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

Y. Eguchi\textsuperscript{1,a}, K. Sagara\textsuperscript{1}, S. Kuroita\textsuperscript{1}, K. Yashima\textsuperscript{1}, T. Shishido\textsuperscript{1}, T. Yabe\textsuperscript{1}, and S. Ishikawa\textsuperscript{2}

\textsuperscript{1} Department of Physics, Kyushu University, Hakozaki, Fukuoka 812-8581, Japan
\textsuperscript{2} Department of Physics, Science Research Center, Hosei University, Chiyoda, Tokyo 102-8160, Japan

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 \textit{nd} SS and experiment is smaller than calculation at \textit{pd} SS. There are also reports on anomaly in quasi-free scattering (QFS) cross section in Nd breakup reaction. At \textit{nd} QFS, experimental cross section was found to be larger than calculation. On the contrary, \textit{pd} QFS cross section measured by K"oln group is smaller than \textit{pd} calculation. We measured QFS cross section in \textit{pd} breakup reaction, and compared the data with recent \textit{pd} calculations to see angular dependence of QFS anomaly.

1 Introduction

After the strength of two-pion exchange three-nucleon force (2\pi3NF) was determined in 1998, there remain two kinds of big problems in three nucleon systems; one is to find remaining 3NF other than 2\pi3NF, and the other is to solve long-standing problems at low energy, A\textsubscript{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\textsubscript{y} puzzle, there are sufficient experimental data, and several candidates for the origin of A\textsubscript{y} puzzle have been investigated theoretically. However, the origin of A\textsubscript{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 \textit{E}_n = 13 \text{ MeV}. Experimental nd breakup cross section at SS was found to be about 30% larger than \textit{nd} calculation [1,2]. Recently a reliable calculation on \textit{pd} breakup reaction have been made using screened Coulomb force [3], and precise studies of the star anomaly in \textit{pd} system have become possible. In \textit{pd} breakup reaction at \textit{E}_p = 13 \text{ MeV}, experimental cross section at SS [4,5] is about 15% smaller than \textit{pd} calculation as shown in Fig. 1. Large charge asymmetry between \textit{nd} and \textit{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 \textit{nd} breakup reaction has been reported at \textit{E}_n = 26 \text{ MeV} by Bonn group [11] and at 25 MeV by Beijing group [12]. At \textit{nd} QFS, experimental cross section was found to be 16% - 18% larger than calculation.

On the contrary, \textit{pd} QFS cross section measured by K"oln group [6,4,7] is about 10%, 3% and 17% smaller than \textit{pd} calculation [3] at \textit{E}_p = 10.5 \text{ MeV}, 13 \text{ MeV} and 19 \text{ 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 \(E_3 = 0\).
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 CD₂ foil of 60 mm in diameter from CD₂ powder. The target CD₂ foil of about 0.3 mg/cm² 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 CD₂ 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, p₁p₂)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 E₁ and E₂, there were many background events produced by accidental coincidence between two counters. True events from D(p, p₁p₂)n reaction have definite time difference calculated from energies, T(E₁) - T(E₂). We made two dimensional time spectra, calculated time difference T(E₁) - T(E₂) vs. measured time difference T₁ - T₂. True events form a line inclined by 45°. Off the line, only backgrounds exist. Using the time spectra, we subtracted backgrounds.

The true E₁ - E₂ events form a curve called S-curve determined by kinematics. The true events were projected onto S-curve to obtain D(p, p₁p₂)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. 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 $\Delta$ effects (3NF) [15]. Blue dashed and blue dotted curves stand for $pd$ and $nd$ calculations without $\Delta$ effects, respectively. Solid curves stand for energy of outgoing neutron.

Curves in Fig. 4 indicate angle pairs of $(\theta_1,\theta_2)$ 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 $\pm 4\%$. Largest sources for systematic error came from evaluation of solid angles for detectors.
The experimental data were compared with $pd$ calculations with and without $\Delta$ 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.](image)

### 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.

### References

1. J. Strate et al., Nucl. Phys. A501, (1989) 51.
2. H. R. Setze et al., Phys. Lett. B388, (1996) 229.
3. A. Deltuva et al., Phys. Rev. C72, (2005) 054004.
4. G. Rauprich et al., Nucl. Phys. A535, (1991) 313.
5. T. Ishida et al., Mod. Phys. Lett. A18, (2003) 436.
6. R. Großmann et al., Nucl. Phys. A603, (1996) 161.
7. H. Patberg et al., Phys. Rev. C53, (1996) 1497.
8. J. Zejima et al., Phys. Rev. C55, (1997) 42.
9. M. Stephan et al., Phys. Rev. C39, (1989) 2133.
10. K. Gebhardt et al., Nucl. Phys. A561, (1993) 232.
11. A. Siepe et al., Phys. Rev. C65, (2002) 034010.
12. X. C. Ruan et al., Phys. Rev. C75, (2007) 057001.
13. M. Allet et al., Few-Body Syst. 20, (1996) 27.
14. K. Sagara et al., Phys. Rev. C50, (1994) 576.
15. A. Deltuva, private communication.