Recent experiments on three nucleon systems and problems to be solved

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Abstract. After 2π3NF was found in 1998, many experiments were made on Nd elastic scattering, Nd breakup and pd capture, and many discrepancies between experiments and calculations were revealed. Systematic experimental data are still being accumulated. From the systematic data, 3NF other than 2π3NF such as πρ3NF and pp3NF, and origins of low-energy anomalies are expected to be found in the future.

1 Introduction

One of the purposes to study three-nucleon (3N) systems is to find effects of three-nucleon forces (3NF) and to determine their strengths. As is well known, Fujita-Miyazawa predicted existence of 2π-exchange three nucleon force (2π3NF) in 1957[1]. Faddeev equations for 3N systems have been numerically solved since late 1960’s. In 1980’s, it became widely known that 3H binding energy cannot be reproduced by 2NF alone and can be reproduced using 2π3NF with an adjustable parameter. To justify the value of the parameter, further evidences were necessary.

From systematic measurement of pd elastic scattering cross section in energy range of E_p = 2 - 18 MeV at Kyushu University tandem laboratory (KULTL), systematic discrepancy between experiment and calculation in the cross section minima around 110° was found in 1994[2]. The discrepancy was, however, paid no attention because Coulomb force was not correctly treated in pd calculations at that time. In 1996, pd scattering cross section was measured at E_p = 270 MeV (E_d = 135 MeV) to construct a d-beam polariometer at RIKEN. Koike found by chance the same discrepancy at the cross section minima also at 135 MeV, and he introduced the discrepancy as Sagara discrepancy in FB15 in 1997[3]. In 1998, Witala et al., excellently solved the binding energy problem and Sagara discrepancy by introducing the same 2π3NF[4].

After 2π3NF was discovered, many theoretical studies and experiments on 3NF have been made. The experimental studies have been widely made at higher energy region on Nd elastic scattering, and also made on pd breakup and pd capture.

In pd elastic scattering, many kinds of spin observables, such as analyzing powers A_yy, A_0, A_1, and A_2, and polarization transfer coefficients have been measured. Also cross section of pd elastic scattering was measured at various energies. In pd breakup, cross section and A_y have been measured. Our experiment on pd breakup at E_p = 247 MeV is presented in this conference[5]. In pd capture, tensor analyzing powers A_00, A_22 and also A_11 have been measured in the last decade at E_d = 100 - 200 MeV.

All the experimental observables at higher energy disagree more or less with calculations even after 2π3NF being included. The disagreements seem, at least in part, to be caused by 3NF other than 2π3NF. We report the disagreements in some detail later.

At low energy region, there are long-standing problems of A_y puzzle and Space Star anomaly (SS anomaly), which seem to be irrelevant to 3NF. Now, we have sufficient data for A_y puzzle. Experimentalists are just waiting for theoretical investigations. As for SS anomaly, which is a discrepancy between experiment and calculation in Nd breakup cross section around 10 MeV, there were a few experiments in 20th century, because there were no reliable calculations on pd breakup and SS anomaly was studied only in nd breakup. Experiments on pd breakup are far more precise and far easier than nd breakup experiments. Experimentalists desired for a long time for pd breakup calculations. During the time, for example, combination of nd breakup Faddeev calculation and Watson-Migdal pp FSI formula was tried to approximate pd breakup calculation, and experimental data were fairly well reproduced.

A breakthrough was made by A. Deltuva et al. in 2005[6]. They succeeded in calculations of all kinds of pd reactions including pd breakup using fast-damping screened Coulomb force. After the success of pd breakup calculation, we started to measure pd breakup cross section systematically, to search for origin(s) of the star anomaly.

Figure 1 illustrates discrepancies in 3N systems. We have already solved discrepancies in 3N binding energy and in pd scattering cross section minimum by 2π3NF. There are still many disagreements remaining at higher energy as well as at lower energy. Some of the disagreements may indicate effects of 3NF other than 2π3NF.
2 Experiments on \(pd\) elastic scattering at higher energy

After \(2\pi\)3NF was discovered, many experiments were made on \(pd\) elastic scattering and \(2\pi\)3NF effects were examined. As so many groups measured \(pd\) and \(nd\) elastic scattering, we Kyushu group did not measure it, instead, of elastic scattering was well reproduced by introducing \(\pi\) in calculations at 250 MeV\(\text{[7]}\). This systematic disagreement seems to indicate less polarization observables are complicated and are not so large as that of the cross section of elastic scattering. Experimental values are about twice of calculated values at 250 MeV\(\text{[7]}\). This systematic disagreement seems to indicate effects of short-range \(3NF\) other than \(2\pi\)3NF and/or relativistic effects.

Many kinds of polarization observables of \(pd\) scattering have been measured. They were found to disagree with calculations. Disagreements in polarization observables are complicated and are not so large as that of the cross section (for example see \(\text{[8]}\)). Besides systematic feature like cross section enhancement has not been found in disagreements of polarization observables.

It may better to investigate first the systematic disagreement in the cross section of elastic scattering, and to study other disagreements after the problems in the cross section are completely solved. Cross section is a basic scalar quantity, and modification of cross section influences more or less polarization observables.

3 Experiments on \(pd\) breakup at higher energy

After \(2\pi\)3NF was discovered, we started \(pd\) breakup experiment at \(E_p = 247\) MeV at RCNP. To see global feature, we first made \(D(p,p_1)p_2n\) experiment by detecting only one proton \(p_1\) out of three outgoing nucleons. To significantly reduce backgrounds from the target, we used an almost pure liquid \(D_2\) target instead of an ordinary \(CD_2\) target. We had developed the liquid hydrogen target for our \(pd\) capture experiment described below.

Experimental results for \(D(p,p_1)p_2n\) cross section at 247 MeV are shown in Figure 2 with calculations by Witała. Measured cross section is larger than calculation. The disagreement increases at forward angle. Effects of \(2\pi3NF\) are not enough to explain the experiment. We measured also \(A_p\) in the same experiment, but we first investigate cross section disagreement.

The disagreement is of similar magnitude with the disagreement in \(pd\) scattering cross section at background at the same energy described above. It may be natural to think that the same origin enhances both cross sections of \(pd\) elastic scattering and of \(pd\) breakup reaction.

In order to see microscopically the enhancement of cross section in \(pd\) breakup, we recently measured \(D(p,p_1)p_2n\) cross section at \(E_p = 247\) MeV by detecting two protons in coincidence. We focused to investigate microscopically enhancement of \(D(p,p_1)p_2n\) cross section at \(\theta_t = 15^\circ\) and \(E_1\) being around 150 MeV. Another proton \(p_2\) was detected at \(\theta_t = 35^\circ, 50^\circ, 65^\circ\) and \(80^\circ\) on the opposite side of the beam axis, as reported in this conference by Kuroita\[5\]. In the same experiment, \(D(p,p_1)p_2n\) cross section was also measured again, and our previous data were completely confirmed.

In figure 3, \(\theta_t\) dependence of \(D(p,p_1)p_2n\) cross section at \(E_1 = 150\) MeV is illustrated with calculations by Kamada\[10\]. Cross section enhancement is large at \(\theta_t = 35^\circ\)
4 Experiments on pd capture at higher energy

By $p + d \rightarrow ^3\text{He} + \gamma$ reaction, pd scattering state comes to $^3\text{He}$ ground state. Momentum transfer is large. It is interesting to search for effects of short-range 3NF in this high-momentum transfer reaction. Cross section of pd capture is, however, very small as below 1μbarn. Hence we used a liquid hydrogen target and detected $^3\text{He}$ recoils simultaneously in a wide angular range from 20° to 160° in c.m. system.

A polarized d-beam of energy of 196 MeV from RCNP cyclotron was used in our first experiment. The beam polarization axis was in the vertical direction, and recoiled $^3\text{He}$ detection was made in the horizontal plane to measure $A_y$ and $A_{yy}$, and in the vertical plane to measure $A_{xx}$. Measured $A_{xx}$ and $A_{yy}$ took roughly the same negative values, $A_{xx} \approx A_{yy}$, and $A_{yy}$ roughly agreed with calculation, but $A_{xx}$ remarkably disagreed with calculation.

Next we measured $A_{xx}$ and $A_{yy}$ of pd capture at $E_d = 137$ MeV. Preliminary data indicated again the relation of $A_{xx} \approx A_{yy}$ and remarkable disagreement in $A_{xx}$. Since pd capture cross section is small and identification of true events was disturbed by overwhelming background events, data analysis took time.

Meanwhile, $A_{yy}$ and $A_{zz}$ of pd capture at $E_d = 180$ MeV and 133 MeV were measured at KVI. Their data agreed with calculations. They used a vertically polarized d-beam and a liquid hydrogen target, and detected $^3\text{He}$ and $\gamma$ ray in coincidence. $A_{yy}$ was measured by detecting $\gamma$-rays in the horizontal plane. $A_{zz}$ was measured by detecting $\gamma$-rays in two planes inclined by $\pm 45°$ from the horizontal plane, and assuming the relation $A_{xx} + A_{yy} + A_{zz} = 0$. KVI $A_{yy}$ data roughly agree with our data, but $A_{zz}$ data are about 1.5 times smaller in magnitude than ours.

Finally, a confirming measurement was made at RCNP on $A_{xx}$, $A_{yy}$ and $A_{zz}$ of pd capture at $E_d = 196$ MeV. The d-beam was polarized in the vertical direction, $^3\text{He}$ recoils were detected in the vertical plane for $A_{xx}$ in the horizontal plane for $A_{yy}$, and in two planes inclined by $\pm 45°$ from the horizontal plane for $A_{zz}$ in a way similar to KVI's. Data-analysis method was improved so as to increase $^3\text{He}$ detection efficiency, and both new data and previous data were analyzed by the new method.

Our previous data and new data essentially agree to each other, and indicate the relation $A_{xx} \approx A_{yy}$ and large discrepancy in $A_{xx}$ (also in $A_{zz}$). Figure 4 shows various $A_{zz}$ data; $A_{zz}$ is $A_{yy}$ in our previous experiment at 196 MeV, $-A_{zz}$ in our new experiment at 196 MeV, and $A_{zz}(\pm 45°)$ in our new experiment at 196 MeV, together with $A_{zz}(\pm 45°)$ in KVI experiment at 180 MeV. Curves are calculations at 200 MeV with and without 2π3NF by Golak. Although our “$A_{zz}$” data are scattered to some extent, there is a large discrepancy between our “$A_{xx}$” data and calculations.

In our data $A_{xx}$, $A_{yy}$ relation holds, but calculated $A_{zz}$ and $A_{yy}$ are significantly different to each other, therefore a large discrepancy in $A_{zz}$ (also in $A_{xx}$) results. The relation $A_{xx} \approx A_{yy}$ means the symmetry of pd capture with respect to the z-axis (the beam axis). When a d-beam is polarized in y-direction (vertically), d-induced reactions in the verti-
5 Experiments on pd star anomaly at low energy

Discrepancies at higher energy have candidates for their origin(s), e.g., short-range 3NF, relativity, high-angular momentum reactions. On the contrary, discrepancies at lower energy have not apparent candidates for their origin(s).

$A_y$ puzzle is well known for a long time. We have already enough data sets for $A_y$ puzzle and no systematic measurements on $A_y$ puzzle have been made recently. Many theoretical attempts such as modifications of 2NF and introduction of LS dependent 3NF have been examined, but $A_y$ puzzle has not been solved yet.

Another big problem at low energy is Space-Star anomaly. SS anomaly was found first in $nd$ breakup at $E_p = 13$ MeV and 10.5 MeV [11], and was confirmed at 13 MeV by another experiment [12]. Experiments of $pd$ breakup at SS configuration were also made, and SS anomaly in $pd$ breakup was first found when a reliable $pd$ calculation was made [6].

At 13 MeV, $nd$ breakup cross section at SS configuration is about 25% higher than calculation, and $pd$ breakup cross section at SS is about 15% lower than calculation. So far no theoretical suggestions have been made for SS anomaly and its large charge asymmetry.

Because a reliable calculation on $pd$ breakup has become available since 2005 [6], we have been making a systematic measurement of $pd$ star cross section at $E_p = 13$ MeV and 9.5 MeV. At Koeln University, measurement of $pd$ star cross section at $E_d = 19$ MeV ($E_p = 9.5$ MeV) was made[13].

When three outgoing nucleons from $Nd$ breakup have the same energy and form an equilateral triangle, we call the configuration as Star. When the Star triangle is perpendicular to the beam axis, we call the configuration as Space Star. An angle between Star plane and the beam axis in c.m. frame is called as $\alpha$, as defined in Fig. 5. We usually detect two protons from $pd$ breakup at symmetrical angles with respect to the beam axis, and we define $\alpha = 0^\circ$ when a $p$-beam is used and two detected protons are at forward angles in the horizontal plane. See Fig. 5.

To see characteristics of Star anomaly, $\alpha$-dependence of $pd$ Star anomaly has been measured recently by Koeln group[13] and Kyushu group. Star configuration at $\alpha=0^\circ$ is close to QFS configuration, and possible anomaly at QFS is also being investigated at Kyushu. Y. Maeda and Y. Eguchi report on these subjects in this conference.

As seen in Figure 6, star anomaly at 13 MeV is confirmed at around 90$^\circ$. The plane perpendicular to the beam axis is special. Only in the perpendicular plane, $pd$ breakup reaction is suppressed. It seems to be enough to think of curious suppression in the perpendicular plane.

At 9.5 MeV, however, remarkable Star anomaly appears also at backward angles, as indicated by Koeln experiment at $E_d = 19$ MeV. Complex consideration may be necessary to explain the wide-range Star anomaly.

Before thinking of origins of $pd$ Star anomaly, it is better to make a confirming experiment at $E_d = 19$ MeV. A polarized $d$-beam was used in Koeln experiment, but an unpolarized $d$-beam will be used in the confirming experiment to measure cross section alone.

Our strategy is (a) confirmation of $pd$ Star anomaly by additional experiments, (b) investigation of origin(s) of $pd$ Star anomaly, then (c) elucidation of $nd$ Star anomaly. So far large charge asymmetry between $nd$ SS anomaly and $pd$ SS anomaly has been reported. The large charge asymmetry is hard to explain. We will first elucidate $pd$ Star anomaly, based on systematic and reliable measurements. Elucidation of $pd$ Star anomaly may include suggestion on the charge asymmetry. Experimental data for $nd$ Star are insufficient at present, and reliable $nd$ experiments are hard.
to make. So we will not investigate \textit{nd} Star anomaly till \textit{pd} Star anomaly is completely elucidated.

6 Experiments on \textit{pd} QFS at low energy

Cross section enhancement of 16-18\% was reported in \textit{nd} QFS at $E_n = 25$ MeV and 26 MeV. Also cross section suppression in \textit{pd} QFS was reported at $E_p = 10.5$ MeV and 19 MeV.

We are making systematic measurement of \textit{pd} QFS cross section at KUTL, and no apparent \textit{pd} QFS anomaly has been found at both 9.5 MeV and 13 MeV. We will measure \textit{pd} QFS cross section at 10.5 MeV and 19 MeV to see if \textit{pd} QFS anomaly exists or not.

7 Summary

Studies of $3N$ systems are summarized and illustrated in Figure 1. We are on the way to search for short-range $3NF$ at higher energy in \textit{pd} scattering, \textit{pd} breakup and \textit{pd} capture, and to investigate origins of Star anomaly as well as of $A_y$ puzzle at low energy. Experimental studies have made steady progress. At low energy, success of reliable \textit{pd} calculation enabled systematic studies of \textit{pd} Star anomaly.

Challenging $3N$ calculations aiming to solve remaining problems in $3N$ reactions are expected.

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