Complete Set of Deuteron Analyzing Powers for Deuteron–Proton Elastic Scattering at 250 MeV/nucleon and Three-Nucleon Forces

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Abstract. Measurements of a complete set of deuteron analyzing powers (iT_{11}, T_{20}, T_{21}, and T_{22}) for elastic deuteron–proton scattering at 250 MeV/nucleon have been performed with polarized deuteron beams at RIKEN RI Beam Factory. The obtained data are compared with Faddeev calculations based on the modern nucleon–nucleon forces together with the Tucson–Melbourne’99 and UrbanaIX three-nucleon forces.

1. Introduction

The study of three-nucleon forces (3NFs) is essential for clarifying nuclear phenomena. The first signal of 3NF effects is found in the binding energies of $^3$H and $^3$He, and recently the significance of 3NFs in describing discrete states in higher mass nuclei has been considered [1]. Three-nucleon (3N) scattering at intermediate energies ($E/A \sim 200$ MeV) is an attractive approach for investigating the dynamical aspects of 3NFs, such as momentum and spin dependences. In 3N scattering strong signals from 3NFs have been theoretically predicted around the cross section minimum at the center-of-mass angle $\theta_{c.m.} \sim 120^\circ$ for incident energies above 60 MeV/nucleon in elastic nucleon–deuteron scattering [2, 3], and have been confirmed experimentally [4]. With the aim of clarifying the detailed properties of the 3NFs in 3N scattering, experimental programs with polarized deuterons beams at intermediate energies are in progress at RIKEN RI Beam Factory (RIBF). As a first step, we have measured a complete set of data for all deuteron analyzing powers ($iT_{11}, T_{20}, T_{21},$ and $T_{22}$) in deuteron–proton ($dp$) elastic scattering at 250 MeV/nucleon.
2. Experiment
A schematic view of the experimental setup is shown in Fig. 1. Vector and tensor polarized deuteron beams are first accelerated by the injector cyclotrons AVF and RRC up to 90 MeV/nucleon, and then up to 250 MeV/nucleon by the new superconducting cyclotron SRC. Measurements of elastic $dp$ scattering were performed with the detector system BigDpol, 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 BigDpol, four pair of plastic scintillators coupled with photo-multiplier tubes are placed symmetrically in the directions of the azimuthal angles, left, right, up, and down. Scattered deuterons and recoil protons were detected in a kinematical coincidence condition by each pair of detectors. The measured angles in the center of mass system are $\theta_{\text{c.m.}} = 36^\circ \text{–} 162^\circ$. The deuteron beams were stopped in the Faraday cup, installed at the focal plane F0 of the BigRIPS spectrometer.

The data were taken with polarized and unpolarized beams, given in terms of the theoretical maximum polarization values as $(p_Z,p_{ZZ}) = (0,0), (1/3,-1), (-2/3,0), \text{and} (1/3,1)$. The beam polarizations were monitored continuously with the beam line polarimeter Dpol prior to acceleration by the SRC. The polarimetry was performed using the analyzing powers for $dp$ elastic scattering at 90 MeV/nucleon. The analyzing powers for this reaction have been calibrated in a previous measurement using the $^{12}\text{C}(d,\alpha)^{10}\text{B}^* [2^+]$ reaction, with $A_{zz}(0^\circ)$ exactly $-1$ because of parity conservation [5]. In the measurement, typical values of the beam polarizations were 80% of the theoretical maximum values.

The polarization axis of the deuteron beam was rotated with a Wien filter system prior to acceleration of the beams [6]. Single turn extraction of the beam was hence required for all the three cyclotrons, AVF, RRC, and SRC, in order to maintain the polarization amplitudes during acceleration. For the measurement of the analyzing powers $iT_{11}$, $T_{20}$, and $T_{22}$, the polarization axis was normal to the horizontal plane. For the $T_{21}$ measurement the spin symmetry axis was rotated in the reaction plane and aligned at an angle $\beta = 38.0^\circ \pm 0.51^\circ$ to the beam direction.

3. Results
In Fig. 2 the data for deuteron analyzing powers $iT_{11}$ and $T_{22}$ at 250 MeV/nucleon are shown as open circles. The statistical uncertainties, which are less than 0.01 for all the deuteron analyzing powers, are also shown. In order to verify the energy dependence, the previously measured deuteron analyzing powers at 70, 100, and 135 MeV/nucleon [4, 7] are included. The data are compared with the Faddeev-type theoretical predictions for the different nucleon–nucleon (NN) forces alone (blue bands) or combined with the Tucson–Melbourne99 3NF [8] (red bands). For the NN inputs, high precision NN potentials, namely CDBonn [9], AV18 [10], and Nijmegen I and II [11], are used. The AV18 NN potential is also combined with the Urbana IX 3NF [12] (solid curves). Note that these two 3NFs are $2\pi$-exchange type 3NFs in which the main ingredient is a $2\pi$-exchange between three nucleons with an intermediate $\Delta$-isobar excitation.

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 the energies 70, 100, and 135 MeV/nucleon. The discrepancies become larger with increasing incident energy. The descriptions of the data are improved by adding 3NFs. The data for the higher energy of 250 MeV/nucleon have a good agreement with the predictions with 3NFs at the forward angles $\theta_{\text{c.m.}} \lesssim 120^\circ$, while the data at the backward angles $\theta_{\text{c.m.}} \gtrsim 120^\circ$ are not explained by the inclusion of 3NFs. The result of comparing with $iT_{11}$ is quite similar to those of the cross section and proton analyzing power [13, 14].

For the tensor analyzing power $T_{22}$, the discrepancies between the data and the predictions based on 2NFs increase in magnitude and expand to the backward angles with increasing incident energy. At the lower three energies, 70, 100, and 135 MeV/nucleon, the agreements deteriorate slightly by the inclusion of 3NFs at the angles $\theta_{\text{c.m.}} = 60$–$120^\circ$. However, at 250 MeV/nucleon,
Figure 1. Schematic view of the experimental setup for $dp$ elastic scattering with 250 MeV/nucleon polarized deuteron beams at RIKEN RI Beam Factory.

the overall agreement is improved by taking into account these 3NFs except for the very backward angles.

4. Summary and Conclusion
We have measured the deuteron analyzing powers ($iT_{11}$, $T_{20}$, $T_{21}$, and $T_{22}$) for $dp$ elastic scattering at 250 MeV/nucleon. This is the first experiment with polarized deuteron beams at RIKEN RI Beam Factory. The data are compared with Faddeev calculations based on various nuclear potentials. At 250 MeV/nucleon a discrepancy which is not resolved by the $2\pi$-exchange 3NFs is found at the backward angles $\theta_{\text{c.m.}} \gtrsim 120^\circ$ in the cross sections and also in the deuteron analyzing powers. The results obtained at the higher energy 250 MeV/nucleon indicate that some significant components are missing in the presented calculations in the region of higher momentum transfer. In the energy dependence, the deficiency of the spin-dependent parts of 3NFs are particularly seen in the tensor analyzing power $T_{22}$ and are rather localized in a momentum transfer region equivalent to the angles $\theta_{\text{c.m.}} = 60^\circ$–$120^\circ$ at 135 MeV/nucleon.

To obtain a consistent understanding of the 3NF effects in 3N scattering, further investigation is necessary. It would be interesting to see how well theoretical approaches, e.g., the inclusion of 3NFs other than $2\pi$-exchange types, a relativistic treatment [15], and the use of potentials based
Figure 2. Deuteron analyzing powers $iT_{11}$ and $T_{22}$ for $dp$ elastic scattering at 70, 100, 135, and 250 MeV/nucleon. The blue shaded bands contain the NN force predictions obtained with the CD-Bonn, AV18, Nijmegen I and II potentials, and the red shaded bands contain predictions when they are combined with the Tucson–Melbourne’99 3NF. The solid curves are the AV18 + Urbana IX 3NF predictions.

on the chiral effective field theory [16], describe these obtained data. Experimentally, it would be interesting to measure deuteron analyzing powers as well as polarization transfer coefficients for backward elastic $dp$ scattering at 200–300 MeV/nucleon.

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