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# Study of Three-Nucleon Force Effect *via* Few-Nucleon Scattering

Yasunori Wada, Kimiko Sekiguchi, Uwe Gebauer, Jumpei Miyazaki, Takahiro Taguchi
*Department of Physics, Tohoku University, Sendai, Miyagi, 980-8578, Japan*
*wada@lambda.phys.tohoku.ac.jp*

Masanori Dozono, Hideyuki Sakai, Naruhiko Sakamoto, Masaki Sasano, Yohei Shimizu, Hiroshi Suzuki, Tomohiro Uesaka
*Nishina Center, RIKEN, Wako, Saitama, 351-0198, Japan*

Shoichiro Kawase, Yuki Kubota, Cheong Soo Lee, Tsz Leung Tang, Kentaro Yako
*Center for Nuclear Study, University of Tokyo, Tokyo, 113-0033, Japan*

Yukie Maeda
*Faculty of Engineering, University of Miyazaki, Miyazaki, Miyazaki, 889-2192, Japan*

Kenjiro Miki, Hiroyuki Okamura
*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, 567-0047, Japan*

Satoshi Sakaguchi, Tomotsugu Wakasa
*Department of Physics, Kyusyu University, Higashi, Fukuoka, 812-8581, Japan*

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A complete set of deuteron analyzing powers for elastic deuteron-proton($dp$) scattering at 250 and 294 MeV/nucleon has been measured. The obtained data are compared with the Faddeev calculations based on the modern nucleon-nucleon forces together with three-nucleon forces.

*Keywords*: Three-nucleon force; $^1\mathrm{H}(\overrightarrow{d},d)^1\mathrm{H}$; Deuteron analyzing powers.

## 1. Introduction

Understanding the nuclear properties from bare nuclear forces is one of the main topic in nuclear physics. Recently the importance of three-nucleon forces (3NFs), which appear when more than two nucleons interact, has been indicated in various

nuclear phenomena, such as few-nucleon scattering, binding energies of nuclei,[1] and equation of state of nuclear matter.[2]

Three-nucleon scattering at intermediate energies ($\gtrsim$ 60 MeV/nucleon) is one attractive approach to investigate the dynamical aspects of 3NFs, such as momentum dependence and/or spin dependence. For few-nucleon scattering rigorous numerical calculations in terms of Faddeev theory by using bare nuclear potentials have been realized. Direct comparison between those calculations and precise data enables us to discuss on the effects of 3NFs quantitatively.

With the aim of clarifying roles of 3NFs in nuclei, the experimental programs with polarized deuteron beams at intermediate energies are in progress at RIKEN RI beam factory (RIBF).[4–6] Here, we report recent results of the measurement of complete set of deuteron analyzing powers ($A_y^d, A_{yy}, A_{xx}, A_{xz}$) for $dp$ elastic scattering at 250 and 294 MeV/nucleon.[6]

## 2. Experiment

The schematic view of the experimental setup is shown in Fig. 1. At RIBF, the vector and tensor polarized deuteron beams were provided by the polarized ion source[3] and accelerated by the injector cyclotron AVF and RIKEN Ring cyclotron (RRC) up to 90(100) MeV/nucleon, and then up to 250(294) MeV/nucleon by the superconducting Ring cyclotron (SRC). The beam polarizations were monitored by the polarimeter Dpol prior to acceleration by the SRC. The measurement for $dp$ elastic scattering was carried out using the polarimeter BigDpol installed at the extraction beam line of the SRC. The beams were stopped by the Faraday cup shown

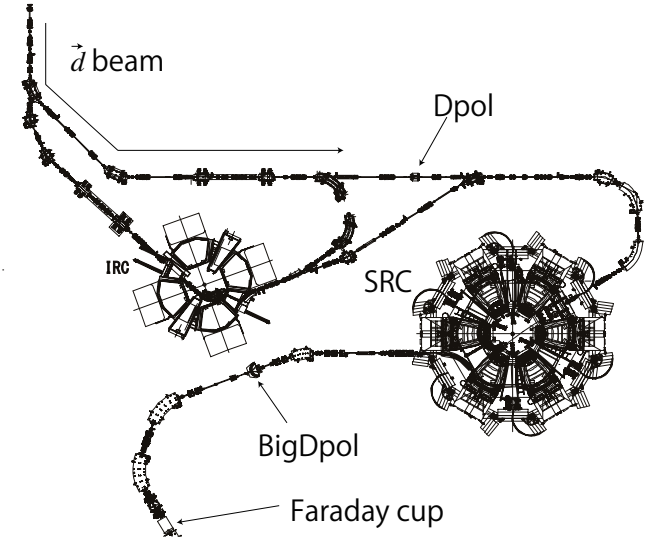


Fig. 1. A schematic view of the experimental setup for measurement of $dp$ elastic scattering at RIKEN.

in Fig. 1. A polyethylene ($CH_2$) film with the thickness of 330 mg/cm$^2$ was used as a hydrogen target, and four pairs of plastic scintillators coupled with photomultiplier tubes were mounted in two independent planes, 90° apart in azimuthal angle, and operated in kinematic coincidence for elastic *dp* scattering. The measured angles in the center of mass system are $\theta_{\rm c.m.} = 40° - 160°$. The direction of beam polarization axis was controlled by the spin rotator Wien filter prior to acceleration. Single turn extraction features of RIBF cyclotrons made it possible to maintain the polarization amplitudes during acceleration. The beam polarizations were 80% of theoretical maximum values during the experiment.

## 3. Result

Figure 2 shows newly obtained experimental data of all deuteron analyzing powers ($A_y^d, A_{yy}, A_{xx}, A_{xz}$) at 250 and 294 MeV/nucleon together with the previously reported data at 135 MeV/nucleon.[7] Open circles are the data with statistical errors. The data are compared with the Faddeev calculations based on the modern NN forces together with the 3NFs. The red(blue) bands in the figure are the Faddeev calculations with(w/o) the Tucson-Melbourne'99 (TM99) 3NF[8] based on the modern NN potentials, namely CDBonn,[9] AV18,[10] Nijmegen I and II.[11] The solid lines are the calculations with the Urbana IX 3NF[12] based on the AV18 potential.

At a lower energy 135 MeV/nucleon, vector analyzing power $iT_{11}$ is well described by adding 3NFs. On the other hands, for $T_{22}$, the calculation based on NN forces only already shows a moderate agreement with the data. Besides, the

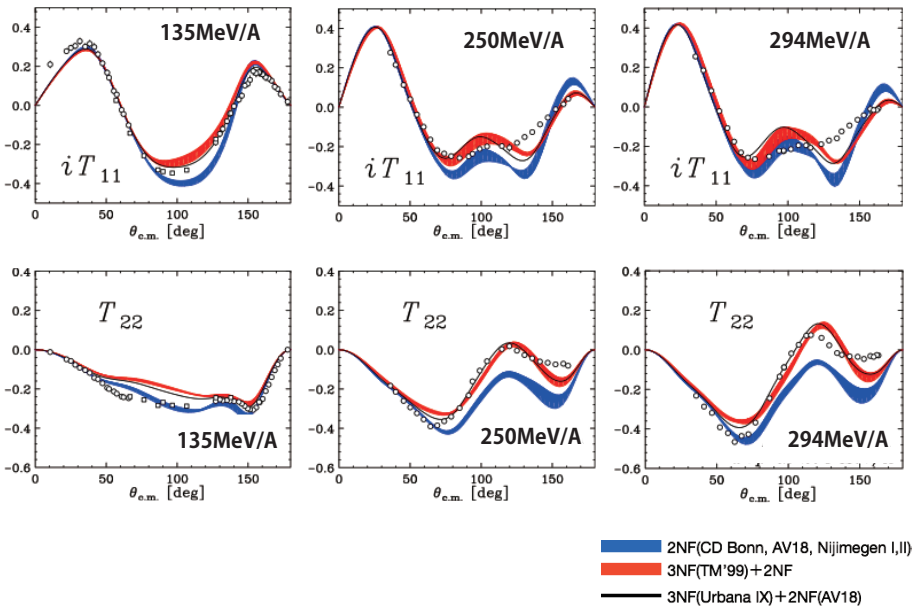


Fig. 2. Deuteron analyzing powers $iT_{11}, T_{22}$ for elastic *dp* scattering at 135 − 294 MeV/nucleon.

3NFs effects cause the discrepancies between the data and the calculation. At higher energies 250 and 294 MeV/nucleon, different results are obtained from those at 135 MeV/nucleon in comparison between the data and the calculations. At these higher energies, all deuteron analyzing powers are well described by the calculation adding 3NFs at forward angles ($\theta_{\mathrm{c.m.}} \lesssim 120^\circ$). However, at backward angles larger than 120°, the effects of 3NFs provided by current models do not explain the difference between the data and the calculations based on NN forces. The relativistic effects are estimated to be small for these polarization observables for *dp* elastic scattering.[6] Therefore, the important components of the 3NF are missing in the calculations, *e.g.* short range parts of three-nucleon forces.

## 4. Summary

We have performed the experiment of *dp* elastic scattering at 250 and 294 MeV/nucleon and measured the complete set of deuteron analyzing powers with high precision. In comparison between the data and the calculations presented here significantly different results are obtained at 250 and 294 MeV/nucleon from those at a lower energy (135 MeV/nucleon). To improve the description of the data at our energies, short-range 3NF components should be applied in the calculations.

## References


1. S. C. Pieper *et al.*, *Phys. Rev. C* **64**, 014001 (2003).
2. A. Akmal *et al.*, *Phys. Rev. C* **58**, 1804 (1998).
3. H. Okamura *et al.*, *AIP Conf. Proc.* **293**, 84 (1994).
4. K. Sekiguchi *et al.*, *Phys. Rev. C* **65**, 034003-1 (2002).
5. K. Sekiguchi *et al.*, *Phys. Rev. C* **83**, 061001-1 (2011).
6. K. Sekiguchi *et al.*, *Phys. Rev. C* **89**, 034003-1 (2014).
7. H. Sakai *et al.*, *Phys. Rev. Lett.* **84**, 5188 (2000).
8. S. A. Coon and H. K. Han, *Few Body Syst.* **30**, 131 (2001).
9. R. Machleidt, *Phys. Rev. C* **63**, 024001 (2001).
10. R. B. Witinga *et al.*, *Phys. Rev. C* **51**, 38 (1995).
11. V. G. J. Stoks *et al.*, *Phys. Rev. C* **49**, 2950 (1994).
12. B. S. Pudliner *et al.*, *Phys. Rev. C* **56**, 1720 (1997).