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Systematic investigation of the elastic proton-deuteron differential cross section at intermediate energies

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To investigate the importance of three-nucleon forces (3NF) systematically over a broad range of intermediate energies, the differential cross sections of elastic proton-deuteron scattering have been measured at proton bombarding energies of 108, 120, 135, 150, 170, and 190 MeV at c.m. angles between 30° and 170°. Comparisons with Faddeev calculations show unambiguously the shortcomings of calculations employing only two-body forces and the necessity of including 3NF. They also show the limitations of the latest few-nucleon calculations at backward angles, especially at higher beam energies. Some of these discrepancies could be partially due to relativistic effects. Data at lowest energy are also compared with a recent calculation based on χPT.

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During the last decade, the addition of three-nucleon forces (3NF) to modern high-quality nucleon-nucleon (*NN*) potentials, such as Nijmegen-I, Nijmegen-II, Reid93, CD-Bonn, and Argonne-V18 (AV18) [1–3] has been shown necessary for many three-nucleon scattering observables, like the differential cross section and the vector-analyzing power A_y of elastic proton-deuteron scattering [4–9]. This necessity has been recognized before from the fact that 3*N* and 4*N* nuclei are underbound by *NN* forces alone [10] and also because low-lying spectra of light nuclei cannot be described correctly without 3NF [11,12]. The most popular 3NF are Urbana-IX [13,14] and a modified Tucson-Melbourne force [15,16] (which no longer violates chiral symmetry). Various combinations of modern *NN* potentials and these 3NF have been worked out, fitted to the ^{3}H binding energy [10], and subsequently applied to 3N scattering. The comparison with data revealed a mixed picture. In some cases *NN* forces alone work very well [17]; in others, when *NN* force predictions fail, the inclusion of 3NF leads to a good or fairly good description [4–9], and in still other cases neither *NN* forces alone nor the inclusion of these 3NF is sufficient to describe the data [4–7,9,18,19]. Recently, results of a systematic study of the nucleon vector-analyzing power of the reaction ^{2}H(p,pd) at several beam energies covering a large range of center-of-mass (c.m.) angles were published [7]. Serious discrepancies were observed at backward angles, showing that the spin structure of 3NF is not yet under control. Even though relatively precise data for the analyzing powers with large c.m. angular coverage exist in the literature [5,7–9] for the differential cross section of the reaction ^{2}H(p,pd) few data sets are available. The existing data [20–23], with the exception of the data from RIKEN [6,9], are limited by low precision or small angular range. Therefore, in order to obtain a comprehensive picture of elastic proton-deuteron scattering at intermediate energies, a systematic measurement of the differential cross section of this reaction as a function of the c.m. scattering angle and the bombarding energy was performed at KVI.

The present data are compared to state-of-the-art solutions of the Faddeev equations based on the above mentioned high-precision *NN* potentials alone and in combination with the 3NF TM99 (the modified version of the old TM 3NF [16]) and Urbana-IX. In addition, we shall include very recent results using *NN* and 3NF derived in chiral perturbation theory (χPT). This new approach to nuclear forces is an extension of ongoing investigations in effective field theory applied to the nucleon itself, the πN, and the π-π systems. It is a systematic perturbative approach based on a smallness parameter, the ratio of generic external momenta to a certain mass scale of the order of the ρ mass. In the case of few-nucleon systems (and in the Weinberg scheme [15]) the nuclear forces are expanded in relation to that smallness parameter (and pion-mass insertions). These forces are then inserted into the Schrödinger equation or equivalent formulations like those of Faddeev-Yakubovsky. Recently, nuclear forces up to next-to-next-to leading order (NNLO) have been worked out [24,25]. At this order, *NN* forces consist of one- and two-pion exchanges, which are parameter-free, and a string of contact forces of low chiral dimensions. The parameters of the latter (so-called low-energy constants) have been fixed by *NN* scattering data [26]. With these parameters, the forces can describe the data up to about 200 MeV quite well. At this order 3NF begin to arise [27] and consist of three

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different types of topologies: (a) a parameter-free two-pion exchange, (b) a one-pion exchange between a nucleon and a contact force between the other two, and (c) a pure three-nucleon contact force. As has been shown in Ref. [25], there are only two parameters entering the 3NF of the types (b) and (c). They can be fixed by adjusting to the ^{3}H binding energy and to the doublet neutron-deuteron scattering length [25]. This new dynamical picture has already been successfully applied in 3*N* and 4*N* systems, especially at lower energies for 3*N* scattering up to 65 MeV [25,26]. It is now of great interest to see whether this approach will work even at 108 MeV, the lowest energy studied in this paper, or if higher orders in the chiral expansion or $1/M_N$ corrections are needed. Other approaches to calculate effective three-body forces exist in the literature [28,29]. At very low energies, techniques to solve the three-nucleon problem differently have been developed in recent years [30,31].

The experiment was performed at KVI using the big-bite spectrometer (BBS) [32] in conjunction with the euro-supernova focal-plane detection system (ESN) [33]. Protons were obtained from either the KVI polarized ion source [34] or the CUSP source and accelerated in the superconducting cyclotron AGOR [35]. Measurements were made at bombarding energies of 108, 120, 135, 150, 170, and 190 MeV. Since the lower acceleration limit of AGOR for polarized protons is at 120 MeV, protons with a kinetic energy of 108 MeV were obtained by passing 120 MeV protons through an energy degrader.

When polarized ions were used, the polarization was continuously measured using the KVI in-beam polarimeter (IBP) [36] in the high-energy beam line. For these measurements, analyzing powers were obtained in addition to cross sections. These analyzing powers were in total agreement with the published data [7] at the corresponding incident-beam energies.

As targets, mixed solid CD_2-CH_2 targets with several thicknesses and a well-known CD_2/CH_2 ratio were used. The target thickness was determined from measurements of the differential cross section of elastic proton-proton scattering at several scattering angles. The measured differential cross sections of this reaction were compared with the results of *NN* calculations using Nijmegen-I, Nijmegen-II, and Reid93 potentials, resulting in a normalization factor for the proton-deuteron differential cross sections. The analyzing power of the same reaction served as a cross check of the polarization of the beam determined with IBP.

The BBS was positioned at laboratory scattering angles between 17° and 50° in steps of 3°. At each scattering angle, deuterons and protons emerging from the reaction ^{2}H(p,pd) were measured alternately. Deuterons were also measured at laboratory scattering angles of 5°, 9°, 11°, and 14°. In this way, c.m. angles between 30° and 170° were covered for all six incident-beam energies.

Measured differential cross sections are shown in Fig. 1. The statistical uncertainty, which is in general of the order of 2%, is smaller than the size of the symbols. The total systematic uncertainty, which is the quadratic sum of the uncertainty in the normalization factor, the uncertainty in the polarization where polarized protons were used, and the uncertainty in the detection efficiency, is in general $\lesssim 7\%$, and should be considered as a point-to-point systematic uncertainty.

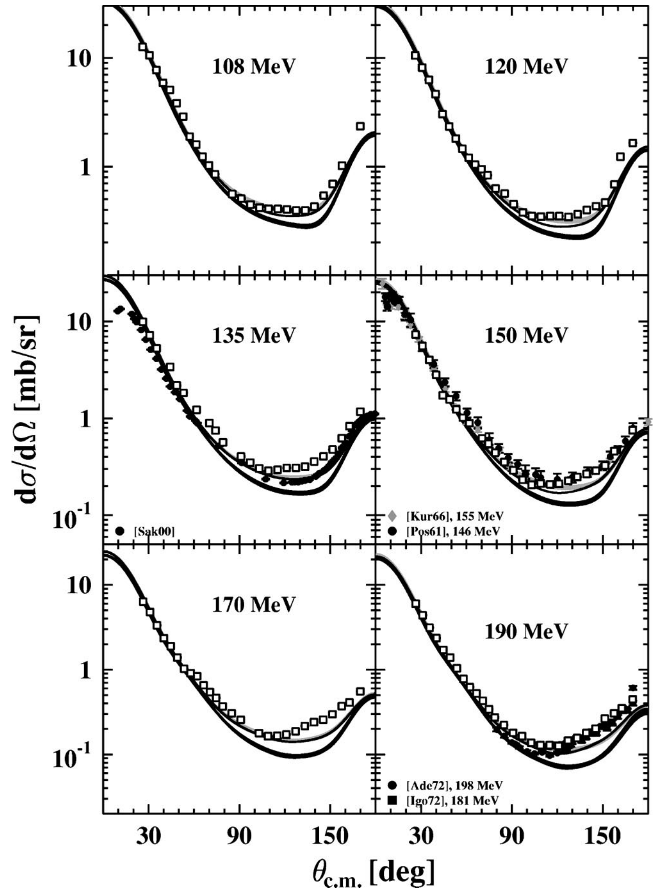

FIG. 1. Differential cross sections as a function of $\theta_{c.m.}$. The data measured in this work are plotted as open squares. The curves shown are calculations based solely on *NN* potentials (black band), calculations from Argonne-V18+Urbana-IX (solid line) and *NN* +TM99 (gray band). At 135 MeV, data from Ref. [6] (circles), at 150 MeV data from Ref. [20] (circles) and Ref. [21] (diamonds) and at 190 MeV, data from Ref. [22] (circles) and Ref. [23] (solid squares) are shown as well.

In all figures, the results of the Faddeev calculations using only two-nucleon interactions are shown as a black band. The width of this band represents the theoretical uncertainties in the calculations. Results from *NN*+TM99 calculations are shown as a gray band. Further results from Argonne-V18+Urbana-IX are shown as solid lines. At 135 MeV, data from Sakai *et al.* [6] are also shown. At 150 MeV, data from Postma *et al.* at 146 MeV [20] and Kuroda *et al.* at 155 MeV [21] have been included in the figure. At 190 MeV, data from Adelberger and Brown [22] at 198 MeV and Igo *et al.* [23] at 181 MeV are shown. As can be seen, our data agree with most other existing data sets, taking into account the experimental uncertainties and the difference in incident-beam energy. At 135 MeV, our data lie systematically above the data from Ref. [6].

To make a better comparison between our data and the theoretical calculations shown in Fig. 1, the relative difference between them is shown in Fig. 2. In this figure, our data

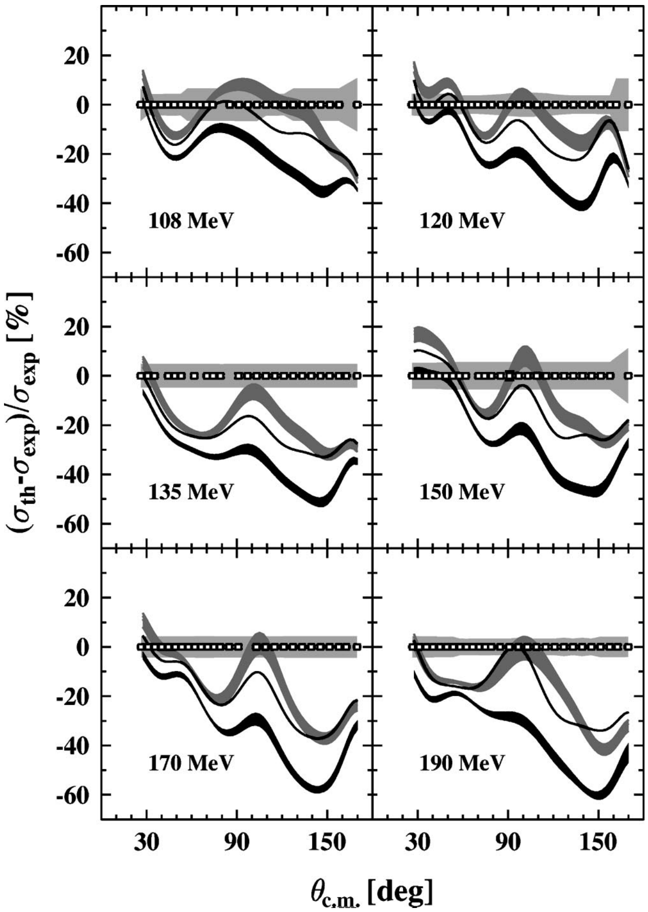

FIG. 2. Relative deviations of modern *NN* and *NN*+3*N* calculations from our data. The data points (open squares) lie at zero with the statistical uncertainties denoted at each data point. The total systematic uncertainty is shown as a light-gray band around zero. The meaning of the curves is the same as in Fig. 1.

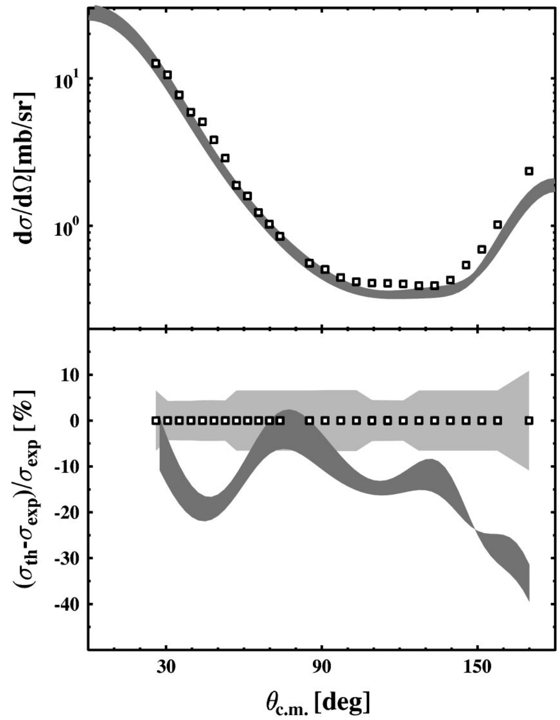

FIG. 3. Absolute values and relative deviations of the calculated differential cross section in the framework of chiral perturbation theory (dark-gray band) in comparison with the data at 108 MeV incident-beam energy. The data points from this work and, in the lower panel, the experimental systematic uncertainty (light-gray band) are also shown.

lie at zero and the calculations are shown by their relative deviations from our data. To avoid local fluctuations, these deviations are calculated by using a polynomial fit through the data points.

In general, predictions based solely on *NN* interactions deviate from our data not more than ≈60% over a range of three orders of magnitude. Inclusion of three-nucleon forces in the calculations leads to improved agreement at all incident-beam energies. With the high-precision data obtained in this work, which covers a broad c.m. angular region for six different incident-beam energies, one can now study systematically the finer details of the calculations.

At angles $\theta_{c.m.}\approx 30°$, almost all calculations overestimate the data. This is probably due to Coulomb effects not accounted for in the calculations. For $30° \lesssim \theta_{c.m.} \lesssim 60°$, the predictions from different calculations with and without 3NF show some small disagreement among themselves. Furthermore, the disagreement between the theoretical predictions and our data is slightly outside the systematic uncertainties. At angles $\theta_{c.m.} \gtrsim 60°$, the predictions start to deviate from each other and from the data. In a large part of the angular range, especially at the higher bombarding energies, calculations using solely two-nucleon potentials fail to describe our data. This deviation is largest around $130° \lesssim \theta_{c.m.} \lesssim 150°$. This angular range is part of the region of the minimum in the differential cross section and the place where three-nucleon force effects are expected to be largest [4]. The inclusion of three-nucleon forces in the calculations remedies these discrepancies, especially at the lower energies. However, starting at 135 MeV, deviations at backward angles around $\theta_{c.m.}\approx 140°$ can be observed. These deviations increase with increasing the bombarding energy. Furthermore, a local minimum in the difference plot in Fig. 2 can be observed around $\theta_{c.m.}\approx 70°$. This minimum is due to a shoulder that begins at $\theta_{c.m.}\approx 60°$ and which is reproduced by the calculations but is more pronounced in our data. A similar pattern of disagreement exists in the vector-analyzing power [7].

For the sake of clarity, we compare in Fig. 3 our results for the lowest energy, 108 MeV, to predictions of chiral perturbation theory in NNLO, including the three types of 3NFs. The theory is shown as a band, which reflects the dependence on a momentum cutoff parameter underlying the specific effective field theory formulation used. The agreement with the data at this order of the theory is comparable to the results based on the conventional forces. Higher-order corrections are expected to improve the description of the data.

The largest deviations of the theoretical predictions from our data occur at high incident-beam energies and large backward angles, i.e., a kinematic regime where the momentum transfer is largest. A plausible explanation for this is the higher-order effects, such as π-ρ or ρ-ρ exchange, which have not been included into the calculations. Part of the disagreement may also be due to relativistic corrections [37] which have not been properly taken into account in the calculations.

In conclusion, the high-precision data presented in this work, covering a large c.m. angular region at several bombarding energies, provide a suitable data base at intermediate energies for a systematic study of the influence and the deficiencies of existing three-nucleon forces. Calculations from *NN*+3*N* models show deficiencies at backward angles at the higher bombarding energies. This may be an indication that the exchange of heavier mesons is missing in the calculations. It may also be an indication that further relativistic corrections must be included. These possibilities are being investigated presently. The calculations based on chiral perturbation theory for an incident-beam energy of 108 MeV are promising since they treat the two- and three-body forces on equal footing. The convergence of these calculations at these intermediate energies can only be guaranteed once N3LO and $1/m_N$ corrections are incorporated into the calculations.

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