Abstract

With the aim of clarifying roles of the 3NFs in nuclei experimental programs with the polarized deuteron beam at intermediate energies are in progress at RIKEN RI Beam Factory. As the first step, we have measured a complete set of deuteron analyzing powers in deuteron–proton elastic scattering at 250 and 294 MeV/nucleon. The obtained data are compared with the Faddeev calculations based on the modern nucleon–nucleon forces together with the Tucson–Melbourne’99, and UrbanaIX three nucleon forces.

1 Introduction

Study of three nucleon forces (3NFs) is essentially important in clarifying nuclear phenomena. In addition to the first signals of the 3NF effects in the binding energies of the $^3$H and $^3$He, the necessity of 3NFs has been recently pointed out for descriptions of discrete states in higher mass nuclei [1,2]. Significance of 3NFs has been further supported by the equation of state of nuclear matter [3]. Three nucleon (3N) scattering at intermediate energies ($E/A \sim 200$ MeV) is one attractive approach to investigate the dynamical aspects of 3NFs, such as momentum and/or spin dependences. With the aim of clarifying roles of the 3NFs in nuclei the experimental programs with the polarized deuteron beam at intermediate energies are in progress at RIKEN RI Beam Factory (RIBF). As the first step, we have measured a complete set of deuteron analyzing powers ($iT_{11}$, $T_{20}$, $T_{21}$, $T_{22}$) in deuteron–proton ($dp$) elastic scattering at 250 and 294 MeV/nucleon.
2 Experiment

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 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 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 were $\theta_{\text{c.m.}} = 40^\circ$–$160^\circ$. In the experiment the deuteron beam was 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 90 (100) MeV/nucleon. In the measurement typical values of the beam polarizations were 80% of the theoretical maximum values.

3 Results

In Fig. 1 the newly obtained data of deuteron analyzing powers $i_{T11}$, $T_{22}$ at 250 and 294 MeV/nucleon [4,5] are shown with open circles together with the previously reported data at 70, 135 MeV/nucleon [6,7]. The figure also shows the differential cross section data at 70–250 MeV/nucleon. As for the cross sections the open circles are the data in Refs. [6,8,9]. The open squares and circles are the $pd$ [10] and $nd$ [11] data at 250 MeV/nucleon, respectively. Statistical errors are only shown. The data are compared with the Faddeev calculations based on the modern nucleon–nucleon forces together with the 3NFs. The red (blue) bands in the figure are the Faddeev calculations with (w/o) Tucson–Melbourne’99 (TM99) 3NF [12] based on the modern NN potentials, namely CDBonn [13], AV18 [14], Nijmegen I and II [15]. The solid lines are the calculations with including Urbana IX 3NF [16] based on AV18 potential.

For the vector analyzing power $i_{T11}$ the discrepancies between the data and the predictions based on 2NFs (blue bands) are seen at the angles $\theta_{\text{c.m.}} \gtrsim 120^\circ$. They become larger with increasing an incident energy. At
lower energies \(\lesssim 135\) MeV/nucleon, 3NFs provide generally good agreements to the data. At higher energies 250 and 294 MeV/nucleon the data have good agreements to the predictions with the 3NFs at the forward angles \(\theta_{c.m.} \lesssim 120^\circ\), while the data at the backward angles \(\theta_{c.m.} \gtrsim 120^\circ\) are not explained even by including the 3NFs. The results of comparison for the \(iT_{11}\) are quite similar to those of the cross section and proton analyzing power. Meanwhile the tensor analyzing power \(T_{22}\) reveals different energy dependence from that of \(iT_{11}\). Starting from \(\sim 135\) MeV/nucleon large 3NF effects are predicted. At 135 MeV/nucleon 3NFs worsens the description of data in a large angular region. It is contrary to what happens at the higher energies above 250 MeV/nucleon, where large 3NF effects are supported by the \(T_{22}\) data, except for the angles \(\theta_{c.m.} \sim 60^\circ\). The relativistic effects are estimated to be small for these polarization observables for \(dp\) elastic scattering [17].

The results obtained for \(dp\) elastic scattering indicate that 3NFs are clearly needed to describe the data. However some significant components are still missing in the calculations, especially in the regions of higher momentum transfer.

4 Summary

We have performed the measurement of complete set of deuteron analyzing powers for \(dp\) elastic scattering at 250 and 294 MeV/nucleon. This is the first experiment with the polarized deuteron beam at RIKEN RI Beam Factory. In comparison between the data and the calculations presented in Fig. 1 remarkably different results are obtained at 250 and 294 MeV/nucleon from those at the lower energies, 70 and 135 MeV/nucleon. In order to obtain consistent understanding the effects of 3NFs in the 3N scattering further investigation should be necessary. It would be interesting to see how well the theoretical approaches, e.g. addition of 3NFs other than 2\(\pi\) exchange types, and the potentials based on the chiral effective field theory [18] describe these obtained data.

References

1. Pieper, S.C., et al.: Realistic models of pion-exchange three-nucleon interactions. Phys. Rev. C. 64, 014001 (2001)
2. Navrátil, P., Ormand, W.E.: Ab initio shell model with a genuine three-nucleon force for the \(p\)-shell nuclei. Phys. Rev. C. 68, 034305 (2003)
3. Akmal, A., et al.: Equation of state of nucleon matter and neutron star structure. Phys. Rev. C 58, 1804–1828 (1998)
4. Sekiguchi, K., et al.: Three nucleon force effects in intermediate-energy deuteron analyzing powers for \(dp\) elastic scattering. Phys. Rev. C 83, 061001 (2011)
5. Sekiguchi, K.: Experimental approach to three nucleon forces via few nucleon systems. Few-Body Syst. doi: 10.1007/s00601-013-0636-y (2012)
6. Sekiguchi, K., et al.: Complete set of precise deuteron analyzing powers at intermediate energies: comparison with modern nuclear force predictions. Phys. Rev. C 65, 034003 (2002)
7. Sekiguchi, K., et al.: Polarization transfer measurement for \(^1\)H(\(d, p\))^2\(^1\)H elastic scattering at 135 MeV/nucleon and three-nucleon force effects. Phys. Rev. C 70, 014001 (2004)
8. Sakai, H., et al.: Precise measurement of \(dp\) elastic scattering at 270 MeV and three-nucleon force effects. Phys. Rev. Lett. 84, 5288 (2000)
9. Sekiguchi, K., et al.: Resolving the discrepancy of 135 MeV \(pd\) elastic scattering cross sections and relativistic effects. Phys. Rev. Lett 95, 162301 (2005)
10. Hatanaka, K., et al.: Cross section and complete set of proton spin observables in \(pd\) elastic scattering at 250 MeV. Phys. Rev. C 66, 044002 (2002)
11. Maeda, Y., et al.: Differential cross section and analyzing power measurements for \(nd\) elastic scattering at 248 MeV. Phys. Rev. C 76, 014004 (2007)
12. Coon, S.A., Han, H.K.: Reworking the Tucson–Melbourne three-nucleon potential. Few Body Syst. 30, 131 (2001)
13. Machleidt, R.: High-precision, charge-dependent Bonn nucleon–nucleon potential. Phys. Rev. C 63, 024001 (2001)
14. Wiringa, R.B., Stoks, V.G.J., Schiavilla, R.: Accurate nucleon–nucleon potential with charge-independence breaking. Phys. Rev. C 51, 38 (1995)
15. Stoks, V.G.J., et al.: Construction of high-quality NN potential models. Phys. Rev. C 49, 2950 (1994)
16. Pudliner, B.S., et al.: Quantum Monte Carlo calculations of nuclei with \(A \leq 7\). Phys. Rev. C 56, 1720 (1997)
17. Witała, H., et al.: Private Communications
18. Epelbaum, E., Hammer, H.-W., Meißner, U.-G.: Modern theory of nuclear forces. Rev. Mod. Phys. 81, 1773 (2009)