of the M_{D2} amplitude is the one sensitive to off-shell effects and