Recent results on deuteron–proton scattering from RIKEN

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Abstract. Nucleon-deuteron (Nd) scattering, for which a rigorous formulation in terms of Faddeev equations exists and exact solutions of these equations for any dynamical input can be obtained, offers a good opportunity to study the dynamical aspects of 3NFs, such as momentum and spin dependences. Since the first indication of 3NF effects in Nd elastic scattering around 100 MeV/nucleon, precise measurements of proton–deuteron / neutron–deuteron scattering have been extensively performed at 60–300 MeV/nucleon. Direct comparison between the data and the Faddeev calculations based on realistic nucleon–nucleon forces plus 2π –exchange three nucleon forces draws the following conclusions. (1) The 3NF is definitely needed in Nd elastic scattering. (2) The spin dependent parts of the 3NFs may be deficient. (3) The shorter-range components of the 3NFs are probably required for the cross section as well as the spin observables at backward angles with increasing an incident energy.

1 Introduction

One of the main interests in nuclear physics is understanding the forces acting between nuclear constituents. A hot topic in the study of nuclear forces is to clarify the roles of three nucleon forces (3NFs) in nuclei, and to describe various phenomena of nuclei by explicitly taking into account nucleon–nucleon (NN) interactions combined with 3NFs. The 3NFs arise naturally in the standard meson exchange picture [1] as well as in the framework of chiral effective field theory (χ EFT) which has a link to QCD [2, 3].

The first evidence for a 3NF was found in the three-nucleon bound states, ^3H and ^3He [4, 5]. The binding energies of these nuclei are not reproduced by exact solutions of three-nucleon Faddeev equations employing modern NN forces only, *i.e.* AV18 [6], CD Bonn [7], Nijmegen I, II [8]. The underbinding of ^3H and ^3He is explained by adding a 3NF, mostly based on 2π –exchange, acting between three nucleons [4, 5, 9]. The importance of 3NFs has been further supported by the binding energies of light mass nuclei, and by the empirical saturation point of symmetric nuclear matter. *Ab initio* microscopic calculations of light mass nuclei, such as Green’s Function Monte Carlo [10] and no-core shell model calculations [11], highlight the necessity of including 3NFs to explain the binding energies and low-lying levels of these nuclei. As for the density of symmetric nuclear matter, it has been reported that all NN potentials provide saturation at too high density, and a short-range repulsive 3NF is one possibility to shift the theoretical results to the empirical point [12]. In the past decade, low energy scattering, binding energies of light [13] and medium mass nuclei [14, 15] and nuclear

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matter [16] have been extensively studied also in the framework of chiral effective field theory (χ EFT). In all these investigations, it became evident that 3NFs are taken as one key element to understand various nuclear phenomena. Therefore, they should be investigated in a wide momentum region to understand their properties in detail.

In order to study the dynamical aspects of 3NFs, such as momentum, spin, and iso-spin dependences, the three-nucleon scattering system is an attractive probe because various kinematical conditions are allowed to measure not only differential cross sections but also a rich set of polarization observables. The importance of 3NFs in three-nucleon scattering was shown in the Nd elastic scattering for the first time in Ref. [17]. Clear signals from 3NFs were found around the cross section minimum occurring at c.m. angle $\theta_{c.m.} \approx 120^\circ$ for incident energies above 60 MeV/nucleon. Since then the pd/nd scattering at 60–200 MeV/nucleon have been performed at the facilities, e.g. RIKEN, RCNP, KVI, and IUCF, providing precise data of the cross sections as well as various types of the spin observables [19]. At RIKEN we performed the measurements of the cross sections and the spin observables with the polarized deuteron beams at the incident energies up to 135 MeV/nucleon [20]. Recently we have extended the measurements at the RIKEN RI Beam Factory (RIBF) with the polarized deuteron beams at 250, and 300 MeV/nucleon which are slightly above the pion emission threshold energy 210 MeV [21, 22].

In the following sections the recent achievements on study of 3NFs via measurements for the dp scattering at the RIKEN RIBF are discussed.

2 Experiment at RIKEN

The schematic view of the experimental setup is shown in Fig. 1.

At the RIBF the vector and tensor polarized deuteron beam was provided by the polarized ion source [31] and was accelerated by the AVF, RRC, and SRC up to 250 (294) MeV/nucleon through the Intermediate-stage Ring Cyclotron (IRC) bypass transport beam line [23]. The measurement for elastic dp scattering was performed with the detector system BigDpol which was installed at the extraction beam line of the SRC. A polyethylene (CH_2) target with a thickness of 330 mg/cm² was used as a hydrogen target. In the BigDpol four pair of plastic scintillators coupled with photomultiplier tubes were placed symmetrically in the directions of azimuthal angles to left, right, up and down. Scattered deuterons and recoil protons were detected in a kinematical coincidence condition by each pair of the detectors. The measured angles in the center of mass system are $\theta_{c.m.} = 40^\circ\text{--}160^\circ$. In the experiment the deuteron beams were stopped in the Faraday cup which was installed at the focal plane F0 of the BigRIPS spectrometer.

The beam polarizations were monitored continuously with a beam line polarimeter Dpol prior to acceleration by the SRC using the reaction of elastic dp scattering at 90 (100) MeV/nucleon. The analyzing powers for this reaction have been calibrated in the previous measurement by using the $^{12}\text{C}(d, \alpha)^{10}\text{B}^* [2^+]$ reaction, the $A_{zz}(0^\circ)$ of which is exactly -1 because of parity conservation [24]. At the RIKEN RIBF the single-turn extractions were available for all the cyclotrons used for the experiments. Therefore depolarizations were expected to be small during beam acceleration. In the measurement typical values of the beam polarizations were 80% of the theoretical maximum values.

3 Results and Discussions

In Fig. 2 some representative experimental results for dp and nd elastic scattering are compared with the Faddeev calculations with and w/o 3NFs. The red (blue) bands are the calculations with (without) Tucson-Melbourne99 (TM99) 3NF [25], which is a version of the Tucson-Melbourne 3NF [26] more

FIG. 1. Schematic view of the experimental setup for dp elastic scattering with polarized deuteron beams at RIKEN RI Beam Factory.

consistent with chiral symmetry [27, 28], based on the modern NN potentials, *i.e.* CD Bonn, AV18, Nijmegen I and II. The solid lines are the calculations based on the AV18 potential with including the Urbana IX 3NF [29].

For the cross section specific features are seen depending on the scattering angles in the center of mass system $\theta_{c.m.}$. At the forward angles $\theta_{c.m.} \lesssim 80^\circ$, the theoretical calculations based on the various NN potentials are well converged and the predicted 3NF effects are very small. The experimental data are well described by the calculations except for the very forward angles. This discrepancy comes from that fact that the calculations shown in the figure do not take into account the Coulomb interactions between protons [30]. At the angles $\theta_{c.m.} \gtrsim 80^\circ$ the clear discrepancies between the data and the calculations based on the NN potentials are found. They become larger as an incident energy increases. At the angles around $\theta_{c.m.} = 80^\circ - 120^\circ$ the discrepancies are explained by taking into account the 2π exchange type 3NF models (TM99, and Urbana IX). However, at the backward angles $\theta_{c.m.} \gtrsim 120^\circ$ the differences appear between the experimental data and the calculations even including the 3NF potentials with increasing an incident energy, which lie to the very backward angle $\theta_{c.m.} \sim 180^\circ$ at a higher energy 250 MeV/nucleon. Since these features are clearly seen as going to higher energies [31, 32], the relativistic effects have been estimated by using the Lorentz boosted NN potentials with the TM99 [33]. However the relativistic effects have turned out to be small and only slightly alter the cross sections (see Fig. 3).

As for the polarization observables the energy dependence of the predicted 3NF effects and the difference between the theory and the data is not always similar to that of the cross section. The deuteron vector analyzing power iT_{11} has features similar to those of the cross section. Meanwhile the tensor analyzing power T_{22} reveals different energy dependence from that of iT_{11} . Starting from ~ 100

FIG. 2. Differential cross sections and deuteron analyzing powers iT_{11} , T_{22} for elastic Nd scattering at 70–294 MeV/nucleon (MeV/N). 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 with including Urbana IX 3NF based on AV18 potential. For the cross sections the open circles at 70 and 135 MeV/nucleon are the dp data in Refs. [20]. The open and solid circles at 250 MeV/nucleon are the pd and nd data, respectively in Refs. [31]. For the deuteron analyzing powers the data at 70 and 135 MeV/nucleon are from Refs. [20]. The data at 250 and 294 MeV/nucleon are taken at the RIBF [21, 22].

FIG. 3. Differential cross sections and deuteron analyzing powers iT_{11} , T_{20} for dp elastic scattering at 250 MeV/nucleon. The solid (blue) and dashed (red) curves show the results of nonrelativistic Faddeev calculations with the CD Bonn potential alone and combined with the TM99 3NF, respectively. The relativistic calculations based on the CD Bonn potential without Wigner spin rotations are shown with blue (dotted) curves. The red (double-dotted-dashed) curves show the relativistic calculations with the TM99 3NF included.

MeV/nucleon large 3NF effects are predicted. At 135 MeV/nucleon and below adding 3NFs worsens the description of data in a large angular region. It is contrary to what happens at the highest energies above 250 MeV/nucleon, where large 3NF effects are supported by the T_{22} data. The relativistic effects are estimated to be small also for these polarization observables for Nd elastic scattering (see Fig. 3) [22].

The results obtained for Nd elastic scattering draw the following conclusions; (1) the 3NF is definitely needed in Nd elastic scattering, (2) the spin dependent parts of the 3NF may be deficient, (3) the components other than the 2π -exchange 3NFs, i.e. the shorter-range components of the 3NFs are probably required for the cross section as well as the spin observables at backward angles as going to higher energies.

4 Summary

3NFs are now accepted as key elements in understanding various nuclear phenomena, e.g. properties of light mass nuclei and equation of state for nuclear matter. The Nd scattering data provide rich sources to explore the properties of 3NFs such as momentum and spin dependence. In this talk the experiments performed with polarized deuteron beams at RIKEN are presented and the recent achievements of study of 3NFs via dp scattering at 100–300 MeV/nucleon are discussed. The energy and angular dependent results of the cross sections as well as the polarization observables show that (1) clear signatures of the 3NF effects are found in the cross section, (2) the spin dependent parts of the 3NFs may be deficient, and (3) the shorter-range components of the 3NFs are probably required for the cross sections as well as the spin observables at backward angles with increasing an incident energies.

As the next step of 3NF study in the few nucleon scattering it would be interesting to see how theoretical approaches, e.g. inclusion of 3NFs other than 2π -exchange types. Recently the calculations based on the χ EFT potentials are becoming available for the Nd scattering up to 200 MeV/nucleon in which the NN forces up to the next-to-next-to-next-to-next leading order are taken into account [34]. Calculated results show possible signatures of 3NF effects at backward angles. Theoretical analysis with 3NFs which include not only the 2π -exchange types but other various diagrams of the 3NFs are now in progress. Together with this, it should also be mentioned that careful treatments for the effects of π -emission might be necessary for Nd scattering around and above the π threshold energy. So far we expect that cross sections for π emission are quite small in analogy of total cross section of pp scattering [35].

Experimentally, it is interesting to measure spin correlation coefficients as well as polarization transfer coefficients for elastic dp scattering at higher energies 200–400 MeV/nucleon. Various kinematic configurations of the exclusive pd breakup reactions should also be measured in order to study the properties of 3NFs as well as relativistic effects. As a first step from few to many body systems it is interesting to extend the measurements to 4N scattering systems, e.g. $p+^3\text{He}$ scattering, which would provide a valuable source of information on 3NFs including their iso-spin dependences.

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