EPJ Web of Conferences **3**, 04007 (2010)
DOI:10.1051/epjconf/20100304007

Systematic measurement of *pd* breakup cross section at quasi-free scattering

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Abstract. Space Star (SS) anomaly in Nd breakup cross section is well known. SS anomaly has large charge asymmetry; experiment is larger than calculation at nd SS and experiment is smaller than calculation at pd SS. There are also reports on anomaly in quasi-free scattering (QFS) cross section in Nd breakup reaction. At nd QFS, experimental cross section was found to be larger than calculation. On the contrary, pd QFS cross section measured by Köln group is smaller than pd calculation. We measured QFS cross section in pd breakup reaction, and compared the data with recent pd calculations to see angular dependence of QFS anomaly.

1 Introduction

After the strength of two-pion exchange three-nucleon force (2π3NF) was determined in 1998, there remain two kinds of big problems in three nucleon systems; one is to find remaining 3NF other than 2π3NF, and the other is to solve long-standing problems at low energy, A_y puzzle and star anomaly, which seem to be irrelevant to 3NF because 3NF effects are very small in general in low energy reactions.

Studies of new 3NF are being made at higher energy regions and some are presented in this conference. As for A_y puzzle, there are sufficient experimental data, and several candidates for the origin of A_y puzzle have been investigated theoretically. However, the origin of A_y puzzle has not been found yet.

On the star anomaly, experimental data are not sufficient, and we have no suggestions on the origin of star anomaly. In Nd breakup reaction, when outgoing three nucleons have the same energy and form an equilateral triangle, we call the configuration as a star. When the triangle is perpendicular to the beam axis in c.m. system, the star is called as Space Star (SS).

SS anomaly was first found in nd breakup reaction at $E_n = 13$ MeV. Experimental nd breakup cross section at SS was found to be about 30% larger than nd calculation [1,2]. Recently a reliable calculation on pd breakup reaction have been made using screened Coulomb force [3], and precise studies of the star anomaly in pd system have become possible. In pd breakup reaction at E_p= 13 MeV, experimental cross section at SS [4,5] is about 15% smaller than pd calculation as shown in Fig. 1. Large charge asym-

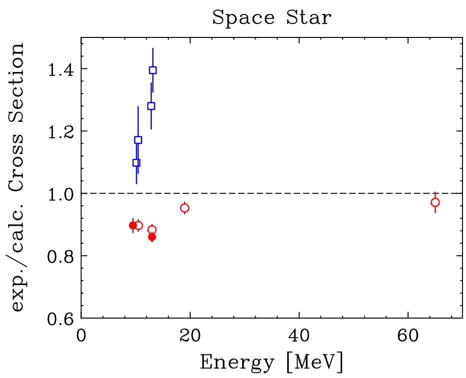

Fig. 1. Energy dependence of space star anomalies. Red solid circles are pd breakup cross section measured at KUTL. The experimental pd breakup cross section (red open circles) are from Ref. [6] at 10.5 MeV, from Ref. [4] at 13 MeV, from Ref. [7] at 19 MeV, and from Ref. [8] at 65 MeV. The experimental nd breakup cross section (blue open squares) are from Ref. [9,10] at 10.3 MeV, and from Ref. [1,2] at 13 MeV.

metry between nd and pd SS anomalies is a curious phenomenon that has not been explained yet.

The charge asymmetry similar to SS anomaly is seen in Quasi-free scattering (QFS) cross section. QFS anomaly in nd breakup reaction has been reported at $E_n = 26$ MeV by Bonn group [11] and at 25 MeV by Beijing group [12]. At nd QFS, experimental cross section was found to be 16% - 18% larger than calculation On the contrary, pd QFS cross section measured by Köln group [6,4,7] is about 10%, 3% and 17% smaller than pd calculation [3] at $E_p = 10.5$ MeV, 13 MeV and 19 MeV, respectively as shown in Fig. 2.

In an Nd breakup experiment with a deuteron target, $1 + (2 + 3) \rightarrow 1 + 2 + 3$, QFS appears at $E_3 = 0$

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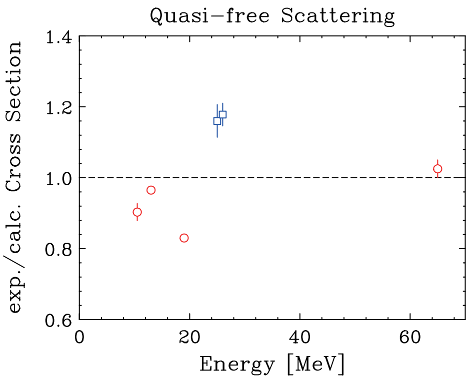

Fig. 2. Energy dependence of quasi-free scattering anomalies. The experimental *pd* breakup cross section (red open circles) are from Ref. [6] at 10.5 MeV, from Ref. [4] at 13 MeV, from Ref. [7] at 19 MeV, and from Ref. [13] at 65 MeV. The experimental *nd* breakup cross section (blue open squares) are from Ref. [12] at 25 MeV, and from Ref. [11] at 26 MeV.

in the laboratory frame. QFS configuration enhances the cross section. All the QFS measurements described above have been made at $\theta_1 = \theta_2$. If QFS anomaly exists, angular dependence of the anomaly may be important information to investigate the origin of the anomaly. We have started a systematic measurement of *pd* QFS cross section at $E_p = 9.5$ MeV and 13 MeV, to see angular dependence of QFS anomaly.

2 Experiment

The experiments were made at Kyushu University tandem accelerator laboratory (KUTL). A proton beam of 9.5 MeV or 13 MeV was incident on a CD_2 foil target, and two protons from $p+d \rightarrow p_1+p_2+n$ reaction were detected in coincidence using Si-detectors. Energies of two protons, E_1 and E_2, and difference of times of flight, $T_1 - T_2$, were measured. The beam current was measured using a Faraday cup, and product of the beam current and the target thickness was monitored by detecting *pd* elastic scattering events using a monitor detector. Setup in a scattering chamber of 1 m in diameter is illustrated in Fig. 3.

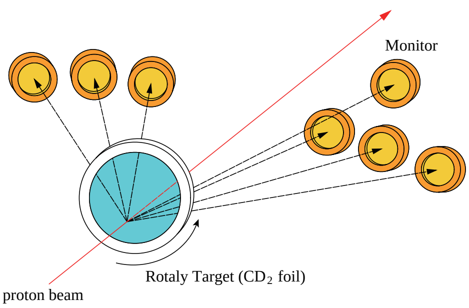

Fig. 3. Schematic view of the experimental setup in a scattering chamber.

We made a target rotation system. A driving motor was placed in the atmosphere, and rotation was transmitted into vacuum by magnetic coupling wheel. We also made a wide uniform CD_2 foil of 60 mm in diameter from CD_2 powder. The target CD_2 foil of about 0.3 mg/cm^2 was rotated in 20 rounds/min. By the rotation, target temperature rise by beam heating was reduced to about 20 degrees, and reduction of D content in CD_2 foil was decreased to about 1/100. In practice, target thickness reduced only 10% in a day by 200 nA *p*-beam at 13 MeV.

As seen in Fig. 3, $D(p, p_1p_2)n$ cross section was measured by a pair of Si-detectors on the left and right of the beam axis. To save time, we used 3 pairs of detectors. One more Si-detector was placed at 40° - 50° to monitor the product of the target thickness and the beam current by detecting protons from *pd* elastic scattering.

In two dimensional energy spectra for E_1 and E_2, there were many background events produced by accidental coincidence between two counters. True events from $D(p, p_1p_2)n$ reaction have definite time difference calculated from energies, $T(E_1) - T(E_2)$. We made two dimensional time spectra, calculated time difference $T(E_1) - T(E_2)$ vs. measured time difference $T_1 - T_2$. True events form a line inclined by 45°. Off the line, only backgrounds exist. Using the time spectra, we subtracted backgrounds.

The true E_1 - E_2 events form a curve called *S*-curve determined by kinematics. The true events were projected onto *S*-curve to obtain $D(p, p_1p_2)n$ cross section. The absolute value of the breakup cross section was evaluated using the monitor counts and the *pd* elastic scattering cross section which had been measured within 1% error at KUTL [14]. The target thickness and the beam current were not used in this evaluation.

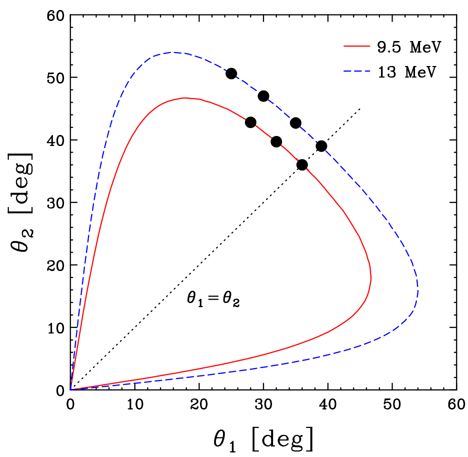

Fig. 4. Angle pairs for QFS in $D(p, p_1p_2)n$ reaction at $E_p = 9.5$ MeV and 13 MeV. Present measurements were made at angle pairs indicated by solid circles.

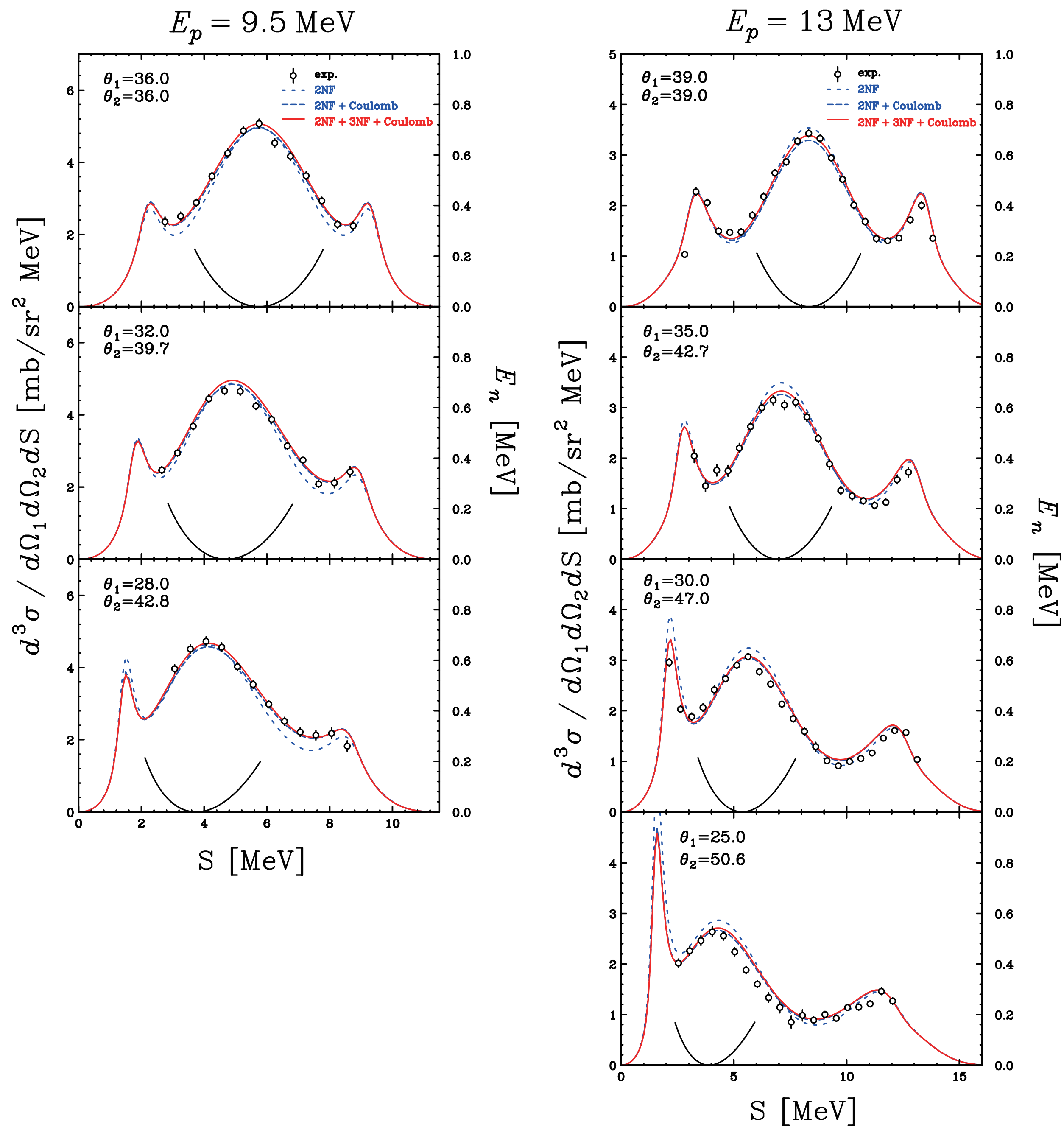

Fig. 5. Open circles represent QFS cross sections of D$(p, p_1p_2)n$ reaction at 9.5 MeV (left) and 13 MeV (right). Red solid curves stand for *pd* calculations with *Δ* effects (3NF) [15]. Blue dashed and blue dotted curves stand for *pd* and *nd* calculations without *Δ* effects, respectively. Solid curves stand for energy of outgoing neutron.

Curves in Fig. 4 indicate angle pairs of (θ_1, θ_2) where D$(p, p_1p_2)n$ QFS occurs. The curves are symmetrical with respect to $\theta_1 = \theta_2$. So far only QFS cross section at $\theta_1 = \theta_2$ was measured. We measured QFS also at $\theta_1 \neq \theta_2$, to see angular dependence of QFS anomaly.

3 Results and Discussions

Experimental results for *pd* breakup cross section around QFS at $E_p = 9.5$ MeV and 13 MeV are shown in Fig. 5. Energy of outgoing neutron is also shown to indicate place for QFS. Not only QFS at $\theta_1 = \theta_2$, but also QFS at $\theta_1 \neq \theta_2$ were measured. Systematic errors in the absolute cross section was estimated about ±4%. Largest sources for systematic error came from evaluation of solid angles for detectors.

The experimental data were compared with *pd* calculations with and without Δ effects (3NF) by Deltuva *et al.*. 3NF effects slightly increase the cross section around QFS. Both at 9.5 MeV and 13 MeV, experimental data agree well with *pd* calculation within errors. The data and calculation agree not only at QFS but also in all the energy range measured. The present data are preliminary ones. We still have to check details in our measurements. We therefore tentatively conclude that no QFS anomaly seems to exist in *pd* breakup at $E_p = 9.5$ MeV and 13 MeV.

Ratio of experimental cross section to calculation at QFS ($\theta_1 = \theta_2$) is presented in Fig. 6. In *pd* QFS, anomaly is seen at 10.5 MeV and at 19 MeV, and there is no anomaly at 9.5 MeV, 13 MeV, and 65 MeV. In *nd* QFS, anomaly is reported at 25 MeV and 26 MeV. A new experiment at 10.5 MeV will be made at KUTL in near future. Also at 19 MeV, a confirming experiment is being planned.

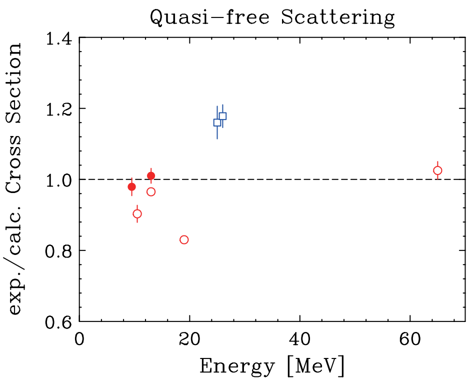

Fig. 6. Energy dependence of quasi-free scattering anomalies. Red solid circles are *pd* breakup cross section measured at KUTL. The experimental *pd* breakup cross section (red open circles) are from Ref. [6] at 10.5 MeV, from Ref. [4] at 13 MeV, from Ref. [7] at 19 MeV, and from Ref. [13] at 65 MeV. The experimental *nd* breakup cross section (blue open squares) are from Ref. [12] at 25 MeV, and from Ref. [11] at 26 MeV.

4 Conclusion

Angular dependence of cross section of *pd* breakup at QFS was measured at E_p= 9.5 MeV and 13 MeV. Preliminary data agree well with *pd* calculation. The results suggest that QFS anomaly does not appear at 9.5 MeV and 13 MeV. Additional experiments may be necessary to obtain clear conclusion on *pd* QFS anomaly.

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