POLARIZATION OBSERVABLES
IN THREE-NUCLEON SYSTEMS

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In the past two decades, several laboratories have produced a large amount of data for cross sections, analyzing powers, and other spin observables from various reactions in the three-nucleon system. The results allow one to arrive at a moderately good description of the data by only using the two-nucleon potentials in Faddeev-type calculations. The remaining discrepancies should, in principle, and aside from Coulomb and relativistic effects, be removed once the effects of three-nucleon forces are implemented. High precision data on elastic and break-up reactions show, however, that even after the inclusion of these effects, the picture is not complete yet and some ingredients are still missing in the calculations.

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INTRODUCTION

In the last few years, several semiphenomenological two-nucleon models, namely, CD-Bonn, Argonne-V18 (AV18), Nijmegen-I, Nijmegen-II, and Reid93 [1–3], have become available, which describe two-nucleon scattering observables accurately. Furthermore, due to the availability of powerful computers, Faddeev-type three-nucleon calculations are nowadays routinely performed. The use of modern two-nucleon potentials, to describe three-nucleon scattering observables, leads to various degrees of agreement between the calculations and the experimental data, depending on the observable being studied and the incident beam energy. At low incident beam energies, up to ≈ 30 MeV, the differential cross section of nucleon–deuteron scattering is described rather well using solely two-nucleon potentials. In contrast, the description of the analyzing power has failed and the inclusion of three-nucleon forces (3NFs) into the calculations has not been able to remedy the discrepancy, leading to the well-known A_y-puzzle. Also for low energies, tensor-analyzing powers and spin-transfer coefficients are rather well described using solely NN forces, whereas at intermediate and higher energies the inclusion of 3N forces is necessary [4–12] although not sufficient.

In order to have a comprehensive picture of the three-body forces, one should not only study spin-averaged cross section but also observables which involve spin such as analyzing power, spin-transfer coefficients, and spin-correlation coefficients for a large energy and angle range. Only with such a reservoir of data,

one can draw a coherent picture of the interplay between the two- and three-body forces. The understanding of the nature of forces is, of course, strongly coupled to the theoretical efforts which try to generate nuclear forces [13–15] in a consistent manner such as those in the effective field theory [16, 17].

On the experimental front, there have been many experiments in the past decades. More recently, high-precision measurements have been performed at various laboratories around the world. Some results have been presented at this Conference and can be found elsewhere in these proceedings.

At KVI, we set up a programme with our Polish collaborators to study many of the observables for various reactions of interest. These include elastic proton–deuteron scattering [6–9, 11], proton–deuteron break-up reaction [18] and proton–deuteron capture reaction [19]. In this presentation, only a fraction of the data obtained in the past few years will be discussed. For a comprehensive investigation of three-nucleon systems at intermediate energy refer to [20].

1. SOME RESULTS ON SPIN OBSERVABLES

In this section, some demonstrative results are presented in the elastic proton–deuteron scattering as well as the break-up channel and, in particular, for spin observables. In Fig. 1, results are shown for the cross sections, $d\sigma/d\Omega$, the vector, A_y, and tensor, A_{yy}, analyzing powers, the induced polarizations, $P_{y'}$, and the vector, $K_y^{y'}$, and tensor, $K_{yy}^{y'}$, spin-transfer coefficients in the elastic deuteron–proton scattering [9]. This experiment was performed with a 180 MeV deuteron beam on a solid CH_2 or a liquid hydrogen target [21]. $P_{y'}$ is the same as the analyzing power in the inverse reaction (with a negative sign). We used the information from our earlier measurements on the analyzing power to fix the overall small asymmetry of the detection system. It should, therefore, be noted that for P_y, only the shape of the observable should be compared with the results of the calculations.

The error bars, which are included for each data point, are for some data points smaller than the symbol size of the point. This error accounts for the statistical uncertainties and a very small point-to-point (PTP) uncertainty. The statistical uncertainties come from the spin-dependent cross sections and the statistical uncertainty in determining the incoming-beam polarization with the in-beam polarimeter [22]. The PTP error accounts for a very small instability of the experimental apparatus over long periods of time and background subtraction. In addition to the statistical and the PTP errors, there are other types of systematic errors. These errors originate from the target thickness measurement, the estimation of the angular opening of the detector, the total collected charge, and the systematic error of the incoming beam polarization. The resultant systematic error is $\sim 5\%$ for the cross sections and $\leqslant 3\%$ for all other spin-dependent observables.
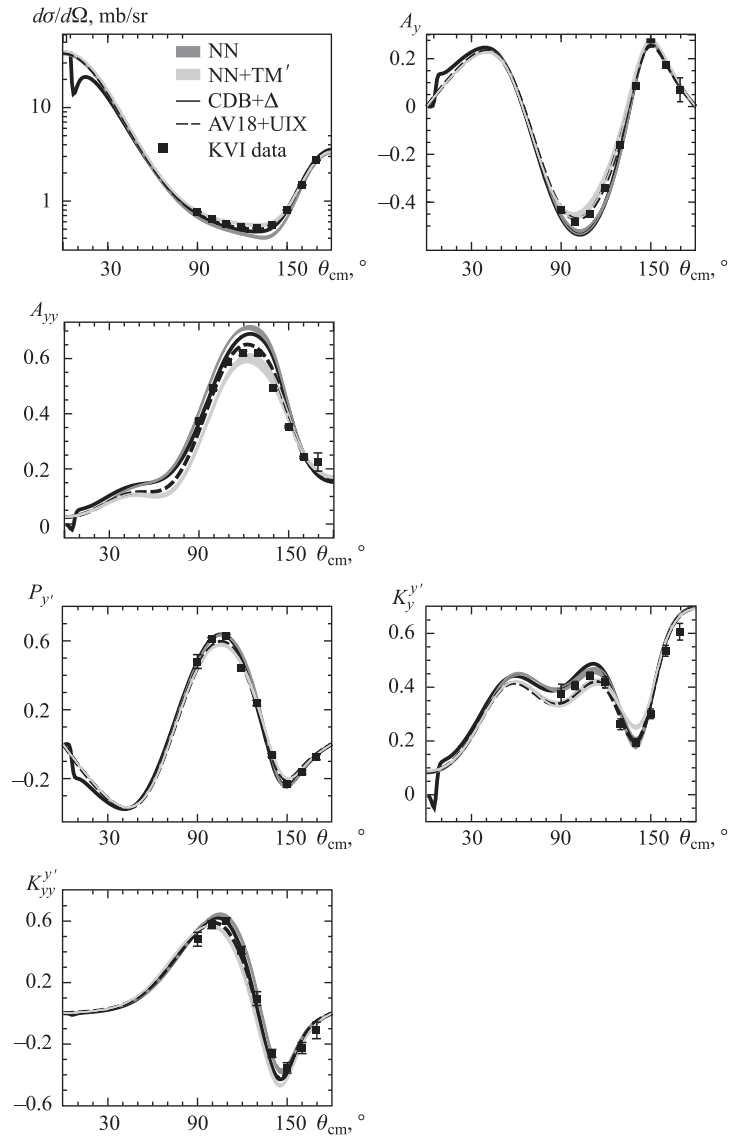
Fig. 1. Data for the cross section, $d\sigma/d\Omega$, the vector, A_y, and tensor, A_{yy}, analyzing powers, the induced polarizations, $P_{y'}$, and the vector, $K_y^{y'}$, and tensor, $K_{yy}^{y'}$, spin-transfer coefficients in the elastic deuteron–proton scattering. Theoretical predictions based on NN forces alone are shown by the dark grey bands, while those with $NN + TM'$ are presented by the light grey bands. Dashed (solid) lines show the predictions using other 3NFs, $AV_{18} + UIX$ (CDB+Δ). For A_y, the solid line is on the lower edge of the dark grey band

For the cross sections, it is clear that the inclusion of the 3NF (three-nucleon forces) is needed and the magnitude of the correction due to 3NF is in agreement with the trend seen in Fig. 1 for these energies. For the analyzing powers (vector and tensor), calculations including 3NF seem to describe the data better than those based only on NN, with the exception of CDB+Δ [23] which comes close to the results of the calculations based only on two-nucleon forces. This picture is completely opposite for the spin-transfer coefficients where the calculations based on 2NF agree with those from CDB+Δ and are also in better agreement with the experimental data. It is obvious that the full spin structure of 3NF is not understood at this energy either and needs further attention. The shape of the induced polarization is in good agreement with the results of all calculations.

For the proton–deuteron break-up reaction, two measurements have been performed using 130 MeV deuteron beam with SALAD and the liquid target developed for this purpose [18, 24], and three measurements have been performed at beam energies of 100 (deuteron), 135 (proton) and 190 (proton) MeV with BINA [25]. Experiments were also performed in Jülich at 130 MeV deuterons [26]. Due to the rich kinematics of the three-body final state, many kinematical configurations have been measured and analyzed. Here, only a very small sample of the analyzing-power results is shown for the experiment done at an incident proton beam energy of 190 MeV. The results shown in Fig. 2 are for configurations where the two protons scatter to forward angles of (25°, 25°) (left panels) and (25°, 20°) (right panels). The azimuthal opening angles between the two protons vary between 180° (top panels) to 20° (bottom panels). The results of various calculations are also shown. As can be seen from the top panels, various models agree with each other and also with experimental data for co-planar geometries. However, as one decreases the co-planarity angle from 180 to 20°, serious disagreements between various calculations set in, and more importantly, they all disagree with the experimental data. Adding a 3NF to two-nucleon potential increases the disagreement even further. Even the effect of relativity [27] goes in the wrong direction. This problem needs to be further investigated.

Finally, in Fig. 3, a global comparison is shown in which all the available data for the analyzing powers in the proton–deuteron elastic scattering in the range of 50 to 250 MeV/nucleon have been compiled and compared with one of the theoretical calculations (CDB + Coulomb and CDB + Coulomb+Δ) [23]. This figure is taken from [20] where many comparisons of this sort are made for various observables. All the comparisons made (of which a number is shown in the figure) give a clear message, namely that the calculations based only on two-nucleon forces are not sufficient to describe the data. However, the addition of three-nucleon forces present on the market, only sometimes helps the situation. The discrepancies generally grow with increasing incident beam energies but also when going to more backward angles. This is clearly seen in Fig. 3. For these particular observables, the addition of 3NF improves the disagreement to some
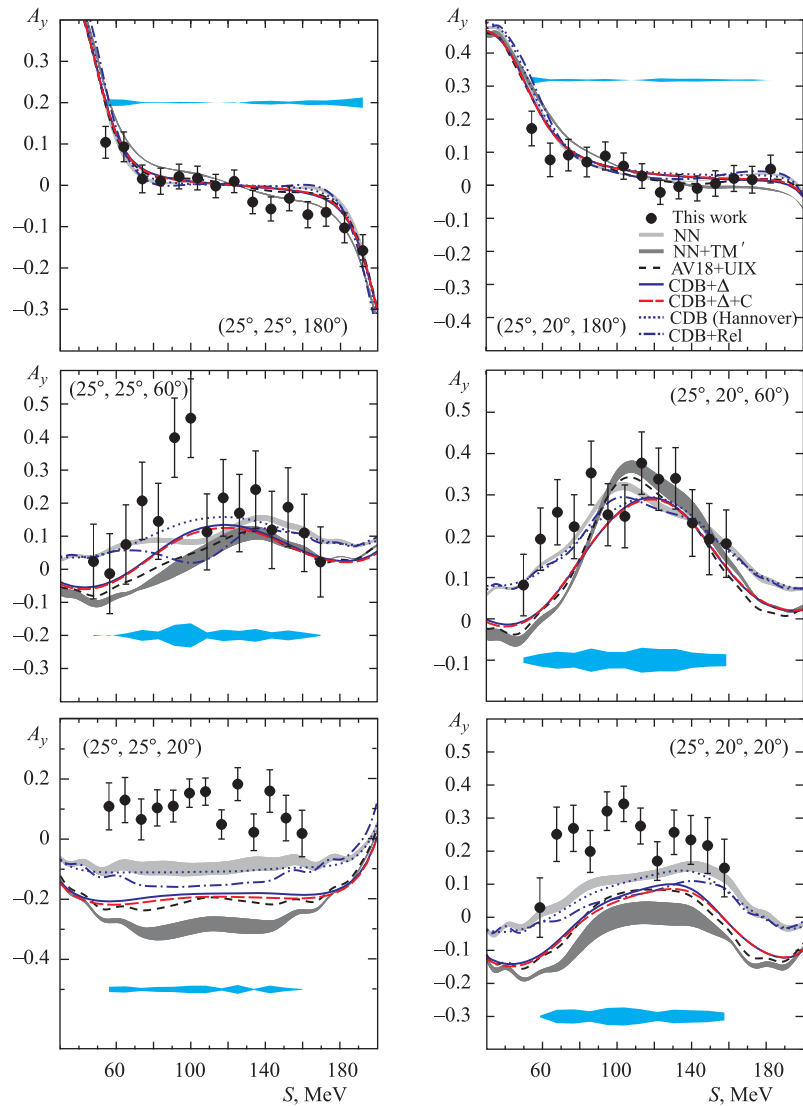
Fig. 2. The results for analyzing powers of proton–deuteron break-up reaction at $E_p = 190$ MeV as a function of the kinematical variable, S, for various polar-angle combinations of the two outgoing protons and the opening azimuthal angle between them as marked in the figure by $(\theta_1, \theta_2, \phi_{12})$. The calculations are from the Hannover–Lisbon group (CDB, CDB $+\Delta$, and CBD $+\Delta+$ Coulomb) and Bochum–Cracow group (NN, NN $+$ TM$'$, AV18 $+$ UIX, and CDB $+$ Relativity). The systematic errors are shown by the light grey (cyan) band in the panels
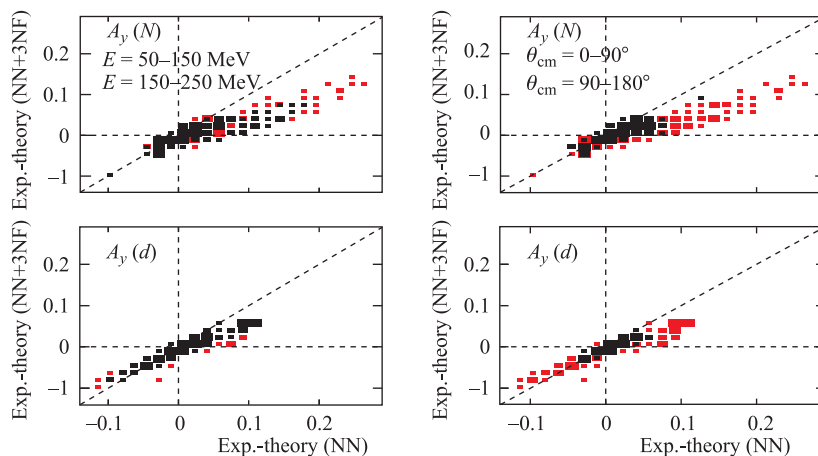
Fig. 3. (Color online). Results of the calculations are subtracted from all corresponding data points available in the literature for elastic scattering for the energy range of 50–250 MeV and center-of-mass angles $\theta_{cm} > 8°$ and plotted as a difference between experimental data and calculations with only 2NF (x-axis) and with 3NF in addition (y-axis). The four panels represent the differences for the proton and deuteron vector analyzing powers: on the left — for two different energy ranges in two different shades and on the right — for two different angle ranges in different shades

extent but clearly not enough. For some other observables, the addition of 3NF even worsens the agreement. This global analysis is meant to point to observables and regions of phase space where theoretical efforts should be spent in the coming years. The spin structure of nuclear forces remains as illusive as their central part.

CONCLUSIONS

In order to understand the properties of the three-nucleon forces, a large data-base including spectra of light nuclei and scattering data in three-body systems with all possible observables measured is mandatory. The measurements presented in this contribution are only a part of this effort. The results show unambiguously the fact that two-nucleon potentials are not enough to describe the bulk of data. However, none of the three-nucleon potentials available in the literature is at a stage of describing all the data presented here and elsewhere consistently. For the cross sections, the minimum of the cross section is filled up by adding any of the three-nucleon potentials but the improvement is certainly not sufficient. The self-consistent treatment of the Δ in the Hannover approach [23] which does a relatively good job in describing the analyzing powers in the elastic

proton–deuteron scattering at energies between 100 and 200 MeV, performs less satisfactorily in some regions of phase space of the same observables (vector and tensor analyzing powers) when a deuteron beam is used. The advantage of this calculation is the inclusion of Coulomb force for the first time which is shown to be rather small in the elastic channel except for small scattering angles, but rather sizable for some configurations in the break-up channel. The illusive nature of three-body forces might be exposed completely when the results of calculations based on effective field theory become available for these intermediate energies.

On the experimental front, efforts are continuing to investigate the nuclear forces and their manifestation in four-nucleon systems. First high-precision measurements with a deuteron beam of 130 MeV impinging on a liquid deuterium target have been performed and results are emerging [28]. For the four-body systems, exact calculations are still not available.

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