EPJ Web of Conferences **3**, 05024 (2010)
DOI:10.1051/epjconf/20100305024

Complete Set of Deuteron Analyzing Powers for dp 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}, 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 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 significance of 3NFs has been recently pointed out for descriptions of discrete states in higher mass nuclei [1]. 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 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 MeV/nucleon.

2 Experiment

The schematic view of the experimental setup is shown in Fig. 1. At RIBF the vector and tensor polarized deuteron beams were accelerated at first by the injector cyclotrons AVF and RRC up to 90 MeV/nucleon up to 250 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 the detectors. The measured angles in the center of mass system are $\theta_{\mathrm{c.m.}} = 40°$–$162°$. In the experiment the deuteron beams were stopped in the Faraday cup which was installed at the focal plane F0 of the BigRIPS spectrometer.

The data were taken with the polarized and unpolarized beams given in terms of the theoretical maximum polarization values as $(p_Z, p_{ZZ}) = (0, 0)$, $(1/3, -1)$, $(-2/3, 0)$ and $(1/3, 1)$. 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 MeV/nucleon. The Dpol was located at the IRC bypass transport beam line (see Fig. 1). The analyzing powers for this reaction have been calibrated in the previous measurement by using the ^{12}C$(d, \alpha)^{10}$B* [2$^+$] reaction, the $A_{zz}(0°)$ of which is exactly -1 because of parity conservation [2]. 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 [3]. Therefore single turn extraction of the beam was required all for 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}, 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 $\beta = 38.0° \pm 0.51°$ to the beam direction.

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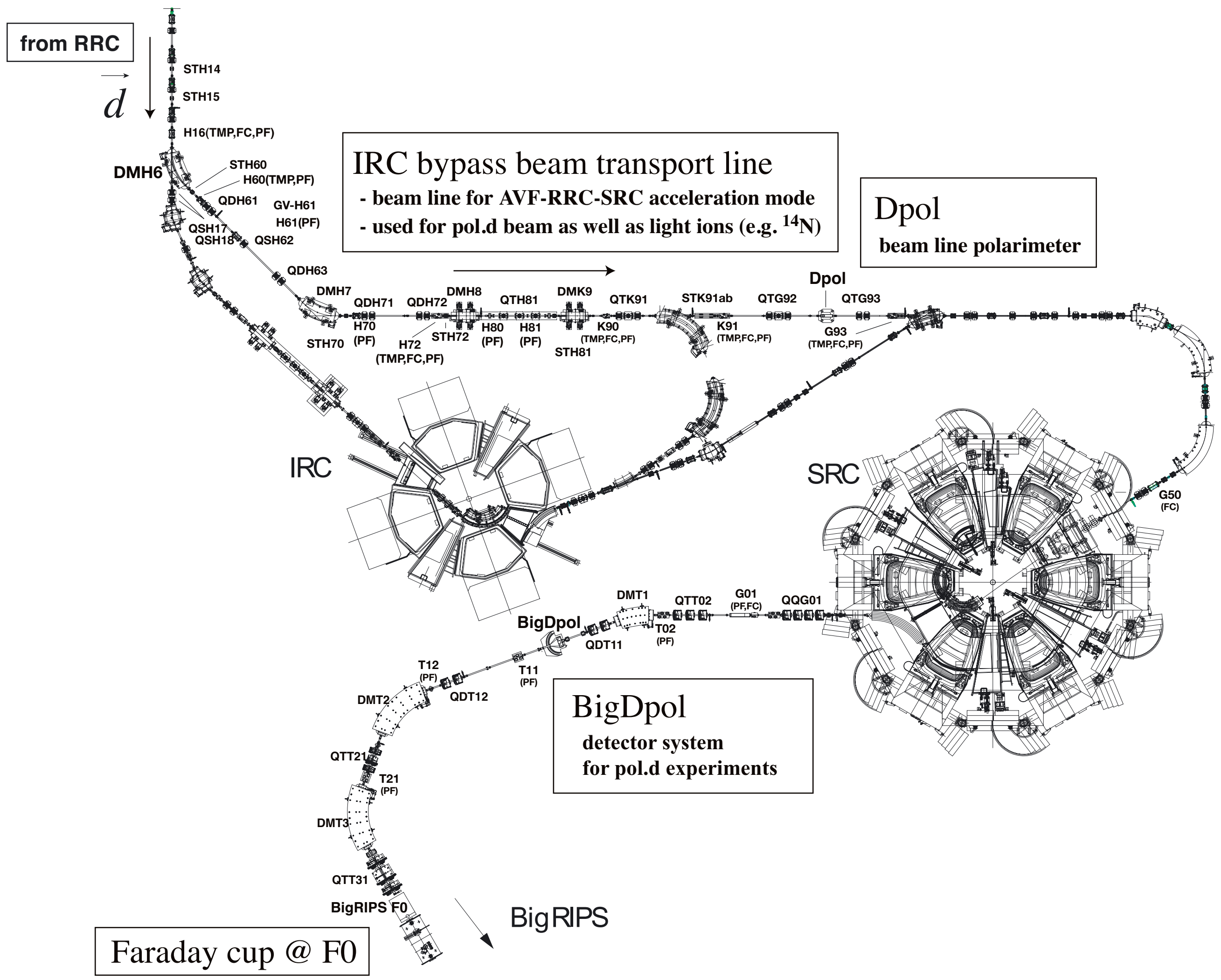

Fig. 1. Schematic view of the experimental setup for *dp* elastic scattering with 250 MeV/nucleon polarized deuteron beams at RIKEN RI Beam Factory.

3 Results

In Fig. 2 the newly obtained data of deuteron analyzing powers iT_{11}, T_{22} at 250 MeV/nucleon are shown with open circles together with the previously reported data at 70, 100, 135 MeV/nucleon [4,5]. The errors are statistical ones only. The statistical errors for all the measured deuteron analyzing powers at 250 MeV/nucleon are less than 0.01. The data are compared with the Faddeev calculations based on the modern nucleon–nucleon forces together with the three nucleon forces [6]. The pink (blue) bands in the figure are the Faddeev calculations with (w/o) Tucson – Melbourne99 (TM99) 3NF [7] based on the modern NN potentials, namely CDBonn [9], AV18 [10], Nijmegen I and II [11]. The dashed lines are the calculations with including Urbana IX 3NF [8] based on AV18 potential.

For the vector analyzing power iT_{11} and the tensor analyzing power T_{20} (which are not shown here) the discrepancies between the data and the predictions based on 2NFs (blue bands) are seen at the angles $\theta_{\mathrm{c.m.}} \sim 120°$ at the energies 70, 100, and 135 MeV /nucleon. They become larger with increasing an incident energy. The descriptions of the data are improved by adding 3NFs. At a higher energy 250 MeV/nucleon the data have good agreements to the predictions with the 3NFs at the forward angles $\theta_{\mathrm{c.m.}} \lesssim 120°$, while the data at the backward angles $\theta_{\mathrm{c.m.}} \gtrsim 120°$ are not explained by inclusion of the 3NFs. The results of comparison for the iT_{11} and T_{20} are quite similar to those of the cross section and proton analyzing power [12,13].

The tensor analyzing power T_{22} have also discrepancies between the data and the predictions based on 2NFs only which become larger with increasing an incident energy. At the lower three energies, 70, 100, and 135 MeV/nucleon the agreements are rather deteriorated by including the 3NFs. However at a higher energy 250 MeV/nucleon the overall agreement is good except for the backward angles $\theta_{\mathrm{c.m.}} \gtrsim 120°$.

The results of comparison are summarized as follows.

1. At 250 MeV/nucleon a new discrepancy which is not resolved by the 2π-exchange 3NFs is found at the back-

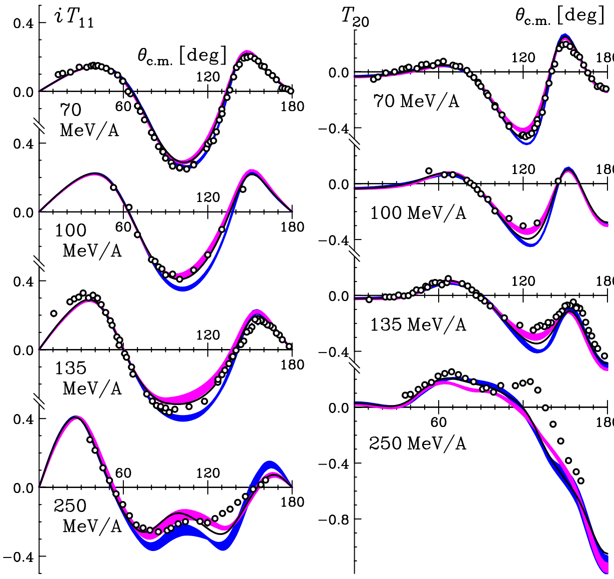

Fig. 2. Deuteron analyzing powers iT_{11} and T_{22} for dp elastic scattering at 70, 100, 135, and 250 MeV/nucleon.

ward angles $\theta_{c.m.} \gtrsim 120°$ not only in the cross sections but also in the proton and deuteron analyzing powers.

2. As for the energy dependence the tensor analyzing power T_{22} has a different tendency from those of the other spin observables.

4 Summary

We have performed the measurement of complete set of deuteron analyzing powers for dp elastic scattering at 250 MeV/nucleon. This is the first experiment with polarized deuteron beams at RIKEN RI Beam Factory. In comparison between the data and the calculations presented in Fig. 2 remarkably different results are obtained at 250 MeV/ nucleon from those at the lower energies, 70, 100, 135 MeV/ nucleon. In order to obtain consistent understanding the effects of three nucleon forces 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 2π exchange types, relativistic treatment [14], and the potentials based on the chiral effective field theory [15] describe these obtained data. Experimentally it would be interesting to measure deuteron analyzing powers as well as polarization transfer coefficients for elastic dp scattering at 200–300 MeV/ nucleon.

We acknowledge the outstanding work of the accelerator group of RIKEN Nishina Center for delivering excellent polarized deuteron beams. We thank the BigRIPS team of RIKEN Nishina Center for their strong support in the measurement with polarized deuteron beams. This work was supported financially in part by the Grants-in-Aid for Scientific Research Numbers 20684010 of the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

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