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Indications of three-nucleon force effects in the proton analyzing power for 70–200 MeV $\vec{p}+d$ elastic scattering

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We compare precise analyzing power measurements for $p+d$ elastic scattering between 70 and 200 MeV proton laboratory energy with three-body Faddeev calculations. Using the CD-Bonn nucleon-nucleon force alone leads to an overprediction of the data at higher energies, suggesting that three-body ($3NF$) forces may be important. The 2π-exchange Tuscon-Melbourne $3NF$ model, adjusted to match the triton binding energy, leads to a better shape for the excitation function but gives too large of an effect. [S0556-2813(99)51511-2]

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Several trends make this time opportune for the investigation of three-nucleon ($3N$) effects in nuclear systems. Models of the nucleon-nucleon (NN) force have reached the stage where agreement is excellent with the large (though carefully selected) set of cross sections and polarization observables below pion production threshold [1–3]. Exact numerical solutions of the Faddeev equations for $n+d$ elastic scattering and breakup process using those new NN force models are now possible on modern supercomputers [4]. It is also becoming possible to obtain much more precise experimental data (see Ref. [5], for example), and new results with polarized beams and targets should be available shortly.

As shown in Ref. [4], theoretical Faddeev predictions of the $N+d$ elastic scattering and breakup observables using the various new models of the NN force nearly always agree with each other, even though these models have different nonlocal or off-shell properties and vary the mix of phenomenological and meson exchange contributions. However, several important differences with data remain, including the inability to match the triton binding energy [6] and the low energy analyzing power for $\vec{p}+d$ or $\vec{n}+d$ elastic scattering [4]. Since these differences are much larger than the scatter among predictions when new NN interactions are used, it now seems unlikely that the problem lies with the quality of the NN models. Instead we must seriously consider whether they arise from genuine $3N$ force mechanisms or perhaps reflect inadequacies in the theory (e.g., treatment of relativity). In this case, the differences between data and theoretical predictions may contain signatures of the strength and spin dependence of such effects that not only test more comprehensive models but could point to the nature of any feature to be added to existing calculations.

Models including $3N$ forces have been adjusted to match the triton binding energy. Such extended Faddeev calculations have built upon the Urbana $3N$ force using the Green's-function Monte Carlo (GFMC) method [7] and the Tuscon-Melbourne force [6,8,9]. Further progress is possible only when other observables can be found and precisely measured to test whether such models contain the correct ingredients. A recent example is the reproduction of the $p+d$ elastic cross section near the minimum of the angular distribution between 50 and 200 MeV [10]. This minimum, which lies between the favored regions for quasielastic scattering and nucleon exchange, is underestimated by Faddeev calculations using only the NN force with a difference that rises with bombarding energy. The addition of the Tuscon-Melbourne $3N$ force [11], scaled to reproduce the triton binding energy [6], nicely fills this minimum in agreement with the data. This same $3N$ force model also reproduces well [12] the deuteron vector analyzing power measured at the equivalent of $E_{\text{lab}}(p)=135$ MeV [13]. Again there are significant differences between calculations with and without the Tuscon-Melbourne force.

In this same energy region, the calibration of the in-beam proton polarimeters at IUCF to a level close to 1% [14] has recently made available very precise analyzing power information where previous data was much less certain [15]. In this contribution, we will compare these data with two $3N$ calculations, one with and one without the Tuscon-Melbourne force, to illustrate that neither provides an adequate description of the data. This particular $3N$ force, while seemingly adequate for the cross section and deuteron vector analyzing power, is not appropriate when compared against the proton spin dependence. Clearly other mechanisms should be investigated, perhaps as was done recently for the low energy analyzing power [16,17]. Indeed, suggestions for modifying the Tuscon-Melbourne mechanism have arisen from considerations of chiral symmetry [18].

The IUCF proton polarimeters [19] observed $p+d$ elastic scattering at a fixed laboratory angle for the recoil deuteron. This angle, chosen to coincide with large $\vec{p}+d$ analyzing powers over a range of proton energies below 200 MeV, lies close to the region of the cross section minimum discussed by Witała [10]. Thus $3N$ force effects should be readily ap-

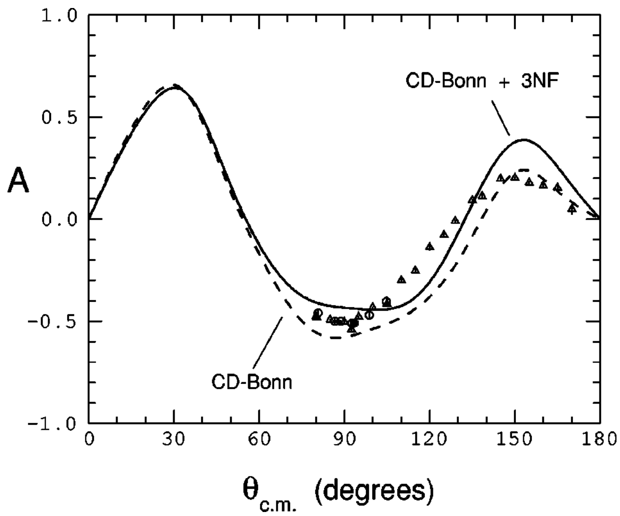

FIG. 1. Measurements of the analyzing power in $\vec{p}+d$ elastic scattering near 200 MeV [14,19,20] along with $3N$ Faddeev calculations with (solid) and without (dashed) $3N$ forces.

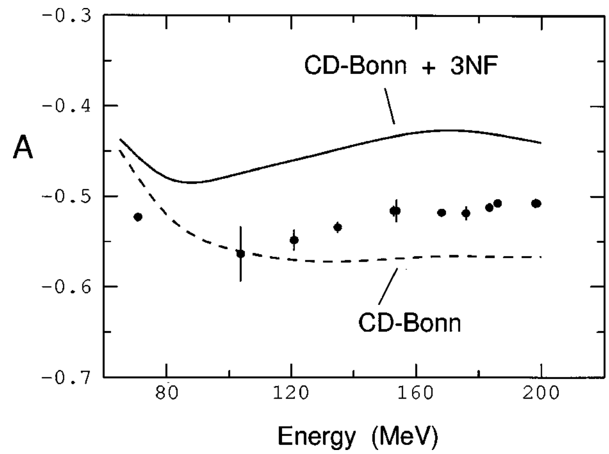

FIG. 2. Measurements of the analyzing power in $\vec{p}+d$ elastic scattering as a function of proton bombarding energy and at a deuteron recoil angle of $\theta_{lab}=42.6°$ [14,19] along with $3N$ Faddeev calculations with (solid) and without (dashed) $3N$ forces.

parent. The recent calibration made use of double scattering to establish an independent, absolute standard for the beam polarization, thus making high precision possible.

Figure 1 contains the highest energy point from this calibration as a solid dot. Other data from Wells [19] (open circles) and Adelberger [20] (triangles) have been included to provide some sense of the analyzing power angular distribution.

The calculations in Fig. 1 make use of the $3N$ program described in Ref. [4]. It is based on the Faddeev equation in the form [21]

$$T=tP+(1+tG_0)V_4^{(1)}(1+P)+tPG_0T \\ +(1+tG_0)V_4^{(1)}(1+P)G_0T, \quad (1)$$

where G_0 is the free $3N$ propagator, t is the NN t matrix, P is the sum of a cyclic and anticyclic permutation of three bodies, and $V_4^{(1)}$ is that part of the 2π-exchange Tuscon-Melbourne $3NF$, which singles out nucleon 1 as the particle that undergoes πN off-shell scattering. Using T, the operator for elastic nd scattering becomes

$$U=PG_0^{-1}+V_4^{(1)}(1+P)+PT+V_4^{(1)}(1+P)G_0T. \quad (2)$$

Equation (1) is solved using NN force components up through total NN angular momentum $j_{max}=5$. The $3N$ force is included up to total $3N$ angular momentum $J=13/2$ with both parities. A calculation performed with $j_{max}=6$ and only the NN force has shown that higher partial waves make only negligible contributions, and that changes in the analyzing power are very small when compared with the differences between theory and experiment discussed here. The NN interaction is CD-Bonn [1], which reproduces the set of NN data with a reduced chi square close to 1.

The Faddeev calculation without $3N$ forces made at 200 MeV is shown by the dashed curve in Fig. 1. For comparison, the calculation including the Tuscon-Melbourne force is shown by the solid line. At angles greater than $\theta_{c.m.}=60°$, the elastic scattering cross section is sufficiently small that the $3N$ force can produce a competitively large amplitude [10]. There these two calculations begin to differ. Near 90° where these differences are close to their largest, the analyzing power data fall in between the calculations. Where the data overlap, good agreement is found among the sets of analyzing power measurements. This would tend to support the Adelberger measurements for the large angle part of the angular distribution. There the data do not follow the shape given by either calculation.

The energy dependence of the analyzing power at the fixed deuteron recoil angle of 42.6° is shown in Fig. 2 between 70 and 200 MeV. Values of the data points are given by Choi [14]. Additional data points from Wells [19] are also included. As in Fig. 1, the Faddeev calculation without $3N$ forces is shown as the dashed line, while the calculation including the Tuscon-Melbourne force is represented by the solid line. The measurements follow neither calculation, although the shape of the excitation function more closely resembles the calculation containing the Tuscon-Melbourne force. (These calculations were made at seven energies between 65 and 200 MeV, and then interpolated to the angle coresponding to the deuteron recoil angle of $\theta_{lab}=42.6°$. Last, a smooth curve with energy was drawn connecting the calculations.) The precision of the measurements is such that they should prove a useful discriminant for models of this type.

It is clear that since the Tuscon-Melbourne $3N$ force appears to explain an anomaly in the $p+d$ elastic cross section and match the deuteron vector analyzing power, it must be tested against other precise measurements. Here we show that the proton analyzing powers measured over the same energy range agree neither with conventional Faddeev calculations nor with calculations containing the Tuscon-

Melbourne force. This represents an opportunity to consider further the spin dependence of the $3N$ models, and illustrates the importance of precise polarization measurements.

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