Measurement of pd breakup cross sections in the off-plane star configurations

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Abstract. We carried out the experiment of the $^1\text{H}(d, pp)n$ reactions at $E_d=26$ MeV at RCNP and that of the $^2\text{H}(p, pp)n$ reactions at $E_p=13$ MeV at KUTL. The data of the differential cross sections was measured and compared with the Faddeev calculations based on the various nucleon-nucleon (NN) interactions with/without the Coulomb interactions or the three-nucleon force (3NF). The data is overestimated by the theoretical predictions by less than 10\%. This result is very different from the data at $E=9.5$ MeV reported from Köln, which showed the large discrepancies between the data and the Faddeev calculations.

1. Introduction

One of the hot topics in the nuclear physics is the study of the nucleon-nucleon (NN) force and the three-nucleon force (3NF) by the three-nucleon scattering. Highly precise data of the nucleon-deuteron (Nd) reactions have been compared with the rigorous results of the Faddeev calculations based on the modern nuclear forces. The data of the differential cross sections for the $p+d$ elastic scattering at low energy region are well reproduced by the predictions with NN forces only, on the other hand these data at the intermediate energy region need 3NFs to be reproduced by the predictions. In the case of the breakup reactions, the status depends on the kinematical configurations. One of the problems in the low energy region is so called SSTanomaly, that the differential cross section data for the space-star (SST) configuration is not reproduced by the Faddeev calculations based on the modern NN forces. The large discrepancies between the data and the predictions can not be explained by the Coulomb force or the 3NF.

Recently, the differential cross sections of the $^1\text{H}(d, pp)n$ breakup reactions were measured at $E_d=19$ MeV\cite{1} at Cologne FN tandem Van de Graaff accelerator facility. The measurements covered the kinematical configurations in which all three nucleons in the final state scattered with equal magnitudes of momenta in the c.m. system. The angle $\alpha$ of the scattered plane in the c.m. system to the beam direction (see Fig.1) was changed from $180^\circ$ (coplanar star) to $124^\circ$ and so-called off-plane star configurations were explored. The results were compared with the Faddeev calculations based on the modern NN potentials with/without the 3NF or with/without the Coulomb effects by the screening and the renormalization approach\cite{2}. The predictions...
including the Coulomb effects well reproduced the data at $\alpha = 180^\circ$ but still overestimate them more than 20% at $\alpha = 124^\circ$. The cause of the discrepancies is still not clear and in the spotlight.

To describe the $3N$ scattering states at lower energy region exactly is important step which lead to the study of $3NF$ effects at intermediate energy region and that of the light nuclei from the first principles. For the systematic study of the off-plane star anomaly, we carried out the measurements of the differential cross sections for the $pd$ breakup reactions at $E=13$ MeV/A by using 13 MeV proton beam at the Kyushu University tandem accelerator facility (KULT) and 26 MeV deuteron beam at Research Center for Nuclear Physics (RCNP). These experiments cover the angular range of $\alpha = 0^\circ - 180^\circ$. In the following section, the detail of the experiment at RCNP will be presented.

![Figure 1. Schematic figure of the off-plane star configuration in the c.m. system. The scattered plane of the space-star configuration is rotated to form angle $\alpha$ with the incoming beam direction.](image)

2. Experimental Procedure

The measurements for $\alpha = 120^\circ$, $140^\circ$, $160^\circ$, $180^\circ$ were performed in the East experimental hall at RCNP. The deuteron beam was accelerated by the AVF cyclotron and transported to the scattering chamber with skipping the Ring cyclotron. We used polyethylene ($\text{CH}_2$) foil as the proton target. The protons in the final states were detected by using the lithium-drifted silicon detectors (Si(Li)-SSD).

2.1. Rotation target

To avoid the decrease of the $\text{CH}_2$ target thickness caused by the energy deposit of the beam in the target, we introduced the target rotating system[3]. Thin $\text{CH}_2$ target[4] with the thickness of 0.3 mg/cm$^2$ and the diameter of 5 cm was installed in the vacuum chamber and rotated at the speed of 20 r.p.m. The beam spot is apart from the target center by about 15 mm. During the measurement with using 200 nA beam intensity, the decrease of the hydrogen target thickness was about 5% per day. The target thickness was monitored by measuring the $d+p$ elastic scattering during the experiment.

2.2. Detector setup

Two protons in the final states were emitted symmetrically to a vertical plane including a beam direction ($z$ axis) and detected by pairs of Si(Li)-SSD detectors (Fig. 2). Four pairs of Si(Li)-SSD detectors were installed to measure the data of four angular setting simultaneously. Another Si(Li)-SSD was installed to measure the $d+p$ elastic scattering as the target thickness monitor. Table 1 shows the scattering angles for all SSD detectors.

We got the energies and the time-of-flight (TOF) data for each coincidence events by DAQ system based on CC7700. In two-dimensional energy spectra of $E_1$ and $E_2$, the true breakup events distribute on the kinematical curve (S-curve). The main contribution to the background events is random coincidences. The random coincidence events on the S-curve can not be
Figure 2. Schematic figure of the detector setup in the vacuum chamber. The four pairs of the Si(Li)-SSD detectors were installed to detect pairs of protons from \( dp \) breakup reactions. The monitor SSD was also used as the luminosity monitor.

distinguished from the true breakup coincidence events by the information from SSD. To estimate the background yields, the time width of the one of the logic pulse for making the coincidence trigger pulse was set to be three times the period of the beam bunch interval. By using the TOF information, the amount of the background contributions were deduced and subtracted from the yields on the S-curve then the yields of the true coincidence events were obtained.

Table 1. The angle \( \alpha \) of the off-plane star planes and the corresponding laboratory angles of detectors. The angular setting of the monitor SSD is also shown.

| \( \alpha \) (deg) | \( \theta \) (deg) | \( \phi_1 \) (deg) | \( \phi_2 \) (deg) | \( \Delta\Omega_1 \) [msr] | \( \Delta\Omega_2 \) [msr] |
|------------------|------------------|------------------|------------------|------------------|------------------|
| 180              | 22.03            | 0.00             | 180.00           | 0.3325           | 0.3209           |
| 160              | 22.70            | 11.17            | 168.83           | 0.3194           | 0.2907           |
| 140              | 24.54            | 20.36            | 159.64           | 0.2715           | 0.2870           |
| 120              | 27.12            | 26.57            | 153.43           | 0.2410           | 0.2426           |
| monitor          | 35.0             | –                | 0.00             | –                | 0.03060          |

3. Results

Figure 3 shows our results of the differential cross sections projected onto the S-curve. The error bars only include the statistical errors. The systematic error is about \( \pm 4\% \) of which the main contribution is the uncertainties of the solid angles of the SSD detectors. In this figure, the results of the Faddeev calculations are also shown[5]. The blue lines show the calculations based on the CD-Bonn potential only and the red ones show that based on the CD-Bonn + \( \Delta \)-isobar 3NF[6]. The solid (dashed) lines show the calculations with (without) including Coulomb force by screening and the renormalization approach[2]. We can see that the predictions including the Coulomb effects almost well reproduce the data. This is different from the case of \( E_d=19 \) MeV at Köln which show the large discrepancies between the data and the theoretical predictions.

We also measured the pd differential cross sections for \( \alpha \leq 90^\circ \) at KUTL by using 9.5 and 13 MeV proton beam[7]. The discrepancies between our data and the theoretical calculations are less than 10\% even at forward angular region of \( \alpha \) or at \( E = 9.5 \) MeV, but except for the case at \( \alpha \sim 90^\circ \) where the SST anomaly problem is left to be solved. The \( dp \) breakup experiment at...
$E_d=19\text{ MeV}$ is expected to be carried out again to account for the energy dependence of the off-plane star anomaly.

![Figure 3](image)

**Figure 3.** Results of the differential cross sections of the off-plane star $dp$ breakup reactions for $\alpha=180^\circ$ (upper left), $160^\circ$ (upper right), $140^\circ$ (lower left), $120^\circ$ (lower right) at $E_d=26\text{ MeV}$. The open circles represent our data. The theoretical predictions which include CD-Bonn only (blue dashed lines), CD-Bonn + Coulomb (blue solid lines), CD-Bonn + $\Delta$-3NF (red dashed lines) and CD-Bonn + $\Delta$-3NF + Coulomb (red solid lines) are also shown. The error bars only show the statistical ones.

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