Search for Three-Nucleon Force Effects in Analyzing Powers for $\vec{p}d$ Elastic Scattering

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A series of measurements have been performed at KVI to obtain the vector analyzing power A_y of the $^2\mathrm{H}(\vec{p}, pd)$ reaction as a function of incident beam energy at energies of 120, 135, 150, and 170 MeV. For all these measurements, a range of $\vartheta_{\mathrm{c.m.}}$ from 30° to 170° has been covered. The purpose of these investigations is to observe possible spin-dependent effects beyond two-nucleon forces. When compared to the predictions of Faddeev calculations, based on two-nucleon forces only, significant deviations are observed at all energies and at center-of-mass angles between 70° and 130°. The addition of present-day three-nucleon forces does not improve the description of the data, demonstrating the still insufficient understanding of the properties of three-nucleon systems.

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The interest in three-nucleon systems has recently increased significantly both on the theoretical as well as on the experimental side. One of the reasons is that during the past years several modern *NN* potentials [1] have become available which can describe *NN*-scattering observables with high precision. These models are partially based on theoretical grounds, e.g., the long-range one-pion exchange, and partially on a phenomenological framework. More recently, *NN* interactions based on chiral symmetry are being developed [2]. A fundamental question is how well these potentials can predict observables in systems consisting of more than two nucleons, e.g., the *pd* system. By applying pure two-nucleon potentials to three-nucleon systems using the Faddeev equations, it was possible to predict many observables. (See the review article [3], and references therein.) Pioneering work at lower energies has also been recently carried out by other groups [4]. In comparing these calculations with data, it became clear that there are deficiencies in predicting certain observables at selected kinematics. Therefore, it is evident that higher-order effects, e.g., so-called three-nucleon forces (3NF), have to be added to the existing two-nucleon potentials.

Construction of 3NF is a tough theoretical challenge. The dynamical process most often considered is the 2π exchange between three nucleons with an intermediate excited nucleon state [5]. The commonly used 2π-exchange Tucson-Melbourne (TM) model is based on a low momentum expansion of the π-N off-mass-shell scattering amplitude [6]. It incorporates, among others, the physics resulting from an intermediate Δ in a static approximation. The cutoff parameter Λ of its strong form factor is used to adjust the ^{3}H binding energy separately for particular *NN* forces [7]. The original approach to construct the TM 3NF [6] was motivated by chiral symmetry in the form of partially conserved axial-vector current and current algebra. A form more consistent with modern chiral perturbation theory, TM′, is obtained by dropping a spurious contact term in the original TM 3NF [8–10]. Another frequently used 3NF model is Urbana IX 3NF [11]. This force is based on the old Fujita-Miyazawa model [12] of an intermediate Δ occurring in the 2π exchange and augmented by a spin- and isospin-independent short-range part. Its partial wave expansion in momentum space is presented in Ref. [13]. The effect of the intermediate Δ was also explicitly included by Nemoto *et al.* in a coupled-channel formulation of nucleon-deuteron scattering [14]. This approach yields an effective 3NF. Other approaches to the calculation of 3NFs were considered by Canton and Schadow [15] and, at lower energies, by Kievsky [16].

Possible observables which might be influenced by effects such as 3NF are, among others, the differential cross section, $d\sigma/d\Omega$, and the vector analyzing power, A_y, in elastic *pd* scattering. The differential cross section has a minimum about $\vartheta_{\mathrm{c.m.}} \approx 100°$. As was pointed out in Ref. [17], 3NF effects should show up in this minimum. It was shown in Ref. [17] that the angular variation of 3NF effects alone is rather flat and its magnitude is much smaller than the cross section at low center-of-mass energies, but becomes comparable in size at higher energies, where the experimental cross section decreases. Therefore, 3NF effects should also be observed more clearly at those higher energies. Within the framework of the present calculations, however, one should avoid going to very high energies where the relativistic effects start to dominate. We therefore keep the discussion to energies below 200 MeV, for which we performed our measurements. The vector analyzing power, A_y, shows large variations over the whole range of $\vartheta_{\mathrm{c.m.}}$, with a strong minimum about $\vartheta_{\mathrm{c.m.}} \approx 100°$. It is thus a good candidate to observe possible spin-dependent higher-order effects.

Presently, only a few experimental data sets are available for the analyzing power. The older data of Kuroda *et al.* [18] at 155 MeV were measured below $\vartheta_{\mathrm{c.m.}} \leq 90°$ only, thus missing the angular range where 3NF effects are expected to show up in the differential cross section. The data set of Adelberger and Brown [19] at 198 MeV covers only the region above $\vartheta_{\mathrm{c.m.}} \geq 70°$. The data set of Postma and Wilson [20] at 146 MeV covers a large range of $\vartheta_{\mathrm{c.m.}}$ but with rather large experimental uncertainties.

Recently, new data measured at KVI at 150 and 190 MeV [21] became available, covering $\vartheta_{\mathrm{c.m.}} = 30°-115°$. New measurements were also made at Indiana University Cyclotron Facility (IUCF) [22]. Here, the recoil angle of the deuteron was kept fixed at $\theta_{\mathrm{lab}} = 42.6°$ and the analyzing power was measured as a function of incident beam energy for this one angle. Also at IUCF, the vector analyzing power was measured around this recoil angle at 120 and 200 MeV [23].

Both the older data as well as the more recent and accurate data sets, with the deficiency of a limited angular range, show disagreements with theory. Calculations for pure NN interactions as well as for (NN + 3N) interactions using the TM force fail to describe the combined data sets at $\vartheta_{\mathrm{c.m.}} \gtrsim 70°$. This shows that, in addition to the well-known analyzing-power puzzle at low energies [24], there seems to be a problem with the vector analyzing power at intermediate energies. Since none of the newer data sets cover a significant region of $\vartheta_{\mathrm{c.m.}}$ and due to the limited energy range covered, it is necessary to make a systematic study of the vector analyzing power at *several* beam energies, covering a *large* range in $\vartheta_{\mathrm{c.m.}}$.

The experiment was performed at KVI using polarized proton beams at bombarding energies of 120, 135, 150 and 170 MeV. The measurements were done with the magnetic big-bite spectrometer (BBS) [25] in combination with the EuroSuperNova (ESN) focal-plane detection system [26]. This detection system consists of two vertical drift chambers and two scintillator planes mounted behind each other, each consisting of five scintillators. The ESN detection system was used to detect and identify one of the outgoing particles. The corresponding recoil particle was measured by a coincidence scintillator mounted inside the scattering chamber and close to the target. A trigger was generated if there was a coincidence between this coincidence scintillator and the two scintillator planes of ESN, resulting in rather clean spectra. Solid CD_2 targets were used, with thicknesses between 2 and 50 mg/cm^2, depending on the kinematics and the count rates. The target was turned towards one of the detectors (BBS or coincidence scintillator) when necessary, to minimize the path length in the target for low-energy particles emerging from the scattering process. The BBS, together with its focal-plane detector, was rotated between 5° and 53° in steps of 3°. Measuring protons and deuterons alternately with the BBS and the corresponding recoil particle with the coincidence scintillator, a scattering angle $\vartheta_{\mathrm{c.m.}} = 30°-170°$ was covered for all bombarding energies. For the two highest energies measured, the lower end of the range of scattering angles was extended to 20°. At angles smaller than 20°, the Coulomb corrections start to become important [17] in the *pd* scattering and, as such, mask the information to be obtained from the hadronic interaction.

Polarized proton beams were obtained from the KVI polarized ion source of the atomic-beam-type [27]. These were accelerated in the superconducting cyclotron AGOR. The proton degree of polarization was determined using the In-Beam Polarimeter (IBP) [21,28]. During each measurement with the BBS, measurements of the polarization with the IBP were made at the same time. Therefore, the polarization of the protons, which was rather stable during each energy run, is known for each data point taken. Typical polarizations measured with the IBP were $p^{\uparrow} \approx 0.6$ and $p^{\downarrow} \approx -0.6$, with respect to the normal to the horizontal plane.

At each angle of the BBS, measurements were made for spin up and spin down. The analyzing power was then calculated from

$$A_y = \frac{I^{\uparrow} - I^{\downarrow}}{p^{\uparrow} I^{\downarrow} - p^{\downarrow} I^{\uparrow}},$$

where $I^{\uparrow(\downarrow)}$ is the number of counted events for spin up (down), normalized to the number of incoming particles and corrected for dead time, and $p^{\uparrow}$ and $p^{\downarrow}$ have opposite signs. Since our detectors were operated at count rates below their maximum capabilities and because the efficiencies in this range were measured to be rather large and independent of count rate, effects such as efficiencies cancel out when taking the ratio. The same holds for the target thickness.

Our results for the vector analyzing powers for all energies measured are shown in Fig. 1. The statistical uncertainties included in the figures are generally smaller than 0.01. The overall relative systematic error, not shown in the figure, which stems from the determination of the beam polarizations, is 3% of the value of A_y. Errors due to the determination of dead time and efficiency are much smaller and thus hardly contribute to the total systematic error. With these high-precision data, one can now discriminate between different calculations with and without 3NF effects.

Together with our data, the data point from IUCF [22], which agrees rather well with our data in the corresponding kinematics, has also been included at each energy. At 120 MeV, the data of Wells *et al.* [23] have also been included in our figure. At 150 MeV, the data from Bieber *et al.* [21], which have been measured with a different detection system and also agree with our data, have been included. For the sake of clarity in this figure, the data sets

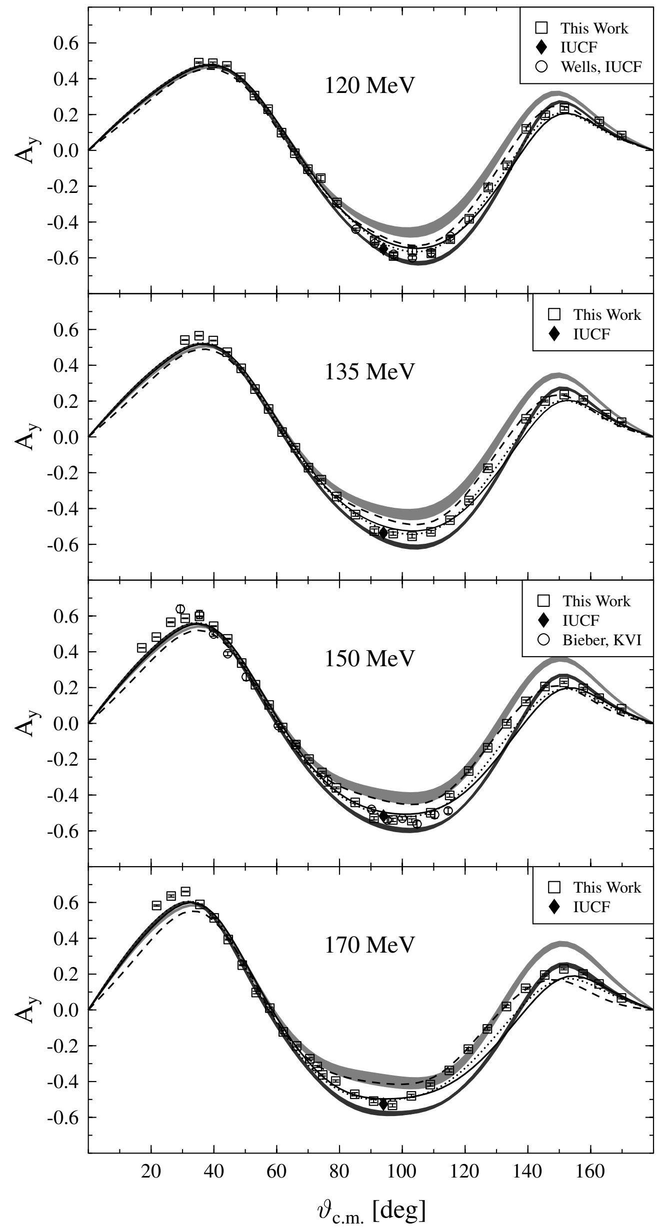

FIG. 1. Results for the vector analyzing power of $^{2}H(\vec{p}, pd)$ scattering at 120, 135, 150, and 170 MeV. Two bands are shown; the dark-shaded one contains *NN*-force predictions based on AV18, CD Bonn, NijmI, and NijmII, the light-shaded one contains the predictions using these *NN* forces and TM 3NF. The dotted lines are the result of an AV18 + URBANA IX calculation, and the solid lines are the predictions of CD Bonn + TM′. The dashed lines represent the result of the calculation from the A2 model of the Hannover group. The experimental uncertainties are explained in the text.

of Kuroda *et al.* [18] and Postma and Wilson [20] have not been shown. These also agree very well, within their statistical errors, with our data.

Theoretical predictions for the *NN* and *NN* + 3NF interactions are shown for each energy. Two bands are shown in each figure section; the dark-shaded band contains *NN*-force predictions based on AV18, CD-Bonn, NijmI, and NijmII potentials, while the light-shaded band shows the results of the calculations when TM 3NF is also included. As can be seen, the results obtained from different potentials form a narrow band and do not describe our data. The dotted lines are predictions of AV18 + Urbana IX 3NF. The solid lines give the result of CD-Bonn + TM′ calculations where TM′ is generated according to [8,9] and its parameters are taken from Ref. [13]. Also the partial-wave decomposition of Ref. [13] has been applied. These calculations seem to do a better job in predicting the analyzing powers around its minimum. To show a different theoretical approach, at all energies calculations from the A2 model of the Hannover group [14,29] are shown (dashed lines). This model is based on the Paris potential [30] and includes the effect of an intermediate Δ. Since the Paris potential is an older model, it does not describe the *NN* data with the level of accuracy of modern *NN* potentials. The predictions therefore include some uncertainty. Still, at least for the lower energies, the A2 model seems to describe our data rather well at backward angles.

In the angular range up to $\vartheta_{\mathrm{c.m.}} = 60°$ the predictions of *NN* and (*NN* + 3N) calculations agree with each other, while our data deviate slightly from them below the center-of-mass angle of 40°. This might be due to Coulomb effects, although the deviation seems to get larger in the range below 40° as one increases the beam energy, which is somewhat puzzling. It might also be an onset of relativistic effects, which are not yet included in the theory. At $\vartheta_{\mathrm{c.m.}} \approx 65°$, the predictions of calculations with and without 3NF start to deviate from each other and from our data. Up to $\vartheta_{\mathrm{c.m.}} \approx 110°$, our data lie somewhere between the two theoretical bands, while, at more backward angles up to $\vartheta_{\mathrm{c.m.}} \approx 135°$, our data seem to move closer to the band which includes the prediction of the (*NN* + TM 3N) calculations. Furthermore, at about $\vartheta_{\mathrm{c.m.}} \approx 100°$ lies the minimum of the analyzing power. Note that this is the angular range, where the differential cross section also has its minimum and 3NF effects are best observed [17]. At $\vartheta_{\mathrm{c.m.}} \approx 150°$, the analyzing power has its second maximum. In this angular region and at large backward angles, our data seem to be better described by the pure *NN*-force calculations. The behavior described here is basically the same for all energies. Comparing the figures for the different energies, it can be seen that the first maximum and the minimum shift towards smaller angles with increasing energy, while the second maximum stays about $\vartheta_{\mathrm{c.m.}} \approx 150°$. The minimum of the calculations becomes shallower with increasing incident energy, whereas the minimum of our data hardly changes its form.

Recent measurements of spin-transfer coefficients and deuteron vector and tensor analyzing powers at E_d = 270 MeV [31] also yield a contradictory picture when compared to calculations with and without 3NF.

In conclusion, the problem of understanding spin-dependent observables in elastic scattering of systems consisting of more than two nucleons, does not seem to be resolved. While, in the differential cross section, reasonable agreement between theory and experiment can be achieved with the inclusion of three-nucleon forces, these forces are not sufficient to describe the analyzing powers at intermediate energies. This indicates that spin-dependent 3NF effects are not yet sufficiently under control. While the TM force clearly overestimates the data, the modified TM$'$ 3NF agrees with the data in the region of the minimum but underestimates the data at backward angles. A similar behavior is shown by Urbana IX 3NF. The proton analyzing power at higher energies thus seems to prefer the modified TM$'$ version of the Tucson-Melbourne model or the Urbana IX 3NF. Including an intermediate Δ in a coupled-channel treatment gives a different picture. Although this calculation overestimates the data in the minimum, it does a better job at backward angles. It remains to be seen whether a more consistent approach, such as chiral perturbation theory, will yield better results for spin observables.

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