Experimental Approach to Three-Nucleon Forces via Three- and Four-Nucleon Scattering

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Abstract

Few-nucleon scattering offers a good opportunities to study dynamical aspects of three-nucleon forces, that are momentum, spin and isospin dependent. In this contribution, the experimental results of deuteron-proton elastic scattering obtained in the course of the study are presented. The data are compared with the state-of-the-art theoretical predictions based on the realistic bare nuclear potentials. Recently the experimental study has been extended to the proton-^{3}He scattering in which the isospin $T = 3/2$ channel in 3NFs could be investigated.

Keywords: *Three-nucleon force, nucleon-deuteron scattering, proton-*^{3}He *scattering*

1 Introduction

One of the main interests of nuclear physics is to understand the forces acting between nuclear constituents. Importance of the three-nucleon force (3NF) in the nuclear Hamiltonian has been studied in few-nucleon systems as well as in many-nucleon systems [1–3].

The nucleon-deuteron (Nd) scattering — a scattering process in the the three-nucleon (3N) system — offers a good opportunity to study dynamical aspects of 3NFs, which are momentum, spin and isospin dependent, since it provides not only cross sections but also a variety of spin observables at different incident nucleon energies. A direct comparison between the experimental data and rigorous numerical calculations in terms of Faddeev theory based on realistic bare nuclear potentials provides information on 3NFs. Indeed, the last two decades have witnessed extensive experimental and theoretical investigations of the Nd scattering performed in a wide range of incoming nucleon energies up to $E \sim 300$ MeV/nucleon.

The four-nucleon (4N) systems could also play an important role for the study of 3NFs. The 3NF effects are expected to be sizable in the 4N system. In addition, while the Nd scattering is essentially a pure isospin $T = 1/2$ state, tests of the $T = 3/2$ channel in any 3NF can be performed in a 4N system such as proton-^{3}He scattering. Note, an importance of the study of isospin dependence of the 3NF has been pronounced for understanding of nuclear system with larger-isospin asymmetry [4, 5]. In

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http://www.ntse.khb.ru/files/uploads/2018/proceedings/Sekiguchi.pdf.

recent years, there has been a large progress in solving the $4N$ scattering problem with realistic Hamiltonians even above the four-nucleon breakup threshold energies [6, 7], which opens up new possibilities to approaching to properties of $3N$Fs.

With the aim of exploring the $3N$Fs, experimental programs of deuteron-proton (dp) scattering as well as proton-^{3}He ($p + {}^3$He) scattering using polarized beams and target systems are in progress at RIKEN, RCNP Osaka University, and CYRIC Tohoku University in Japan. In this contribution we introduce recently conducted experiments and present results of comparison between the experimental data and theoretical predictions based on realistic bare nuclear potentials.

2 Experimental results for *dp* scattering

Experiments on the dp scattering were performed at the RIKEN Accelerator Facility using the polarized deuteron beams at the incident energies up to 135 MeV/nucleon. The measured observables are the cross sections, all deuteron analyzing powers (iT_{11}, T_{20}, T_{21}, and T_{22}), and the deuteron to proton polarization transfer coefficients [8]. Later the experiments were extended to the RIKEN RI Beam Factory (RIBF). All deuteron analyzing powers were obtained at the energies of 190, 250, and 294 MeV/nucleon [9–11].

In Fig. 1 some representative experimental results for the dp and nd elastic scattering are compared with the Faddeev calculations with and w/o the $3N$Fs. The red (blue) bands are the calculations with (without) the Tucson–Melbourne99 (TM99) $3N$F [12], which is a version of the Tucson–Melbourne $3N$F [13] more consistent with the chiral symmetry [14, 15], based on modern NN potentials, i. e., CD Bonn, AV18, Nijmegen I and II. The solid lines are the calculations based on the AV18 potential and including the Urbana IX $3N$F [16].

specific features are seen in the dependence on scattering angles in the center-of-mass system, $\theta_{\text{c.m.}}$. At the forward angles, $\theta_{\text{c.m.}} \lesssim 80^\circ$, the theoretical calculations based on various NN potentials are well converged and the predicted $3N$F effects are very small. The experimental data are well described by the calculations except for the very forward angles. This discrepancy comes from the fact that the calculations shown in the figure do not take into account the Coulomb interactions between protons [17]. At the angles $\theta_{\text{c.m.}} \gtrsim 80^\circ$, clear discrepancies between the data and the calculations based on the NN potentials are found. They become larger with the incident energy. At the angles around $\theta_{\text{c.m.}} = 80^\circ$–$120^\circ$, the discrepancies are explained by taking into account the 2π-exchange-type $3N$F models (TM99 and Urbana IX). At the backward angles, $\theta_{\text{c.m.}} \gtrsim 120^\circ$, with increasing the incident energy, the differences appear between the experimental data and even the calculations including the $3N$F potentials and are seen up to the very backward angle, $\theta_{\text{c.m.}} \sim 180^\circ$, at a higher energy of 250 MeV/nucleon. Since these features are more pronounced as going to higher energies [18, 19], the relativistic effects were estimated by using the Lorentz-boosted NN potentials with the TM99 [20]. However, the relativistic effects have turned out to be small and only slightly alter the cross sections [10].

For the vector analyzing power iT_{11}, the discrepancies between the data and the predictions based on $2N$Fs (blue bands) are seen at the angles $\theta_{\text{c.m.}} \sim 120^\circ$. At 135 and 190 MeV/nucleon, the data agree well with the predictions with the $3N$Fs, while at 250 MeV/nucleon, a discrepancy is seen at the backward angles $\theta_{\text{c.m.}} \gtrsim 120^\circ$. The tensor analyzing power T_{22} reveals a different energy dependence than that of iT_{11}.

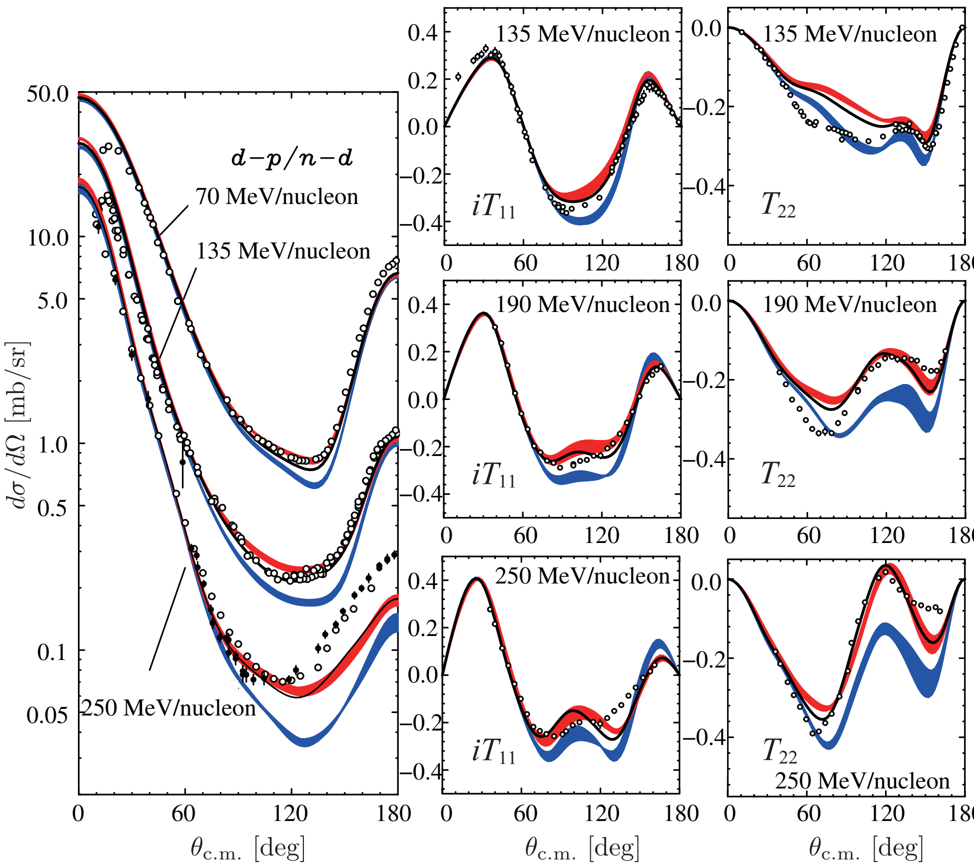

Figure 1: Differential cross section and deuteron analyzing powers iT_{11}, T_{22} for elastic Nd scattering. The red (blue) bands are the calculations with (w/o) TM99 3NF based on the modern NN potentials, namely CD Bonn, AV18, Nijmegen I and II. The solid lines are the calculations based on the AV18 potential with inclusion of Urbana IX 3NF. For the cross sections, the open circles at 70 and 135 MeV/nucleon are the dp data from Refs. [8]. The open and solid circles at 250 MeV/nucleon are the pd and nd data, respectively, from Refs. [18]. For the deuteron analyzing powers, the data at 70 and 135 MeV/nucleon are from Refs. [8]. The data at 250 MeV/nucleon are taken at the RIBF [9].

At 135 MeV/nucleon, adding the 3NFs worsens the description of data in a large angular region. It is contrary to what happens at 190 and 250 MeV/nucleon, where large 3NF effects are supported by the measured data. The results of comparison show that the 3NF is definitely needed in the Nd elastic scattering. However the spin-dependent parts of the 3NF may be deficient.

It is interesting to see how the potentials of the chiral effective field theory (χEFT) describe the deuteron analyzing powers for the dp elastic scattering. In Fig. 2, the data are compared with the calculations based on the χEFT N4LO NN potentials [21]. For the cross section, a large difference is seen at the backward angles, that is quite similar to the results shown in Fig. 1 The vector analyzing power iT_{11} data are well

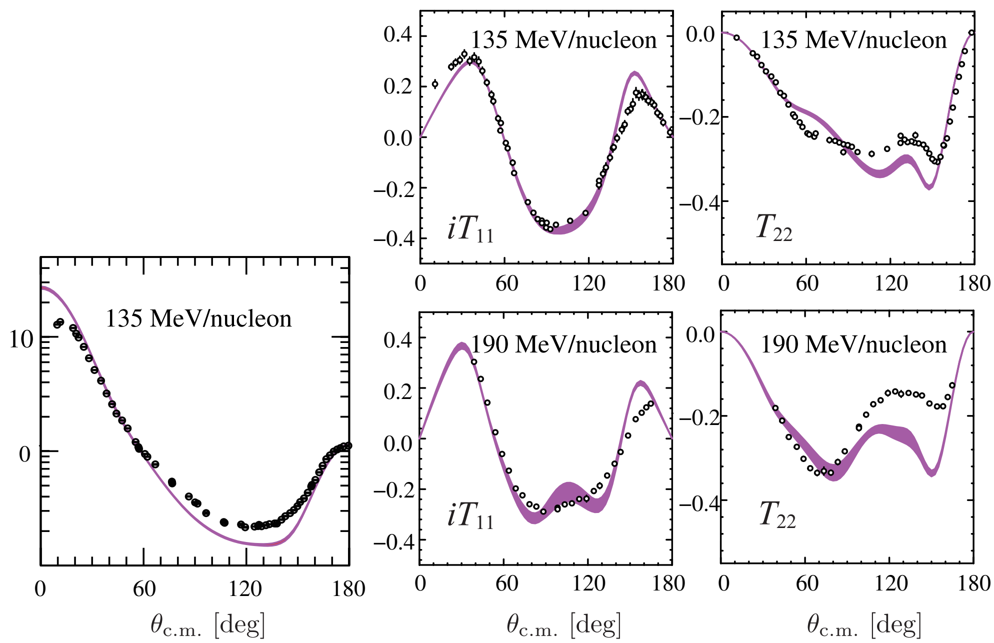

Figure 2: Differential cross section and deuteron analyzing powers iT_{11}, T_{22} for the elastic Nd scattering. The bands are the calculations based on the χEFT N4LO NN potentials.

described by the χEFT N4LO NN potentials, while large discrepancies are found for the tensor analyzing power T_{22}. In order to see how χEFT 3NFs describe the data, the theoretical treatments are now in progress [22].

3 Experiment on $p + {}^3$He scattering

Following the experiments on the dp scattering, we proceeded to the experiments on the $p + {}^3$He scattering at energies around 100 MeV/nucleon. The experiment consisted of two measurements. The measurement of the cross section and proton analyzing power was performed by using a 65 MeV polarized proton beam at RCNP, Osaka University. The measurement of the ^{3}He analyzing power at an incident proton energy of 70 MeV was performed by using the newly constructed ^{3}He target [23] at Cyclotron Radioisotope Center (CYRIC), Tohoku University. Both measurements covered a wide angular range in the center-of-mass system. In Fig. 3, a part of the data is compared with rigorous numerical four-nucleon calculations in terms of the Alt–Grassberger–Sandhas equation based on modern NN potentials (CD Bonn and INOY04 [24]) [25]. The clear discrepancies are found in the ^{3}He analyzing power at the angles 80–120° in the center-of-mass system. The data analysis is now in progress.

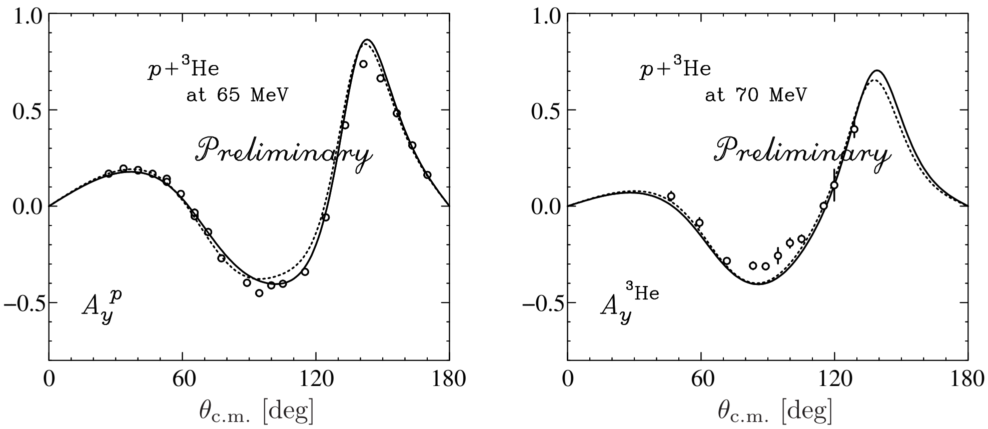

Figure 3: Proton analyzing power (left) and ^{3}He analyzing power (right) for the $p + {}^3$He elastic scattering. The data for the proton analyzing power were taken with a polarized proton beam at 65 MeV; those for the ^{3}He analyzing power at 70 MeV were obtained using a polarized ^{3}He target. The solid (dotted) lines are the calculations based on the INOY04 (CD Bonn) NN potential.

4 Summary

The few-nucleon scattering provides rich sources to explore the properties of 3NFs that are momentum, spin and isospin dependent. The last two decades have witnessed an extensive study of the Nd scattering, that is an example of scattering in a three-nucleon system, both from theory and experiment. The experiments performed with polarized deuteron beams at RIKEN are presented and recent achievements in the study of 3NFs via dp scattering are discussed. The energy and angular dependent results for the cross sections as well as the polarization observables show that clear signatures of the 3NF effects are found in the cross section. Meanwhile the spin-dependent parts of the 3NFs may be deficient. In order to obtain a consistent understanding of the effects of three-nucleon forces in the 3N scattering, a further investigation is necessary. It would be interesting to see how well new theoretical approaches, e. g., an addition of the 3NFs other than that of the 2π-exchange type, and the potentials based on the chiral effective field theory, will be able to describe these data.

The 3NF effects could also be sizable in the four-nucleon scattering systems, such as the $p + {}^3$He scattering, where tests of the isospin $T = 3/2$ channel in 3NFs can be performed. As the first step, we have conducted experiments on the $p + {}^3$He elastic scattering at around 65 MeV. The obtained data would provide a valuable source of information on the 3NFs including their isospin dependences.

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