Experimental approach to three nucleon forces via few nucleon systems

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Abstract. Recent progress on three nucleon force study with three nucleon scattering at intermediate energies ($E \gtrsim 100$ MeV/nucleon) are presented, especially focusing on the experimental work on deuteron–proton elastic scattering at RIKEN.

1. Introduction

A hot topic of present day few-nucleon system studies is to explore the properties of three-nucleon forces (3NFs) that appear when more than two nucleons ($A \geq 3$) interact. 3NFs arise naturally in the standard meson exchange picture in which the main ingredient is considered to be a $2\pi$–exchange between three nucleons along with the $\Delta$–isobar excitation, initially proposed by Fujita and Miyazawa a half century ago [1]. Further augmentations have led to the Tucson–Melbourne (TM) [2], the Urbana IX 3NF [3], etc. New impetus to study 3NFs has come from chiral effective field theory ($\chi$EFT) 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 $\chi$EFT at the next-to-next-to-leading order ($N^2$LO) of the chiral expansion. That explains why 3NFs are relatively small compared to NN forces (2NFs) and why their effects are easily masked. Therefore, it is, in general, hard to find evidence for them.

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 and 93 [10]. The underbinding of $^3$H and $^3$He can be explained by adding a 3NF, mostly based on $2\pi$-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 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 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 a density, and a short-range repulsive 3NF is one possibility to shift the theoretical results to the empirical point [14].

Three nucleon (3N) reactions have been studied for a long time as one of the most promising tools to explore the properties of 3NFs, because this system 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, and in breakup reactions. However, theoretically predicted $3NF$ 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].

Study of the $3NF$ has changed since the end of 1990’s. The following advances have made it
possible to explore the $3NF$ effects contained in 3N scattering. (i) Generation of the so–called
realistic NN forces (e.g., AV18 [8], CDBonn [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 $\pi$–threshold energy (the incident nucleon energy $E/A \leq 215$ MeV) [15]. (iii)
Development of experimental techniques to obtain precision data for 3N scattering

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, 18, 19, 20, 21, 22, 23, 24,
25, 26]. This is partly due to the fact that the first indication of 3NF was pointed out [27, 28]
in the elastic channel. Compilations of recent experiments for $pd$ scattering have been recently
extended at the new facility of RIKEN RI beam factory (RIBF) [29, 30] where polarized deuteron beams are available up to \( \sim 400 \text{ MeV/nucleon} \).

In Section 2 the experiments performed at RIKEN RIBF is described briefly. The
experimental results for elastic $dp$ scattering are compared with the theoretical predictions in

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1 As for the $\chi$EFT potential calculations have been performed up to the NNLO for the 3N scattering system,
providing reasonable agreement with experimental data at a laboratory energy of 100 MeV/nucleon [5]. Since here
we discuss on the experimental results at $E \gtrsim 100$ MeV/nucleon the calculations based on the $\chi$EFT potential
are not shown.
Figure 2. Schematic view of the experimental setup for $dp$ elastic scattering with polarized deuteron beams at RIKEN RIBF.

Section 3. Summary follows in Section 4.

The recent achievements of study of 3NFs in intermediate–energy $Nd$ scattering are discussed.

2. Experiments with polarized deuteron beams at RIBF

The schematic view of the experimental setup is shown in Fig. 2. At RIBF the vector and tensor polarized deuteron beams were accelerated at first by the injector cyclotrons AVF and RRC up to 90 (100) MeV/nucleon, and then up to 250 (294) MeV/ nucleon by the new superconducting cyclotron SRC. The polarization axis of the deuteron beam was rotated with a Wien filter system prior to acceleration of the beams. Single turn extraction of the beam was required and achieved all for the three cyclotrons, AVF, RRC and SRC, in order to maintain the polarization amplitudes during acceleration. In the measurement typical values of the beam polarizations were 80% of the theoretical maximum values which 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 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 ($\text{CH}_2$) 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 mounted in two independent planes, 90° apart in azimuthal angle and operated in kinematical coincidence of elastic $dp$ scattering. The measured angles in the center of mass system are $\theta_{\text{c.m.}} = 40°$–162°. In the experiment the deuteron beams were stopped in the Faraday cup which was installed at the focal plane F0 of the BigRIPS spectrometer.
3. Experimental Results and Theoretical Predictions

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 [31], which is a version of the Tucson-Melbourne 3NF more consistent with chiral symmetry [32, 33], 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.

For the cross section specific features are seen depending on the scattering angles in the center of mass system \( \theta_{c.m.} \). (i) At forward angles \( \theta_{c.m.} \lesssim 80^{\circ} \), where the direct processes by the NN interactions are dominant, 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 [34]. (ii) At middle angles \( \theta_{c.m.} \sim 80^{\circ} - 140^{\circ} \), 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 an incident energy increases. The discrepancies are explained by taking into account the \( 2\pi \) exchange type 3NF models (TM'99, and Urbana IX ). (iii) At backward angles \( \theta_{c.m.} \gtrsim 140^{\circ} \), 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 an incident energy. Since this feature are clearly seen at higher energies the relativistic effects have been estimated by using the Lorentz boosted NN potentials with the TM'99 [35, 36, 37]. However the relativistic effects have turned out to be small and only slightly alter the cross sections (see Fig. 4).

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 \( \sim 100 \text{ MeV/nucleon} \) 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. 4).

The results obtained for \( Nd \) elastic scattering indicate that some significant components are missing in the calculations, especially in the regions of higher momentum transfer.

4. Summary

3NFs are now accepted as key elements in understanding various nuclear phenomena, such as the binding of light mass nuclei and the empirical saturation point of nuclear matter density. The \( Nd \) scattering data provide rich sources with which to explore the properties of 3NFs such as momentum and spin dependence. In this talk the recent achievements of study of 3NFs in intermediate–energy \( Nd \) scattering are discussed.

In the last decade extensive experimental study of \( pd \) and \( nd \) elastic scattering at intermediate energies (\( E \gtrsim 100 \text{ MeV} \)) were performed at several facilities. As for the \( pd/nd \) elastic scattering the energy and angular dependent results of the cross sections as well as the polarization observables show that the experimental data are generally described by the calculations with the \( 2\pi \)-exchange 3NFs at the angles \( \theta_{c.m.} \lesssim 140^{\circ} \). However the serious discrepancies between the data and the calculations appear at the backward angles and increase with the incident energy. The discrepancies are not remedied even by including the \( 2\pi \)-exchange 3NFs nor taking into account the relativity. This feature indicates that some significant components are missing in the calculations in the higher momentum transfer region.
Figure 3. Differential cross sections and deuteron analyzing powers $iT_{11}, T_{22}$ for elastic $Nd$ scattering at 70–400 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 in Refs. [17, 18, 20]. The solid squares and open circles are the $pd$ [21] and $nd$ [25] data at 250 MeV/nucleon, respectively. The open diamonds show the data at 400 MeV/nucleon [26]. For the deuteron analyzing powers the data at 70 and 135 MeV/nucleon are from Refs. [17, 18, 19]. The data at 250 and 294 MeV/nucleon are taken at the RIBF [29, 30].

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 with the blue solid lines. The calculations based on the Lorentz boosted NN potential with the 3NF are shown with the red dashed lines. For description of symbols see Fig.3.
As the next step of 3NF study in the few nucleon scattering it would be interesting to see how well the theoretical approaches, e.g. inclusion of 3NFs other than $2\pi$–exchange types, 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 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 which would provide a valuable source of information on 3NFs.

References
[1] Fujita J and Miyazawa H 1957 Prog. Theor. Phys. 17 360
[2] Coon S A and Glöckle W 1981 Phys. Rev. C 23 1790
[3] Pudliner B S et al. 1997 Phys. Rev. C 56 1720
[4] van Kolck U 1994 Phys. Rev. C 49 2932
[5] Epelbaum E, Hammer H W and Meißner U G 2009 Rev. Mod. Phys. 81 1773
[6] Sekiguchi K. et al. 1986 Phys. Rev. C 33 1740
[7] Hatanaka K. et al. 1997 Phys. Rev. C 55 051001; Machleidt R 2001 Phys. Rev. C 63 024001
[8] Stoks V G J et al. 1994 Phys. Rev. C 49 2950
[9] Nogga A et al. 2002 Phys. Rev. C 65 054003
[10] Pieper S C et al. 2001 Phys. Rev. C 66 044310
[11] Navrátil P and Ormand W E 2003 Phys. Rev. C 68 034305
[12] see for example, Akmal A et al., 1998 Phys. Rev. C 58 1804
[13] Thews H, Witała H, Hübner D, Kamada H and Golak J 1996 Phys. Rep. 274 107
[14] Glöckle W, Witała H, Hübner D, Kamada H and Golak J 1996 Phys. Rep. 274 107
[15] Kievsky A, Vivanini M and Rosati S 2001 Phys. Rev. C 64 024002
[16] Hatanaka K et al. 2002 Phys. Rev. C 66 044002
[17] Bielewicz R et al. 2000 Phys. Rev. Lett. 84 5288
[18] Sekiguchi K et al. 2002 Phys. Rev. C 65 034003
[19] Sekiguchi K et al. 2004 Phys. Rev. C 70 014001
[20] Sekiguchi K et al. 2005 Phys. Rev. Lett. 95 162301
[21] Hatanaka K et al. 2002 Phys. Rev. C 66 044002
[22] Pieper S C 2001 Phys. Rev. Lett. 84 606; Ermisch K et al. 2001 Phys. Rev. Lett. 86 5862; Ermisch K et al. 2003 Phys. Rev. C 68 051001; Ermisch K et al. 2005 Phys. Rev. C 71 064004; Amir-Ahmadi H R et al. 2007 Phys. Rev. C 75 041001; Mardanpour H et al. 2007 Eur. Phys. J. A 31 383
[23] Bielewicz R et al. 2000 Phys. Rev. Lett. 84 606; Ermisch K et al. 2001 Phys. Rev. Lett. 86 5862; Ermisch K et al. 2003 Phys. Rev. C 68 051001; Ermisch K et al. 2005 Phys. Rev. C 71 064004; Amir-Ahmadi H R et al. 2007 Phys. Rev. C 75 041001; Mardanpour H et al. 2007 Eur. Phys. J. A 31 383
[24] Stephenson E J et al. 1999 Phys. Rev. C 60 061001; Cadman R V et al. 2001 Phys. Rev. Lett. 86 967; Przewoski B v et al. 2006 Phys. Rev. C 74 064003
[25] Mermod P et al. 2005 Phys. Rev. C 72 061002
[26] Tamii A et al. 2007 AIP Conference Proceedings 915 765
[27] 1998 Witała H et al. Phys. Rev. Lett. 81 1183
[28] Nemoto S et al. 1998 Phys. Rev. C 58 2599
[29] Sekiguchi K et al. 2011 Phys. Rev. C 83 061001
[30] Sekiguchi K et al. 2012 paper in preparation
[31] Coon S A and Han H K 2001 Few Body Syst. 30 131
[32] Friar J L et al. 1999 Phys. Rev. C 59 53.
[33] Hübner D et al. 2001 Few-Body Syst. 30 95
[34] Deltuva A et al. 2005 Phys. Rev. C 71 054005
[35] Witała H et al. 2005 Phys. Rev. C 71 054001
[36] Witała H et al. 2008 Phys. Rev. C 77 034004
[37] Witała H private communications
[38] Witała H et al. Phys. Rev. C 83 044001