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Complete Set of Deuteron Analyzing Powers for dp Elastic Scattering at Intermediate Energies and Three Nucleon Forces

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Abstract. Experimental programs with polarized deuterons beams at intermediate energies are in progress at RIKEN RI Beam Factory. 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

The 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]. Significance of 3NFs has been further supported by the equation of state of nuclear matter [2]. 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 the role of the 3NFs in nuclei the experimental programs with polarized deuterons beams 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

The schematic view of the experimental setup is shown in Fig. 1.

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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 (CH_2) target with a thickness of 330 mg/cm^2 was used as a hydrogen target. In the BigDpol four pair 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 detectors. The measured angles in the center of mass system are $\theta_{\rm c.m.} = 40°–160°$. In the experiment the deuteron beams were 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.

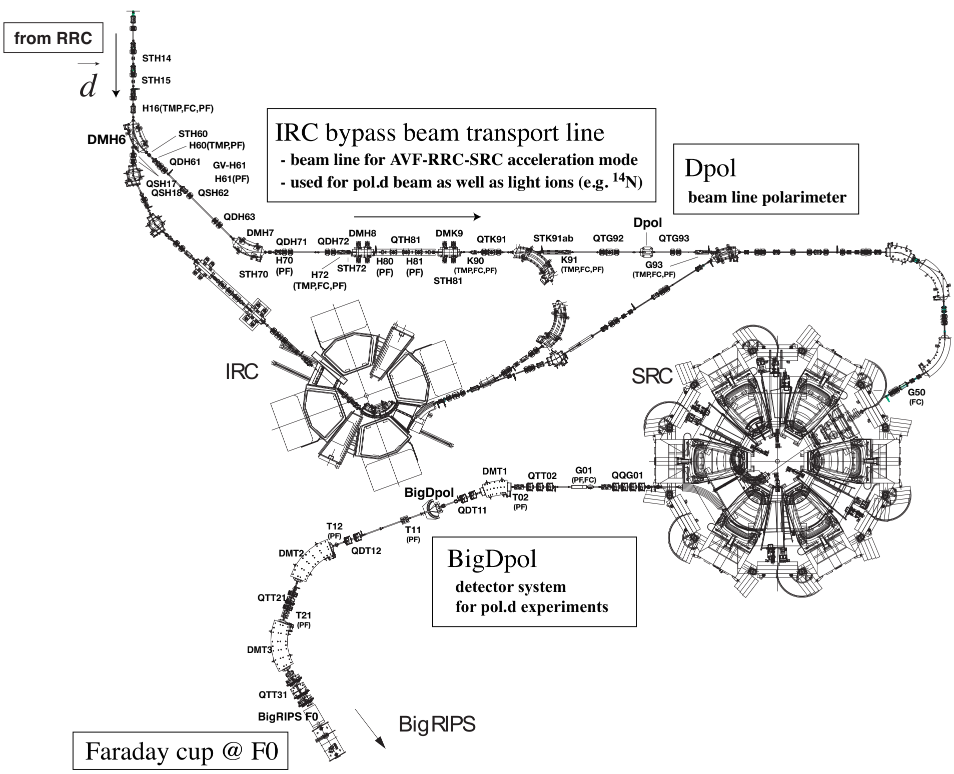

Figure 1. Schematic view of the experimental setup for dp elastic scattering with 250 MeV/nucleon polarized deuteron beams at RIKEN RI Beam Factory.

3 Results

In Fig. 2 the newly obtained data of deuteron analyzing powers iT_{11}, T_{22} at 250 and 294 MeV/ nucleon [3, 4] are shown with open circles together with the previously reported data at 70, 135

MeV/nucleon [5, 6]. 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. [5, 7, 8]. The open squares and circles are the *pd* [9] and *nd* [10] data at 250 MeV/nucleon, respectively. Only statistical errors are shown. The data are compared with the Faddeev calculations based on the modern nucleon–nucleon forces together with the three nucleon forces. The red (blue) bands in the figure are the Faddeev calculations with (w/o) Tucson – Melbourne'99 (TM99) 3NF [11] based on the modern NN potentials, namely CDBonn [12], AV18 [13], Nijmegen I and II [14]. The dashed lines are the calculations with Urbana IX 3NF [15] based on AV18 potential.

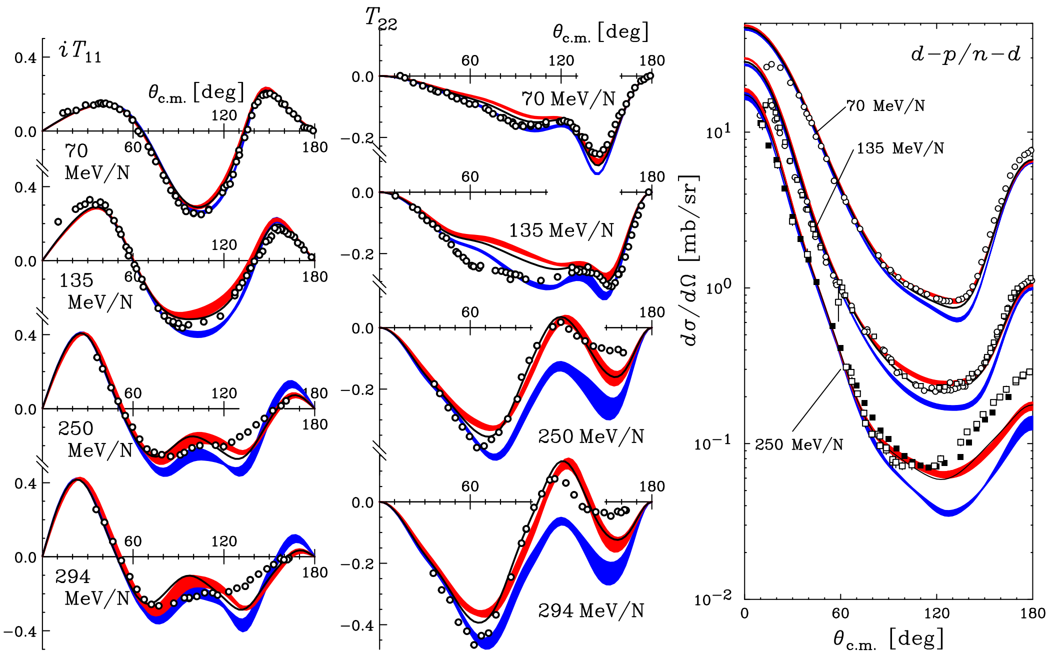

Figure 2. Deuteron analyzing powers iT_{11}, T_{22} and differential cross sections for elastic *Nd* scattering at 70–300 MeV/nucleon (MeV/N). See text for explanation of symbols, lines and colored bands.

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 $\theta_{\rm c.m.} \sim 120^\circ$ at the energies 70, and 135 MeV /nucleon. They become larger with increasing an incident energy. At higher energies 250 and 294 MeV/nucleon the data have good agreements to the predictions with the 3NFs at the forward angles $\theta_{\rm c.m.} \lesssim 120^\circ$, while the data at the backward angles $\theta_{\rm c.m.} \gtrsim 120^\circ$ are not explained even by including the 3NFs. The results of the 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 $\sim$ 100 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 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 for these polarization observables for *dp* elastic scattering [16].

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 polarized deuteron beams at RIKEN RI Beam Factory. In the comparison between the data and the calculations presented in Fig. 2 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 a consistent understanding of the effects of three nucleon forces in the 3N scattering further investigation is necessary. It would be interesting to see how well the theoretical approaches, e.g. addition of 3NFs other than 2π exchange types, relativistic treatment [17], and the potentials based on the chiral effective field theory [18], describe these obtained data.

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