Experiments of Few-Nucleon Scattering and Three-Nucleon Forces

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Abstract

We have measured a complete set of deuteron analyzing powers in deuteron–proton elastic scattering at 190, 250, and 294 MeV/nucleon. The obtained data are compared with Faddeev calculations based on modern nucleon-nucleon forces together with the Tucson–Melbourne'99 and UrbanaIX three-nucleon forces. The data are also presented with the calculations based on the N4LO NN potentials of the chiral effective field theory.

Keywords: *Three-nucleon force,* ${}^{1}\mathrm{H}(d,d){}^{1}\mathrm{H}$ *reaction,* iT_{11}, T_{20}, T_{21}, T_{22}

1 Introduction

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

The first evidence for a $3N$F was found in the three-nucleon bound states, ^{3}H and ^{3}He [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 ^{3}H and ^{3}He is removed by adding a $3N$F, mostly based on 2π-exchange, acting between three nucleons [4, 5, 9]. The importance of $3N$Fs is 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 $3N$Fs 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 the inclusion of a short-range repulsive $3N$F is a 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 matter [16] have been extensively studied also in

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http://www.ntse-2016.khb.ru/Proc/Sekiguchi.pdf.

the framework of chiral effective field theory (χEFT). In all these investigations, it became evident that $3N$Fs are taken as the 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 $3N$Fs, such as momentum, spin, and isospin dependences, the three-nucleon scattering system is an attractive probe because various kinematical conditions allow to measure not only differential cross sections but also a rich set of polarization observables. The importance of $3N$Fs in three-nucleon scattering has been shown in the Nd elastic scattering for the first time in Ref. [17]. Clear signals from $3N$Fs has been 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 experiments at 60–200 MeV/nucleon were performed at various facilities, e. g., RIKEN, RCNP, KVI, and IUCF, providing precise data of the cross sections as well as various types of spin observables [18]. At RIKEN we performed the measurements of the cross sections and spin observables with the polarized deuteron beams at the incident energies up to 135 MeV/nucleon [19]. Recently we extended the measurements at the RIKEN RI Beam Factory (RIBF) with the polarized deuteron beams to the energies of 250 and 300 MeV/nucleon which are slightly above the pion emission threshold energy of 210 MeV [20, 21].

In the following sections the recent achievements in the study of $3N$Fs via measurements of the dp scattering at the RIKEN RIBF are discussed.

2 Experiment at RIKEN

At the RIBF the vector and tensor polarized deuteron beam was provided by the polarized ion source and was accelerated by the AVF, RRC and SRC. 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/cm^2 was used as a hydrogen target. In the BigDpol four pairs of plastic scintillators coupled with photo-multiplier 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 $\theta_{\text{c.m.}} = 40^\circ - 160^\circ$. 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 70, 90 and 100 MeV/nucleon. At the RIKEN RIBF the single-turn extractions were available for all 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

The obtained data of the deuteron analyzing powers iT_{11} and T_{22} at 190 and 250 MeV/nucleon are shown in Fig. 1 with open circles together with the previously reported data at 135 MeV/nucleon [19]. Statistical errors are only shown. The data

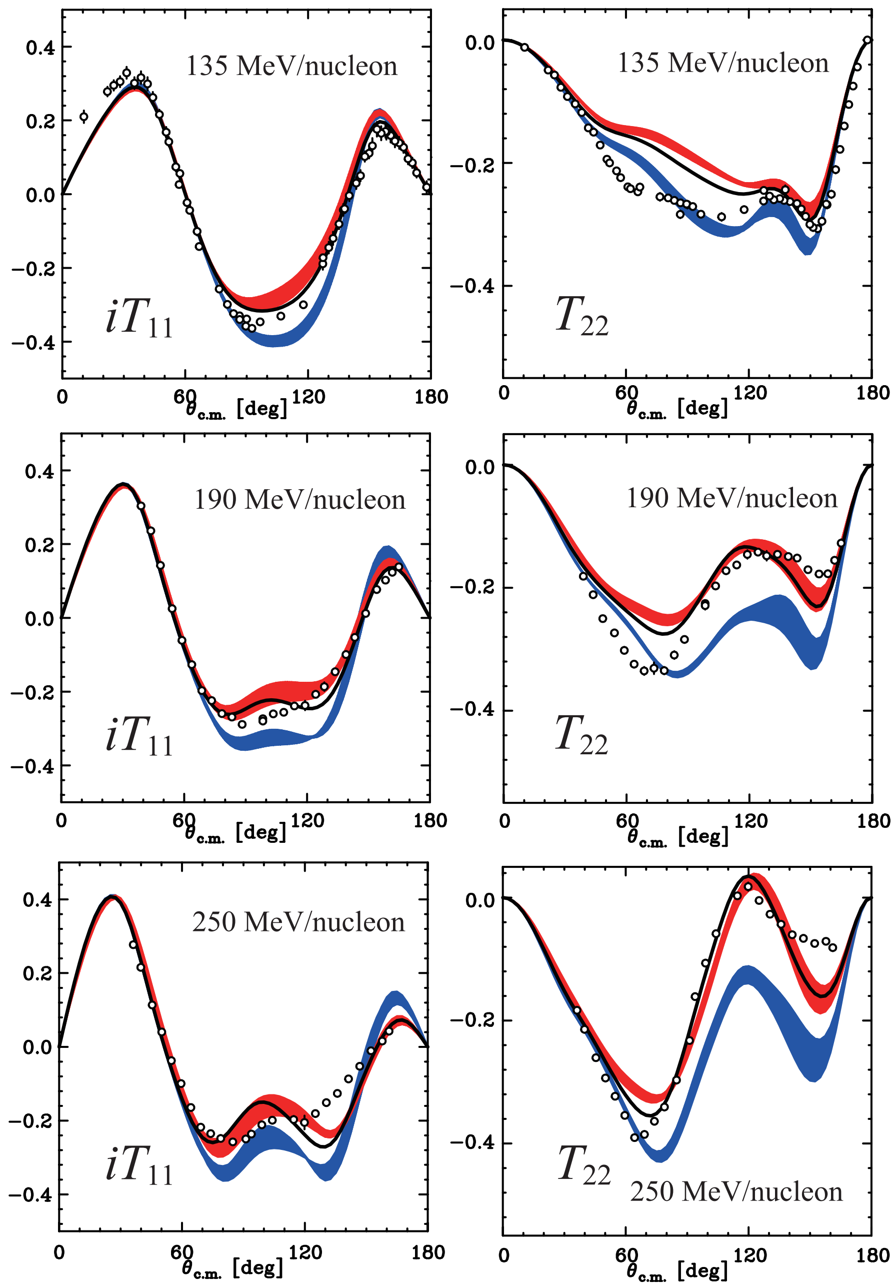

Figure 1: Deuteron analyzing powers iT_{11}, T_{22} for elastic Nd scattering at 135, 190 and 250 MeV/nucleon. See the text for the descriptions of calculations.

are compared with the Faddeev calculations based on the modern nucleon-nucleon forces combined with the three-nucleon forces. The red (blue) bands in the figure are the Faddeev calculations with (w/o) Tucson–Melbourne'99 (TM99) 3NF [22] based on the modern NN potentials, namely CDBonn [7], AV18 [23], Nijmegen I and II [8].

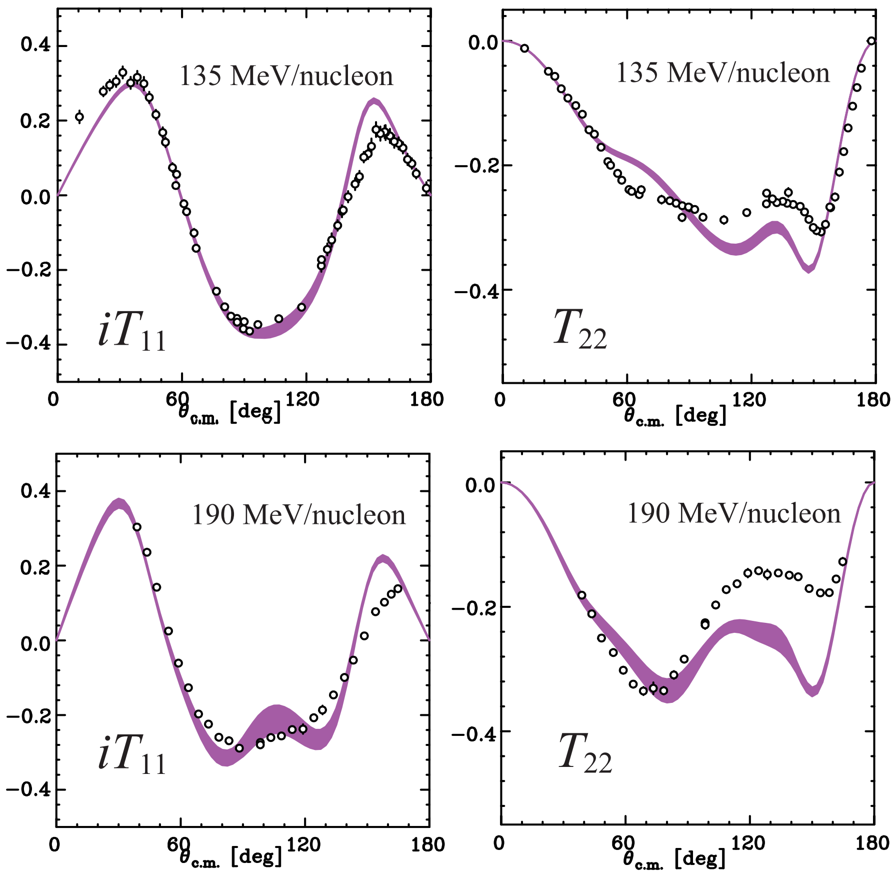

Figure 2: Deuteron analyzing powers iT_{11}, T_{22} for elastic Nd scattering at 135 and 190 MeV/nucleon. See the text for the descriptions of calculations.

The solid lines are the calculations with the Urbana IX 3NF [24] and the AV18 NN potential.

For the vector analyzing power iT_{11} the discrepancies between the data and the predictions based on 2NFs (blue bands) are seen at the angles $\theta_{\text{c.m.}} \sim 120^\circ$. At 135 and 190 MeV/nucleon, the data have good agreements to the predictions with the 3NFs while at 250 MeV/nucleon a discrepancy exists at backward angles $\theta_{\text{c.m.}} \gtrsim 120^\circ$. The tensor analyzing power T_{22} reveals a different energy dependence from that of iT_{11}. 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 shows that the 3NF is definitely needed in Nd elastic scattering. However the spin dependent parts of the 3NF may be deficient.

It is interesting to see how the potential of the chiral effective field theory (χEFT) describes 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 [25]. The vector analyzing power iT_{11} data are well described by the χEFT N4LO NN potential, 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 [26].

4 Summary and Outlook

3NFs are now accepted as the 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 the 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) shorter-range components of the 3NFs are probably required for the description of the cross sections as well as of the spin observables at backward angles with contributions increasing with incident energies.

As the next step of 3NF study in the few nucleon scattering it would be interesting to see new theoretical approaches, e. g., an inclusion of 3NFs other than of the 2π-exchange type. Recently the calculations based on the χ EFT potentials become 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-to leading order are taken into account [25]. The results show possible signatures of 3NF effects at backward angles. Theoretical analyses with 3NFs which include not only the 2π-exchange type but also other various diagrams of the 3NFs, are now in progress. Together with this, it should be also mentioned that careful treatments for the effects of π-emission might be necessary for Nd scattering around and above the π-creation threshold energy. So far we have expected that the cross sections for the π emission are quite small in analogy with the total cross section of the pp scattering [27].

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., $p+^3$ He scattering, which would provide a valuable source of information on 3NFs including their isospin dependences.

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