Approach to Three Nucleon Forces from Experiment

Kimiko Sekiguchi

Department of Physics, Tohoku University, Sendai, 980-8578, JAPAN

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, 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 60–250 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 3NF may be deficient, (3) the short-range components of the 3NF are probably required for high momentum transfer region, and (4) establishment of 3NFs in Nd breakup processes should be performed in the framework of relativistic Faddeev calculations.

Keywords: *Three-nucleon force; few-nucleon systems; nucleon-deuteron scattering*

1 Introduction

Experimentally, one must utilize systems with more than two nucleons ($A \geq 3$) to investigate properties of three nucleon forces (3NFs). The 3NFs arise naturally in the standard meson exchange picture in which the main ingredient is considered to be a 2π-exchange between three nucleons along with the Δ-isobar excitation initially proposed by Fujita and Miyazawa in 1957 [1]. Further augmentations have led to the Tucson–Melbourne (TM) [2], the Urbana [3] 3NFs, etc. A new impetus to study 3NFs has come from chiral effective field theory (χEFT) descriptions of nuclear interactions. In that framework consistent two-, three-, and many-nucleon forces are derived on the same footing [4, 5]. The first non-zero contribution to 3NFs appears in χEFT at the next-to-next-to-leading order (N^{2}LO) of the chiral expansion. Generally, the 3NFs are relatively small compared to the nucleon-nucleon (NN) forces and their effects are easily masked. Therefore it is hard to find an evidence for them experimentally.

The first evidence for a 3NF was found in the three-nucleon bound states, ^{3}H and ^{3}He [6, 7]. 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 [8], CD Bonn [9], Nijmegen I, II [10]. The underbinding of ^{3}H and ^{3}He can be explained by adding a 3NF, mostly based on 2π-exchange, acting between three nucleons [6, 7, 11]. 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*

Proceedings of the International Conference 'Nuclear Theory in the Supercomputing Era — 2014' (NTSE-2014), Khabarovsk, Russia, June 23–27, 2014. Eds. A. M. Shirokov and A. I. Mazur. Pacific National University, Khabarovsk, Russia, 2016, p. 241.

http://www.ntse-2014.khb.ru/Proc/Sekiguchi.pdf.

initio microscopic calculations of light mass nuclei, such as Green's Function Monte Carlo [12] and no-core shell model calculations [13], 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 a too high density, and a short-range repulsive $3N$F is one possibility to shift the theoretical results to the empirical point [14].

Three-nucleon ($3N$) scattering has been studied for a long time as one of the most promising tools to explore the properties of $3N$Fs because this process provides a rich set of energy dependent spin observables and differential cross sections. At lower energies ($E/A \leq 20$ MeV), very high precision measurements were carried out in proton-deuteron (pd) and neutron-deuteron (nd) scattering, including elastic and breakup reactions. However, theoretically predicted $3N$F effects are rather small and a generally good description for nucleon-deuteron (Nd) elastic scattering data is obtained by exact solutions of $3N$ Faddeev equations employing only NN forces [15, 16][1]. Study of the $3N$F has changed since the end of 1990's. The following advances have made it possible to explore the $3N$F effects contained in $3N$ scattering.

(i) Generation of the so-called realistic NN forces (e. g., AV18 [8], CD Bonn [9], Nijmegen I, II and 93 [10]) which reproduce a rich set of experimental NN data for laboratory energy up to 350 MeV with an accuracy of $\chi^2 \sim 1$.

(ii) Achievement of rigorous numerical Faddeev calculations based on the realistic NN potentials below the π-threshold energy (the incident nucleon energy $E/A \leq 215$ MeV) [15].

(iii) Development of experimental techniques to obtain precision data for $3N$ scattering at intermediate energies ($E/A \approx 100$ MeV).

In the last decade the experimental studies of intermediate-energy pd and nd elastic scattering have been extensively performed by groups at RIKEN, KVI, RCNP, and IUCF providing precision data for cross sections and a variety of spin observables [17–21]. This is partly due to the fact that the first indication of $3N$F was pointed out [22, 23] in the elastic channel. A compilation of recent experiments for pd and nd elastic scattering at intermediate energies is shown in Fig. 1. It should be noted that the experimental study of dp scattering have been recently extended at the new facility of RIKEN RI beam factory (RIBF) [24] where polarized deuteron beams are available up to ~ 400 MeV/nucleon.

Complete dp breakup ($d + p \to p + p + n$) reactions would be more interesting because they cover different kinematic conditions. By selecting a particular kinematic configuration, one hopes to enhance the effects which are sensitive to specific components of $3N$Fs. Thus the study of dp breakup reactions has been in progress as the second step in investigating $3N$F dynamics [25–28].

The experiments for dp scattering at RIKEN [17, 27] are described in Section 2. The recent achievements in the study of $3N$Fs in intermediate-energy Nd scattering are discussed in Section 3. Section 4 presents a summary.

2 Experiment

The experiments at RIKEN have been performed with unpolarized/polarized deuteron beams. The observables we have obtained for elastic dp scattering are: **(i)** differential cross section $\frac{d\sigma}{d\Omega}$ at 70–135 MeV/nucleon, the angles in the center of mass system $\theta_{\text{c.m.}} = 10^\circ\text{–}180^\circ$; **(ii)** all deuteron analyzing powers (A_y^d, A_{yy}, A_{xx}, and A_{xz}) at 70–294 MeV/nucleon, $\theta_{\text{c.m.}} = 10^\circ\text{–}180^\circ$; **(iii)** deuteron-to-proton polarization transfer coefficients ($K_y^{y'}$, $K_{xx}^{y'}$–$K_{yy}^{y'}$, and $K_{xz}^{y'}$) at 135 MeV/nucleon, $\theta_{\text{c.m.}} = 90^\circ\text{–}180^\circ$. We also extended the measurement to the dp breakup reaction at 135 MeV/nucleon. Spin observables for specific kinematical conditions have been measured.

[1]Exceptions are the vector analyzing powers A_y and iT_{11} for pd elastic scattering.

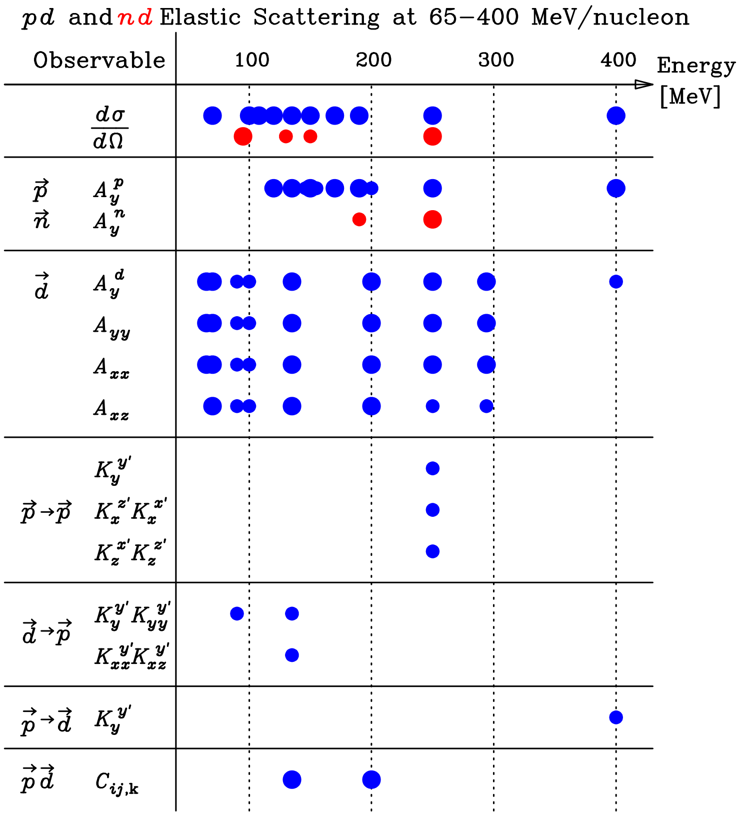

Figure 1: Compilation of recent experiments of *pd* and *nd* elastic scattering at 65–400 MeV/nucleon. Solid blue circles denote *pd* experiments and solid red circles denote *nd* experiments. The measurements with large circles cover a wide angular range while those with small circles cover a limited angular range.

A schematic view of the experimental setup is shown in Fig. 2. The vector and tensor polarized deuteron beams [29] accelerated by the cyclotrons bombarded a hydrogen target [liquid hydrogen or polyethylene (CH_2)]. Either the scattered deuteron or the recoil proton was momentum analyzed by the magnetic spectrograph SMART (Swinger and Magnetic Analyzer with Rotator and Twister) [30] depending on the scattering angle and detected at the focal plane. For the polarization transfer measurement, a double scattering experiment was performed to obtain the polarizations of elastically scattered protons from the hydrogen target [31]. One characteristic feature of the RIKEN polarized deuteron beams was that we could obtain beams which axis was controlled in an arbitrary direction on the target making it possible to obtain all the deuteron analyzing powers A_y^d, A_{yy}, A_{xx}, A_{xz}. The polarization axis of the deuteron beams was controlled by the spin rotator Wien Filter prior to acceleration [32]. Due to the single-turn extraction feature of the RIKEN cyclotrons the polarization amplitudes were maintained during acceleration. The beam polarizations were monitored with the beam line polarimeter by using the analyzing powers for *dp* elastic scattering. To obtain the absolute values of the deuteron beam polarizations, the analyzing powers for *dp* elastic scattering were calibrated by the $^{12}C(d,\alpha)^{10}B^*\,[2^+]$ reaction which $A_{yy}\,(0°)$ is exactly $-1/2$ because of parity conservation [33]. In all measurements the actual magnitudes of the polarizations were 60–80% of theoretical maximum values.

It was essential to obtain precise absolute values of the cross section to compare with the state-of-the-art Faddeev calculations. However, it is usually difficult to know experimentally the systematic uncertainty. We performed the cross section

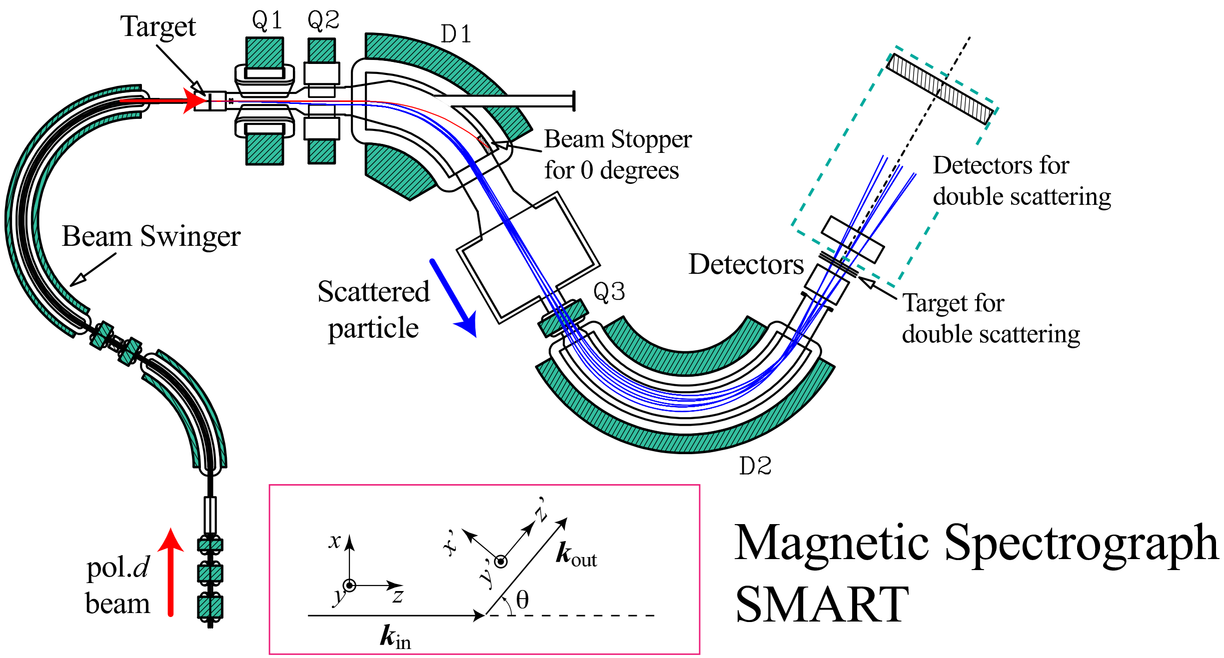

Figure 2: Schematic view of the experimental setup for the measurements of dp elastic and breakup reactions at RIKEN.

measurements with three different experimental techniques and tried to estimate the systematic uncertainties. First, we made a measurement at RIKEN with the proton beam at 135 MeV and a CD_2–CH_2 sandwiched solid target at the angles where the *pp* and *pd* elastic scattering were simultaneously measured with the magnetic spectrograph SMART. Using the well-known elastic *pp* cross sections we can estimate the overall systematic uncertainty for the *pd* cross section. Secondly, to confirm the angular distribution, we performed a measurement with 135 MeV/A deuterons, a CH_2 solid target, and the SMART system. In this measurement we tried to check the fluctuations of the target thickness during the experiment by measuring the *dp* scattering at the fixed angle $\theta_{\rm c.m.} = 69.7^\circ$ where the scattered deuterons and recoil protons were detected in coincidence in the scattering chamber. The cross section at $\theta_{\rm c.m.} = 165.1^\circ$ was measured for that same purpose with the SMART system several times during the experiment. We also measured the carbon background events. Finally, we performed a totally independent measurement at the Research Center for Nuclear Physics (RCNP) of Osaka University using a 135 MeV proton beam and deuterated polyethylene target. The absolute normalization of the cross sections has been performed by taking the data with a D_2 gas target and the double slit system for which the RCNP group has already established the procedure to obtain the absolute *pd* cross section [18]. A very good agreement between these independent measurements allows us to conclude that the systematic uncertainty due to the detection setup is small [17].

3 Results and discussion

Elastic Nd scattering

In Fig. 3 some representative experimental results for *pd* and *nd* elastic scattering are compared with the Faddeev calculations with and w/o 3NFs. The red (blue) bands are the calculations with (without) TM′99 3NF [34] which is a version of the Tucson–Melbourne 3NF consistent with chiral symmetry [35, 36], 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 with including the Urbana IX 3NF.

Note, so far the calculations with the next-to-next-to-leading order χEFT potential have been available for three-nucleon scattering [5] up to 100 MeV/nucleon. Since our discussion is on 3NF effects for higher energies ($\gtrsim$100 MeV/nucleon) we don't show the results on χEFT potentials here. The theoretical analysis for energies $\gtrsim$100 MeV/nucleon is now in progress [37].

For the cross section, specific features are seen depending on scattering angles in the center of mass system $\theta_{\rm c.m.}$. **(i)** At forward angles $\theta_{\rm c.m.} \lesssim 80^\circ$ where the direct processes by the NN interactions are dominant, the theoretical calculations based on 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 interaction between protons [38]. **(ii)** At middle angles $\theta_{\rm c.m.} \sim 80^\circ$–$140^\circ$ where the cross sections take minimum, the clear discrepancies between the data and the calculations based on the NN potentials are found. They become larger as the incident energy increases. The discrepancies are explained by taking into account the 2π exchange type 3NF models (TM′99 and Urbana IX). **(iii)** At backward angles $\theta_{\rm c.m.} \gtrsim 140^\circ$ where the exchange processes by the NN interactions are dominant, the differences begin to appear between the experimental data and the calculations even including the 3NF potentials with increasing the incident energy. Since this feature is clearly seen at higher energies, the relativistic effects have been estimated by using the Lorentz boosted NN potentials with the TM′99 [39]. However the relativistic effects have turned out to be small and only slightly alter the cross sections (see Fig. 4).

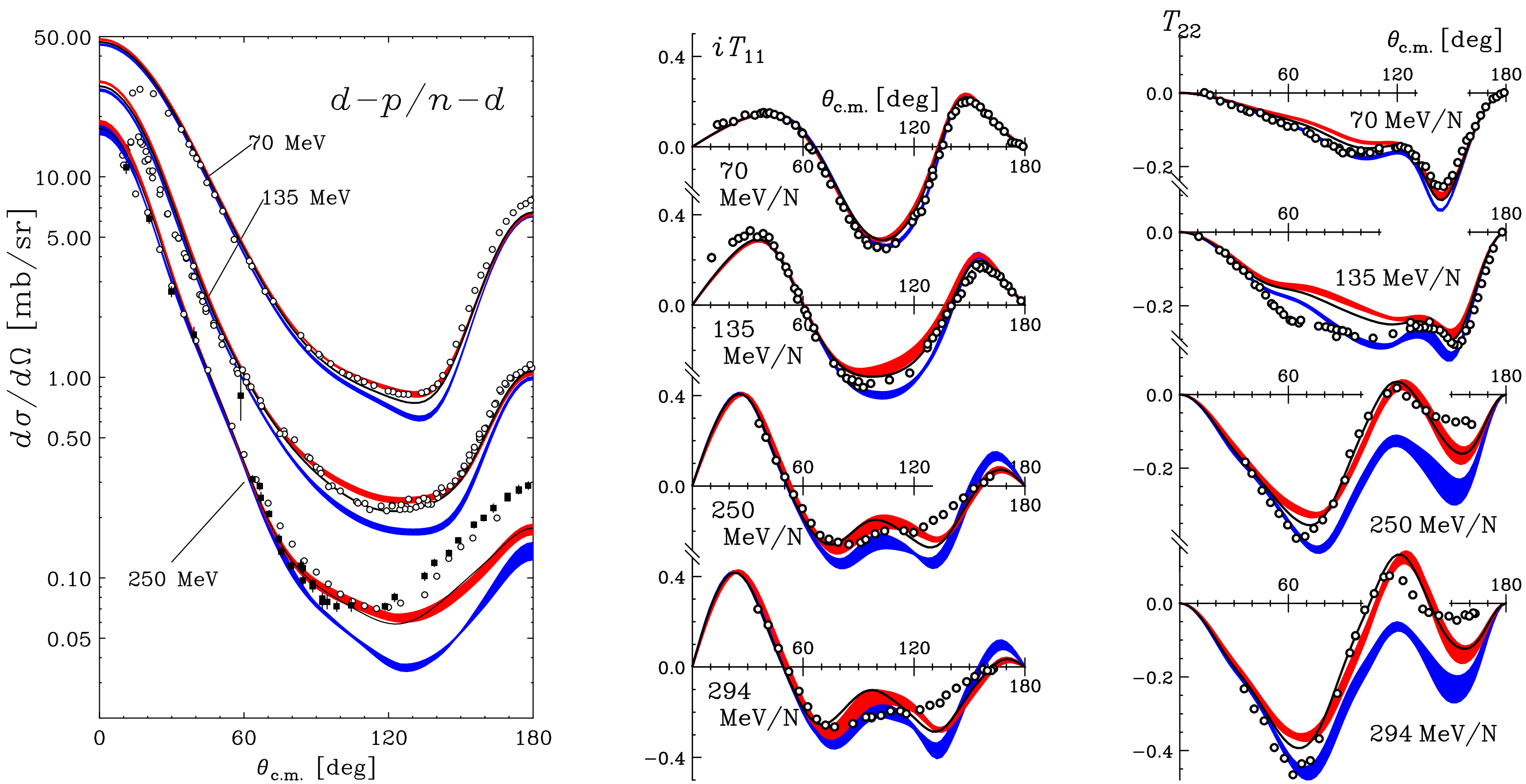

Figure 3: Differential cross sections and deuteron analyzing powers iT_{11}, T_{22} for elastic Nd scattering at 70–294 MeV/nucleon (MeV/N). The red (blue) bands are the calculations with (w/o) TM99 3NF based on the modern NN potentials, namely CD Bonn, AV18, Nijmegen I and II. The solid lines are the calculations with including Urbana IX 3NF based on AV18 potential. For the cross sections, the open circles are the data of Refs. [17]. The open squares and circles are the pd and nd data at 250 MeV/nucleon [18], respectively. For the deuteron analyzing powers, the data at 70 and 135 MeV/nucleon are from Refs. [17]. The data at 250 and 294 MeV/nucleon are taken at the RIBF [24].

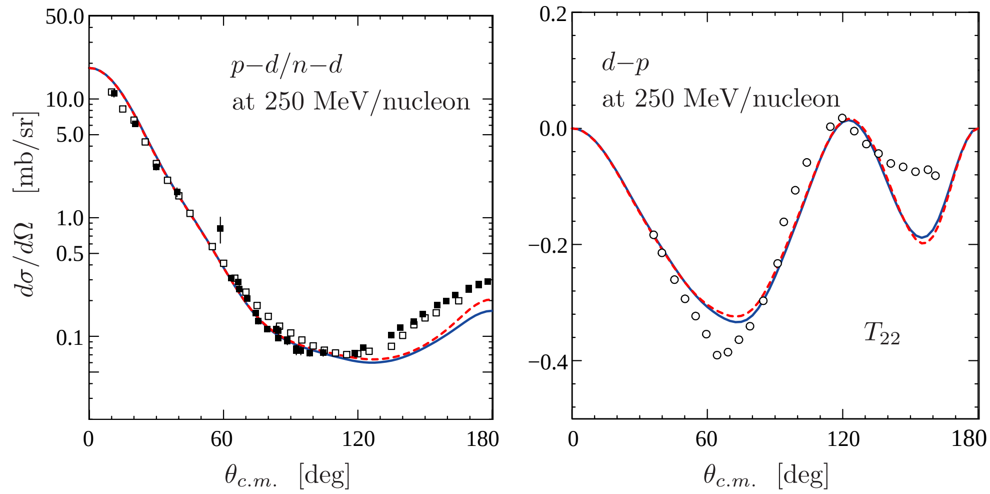

Figure 4: Differential cross section and the tensor analyzing power T_{22} for Nd elastic scattering at 250 MeV/nucleon. Faddeev calculations based on the CD Bonn potential with the TM′99 3NF are shown by blue solid lines. The calculations based on the Lorentz boosted NN potential with the 3NF are shown by red dashed lines.

As for the polarization observables, the energy dependence of the predicted 3NF effects and the difference between the theory and the data are 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 a different energy dependence from that of iT_{11}. Large 3NF effects are predicted starting from $\sim$100 MeV/nucleon. 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 higher 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. 4).

The results obtained for Nd elastic scattering draw the following conclusions: **(i)** the 3NF is definitely needed in Nd elastic scattering; **(ii)** the spin dependent parts of the 3NF may be deficient; **(iii)** the short-range components of the 3NF are probably required for backward scattering at higher energies.

Breakup *Nd* reactions

Studies in a large amount of kinematical configurations for the deuteron breakup reactions have been reported for the cross section as well as deuteron analyzing powers at the incident nucleon energy of 65 MeV/nucleon [25]. Generally the effects of 3NFs are predicted to be small at 65 MeV/nucleon, and the agreement to the data is good for all calculations both including and not including 3NFs. Focusing on particular kinematical configurations strong effects of the Coulomb interaction are found in the cross section.

The situation seems to change at higher energies $\gtrsim$100 MeV/nucleon. In recently reported relativistic Faddeev calculations with the TM′99 3NF, large relativistic effects are predicted in specific kinematical configurations [39]. For example, the agreement to the data for the polarization transfer coefficient $K_{yy}^{y\prime}$ at 135 MeV/nucleon is rather improved by taking into account the relativistic effects in the calculation with 3NF (see Fig. 5). The results of these new calculations suggest that the final explanation of the breakup reactions will be achieved when both two- and three-nucleon forces will be treated in the framework of relativistic Faddeev calculations.

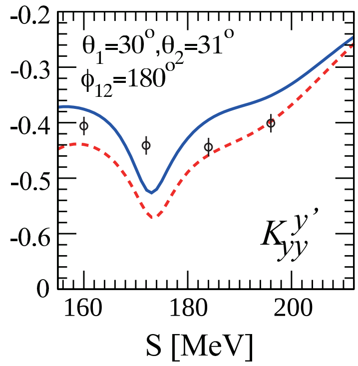

Figure 5: Polarization transfer coefficient $K_{yy}^{y'}$ for $^1\mathrm{H}(\vec{d},\vec{p}_1p_2)n$ at 135 MeV/nucleon shown as a function of S-curve arc-length. For descriptions of the calculations, see Fig. 4.

4 Summary

The 3NFs are now accepted as key elements in understanding various nuclear phenomena such as the binding of light mass nuclei and the equation of state for nuclear matter properties. The Nd scattering data provide rich sources to explore the properties of 3NFs such as momentum and spin dependences. In this talk the experiments performed with polarized deuteron beams at RIKEN are presented and recent achievements in the study of 3NFs in intermediate-energy Nd scattering are discussed.

In the last decade extensive experimental studies of pd and nd elastic scattering at intermediate energies ($E \gtrsim 100$ MeV) were performed at several facilities. The energy and angular dependent results for the cross section as well as the polarization observables show that **(i)** clear signatures of the 3NF effects are found in the cross section, **(ii)** the spin dependent parts of the 3NF may be deficient, and **(iii)** short-range components of the 3NF are probably required for description of backward scattering at higher energies.

Studies of pd breakup reactions ($p + d \to p + p + n$) followed as the second step in investigation of the 3NF dynamics. In the break up reactions at 65 MeV/nucleon in a wide range of kinematical configurations the 3NF effects are predicted to be small and the agreements to the data are generally good. At a higher energy of 135 MeV/nucleon, large 3NF effects as well as those of the relativity are predicted for some observables in relativistic Faddeev calculations recently reported. The calculations indicate that the establishment of 3NFs in the pd breakup reactions will be achieved when both two- and three-nucleon forces will be treated in the framework of relativistic Faddeev calculations.

As the next step of the 3NF study in few-nucleon scattering, it would be interesting to see how well the theoretical approaches, e. g., inclusion of 3NFs other than that of the 2π-exchange type and the potentials based on chiral effective field theory, describe these data. Experimentally, it is interesting to measure spin correlation coefficients as well as polarization transfer coefficients for elastic pd scattering at higher energies of 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.

Acknowledgments

The author would like to thank the collaborators for the experimental work performed with the polarized deuteron beams at RIKEN RI Beam Factory. She is also grateful to the strong supports from the theorists, H. Witała, W. Glöckle, H. Kamada, J. Golak, A. Nogga, R. Skibiński, P. U. Sauer, A. Deltuva, and A. C. Fonseca.

References

[1] J. Fujita and H. Miyazawa, Progr. Theor. Phys. **17**, 360 (1957).

[2] S. A. Coon and W. Glöckle, Phys. Rev. C **23**, 1790 (1981).

[3] B. S. Pudliner *et al.*, Phys. Rev. C **56**, 1720 (1997).

[4] U. van Kolck, Phys. Rev. C **49**, 2932 (1994).

[5] E. Epelbaum, H.-W. Hammer and U.-G. Meißner, Rev. Mod. Phys. **81**, 1773 (2009).

[6] C. R. Chen *et al.*, Phys. Rev. C **33**, 1740 (1986).

[7] T. Sasakawa and S. Ishikawa, Few-Body Syst. **1**, 3 (1986).

[8] R. B. Wiringa *et al.*, Phys. Rev. C **51**, 38 (1995).

[9] R. Machleidt, Phys. Rev. C **63**, 024001 (2001).

[10] V. G. J. Stoks *et al.*, Phys. Rev. C **49**, 2950 (1994).

[11] A. Nogga *et al.*, Phys. Rev. C **65**, 054003 (2002).

[12] S. C. Pieper *et al.*, Phys. Rev. C **66**, 044310 (2002).

[13] P. Navrátil and W. E. Ormand, Phys. Rev. C **68**, 034305 (2003).

[14] See, for example, A. Akmal *et al.*, Phys. Rev. C **58**, 1804 (1998).

[15] W. Glöckle, H. Witała, D. Hüber, H. Kamada and J. Golak, Phys. Rep. **274**, 107 (1996).

[16] A. Kievsky, M. Viviani and S. Rosati, Phys. Rev. C **64**, 024002 (2001).

[17] N. Sakamoto *et al.*, Phys. Lett. B **367**, 60 (1996); H. Sakai *et al.*, Phys. Rev. Lett. **84**, 5288 (2000); K. Sekiguchi *et al.*, Phys. Rev. C **65**, 034003 (2002); K. Sekiguchi *et al.*, *ibid.* **70**, 014001 (2004); K. Sekiguchi *et al.*, Phys. Rev. Lett **95**, 162301 (2005).

[18] K. Hatanaka *et al.*, Phys. Rev. C **66**, 044002 (2002); Y. Maeda *et al.*, *ibid.* **76**, 014004 (2007).

[19] R. Bieber *et al.*, Phys. Rev. Lett. **84**, 606 (2000); K. Ermisch *et al.*, *ibid.* **86**, 5862 (2001); K. Ermisch *et al.*, Phys. Rev. C **68**, 051001 (2003); K. Ermisch *et al.*, *ibid.* **71**, 064004 (2005); H. R. Amir-Ahmadi *et al.*, *ibid.* **75**, 041001 (2007); H. Mardanpour *et al.*, Eur. Phys. J. A **31**, 383 (2007).

[20] E. J. Stephenson *et al.*, Phys. Rev. C **60**, 061001 (1999); R. V. Cadman *et al.*, Phys. Rev. Lett. **86**, 967 (2001); B. v. Przewoski *et al.*, Phys. Rev. C **74**, 064003 (2006).

[21] P. Mermod *et al.*, Phys. Rev. C **72**, 061002 (2005).

[22] H. Witała *et al.*, Phys. Rev. Lett. **81**, 1183 (1998).

[23] S. Nemoto *et al.*, Phys. Rev. C **58**, 2599 (1998).

[24] K. Sekiguchi *et al.*, Phys. Rev. C **83**, 061001 (2011); K. Sekiguchi *et al.*, *ibid.* **89**, 064007 (2014).

[25] St. Kistryn *et al.*, Phys. Rev. C **68**, 054004 (2003); St. Kistryn *et al.*, *ibid.* **72**, 044006 (2005); St. Kistryn *et al.*, Phys. Lett. B **641**, 23 (2006); H. Mardanpour *et al.*, *ibid.* **687**, 149 (2010); E. Stephan *et al.*, Phys. Rev. C **82**, 014003 (2010).

[26] H. O. Meyer *et al.*, Phys. Rev. Lett. **93**, 112502 (2004).

[27] K. Sekiguchi *et al.*, Phys. Rev. C **79**, 054008 (2009).

[28] K. Sagara, Few-Body Syst. **48** 59 (2010).

[29] H. Okamura *et al.*, AIP Conf. Proc. **293**, 84 (1994).

[30] T. Ichihara *et al.*, Nucl. Phys. A **569**, 287c (1994).

[31] S. Ishida *et al.*, AIP Conf. Proc. **343**, 182 (1995).

[32] H. Okamura *et al.*, AIP Conf. Proc. **343**, 123 (1995).

[33] K. Suda *et al.*, Nucl. Instr. Meth. Phys. Res. A **572**, 745 (2007).

[34] S. A. Coon and H. K. Han, Few-Body Syst. **30**, 131 (2001).

[35] J. L. Friar *et al.*, Phys. Rev. C **59**, 53 (1999).

[36] D. Hüber *et al.*, Few-Body Syst. **30**, 95 (2001).

[37] E. Epelbaum, private communications.

[38] A. Deltuva *et al.*, Phys. Rev. C **71**, 054005 (2005).

[39] H. Witała *et al.*, Phys. Rev. C **83**, 044001 (2011); H. Witała *et al.*, *ibid.* **88**, 069904(E) (2013).