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Review of the experimental activity at RIKEN to explore the three-nucleon interections

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Three–nucleon scattering offers a good opportunities to study dynamical aspects of three-nucleon forces that are momentum, spin and iso-spin dependent. At RIKEN the experimental programs of the deuteron-proton scattering at 70–300 MeV/nucleon are on going with the aim of exploring three-nucleon forces. In this contribution, representative experimental results of deuteron–proton elastic scattering are presented. The data are compared with state-of-the art theoretical predictions based on realistic bare nuclear potentials.

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1. Introduction

One of the open questions in nuclear physics nowadays is a complete knowledge of the interactions acting among nucleons. Modern nucleon-nucleon (NN) potentials reproducing the NN observables up to 350 MeV with very high precision do not describe that well various nuclear phenomena, e.g., some few-nucleon scattering observables, nuclear binding energies, and nuclear matter properties [1–3]. Natural candidates to improve these situations are three-nucleon forces (3NFs), that appear when more than two nucleon $A \geq 3$ interact. 3NFs arise naturally in the standard meson-exchange picture in which the main ingredient is considered to be 2π exchange between three nucleons along with the Δ-isobar excitation, the mechanism initially proposed by Fujita and Miyazawa in 1957 [4]. Further investigations have led to the Tucson-Melbourne'99 (TM'99) [5] and the Urbana IX [6] models. New impetus to study 3NFs has come from chiral effective field theory (χEFT) descriptions of nuclear interactions which has a firm link to QCD through symmetries [7, 8]. In that framework, consistent two-, three-, and many nucleon forces are derived on the same footing. χ EFT predicts rich structure of 3NFs.

Three–nucleon scattering 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. Direct comparison between the experimental data and the rigorous numerical calculations in terms of Faddeev theory based on the realistic bare nuclear potentials provides information on 3NFs. The importance of 3NFs in few-nucleon scattering was shown in nucleon–deuteron (Nd) elastic scattering for the first time in Ref. [9]. 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 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 [3]. Compilations of recent experiments for pd and nd elastic scattering at intermediate energies are shown in Fig.1.

In this contribution we introduce conducted experiments at RIKEN and present the results of comparison between the experimental data and the theoretical predictions based on the realistic bare nuclear potentials. We also touch the experiments planned at RIKEN.

2. Experiments and Results of elastic dp scattering at RIKEN

The experiments of dp scattering were performed at the RIKEN Accelerator Research Facility using polarized deuteron beams at the incident energies up to 135 MeV/nucleon. Measured observables are the cross section, all deuteron analyzing powers (iT_{11}, T_{20}, T_{21}, and T_{22}), and deuteron to proton polarization transfer coefficients ($K_y^{y'}$, $K_{yy}^{y'}$, $K_{xx}^{y'}$, and $K_{xz}^{y'}$) [10]. Later, the experiments were extended to the RIKEN RI Beam Factory (RIBF). All deuteron analyzing powers were obtained at 190, 250, 294 MeV/nucleon [11–13].

Figure 2 shows some representative results reported in Refs. [10, 12, 13]. The experimental data are compared with the Faddeev calculations with and w/o 3NFs. The red (blue) bands are the calculations with (without) Tucson-Melbourne99 (TM99) 3NF based on the modern NN potentials, *i.e.* CD Bonn [14], AV18 [15], Nijmegen I and II [16]. The solid lines are the calculations based on

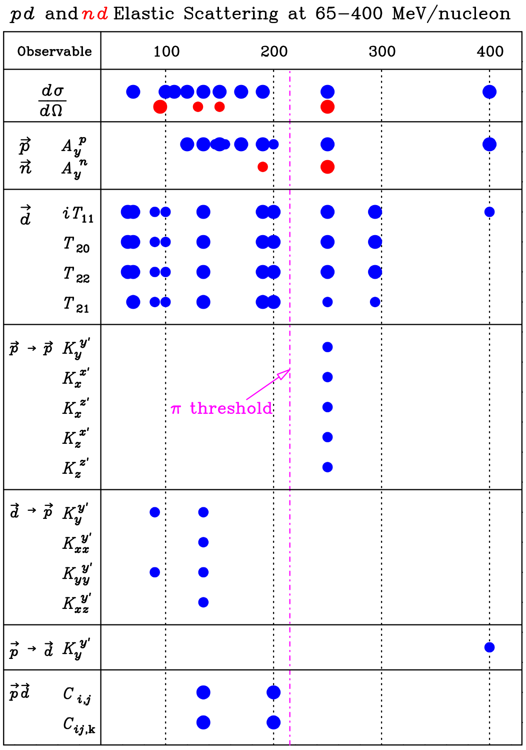

Figure 1: Compilations of recent experiments of *pd* and *nd* elastic scattering at 65–400 MeV/nucleon. Solid circles denote *pd* experiments and open circles denote *nd* experiments. The measurements with large circles cover the wide angular range, while those with small circles cover the limited angular range.

the AV18 potential with including the Urbana IX 3*N*F. The 3*N*Fs considered here are 2π–exchange types. For most of the observables shown in the figure large differences are found between the data and the calculations based on *NN* forces only at the backward angles. These discrepancies become larger with increasing an incident energy. For the cross section the 3*N*Fs remove the discrepancies at lower energies. At higher energies the differences still remain even including the 3*N*F potentials at the angles $\theta_{\mathrm{c.m.}} \gtrsim 120^\circ$, which lie to the very backward angles $\theta_{\mathrm{c.m.}} \sim 180^\circ$ at 250 MeV/nucleon. For the vector analyzing power iT_{11} the results of comparison are quite similar to those for the cross section. However for the tensor analyzing power T_{22} the different features are found. The calculations taking into account the 3*N*Fs do not explain at the lower two energies.

Direct comparison between the data and the Faddeev calculations in elastic *dp* scattering draws the following conclusions so far : (1) the 3*N*F is definitely needed in elastic *dp* scattering; (2) the 3*N*F effects are clearly seen at the angles where the cross section takes minimum, and their effects become larger with increasing an incident energy; (3) spin dependent parts of the current 3*N*F models are deficient; (4) the short-range components of the 3*N*F are probably required for high momentum transfer region (very backward angles).

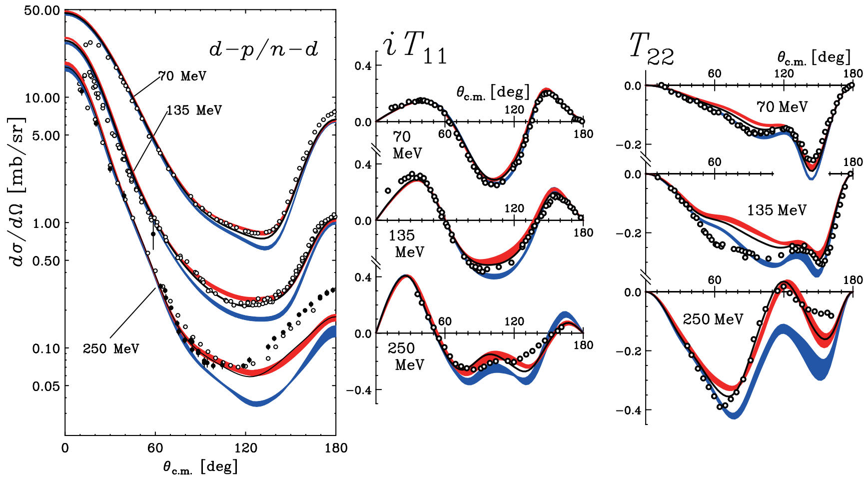

Figure 2: Differential cross section and the deuteron analyzing powers iT_{11} and T_{22} for elastic Nd scattering at 70, 135 and 250 MeV/nucleon. The dp (nd) data are shown with open (solid) circles. Red (blue) shaded bands are the calculations based on the modern NN forces, namely CDBonn, AV18, Nijmegen I, II with (w/o) the TM99 3NF. Solid lines are predictions with the AV18 NN potential + the Urbana IX 3NF. Cross section data at 250 MeV/nucleon are from Refs. [17, 18]

3. Experiments of deuteron–proton elastic scattering planned at RIKEN

The 3NF problem raised by elastic dp scattering can be cured in the chiral effective field theory approach. It provides consistent NN and 3N forces in a systematically improvable way: order by order in chiral expansion, starting from the leading order (LO). The first non-vanishing 3NF diagram appears at the next-next-leading order (N2LO), consisting of 2π-exchange (Fujita-Miyazawa type), 1π-exchange-contact, and 3N-contact interaction topologies [19]. At higher orders, there exist variety of spin and iso-spin dependent term 3NFs as well as short-range terms [20–22].

The past few years have seen remarkable advances towards pushing to the precision frontier of the nuclear potential in chiral effective field theory [8, 23, 24]. Two-nucleon sector of χ EFT has achieved to the level of high-precision. Semi-local momentum-space regularized chiral 2N potentials up to the fifth-oder (N4LO$^+$), called SMS chiral potential, reproduce the p-p (n-p) data from the 2013 Granada database [25] up to 300 MeV with an accuracy of χ^2/datum = 1.00(1.06) [28], giving small theoretical truncation uncertainties with small cut-off Λ dependence. Indeed, the N4LO NN potential applied for Nd elastic scattering at 70–190 MeV/nucleon [13] have small theoretical truncation uncertainties. The calculated results deviate largely from the experimental data (see Fig. 3), indicating necessities of incorporating χ EFT 3NFs up to the fifth order.

In the N4LO 3NF, there exist the 13 LECs for the contact terms [30, 31]. 11 of these LECs are to be proved in elastic dp elastic scattering at the cross section minimum region at intermediate energies [32], where 3NF effects are expected to be clearly seen. Two LECs of the isospin-3/2 channel are to be determined by 4N scattering or nuclei with $A \geq 4$. In view of giving constrains of LECs of the N4LO 3NFs the experiments of spin correlation coefficients for dp elastic scattering at 100 MeV/nucleon are planned at RIKEN RIBF [33]. In dp scattering, 3NF effects become larger at a higher energy, while theoretical uncertainties in χEFT are small at a lower incident nucleon

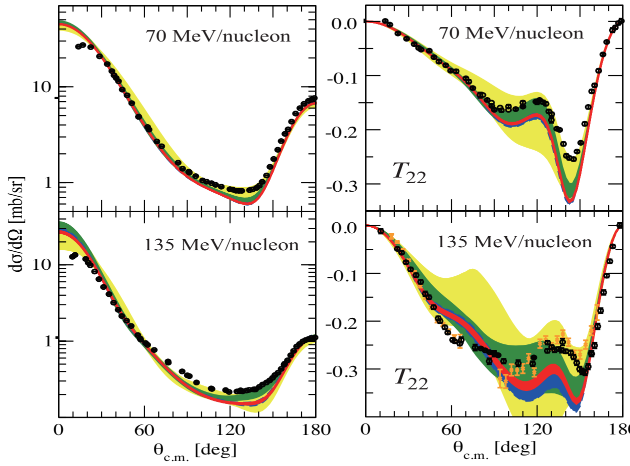

Figure 3: Calculations based on the N4LO chiral NN [29] potential of the cross section and the deuteron tensor analyzing power T_{22} for elastic Nd scattering at 70 and 135 MeV/nucleon. Estimated theoretical uncertainties at different order of chiral expansion are shown by the bands of increasing width at: N4LO (red), N3LO (blue), N2LO (green), and NLO (yellow).

energy [27]. In this respect, the incident deuteron energy chosen is optimal. The experiments are to be performed with the polarized deuteron beam in conjunction with the polarized proton solid target.

4. Summary and Outlook

Three-nucleon scattering provides rich sources to explore the properties of 3NFs that are momentum, spin and iso-spin dependent. With the aim of exploring the 3NFs, experimental programs of deuteron–proton (dp) scattering using the polarized beam and target systems are ongoing at RIKEN in Japan.

In this contribution, the experimental results obtained with polarized deuteron beams at RIKEN are presented and recent achievements of theoretical descriptions based on the χEFT NN potential via dp scattering are discussed. The energy and angular dependent results of the cross sections as well as the deuteron analyzing powers show that one needs to take into account chiral 3NFs in future calculations.

As the next step we are planning the measurements of spin-correlation coefficients for dp scattering at 100 MeV/nucleon. These data would provide a valuable source to test nuclear potentials including 3NFs and/or to determine the low-energy constants of the chiral EFT nuclear potentials. Such theoretical work is now in progress.

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