Three-Nucleon Force and the A_y Puzzle in Intermediate Energy $\vec{p} + d$ and $\vec{d} + p$ Elastic Scattering

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New vector analyzing-power data on $\vec{p} + d$ elastic scattering at $E_p = 150$ and 190 MeV have been measured. These are presented together with existing data and with recent $\vec{d} + p$ vector and tensor analyzing power data at $E_d = 270$ MeV. The strong negative extremum of both vector analyzing powers A_y^p and A_y^d at $\theta_{\text{c.m.}} \simeq 80°-120°$ is underestimated by Faddeev calculations using modern NN forces. Inclusion of the Tucson-Melbourne $3N$ force shifts the minima upwards, but with conflicting results for A_y^p, and leading to a good description for A_y^d. An A_y^p puzzle, previously thought to exist at energies $E_N \leq 30$ MeV only, appears to exist also at intermediate energies.

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The three-nucleon system has attracted much attention over the years because it is the simplest possible system where one can study a nuclear Hamiltonian beyond the nucleon number $A = 2$. Despite many decades of research, the NN force still cannot yet be calculated from first principles and therefore has to be adjusted to the NN bound state and scattering observables. This is possible and perfect fits result, yielding so-called "realistic" NN forces (see below). The question then arises whether those pair forces are sufficient to also describe systems with more than two nucleons or whether many-body forces and thus, first of all, three-nucleon forces are needed. A first hint in that direction appeared through the fact that those realistic NN forces alone do not provide sufficient binding energy for the light nuclei with $A = 3, 4, \ldots$.

At an early stage of investigating nuclear forces in the framework of meson theory, $3N$ forces were already predicted [1]. Among those early versions is the Fujita-Miyazawa force [2], a two-pion exchange between three nucleons with an intermediate excitation of one nucleon into its first excited state, the delta. In later years this mechanism was incorporated, among others, into more refined theoretical models for $3N$ forces. One of these is the Tucson-Melbourne (TM) model [3,4], which parametrizes the general off-the-mass-shell π-N scattering amplitude, entering the above-mentioned two-pion exchange between three nucleons, in a low momentum expansion. It was recently recognized [5] that one of its ingredients is in conflict with chiral symmetry. Nevertheless, this force still serves as a "working horse" to explore possible three-body effects. In any case it describes the longest range contribution to $3N$ forces: the exchange of two pions between three nucleons. Another often used $3N$ force model is the Urbana-Argonne force [6], which supplements the two-pion exchange by a phenomenological short-range part, necessary to prevent overbinding in nuclear matter. For a very informative review on $3N$ forces we refer to [7].

More recently, chiral perturbation theory has provided a systematic insight into the nuclear dynamics and one outcome for $3N$ forces is given in [5]. It has still to be implemented into numerical studies and requires further theoretical thought. Right now, for practical calculations in momentum space and taking all the higher angular momenta properly into account, only the Tucson-Melbourne model [4] is available and we will use it in this Letter.

Attention has recently been focused on specific observables in Nd and dN scattering which defy a consistent description in terms of the latest, data-equivalent NN forces. The longest standing of these disagreements is the vector analyzing power, A_y^p, at low energies, $E_N \leq 30$ MeV. The analyzing power is very sensitive to the $3P_J$ NN force components. Hüber and Friar [8] gave arguments that changes in the NN forces that do not violate the general agreement with the NN data base, and respect the well-established property of the one-pion exchange, are not capable of reproducing A_y^p. At the same time present-day $3N$ forces have insignificant effects at these energies and cannot account for that discrepancy. On the other hand, there are still doubts whether the $3P_J$ NN force components have been constrained sufficiently well by the NN data basis, which might leave some room to modify those NN force components [9].

At about $E_N \simeq 30$ MeV, A_y has one single maximum. As one proceeds to higher incident energies this maximum in A_y is pushed to larger angles and at forward angles a new, sharper, maximum appears. In between, a strong negative extremum develops. At intermediate energies, $E_N = 50-200$ MeV, this resides at about $\theta_{\text{c.m.}} >= 100°$,

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in the region where the unpolarized differential cross section, $d\sigma/d\Omega_{\mathrm{c.m.}}$, is minimal. Witała *et al.* [10] have shown that this cross-section minimum is underestimated by all modern data-equivalent NN forces and that the inclusion of the Tucson-Melbourne $3N$ force [4] diminishes drastically the discrepancy between the theory based on NN forces only and the data. It seems logical that the effect of the $3N$ force should show up most prominently where the cross section, as it is predicted from $2N$ forces alone, shows a minimum. The fact that A_y has an extremum in the same region of center-of-mass (c.m.) angles makes it an obvious candidate to further investigate such $3N$ force effects.

In this Letter we present new data on the $\vec{p}d$ analyzing power, A_y^p, for $E_p = 150$ and 190 MeV and spanning the angular range of 30°–115° in c.m. angle. The change of A_y with incident energy is slow enough to allow a combination of existing data at close-by energies. Thus, our 190 MeV data are combined with those of Adelberger and Brown [11] at 198 MeV which cover the range $\theta_{\mathrm{c.m.}} =$ 80°–170°. Also, the recent data of Wells *et al.* [12], taken at 200 MeV and covering $\theta_{\mathrm{c.m.}} =$ 80°–110°, are included. The three data sets overlap in the region of prime interest and together they constitute a full angular distribution.

Our 150 MeV data are combined with those taken at 146 MeV by Postma and Wilson [13] and with the data at 155 MeV of Kuroda *et al.* [14].

We include in our analysis the $d\vec{p}$ analyzing-power data, A_y^d, A_{xx}, A_{yy}, and A_{xz} at $E_d = 270$ MeV, which were recently measured at RIKEN [15] and which have been compared with the Faddeev calculations by Koike, based on the finite-rank approximations of the older AV14 force [16], without inclusion of a $3N$ force.

The proton beams of 150 and 190 MeV were accelerated in the new superconducting cyclotron AGOR of KVI. Polarized proton beams were obtained from the atomic-beam type polarized-ion source [17]. The data were taken with the new in-beam polarimeter of KVI. In this instrument eight detector pairs are mounted in four independent planes, 45° apart in azimuthal angle and operated in kinematical coincidence. They are of phoswich construction which provides good particle identification. The target was mixed CH_2-CD_2. The detector pairs in the vertical plane and in one of the 45° planes were set for pp coincidences, to monitor the beam intensity and polarization, and those in the horizontal plane and the remaining 45° plane were set for pd coincidences.

At each angle setting, runs were made for spin up (strong-field setting), for spin down (weak-field setting), and for both cavities off.

Simultaneous least-squares fitting of the three runs, with $A_y(\vec{p}, p)$ taken from the Nijmegen partial-wave analysis [18], provides values for the three polarizations, $P^{\uparrow}$, $P^{\downarrow}$, and P_0 and for the analyzing power $A_y(\vec{p}, d)$.

For the weak-field and the strong-field settings, typical source polarizations of $P^{\downarrow} \simeq -60\%$ and $P^{\uparrow} \simeq +60\%$ were obtained, respectively. The rest polarization, P_0, is nonzero due to the relatively low magnetic field in the electron cyclotron resonance ionizer. Its value was found to be $P_0 \simeq 7\%$. This value was determined more precisely as $(7.3 \pm 0.1)\%$ against separate zero-polarization measurements with protons injected from an unpolarized source as well as with protons whose polarization axis was turned into the plane of the cyclotron before injection. P_0 was subsequently constrained accordingly in the fitting procedure.

Our experimental A_y^p data for $E_p = 150$ and 190 MeV are displayed in Figs. 1 and 2, together with the existing older data at close-by energies that were specified above. Figure 3 shows the recent A_y^d data of Sakamoto *et al.* [15].

Our analysis in terms of Faddeev equations uses an elastic Nd scattering transition amplitude between the incoming ($|\phi\rangle$) and outgoing ($|\phi'\rangle$) asymptotic nucleon-deuteron states [19,20]:

$$\langle\phi'|U|\phi\rangle = \langle\phi'|PG_0^{-1} + V_4^{(1)}(1 + P) + P\tilde{T} + V_4^{(1)}(1 + P)G_0\tilde{T}|\phi\rangle. \quad (1)$$

The operator for elastic scattering U embodies various processes. The first one on the right-hand side of Eq. (1) is PG_0^{-1}, which stands for the single-nucleon exchange part. Here, P is the sum of a cyclical and anticyclical permutation of three particles and G_0 is the free $3N$ propagator. The second process is the direct action of a $3N$ force, which enters in the form, $V_4^{(1)}(1 + P)$. The remaining terms are the multiple rescattering contributions caused by $2N$ and $3N$ forces. They are generated by the operator $\tilde{T}$, which obeys the central Faddeev equation [20]:

$$\tilde{T}|\phi\rangle = tP|\phi\rangle + (1 + tG_0)V_4^{(1)}(1 + P)|\phi\rangle + tPG_0\tilde{T}|\phi\rangle + (1 + tG_0)V_4^{(1)}(1 + P)G_0\tilde{T}|\phi\rangle. \quad (2)$$

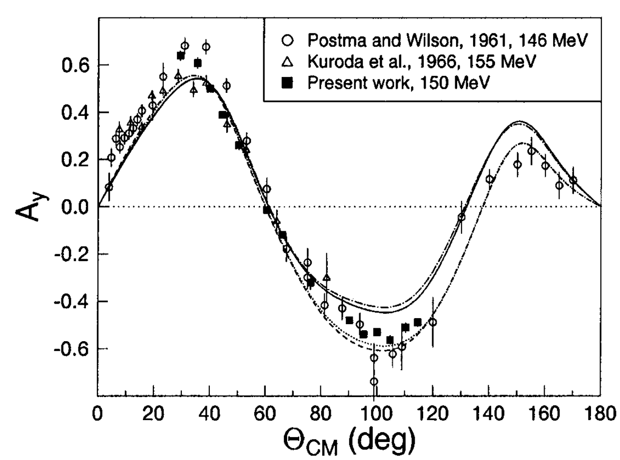

FIG. 1. A_y^p data at 150 MeV (this paper), 146 MeV [13] and 155 MeV [14], compared with $j_{\max} = 5$ Faddeev calculations for $E_p = 150$ MeV. $2N$ forces alone: CD Bonn (dotted line) and AV18 (dashed line). $2N$ forces + TM $3N$ force: CD Bonn (solid line) and AV18 (dashed-dotted line).

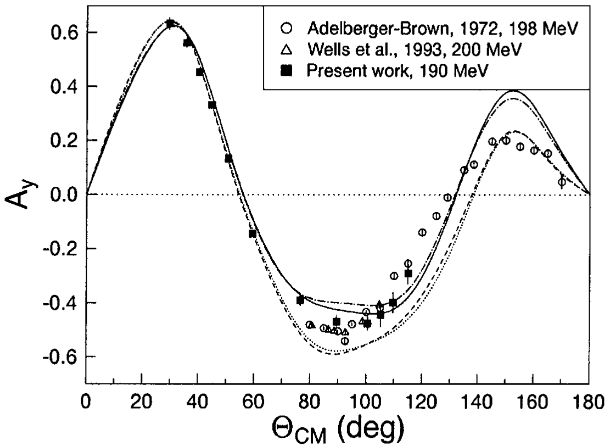

FIG. 2. A_y^p data at 190 MeV (this paper), 198 MeV [11], and 200 MeV [12]. The Faddeev calculations are for $E_p = 190$ MeV. For the explanation of the curves, See Fig. 1.

In the driving term, one recognizes the NN t operator, t, acting on the asymptotic Nd state $|\phi\rangle$ and a corresponding term caused by the $3N$ force $V_4^{(1)}(1 + P)$. The kernel parts are responsible for the multiple rescattering mechanisms. The operator $\tilde{T}$ by itself leads to the $3N$ break-up process for Nd scattering which can be used to generate the process of elastic scattering by quadrature, as shown in Eq. (1).

Recently a new generation of $2N$ forces has appeared that fits the Nijmegen data base [21] with a χ^2 per datum close to unity. These forces are often called phase equivalent. However, they do not produce identical phase shifts and it might be better to call them data equivalent [22]. They are the potentials AV18 [23], Nijm I, Nijm II, Reid93 [24], and CD Bonn [25]. We use the CD Bonn and AV18 potentials in our analysis. For the $3N$ force we use the Tucson-Melbourne force [4], which is based on 2π exchange, with a cutoff parameter Λ, adjusted to fit the triton binding energy [26]. In all calculations $3N$ partial-wave states with up to total angular momenta $j_{\max} = 5$ for the $2N$ subsystem have been taken into account, leading to practically convergent results at the energies that concern us in this paper.

In Figs. 1 and 2, our theoretical results for A_y^p are shown, together with the data. The A_y^d theoretical results together with the tensor analyzing powers A_{xx}, A_{yy} and A_{xz} are given in Fig. 3 together with the data of Sakamoto *et al.* [15].

At 150 MeV, one notices a large scatter of the older data, especially at forward angles and in the minimum.

Our new data overshoot slightly the predictions for a pure NN force in the region of the minimum and otherwise are rather well described. The older data of Postma and Wilson deviate from the NN force predictions at about 80° and 130°. They agree nicely with the theoretical calculations, based on $2N$ forces only, at backward angles. The $3N$ force prediction shifts the calculations upwards for $\theta_{\rm c.m.} > 70°$ and generally moves away from the data. At 190 MeV the NN force prediction alone agrees quite well with the data at forward and very backward angles. In the minimum all the data lie clearly above the calculations. Adding the $3NF$ again shifts those calculations upwards with conflicting results: in the minimum and the backward maximum it overshoots the data and underestimates them in the region around 120°.

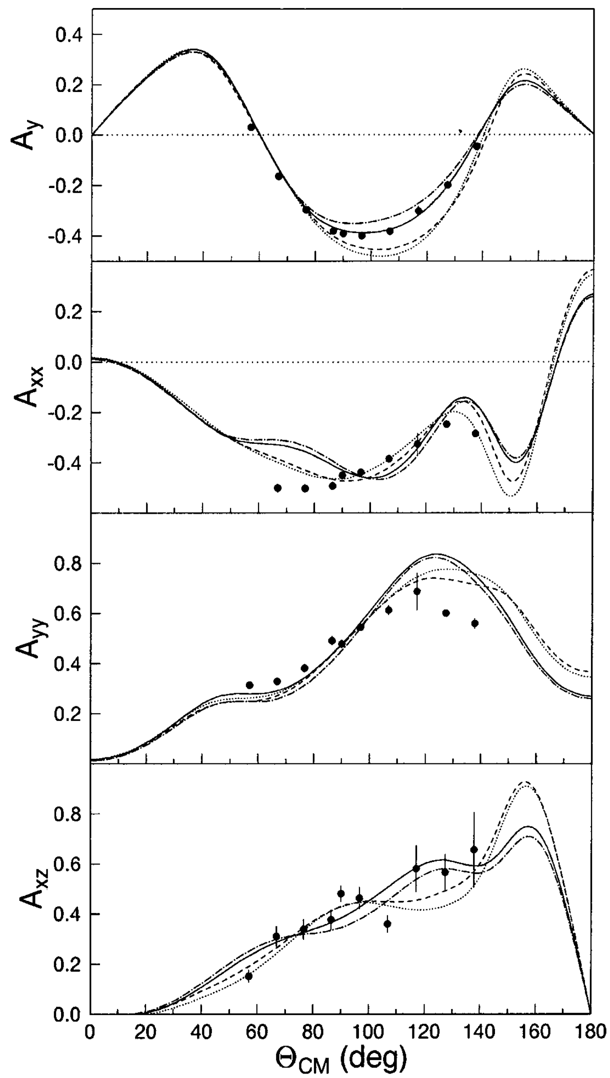

FIG. 3. Data from Sakamoto *et al.* [15] for $\vec{d} + p$ at $E_d = 270$ MeV compared with Faddeev calculations at the same energy. For the explanation of the curves, see Fig. 1.

It would be very desirable to have new measurements in the region of angles beyond 120°, where the theoretical predictions with and without $3NF$ are clearly different. In any case, at the higher energy the theory with NN forces only does not describe the data.

In contrast to A_y^p, A_y^d is well described after adding the $3NF$, especially in combination with CD Bonn, whereas the NN force prediction alone clearly underestimates the data in the minimum. For the tensor analyzing powers the inclusion of the $3NF$ leads to some improvements for A_{xz} but slightly deteriorates the description of A_{xx} and A_{yy}.

In view of the results of Ref. [15] where predictions with the older AV14 NN force are shown, without $3N$ force, we would like to comment that we have also made AV14 calculations at $E_d = 270$ MeV and found very similar results as in [15]. The quality of the description for the tensor analyzing powers is similar to that for the modern potentials, but for A_y^d the AV14 gives closer agreement with the data than the modern *NN* force predictions. This agreement is, however, fortuitous as the older AV14 gives a much poorer description of the *NN* data than the modern *NN* interactions.

Given the accuracy of the new generation of *NN* forces and the *NN* data on which they are based, it must be concluded that at the intermediate energies under study here, the underestimation of A_y^p at 190 MeV and A_y^d at 270 MeV in the region of the cross-section minimum is real. Inclusion of a 3*N* force in the form of the 2π-TM model shifts the theoretical predictions of both vector analyzing powers upwards and leads to a good agreement for A_y^d but conflicting results for A_y^p. In the minima for A_y^p the TM 3*NF* effects are too strong. In view of the stable results given by different *NN* force models it is improbable that the discrepancy with the data can be eventually removed by future *NN* forces. Therefore we think we see here 3*NF* effects, which are not properly accounted for by the TM force.

At this point we must revisit a conclusion from an earlier work: in Ref. [19] it was concluded that the A_y^p puzzle would exist only at low energies and that the agreement of the data with *NN* calculations at higher energies up to 155 MeV was perfect. In view of our new data we are led to conclude that an A_y^p puzzle exists also at higher energies.

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