Kenshi Sagara

Experimental Investigations of Discrepancies in Three-Nucleon Reactions

Received: 4 March 2010 / Accepted: 3 June 2010 / Published online: 11 August 2010
© The Author(s) 2010. This article is published with open access at Springerlink.com

Abstract Experiments on pd scattering, pd capture and pd breakup performed by our Kyushu University group since 1988 are reviewed. Various discrepancies between the experimental results and 3N Faddeev calculations have been found, and systematical measurements of the discrepancies have been made. From discrepancies in pd scattering cross section and in 3N binding energy, 2π-exchange 3N force was determined, and the discrepancies were satisfactorily diminished. There are, however, still many discrepancies awaiting theoretical investigation, as described in this report.

1 Introduction

A precise experimental study of three-nucleon (3N) reactions at Kyushu University Tandem Accelerator Laboratory (KUTL) was started in 1988. Before the 3N experiments, high-intensity polarized \( \vec{p} \) - and \( \vec{d} \) -beams had been already developed at KUTL to measure \((\vec{d}, \vec{p})\) polarization transfer coefficients. These beams were used to obtain high-statistics 3N data. To obtain high-precision and reliable 3N data, experimental facilities were improved.

Beam polarization and beam position on the target should be stable in order to obtain reliable data. Also beam intensity should be stable to correctly estimate counting efficiency of detectors. Beam polarization, integrated beam charge, and target thickness (gas pressure and length along the beam axis) should be accurately measured. To obtain high-statistic data, data acquisition speed should be fast enough to accumulate many counts with low counting loss. These requirements were not easily satisfied in a university laboratory.

Our purpose for starting 3N experiments at that time was to find 3N forces and to solve \( A_y \) puzzle. Numerical calculations of Faddeev equations were greatly developed in 1980’s. Speeds of computers became faster every year. Koike and Heidenbauer pointed out presence of \( A_y \) puzzle (1986) [1]. Faddeev calculations with realistic NN potentials instead of separable potentials were made first by Takemiya [2], then by Bochum group [3,4].

We decided therefore, to obtain precise and systematic experimental data of 3N reactions. When the precise data were compared with reliable Faddeev calculations, shortage of 2N force (2NF) might appear as a discrepancy between the data and the calculations. The discrepancy might indicate effects of 3NF or other origins which we were looking for. If a discrepancy was confirmed, theoretical investigations would reveal its origin(s), which would be 3NF or others. On this thought, we started precise and systematic experiments on pd system at KUTL in 1988.

By 2009 we have made many experiments on

(a) \( pd \) scattering in a beam energy range of 2–18 MeV,
2 Experiments on $p + d$ Scattering at Low Energy

2.1 Introduction

A high-intensity Lomb-shift type polarized ion source was developed at KUTL (Kyushu University Tandem Accelerator Laboratory) in 1978–1985. An 80% polarized $\vec{p}$-beam of 1.5$\mu$A intensity at the best record was produced in the ion source. We also developed a spin processor to tilt the beams polarization axis in any direction on the target. Polarizations of the accelerated beams were measured accurately during the experiment by using a polarimeter. We developed a $\vec{p}$-beam polarimeter and a $\vec{d}$-polarimeter, and accurately calibrated the polarimeters in separate experiments.

Using a polarized $\vec{d}$-beam, polarization transfer coefficients of $(\vec{d}, \vec{p})$ reactions were measured in 1985–1989, and the $(\vec{d}, \vec{p})$ experimental results were compared with DWBA calculations. We tried to extract information on deformation of the target nuclei as well as on reaction mechanism of $(\vec{d}, \vec{p})$ reaction, however, concrete conclusions could not be obtained from DWBA calculation.

Then, we stopped our $(\vec{d}, \vec{p})$ experiment, and started three-nucleon (3N) experiments, first on $p + d$ scattering. 3N Faddeev calculations have no approximations in principle. Furthermore, numerical methods for Faddeev calculations were greatly developed in 1980’s. We thought that if we made precise experiments and compared the data with rigorous 3N Faddeev calculations, we could obtain concrete conclusions on nuclear interactions, such as 3N force and/or off-energy-shell 2N interactions.

The greatest problem in 3N reactions in late 1980’s was $A_y$ puzzle. Koike first pointed out existence of $A_y$ puzzle in 1986 [1]. Y. Koike and the author (K.S.) discussed how to investigate $A_y$ puzzle. The author also discussed on the possible origins for $A_y$ puzzle with N. Takemiya, who made Faddeev calculations first using realistic (not separable) 2N potentials in 1985 [2].

Test experiments on $p + d$ scattering using polarized $\vec{p}$-and $\vec{d}$-beams started in 1986. From 1989, we made accurate and systematic measurements on analyzing powers, $A_y, iT_{11}, T_{20}, T_{21}, T_{22}$ of $p + d$ scattering in the energy range of $E_{\vec{p}} = 2–18$ MeV using a polarized $\vec{p}$-beam and in the range of $E_{\vec{d}} = 5–18$ MeV using a polarized $\vec{d}$-beam [6,7].

2.2 Polarized $\vec{p}$ and $\vec{d}$ Beams

2.2.1 Polarized Ion Source (PIS)

Development of a high-intensity polarized ion source at KUTL took a long time (about 7 years), under the leadership of Prof. A. Isoya who also designed the Kyushu University Tandem Accelerator. The polarized ion
source (PIS) was a Lamb-shift type one. A block diagram of PIS is shown Fig. 1. It had a distinct features that our Cs-cell, spin filter and Ar-cell had large aperture so as to allow passage of a high-intensity beam.

In an ion source in (Fig. 1), $H^+(D^+)$ ion were produced in plasma which was confined in a quartz tube by a magnetic field. From the plasma, a $H^+(D^+)$ beam of about 20 mA was extracted by electric potential. In the next cylindrical drift section, the extracted beam was expanded in space uniformly by a strong magnetic field near the cylindrical wall. Then, the $H^+(D^+)$ beam was accelerated to about 2 keV and then decelerated to 0.5 keV (1 keV) by passing through three sheets of grid electrodes perpendicular to the beam axis. This method was called an accel–decel extraction. Direction of $H^+$ ions should be uniform, because the $H^+$ ions were transformed into neutral $H^0$ ions in the Cs-cell and passed along a distance of about 2 m till the Ar-cell, where $H^0$ ions were transformed to $H^-$ ions.

After the accel–decel extraction, the intense beam was spread by Coulomb repulsion (space-charge effects) between $H^+ (D^+)$ ions. The spreading angle was fairly large because the beam energy was as low as 500 eV (1000 eV). To reduce the space-charge effects, thermal electrons were supplied into the $H^+$ beam from a hot filament.

In the Cs-cell, $H^+ + Cs \rightarrow H^0 + Cs^+$ reaction took place and about 1/3 of $H^0$ could be transformed to $H^0(2S)$. In the spin filter, where a magnetic field and a rf field existed, 1/2 of $H^0(2S)$ was de-excited to $H^0(1S)$, and the remaining half survived in $H^0(2S)$. In the $H^0(2S)$ state, the electron was polarized, and the proton was gradually polarized due to spin–spin interaction. In the Ar-cell, more than 95% of $H^0(2S)$ became $H^-(2S)$ and a few % of $H^0(1S)$ became $H^-(1S)$. The beam was composed of nuclear-polarized $H^-(2S)$ and unpolarized $H^-(1S)$.

### 2.2.2 Selection of Spin Axis

After the beam was made negative ($H^-$) in the Ar-cell, the beam was accelerated up to 30 keV. Due to the acceleration, the beam radius became small. The small-sized beam then passed through the spin processor, where an electric field $E$ and a magnetic field $B$ were applied perpendicularly to the beam axis to satisfy $E + v \times B = 0$, with $v$ being the beam velocity. The $H^-$ beam passed through the spin processor without bending, but the beam spin ($s$) was rotated by a force proportional to $s \times B$.

As the spin processor was rotatable with respect to the beam axis, we could choose the direction of $B$ in a plane perpendicular to the beam axis. Using the spin processor, we could select the spin direction in the range of $0^\circ \leq \theta \leq 90^\circ$ and $0^\circ \leq \phi \leq 180^\circ$ where $\theta$ is the polar angle between the beam axis and the beam spin axis, and $\phi$ is the azimuth angle of the beam spin axis around the beam axis.

As our accelerator was a tandem accelerator, which was electro-static and did not rotate the beam spin, the spin direction of the beam after the spin processor and the spin direction on the target were in one-to-one correspondence, although the two spin directions were not equal to each other owing to magnetic deflectors in the beam line. Therefore, we could measure any of $A_y$, $iT_{11}$, $T_{20}$, $T_{21}$ and $T_{22}$ by adjusting the spin processor.

### 2.2.3 Determination of Beam Polarization

As illustrated in Fig. 2, the beam polarization was measured during the experiment using a $\vec{p}$-beam polarimeter or a $\vec{d}$-beam polarimeter. The $\vec{p}$-beam polarimeter used $\vec{p} + ^4\text{He}$ scattering which has $A_y = 1.0$ (the maximum) point at around $E_p = 12$ MeV and at around 112°. The $\vec{d}$-beam polarimeter used $\vec{d} + ^3\text{He} \rightarrow p + ^4\text{He}$ reaction which has large analyzing powers for both vector and tensor polarized $\vec{d}$-beams. Not only the absolute value of the beam polarization but also the direction of the beam polarization axis were always measured using the polarimeter.

An experimental observable was asymmetry in number of events between left and right counters, or between different spin modes. The asymmetry is proportional to $p \cdot A$ where $p$ is the beam polarization and $A$ is the analyzing power of the polarimeter. Precise measurement of $A$ in a separate experiment is necessary to determine the beam polarization precisely.
In our calibration of the $\vec{p}$-beam polarimeter [5], we utilized $A_y = 1$ point of $\vec{p} - ^4\text{He}$ scattering at around $E_p = 12$ MeV and at around $\theta_p = 112^\circ$. From phase shift analyses, $A_y$ of $\vec{p} - ^4\text{He}$ scattering is known to take the maximum value of 1.0 near $E_p = 12$ MeV and $112^\circ$. Around the $A_y = 1.0$ point, $A_y$ varies slowly with angle and energy. For example, $A_y$ is higher than 0.995 in the area of $12 \pm 0.3$ MeV and $112^\circ \pm 5^\circ$. At 12 MeV, we found that $A_y$ took the maximum value at $113^\circ$. We presumed therefore $A_y = 1.000 \pm 0.003$ at $113^\circ$ at 12 MeV.

To calibrate the $\vec{p}$-beam polarimeter at energy $E_m$, we used the setup in Fig. 2 and measured asymmetry using a $\vec{p}$-beam at 12 MeV and $E_m$ alternatively. At 12 MeV we determined the $\vec{p}$-beam polarization, and we assumed the $\vec{p}$-beam polarization was the same when the beam energy was changed to $E_m$ because the polarized ion source was kept unchanged.

In our calibration of the $\vec{d}$-beam polarimeter [5], we utilized $^{16}\text{O}(\vec{d}, \alpha)^{14}\text{N}$ reaction whose analyzing power $A_{zz}$ was theoretically known to be 1.0 at any energy and at any angle from spin selection rules. One disadvantage of this method was the small cross section of this reaction because the reaction is forbidden in the first-step process and at least two steps are necessary to cause the reaction.

At each energy $E_m$, we sought the angle of $\theta_{\text{max}}$, where $^{16}\text{O}(\vec{d}, \alpha)^{14}\text{N}$ cross section becomes the maximum, and calibrated the analyzing powers of the $\vec{d}$-beam polarimeter. The setup for the $\vec{d}$-beam polarimeter calibration was essentially similar to that in Fig. 2, though details were a little different.

2.3 Measurement of $A_y$ of $p + d$ Scattering

To measure analyzing powers, a polarized beam, a target, detectors and a data acquisition system were necessary. Preparations for polarized $\vec{p}$- and $\vec{d}$-beams and polarimeters were already described in the preceding section. Beam polarization was always measured with a polarimeter during an experiment.

For $p + d$ scattering experiments we used $\text{D}_2$ and (H$_2$) gas targets. The target gas was almost pure, without any dominant obstacles such as C in a CD$_2$ foil target. In a D$_2$ gas target, there were trace contaminations of H, O, N, and C but they were not harmful for the measurement.

Figure 3 shows a schematic view of setup of a gas target and detectors. Metal foils (Al or Havar) were used for windows at the beam entrance and beam exit because polymer foils were melted by the beams.
A polymer foil (Mylar) was used for side windows through which scattered particles exited. Depending on the beam energy, Mylar foils of 1.5–6\,\mu m were used for the side windows, and target gas pressure was 0.2–0.8 atm.

Si solid state detectors were used to detect scattered $p$ and $d$. A double-slit system was placed in front of each detector. The target region was defined by the double-slit system and the beam.

Two detectors were placed at the same angle on the left and right side of the beam axis. Polarization of the $\vec{p}$-beam was in the vertical direction and the beam polarization was switched up and down periodically. We had four counts, $L_{\text{up}}$, $R_{\text{up}}$, $L_{\text{down}}$, and $R_{\text{down}}$ which were normalized by solid angles and the beam charge. Experimental asymmetry was obtained in four ways,

$$
\frac{(L_{\text{up}} - L_{\text{down}})}{(L_{\text{up}} + L_{\text{down}})}
$$

$$
\frac{(R_{\text{up}} - R_{\text{down}})}{(R_{\text{up}} + R_{\text{down}})}
$$

$$
\frac{(L_{\text{up}} - R_{\text{up}})}{(L_{\text{up}} + R_{\text{up}})}
$$

$$
\frac{(L_{\text{down}} - R_{\text{down}})}{(L_{\text{down}} + R_{\text{down}})}
$$

and consistency among the four values was checked. Consistency checks in various forms were very important in order to obtain reliable data.

In the energy spectra from the left and right detectors, the scattered protons and deuterons formed two prominent peaks. Backgrounds from contamination gases were small typically less than 1% in number. Main contaminations were outgas from the inner walls of the target cell, the gas feeding pipes, and sealing O-rings. The outgas built up with time. Therefore, we occasionally drained the target gas and replaced it with new gas.

Furthermore, we used a narrowing-width method. For example, $L_{\text{up}}$ and $L_{\text{down}}$ were obtained by summing up proton counts within the same width $w$. As illustrated in Fig. 4, we reduced the width as $w_1 \rightarrow w_2 \rightarrow w_3$, and calculated the asymmetry in the Eq. (1). As the width decreased, the backgrounds in $L_{\text{up}}$ and $L_{\text{down}}$ relatively decreased, and the calculated asymmetry became closer to the true value, although statistical error increased. The asymmetry at zero width was estimated, and was adopted as the true value.

A fast data-taking system using a ring-memory was developed during the experiment. Using this system, we could accumulate $10^6$–$10^7$ counts of data in 10 min with a dead time of less than 5%.

Angular distribution of $A_y$ of $p+d$ scattering was measured at 16 energies, $E_p = 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 6.5, 7.0, 8.0, 8.5, 9.0, 10.0, 12.0, 14.0, 16.0$ and 18.0 MeV. Measurements at $E_p = 6.5$ MeV and at 8.5 MeV were included because $n+dA_y$ had been measured at these energies at TUNL.

Our $p+dA_y$ data were very precise and systematic. Statistical errors in $A_y$ were typically $\pm 0.003$ and the error in scale was about 2%. Some of the $A_y$ data are displayed in Fig. 5. The data were compared with Faddeev calculations using Paris NN potential by Takamiya. In these calculations, effects of Coulomb force were included only through Coulomb phase shifts. Therefore, calculation of $p+dA_y$ was an approximate one.

We fitted our $p+dA_y$ data with Legendre polynomials and extracted $A_y$ peak values. The experimental $A_y$ peak values were compared with calculated $p+dA_y$ peak values. Normalized difference, (calc-exp)/exp for $p+dA_y$ peak value, is plotted in Fig. 6 with solid circles. Takamiya modified $LS$ potential in NN force in order to investigate the origin of $A_y$ puzzle [12]. We also compared the experimental $p+dA_y$ peak value to the modified calculation, as shown in Fig. 6 with open circles. The modification in $LS$ potential improved the reproduction of the $p+dA_y$ data but the reproduction was not perfect. Besides, the modification deteriorated fit to $N+NA_y$ data. Therefore we thought that there might be other origin(s) of $A_y$ puzzle.
Fig. 5 Examples of measured $\vec{p}d A_y$ (solid circle). Open circles are $\vec{p}d A_y$ at the same energy measured at TUNL. Solid and dashed curves are $pd$ and $nd$ calculations, respectively by Takemiya. Coulomb force was approximately included.

Fig. 6 Energy dependence of discrepancy at $\vec{p}d A_y$ peak. Present $\vec{p}d A_y$ data were compared to $pd$ calculation with Paris potential (solid circle), to $pd$ calculation with LS modified potential (open circle). $\vec{n}d A_y$ data were also compared to the modified LS calculation.

We completed our $p + dA_y$ measurement in 1994. Our purpose of systematic and very accurate measurement of $p + dA_y$ at $2 \sim 18$ MeV was to promote many theoretical challenges to solve $A_y$ puzzle. We think that the precise energy dependence of $A_y$ puzzle will be helpful to find the origin(s). Witala and Gloeckle suggested that $NN^3P_J$ interactions largely influence $N + dA_y$ value and have some relation to $A_y$ puzzle [13]. Kievsky studied the possibility of LS potential in 3NF [14]. Other theoretical attempts also have been made for $A_y$ puzzle, but $A_y$ puzzle has still not been solved.
Using the facility for polarization experiments developed at KUTL, we measured also $E_{16}$ energies but also $iT_{iT}$.

In the next section. It was an elaborate task because it was our first neutron experiment. The puzzle is now possible. Utilizing the precise and systematic $1.33 2$

List of measured cross section and analyzing powers of $p + d$ scattering

| $E_{c.m.}$ | $E_{\beta}$ | $E_{\bar{d}}$ | $A_y$ | $iT_{11}$ | $T_{20}$ | $T_{21}$ | $T_{22}$ | $\sigma$ |
|------------|-------------|-------------|------|----------|----------|----------|----------|---------|
| 1.33       | 2.0         | -           | o    | -        | -        | -        | -        | o       |
| 1.67       | 2.5         | 5.0         | o    | o        | o        | o        | o        | o       |
| 2.00       | 3.0         | 6.0         | o    | o        | o        | o        | o        | o       |
| 2.67       | 4.0         | 8.0         | o    | o        | o        | o        | o        | o       |
| 3.33       | 5.0         | 10.0        | o    | o        | o        | o        | o        | o       |
| 4.00       | 6.0         | -           | o    | -        | -        | -        | -        | o       |
| 4.33       | 6.5         | -           | o    | -        | -        | -        | -        | o       |
| 4.67       | 7.0         | 14.0        | o    | o        | o        | o        | o        | o       |
| 5.33       | 8.0         | -           | o    | -        | -        | -        | -        | o       |
| 5.67       | 8.5         | -           | o    | -        | -        | -        | -        | o       |
| 6.00       | 9.0         | 18.0        | o    | o        | o        | o        | o        | o       |
| 6.67       | 10.0        | -           | o    | -        | -        | -        | -        | o       |
| 8.00       | 12.0        | -           | o    | -        | -        | -        | -        | o       |
| 9.33       | 14.0        | -           | o    | -        | -        | -        | -        | o       |
| 10.67      | 16.0        | -           | o    | -        | -        | -        | -        | o       |
| 12.00      | 18.0        | -           | o    | -        | -        | -        | -        | o       |

After our $p + d$ measurement, we measured $n + d A_y$ at $E_n = 12$ MeV and $E_p = 16$ MeV, as described in the next section. It was an elaborate task because it was our first neutron experiment.

At present Coulomb force in $p + d$ scattering can be treated fairly reliably. Detailed investigation of $p + d A_y$ puzzle should be solved first, and the solution should be examined by $n + d A_y$ data.

2.4 Measurement of $iT_{11}$, $T_{20}$, $T_{21}$, $T_{22}$ of $p + d$ Scattering

Using the facility for polarization experiments developed at KUTL, we measured also $iT_{11}$, $T_{20}$, $T_{21}$ and $T_{22}$ of $p + d$ scattering using a polarized $d$-beam at $E_d = 5.0, 6.0, 8.0, 10.0, 14.0$ and $18.0$ MeV. The center-of-mass energy $E_{c.m.}$ of $p + d$ system is $2E_d/3$ in a $\bar{p}$-beam experiment, and is $E_d/3$ in a $d$-beam experiment. We measured the data listed in Table 1.

| $E_{c.m.}$ | $E_{\beta}$ | $E_{\bar{d}}$ | $A_y$ | $iT_{11}$ | $T_{20}$ | $T_{21}$ | $T_{22}$ | $\sigma$ |
|------------|-------------|-------------|------|----------|----------|----------|----------|---------|
| 1.33       | 2.0         | -           | o    | -        | -        | -        | -        | o       |
| 1.67       | 2.5         | 5.0         | o    | o        | o        | o        | o        | o       |
| 2.00       | 3.0         | 6.0         | o    | o        | o        | o        | o        | o       |
| 2.67       | 4.0         | 8.0         | o    | o        | o        | o        | o        | o       |
| 3.33       | 5.0         | 10.0        | o    | o        | o        | o        | o        | o       |
| 4.00       | 6.0         | -           | o    | -        | -        | -        | -        | o       |
| 4.33       | 6.5         | -           | o    | -        | -        | -        | -        | o       |
| 4.67       | 7.0         | 14.0        | o    | o        | o        | o        | o        | o       |
| 5.33       | 8.0         | -           | o    | -        | -        | -        | -        | o       |
| 5.67       | 8.5         | -           | o    | -        | -        | -        | -        | o       |
| 6.00       | 9.0         | 18.0        | o    | o        | o        | o        | o        | o       |
| 6.67       | 10.0        | -           | o    | -        | -        | -        | -        | o       |
| 8.00       | 12.0        | -           | o    | -        | -        | -        | -        | o       |
| 9.33       | 14.0        | -           | o    | -        | -        | -        | -        | o       |
| 10.67      | 16.0        | -           | o    | -        | -        | -        | -        | o       |
| 12.00      | 18.0        | -           | o    | -        | -        | -        | -        | o       |

Experimental setup of the present $d$-beam experiment on $p + d$ scattering was similar to that of the $\bar{p}$-beam experiment which is shown in Fig. 3. A $H_2$ gas target was used. A $d$-beam polarimeter was placed downstream of the $H_2$ target.

We made three kinds of measurements on $p + d$ scattering with the $d$-beam polarization axis being (a) in the vertical direction ($y$), (b) in the beam direction($z$), and (c) in the horizontal plane ($xz$-plane) with the beam polarization axis inclined $45^\circ$ from the beam axis. In each measurement, three magnetic sub-states of deuteron, $m_Z = 1, 0, -1$, were cyclically selected by changing the magnetic field strength in the spin filter in the polarized ion source (Fig. 1). By using this method, we measured (a) $A_y$, (b) $A_{zz}$ and (c) $A_{xz}$, and we finally obtained $ iT_{11} = \sqrt{3} A_y/2$, $T_{20} = A_{zz}/\sqrt{2}$, $T_{21} = -A_{xz}/\sqrt{3}$, and $T_{22} = (A_{xx} - A_{yy})/2\sqrt{3} = (-2A_{yy} - A_{zz})/2\sqrt{3}$.

Typical experimental results at $E_d = 6.0$ MeV are shown in Fig. 7. The data have very small experimental errors. Also at $E_d = 5.0, 8.0, 10.0, 14.0$ and $18.0$ MeV, similarly precise data as in Fig. 7 were obtained.

The experimental data were compared with Faddeev calculations by Takamiya in 1995. Treatment of Coulomb force in any Faddeev calculations was not exact at that time. We had tentatively the following characteristic features:

(1) There is also a large discrepancy in $iT_{11}$ similar to $A_y$ puzzle.
(2) $T_{22}$ has a simple-shape angular distribution, and a discrepancy seems to occur at around $T_{22}$ minimum at around $115^\circ$.
(3) It is not clear whether discrepancies exist in $T_{20}$ and $T_{21}$, although experimental data fairly disagreed with the approximate Coulomb calculation.

We had obtained systematic and precise data set of $p + d$ scattering analyzing powers, not only $A_y$ at 16 energies but also $iT_{11}$, $T_{20}$, $T_{21}$ and $T_{22}$ at 6 energies in a range of 2–18 MeV as indicated in Table 1.
Example of measured analyzing powers of $\vec{d} + p$ scattering at $E_d = 6$ MeV. Nuclear-Coulomb interference in $T_{20}$ was well reproduced. Experimental data disagree with the $pd$ calculation at around $120^\circ$ although Coulomb force was not correctly treated.

The data set is waiting for challenging calculations to find the origin(s) of $A_y$ puzzle as well as to examine tensor forces in detail. Coulomb force can be treated considerably correctly in $p + d$ reactions now. Therefore, new theoretical ideas can be investigated accurately by comparing calculations with our data set.

2.5 Measurement of Cross Section of $p + d$ Scattering

After we had finished the measurement of analyzing powers of $p + d$ scattering, we also measured $p + d$ scattering cross section from $E_p = 2–18$ MeV. Measurement of cross section does not require polarized beams, and $p + d$ scattering cross section measurements had existed since 1940’s. Even before our experiment, there were already a lot of data in $E_p = 2–18$ MeV region. The data were acquired at several laboratories in different eras by different groups. We aimed to obtain a complete data set, which was consistently measured at a laboratory by an experimental group. Consistency and accuracy are important criteria for a data set. Therefore, we began systematic and precise measurement of $p + d$ scattering cross section at 16 energies in $E_p = 2–18$ MeV region.

Precise measurement of cross section was far more difficult to perform than precise measurement of analyzing powers. In analyzing power experiments, production of polarized beam and precise determination of the beam polarization were hard tasks. After the polarized beams were prepared, measurements of analyzing power were rather easy because we just measured the relative difference (asymmetry) between different spin modes or between left and right counts. No absolute values were necessary.

On the contrary, in a cross section measurement, preparation of an unpolarized beam was easy, but an accurate determination of the absolute cross section was a very hard task. We had to determine the number of the beam particles, the target thickness, solid angle of the detector, the detection efficiency of the detector, the true count of detected particles after background subtraction, and so on. To measure the cross section within $\pm 1\%$ error, each factor listed above had to be determined within about $\pm 0.3\%$. In solid angle estimation, for example, error of $\pm 20 \mu m$ in 6 mm slit width causes $\pm 0.33\%$ error.

The most difficult task was estimation of the true proton and deuteron counts from the energy spectra within a $\pm 0.5\%$ error. Our methodology was described in detail in [6]. We used two detectors at the same angle on the left and right sides of the beam axis, similar to the measurement of analyzing powers. Obtained left- and right-spectra were used to make a double-check of our count estimation. In Si-detectors some incoming protons of energy higher than 10 MeV excited Si-nuclei and caused a count loss of protons. We also corrected the count loss which amounted to 0.6% at $E_p = 18$ MeV. In order to check our method we also measured $p + p$ scattering cross section at several energies using the same system. Our $p + p$ data agreed with other existing data within experimental errors of $\pm 1\%$. 

Fig. 7
Some of the measured data are shown in Fig. 8. Very precise and systematic data for angular distribution at 16 different energies were obtained. Systematic errors were within ±1.1% and statistical errors were typically ±0.3%. A precise data set of $p + d$ scattering cross section in 2–18 MeV region was completed.

The experimental data were compared with calculations by Takamiya (Private Communication), in which only long-range part of Coulomb force was taken into account using Coulomb phase shift. Our data matched his calculation on the whole. A dip caused by interference between Coulomb force and the nuclear force at forward angle was also fairly well reproduced.

2.6 Sagara Discrepancy

We found that the results of the measured cross section slightly disagreed with calculation, and the disagreement varied gradually with energy. The angular distribution of the $p + d$ cross section has only one minimum at around 120°, and has no maximum. The value of the minimum or the maximum is reliable because it is determined by fitting several data points and it does not depend on the origin of angle. Therefore we were able to precisely compare the measured cross section minimum with the calculated one. The experimental minimum was estimated accurately by fitting data with Legendre polynomials.

Figure 9 shows the ratio of calculated minimum to the measured minimum of $p + d$ scattering cross section. The ratio largely varies with energy. Although $p + d$ calculations at that time (1994) were not correct in the treatment of Coulomb force, systematic variation of the calculation/experiment ratio shown in Fig. 9 seemed to indicate some sort of anomalous phenomena.

Both the cross section minimum and $A_y$ peak appear at about 120°. The ratio of (calculation−experiment)/experiment at $A_y$ peak varies from −20 to −40% as in Fig. 6, and (calculation−experiment)/experiment of the cross section minimum varies from +20% to −30% as in Fig. 9, when the approximate Coulomb calculation is adopted. The two discrepancies are similar, but there is one definite difference, $A_y$ is a vector observable and cross section is a scalar one. Therefore, we guessed that the two discrepancies in $A_y$ and in cross section might have different origins, one is a vector-type and the other is a scalar-type.

Unfortunately, our discovery of the discrepancy of the cross section minimum in 1994 did not receive attention because the $p + d$ calculation at that time was not reliable in treatment of Coulomb force. Y. Koike
Fig. 9 Energy dependence of discrepancy at the cross section minimum of \( pd \) scattering. Present \( pd \) data were compared to \( pd \) calculation with Paris potential (solid circle), and to \( pd \) calculation with LS modified potential (open circle). Coulomb force was approximately treated.

Fig. 10 Transparency shown by Koike in 15th Few-Body conference (1997) at Groningen

Koike knew well of our discovery, but he did not show any interest in it till 1996. In 1996, a cross section of \( p + d \) scattering at \( E_d = 270 \text{ MeV} \) (equivalent to \( E_p = 135 \text{ MeV} \)) was measured at RIKEN on the way of constructing a \( \vec{d} \)-beam polarimeter which used \( p + d \) scattering [9]. Koike compared the RIKEN \( p + d \) data with his \( n + d \) calculation, and he found \(-30\%\) discrepancy between his calculation and the experiment at the cross section minimum, and he found that the \(-30\%\) discrepancy at 135 MeV was on the line extended from the discrepancies at 2–18 MeV. At 135 MeV, Coulomb effects are small, and the presence of \(-30\%\) discrepancy is of no doubt.

At FB15 conference in 1997 in Groningen, Koike gave a talk on the discrepancy at the minimum of \( p + d \) scattering cross section showing a transparency in Fig. 10. At the talk, he named the discrepancy at cross section minimum in all energy ranges as Sagara discrepancy. There were many questions about the discrepancy, and attendants understood the existence of the discrepancy.
The following year 1998, Witała et al. found that the discrepancy in $p + d$ scattering cross section (Sagara discrepancy) and the shortage of $^3$He binding energy were simultaneously solved by using the same $2\pi$3NF [10]. It was known before 1998 that the $^3$He binding energy could be reproduced by adjusting a cut-off parameter in $2\pi$3NF. Reproduction of only one observable by adjusting one parameter in $2\pi$3NF could not be evidence for $2\pi$3NF. In 1998, both the binding energy and many data on the cross section minimum in a wide energy range were excellently reproduced by adjusting a single parameter in $2\pi$3NF. Therefore, existence of $2\pi$3NF was confirmed and the strength of $2\pi$3NF was determined. It was a landmark event as 41 years had passed since the first paper on $2\pi$3NF in 1957 by Fujita and Miyazawa was written. Compared to the confirmation of Yukawa prediction on 2NF, confirmation of the existence of 3NF took a far longer time due to the weakness of 3NF.

After 1998, many experiments and theoretical studies were made regarding $2\pi$3NF. It was as if we were in 3NF boom. Most of the experiments were made on $p + d$ scattering at higher energies, and the cross section, the analyzing powers, the spin transfer coefficients, and even the spin correlation coefficients of $p + d$ scattering were measured.

We, KUTL group, took a different approach. We began our experiments on $pd$ capture and on $pd$ breakup at higher energy, searching for evidences of short-range 3NF such as $\pi\rho$3NF and $\rho\rho$3NF, essentially anything other than $2\pi$NF. Our studies have succeeded in finding new large discrepancies in $pd$ capture and in $pd$ breakup as described later in Sects. 4, 5, 6.

3 Experiment on $nd$ Scattering $A_y$

3.1 Planning for $nd A_y$ Experiment

When our systematic experiments on $pd$ scattering came to the fruition, we started preparations for experiments of $nd$ scattering $A_y$. At that time, in the early 1990’s, $pd$ calculations with realistic Coulomb force were not yet established. We had obtained high-precision systematic data of $pd$ scattering below 18 MeV using the tandem accelerator at KUTL. We had expected that $pd$ calculations would be made before we completed our $pd$ scattering experiments, by inventing versatile screening methods to treat Coulomb force.

It was estimated that calculations with realistic $NN$ potentials might be far more difficult than calculations with separable $NN$ potentials, because realistic $NN$ potentials require 2-dimensional integrals but separable potentials need 1-dimensional integrals. Calculations with realistic $NN$ potentials were made, however, $pd$ calculations could not be made even in 1994, when we finished our $pd$ experiments. There were no $pd$ calculations to be compared to our systematic $pd$ data. Investigation of discrepancies based on our $pd$ scattering data was postponed for a while.

Calculations of $nd$ scattering were correct enough, and discrepancies between $nd$ data and $nd$ calculations were reliable so far as $nd$ data were reliable. Precise determination of neutron detection efficiency in each experiment is very difficult, and a measurement of absolute cross section of $nd$ reactions needs high experimental techniques. Measurement of analyzing power $A_y$ does not need determination of detection efficiency, and $A_y$ data of $nd$ reactions were more reliable than that of cross section data of $nd$ reactions.

In order to investigate $A_y$ puzzle early in the 1990’s, precise and systematic data of $\bar{n}d$ scattering $A_y$ were indispensable. Experiments for $\bar{n}d$ scattering $A_y$ were made at $E_{\bar{n}} = 3$ MeV in Wisconsin [15], and above 5 MeV at TUNL at $E_{\bar{n}} = 5$ and 6.5 MeV [16], 8.5 MeV [17], 10 MeV [18], 12 MeV [19] and 14.1 MeV [20]. Measured $A_y$ data were about 25% higher than $\bar{n}d$ calculations around $A_y$ peak near 120°. That was $A_y$ puzzle.

To make sure of the presence of $A_y$ puzzle, we thought that other $\bar{n}d A_y$ data from other laboratories would be necessary. Important data such as $\bar{n}d A_y$ should be confirmed by several experiments at different laboratories. The more precise data would be very useful to investigate the origin of $A_y$ puzzle in detail. $A_y$ data over a wider energy range were also helpful to study $A_y$ puzzle.

We therefore planned in 1991 to make $\bar{n}d A_y$ experiments, first at $E_{\bar{n}} = 12$ MeV. After great efforts, we succeeded in our first $A_y$ experiment at 12 MeV. We then began the second experiment at 16 MeV. In 1991–1997, we managed to precisely measure $\bar{n}d$ scattering $A_y$ at $E_{\bar{n}} = 12$ and 16 MeV.

We had no previous experience on $n$-beam experiments as well as on production of a polarized $\bar{n}$-beam. It was a challenging experiment for us. In 1991 N. Nishimori entered graduate school of Kyushu University and joined our experimental group. He made many excellent pioneering works on our $\bar{n}d A_y$ project, collaborating with K. Sagara who was in his early 40s.
Our first task was to prepare a polarized $\vec{n}$-beam, which had enough intensity and its polarization, $p_n$, was precisely known. Compared to the preparation of a high-quality polarized $\vec{n}$-beam, measurement of $\vec{n}d A_y$ using the developed $\vec{n}$-beam was rather easy. Figure 11 shows a schematic view of setup for the production of a polarized $\vec{n}$-beam and calibration of the $\vec{n}$-beam polarization. Production of $\vec{n}$-beam from $\vec{d}$-beam, measurement of the polarization of the primary $\vec{d}$-beam, and measurement of the polarization of the produced $\vec{n}$-beam were necessary. When the target $^4$He in Fig. 11 was replaced by a CD$_2$ target, we were able to measure $\vec{n}d A_y$.

We adopted $^2$H($\vec{d}, n$)$^3$He reaction at $0^\circ$ for the $\vec{n}$-beam production. For example, a 12 MeV $\vec{n}$-beam was produced by $^2$H($\vec{d}, n$)$^3$He reaction using a 8.92 MeV $\vec{d}$-beam. Background neutrons were produced by $^2$H($\vec{d}, n$)pd breakup reaction. The background neutrons have continuum energy below 6.5 MeV. Due to an energy difference of more than 5.5 MeV between the $\vec{n}$-beam and n backgrounds, we could rather easily separate true events from background events. For example, times of flight of a 12 MeV neutron and a 6.5 MeV neutron to pass a 1m distance are 20.8 ns and 28.2 ns, respectively. The difference of 7.4 ns was enough to identify two neutrons.

Development of a $\vec{d}$-beam production system and precise determination of $\vec{n}$-beam polarization needed many test experiments and many improvements. These tasks were done in our home laboratory, KUTL. Repeated experiments were essentially important to obtain reliable consistent results. We developed a fast $n$-detection system, and the system was also repeatedly tested at KUTL.

Measurements of $\vec{n}d A_y$ were made at RIKEN using an intense polarized $\vec{d}$-beam from an injector AVF cyclotron. The beam intensity was several times higher at RIKEN than at KUTL. Owing to the high-intensity beam, $\vec{n}d A_y$ measurement at an energy (12 MeV or 16 MeV) was made in about 1 week.

We measured the angular distribution of $\vec{n}d A_y$ at $E_{\vec{n}} = 12$ MeV and 16 MeV. Our data at 12 MeV agreed well with TUNL data at the same energy. There were no preceding $\vec{n}d A_y$ data at 16 MeV. Experimental details are described in subsequent sub-sections.
Experimental Investigations of Discrepancies in Three-Nucleon Reactions

71

Fig. 12 D2 target for $\vec{n}$-beam production and $^3$He target for $\vec{d}$-beam polarimeter. Top view

The $\vec{d}$-beam, after passing through the D2 target, entered into the $^3$He gas target of 1.5 atm through a 3—µm thick Ta window foil. Polarization of the $\vec{d}$-beam was then measured using $^3$He($\vec{d}$, $p$)${}^4$He reaction which has large analyzing powers for both the vector and tensor polarized beams. The $^3$He($\vec{d}$, $p$)${}^4$He reaction has a high Q-value of 18.4 MeV, and ejected protons have high energy. The ejected protons were detected by Si-SSDs placed in the atmosphere, as shown in Fig. 12.

By this $^3$He($\vec{d}$, $p$)${}^4$He polarimeter, we measured the $\vec{d}$-beam vector and tensor polarizations $p_y$ and $p_{yy}$ which were necessary to determine the $\vec{n}$-beam vector polarization in the vertical direction, $p_{ny}$. To measure the beam $p_y$ and $p_{yy}$, analyzing powers $A_y$ and $A_{yy}$ of the $^3$He($\vec{d}$, $p$)${}^4$He polarimeter should be known. As described in Sect. 2, we had a $\vec{d}$-beam polarimeter whose analyzing powers were calibrated using $^{16}$O($\vec{d}$, $^4$He)$^{14}$N reaction, whose $A_{yy}$ was theoretically known from the spin selection rule. In a separate experiment, we measured $A_y(\theta, E)$ and $A_{yy}(\theta, E)$ of $^3$He($\vec{d}$, $p$)${}^4$He reaction by measuring the $\vec{d}$-beam polarization with the $\vec{d}$-beam polarimeter. Proton detectors of the $^3$He($\vec{d}$, $p$)${}^4$He polarimeter were set at an optimum angle to measure $p_{yy}$ and $p_y$ of a $\vec{d}$-beam simultaneously.

As seen in Fig. 12, all the beam slits, target foil windows, and the beam stopper were made of Ta. High Coulomb barrier produced by Ta ($Z = 73$) suppressed Ta + $d$ reaction induced by a low-energy $d$-beam. In production of a 12 MeV $n$-beam, neutron backgrounds were two orders of magnitude increased if we used widely-used Havar (Fe, Ni, Co) window foils instead of Ta foils.

The D2 target and $^3$He target were insulated from the beam duct, as indicated in Fig. 12, in order to measure the $\vec{d}$-beam current.

3.3 Polarization of $\vec{n}$-Beam

3.3.1 Overview

As described in the previous sub sections, a polarized $\vec{n}$-beam was produced by $^2$H($\vec{d}$, $n$)${}^3$He reaction at 0°. The $\vec{n}$-beam was used to measure $A_y$ of $\vec{n} + d$ scattering. In the $\vec{n}d$ $A_y$ experiment, polarization of $\vec{n}$-beam should be always measured (or monitored), because a long time was necessary for $\vec{n}d$ $A_y$ experiment and the $\vec{n}$-beam polarization would vary during the time. To measure directly the $\vec{n}$-beam polarization is ideal, but it is not practical owing to low $n$-detection efficiency and huge neutron backgrounds. Therefore we measured $\vec{d}$-beam polarization during the experiment using $^3$He($\vec{d}$, $p$) reaction because $p$-detection is much easier than $n$-detection.
The $\bar{n}$-beam polarization $p_{ny}$ has following relation with the $\vec{d}$-beam polarizations $p_y$ and $p_{yy}$ as,

$$p_{ny} = (3/2)p_y K_y^y(0^\circ)/\left\{1 - p_{yy} A_{yy}(0^\circ)/4\right\}$$

(5)

where $K_y^y(0^\circ)$ and $A_{yy}(0^\circ)$ are respectively the polarization transfer coefficient and the tensor analyzing power of $D(\vec{d}, n)^3\text{He}$ reaction at $0^\circ$.

We first determined the $K_y^y(0^\circ)$ and $A_{yy}(0^\circ)$ of $D(\vec{d}, n)^3\text{He}$ reaction by measuring $\vec{d}$-beam polarizations using $^3\text{He}(\vec{d}, p)^4\text{He}$ reaction and by measuring $\bar{n}$-beam polarization using $\bar{n}^+^4\text{He}$ scattering. Experimental setup is illustrated in Fig. 11.

Our next tasks were preparation of $\bar{n}$-detectors equipped with fast $n - \gamma$ separation system, and development of a liquid $^4\text{He}$ target which was also used as a scintillator.

### 3.3.2 Neutron Counter

We used standard liquid scintillation $n$-counters (NE213) with photo-multiplier tubes, shown in Fig. 13. A photo-signal produced by a neutron or a $\gamma$-ray rise up to the maximum and decays in a long time. A neutron photo-signal takes longer time to reach the maximum than a $\gamma$-ray photo-signal. Using the difference between the pulse shapes, N. Nishimori developed a fast and simple $n - \gamma$ separation circuit, and fabricated many copies with low cost. Typical time spectrum of $n - \gamma$ separation is shown in Fig. 14. Signals from $\gamma$-rays were almost completely discriminate out. In a $\vec{n}d$ $A_y$ experiment with a high-intensity beam, rejection of numerous background $\gamma$-rays by the circuits was very helpful.

We also developed a ring-memory system for fast data acquisition. Signals from $n$-counters were random in time and in high-counting rate. A signal was digitized by ADC in a few $\mu$-seconds and stored in a memory typically in $100$ $\mu$s. It was a considerably long time, causing $10\%$ counting loss for $1$ kcps data taking.

A ring memory accepted a signal from ADC in a few $\mu$s. A main memory accepted a signal from the ring memory in a constant speed of $100$ $\mu$s per signal. By use of the ring memory, dead time for one event was reduced from about $100$ $\mu$s to about $5$ $\mu$s. We could count signals of 10 kcps with only $5\%$ count loss. It was a great progress.
Fig. 14 Rise time spectrum from developed $n - \gamma$ separation circuit. We rejected $\gamma$-rays in the left peak.

Fig. 15 Liquid $^4$He target system. Target $^4$He was kept as super fluid. The liquid target worked also as a scintillator for $^4$He recoiled by $n$-beam.

3.3.3 Liquid $^4$He Target

To make $\bar{n} + ^4$He scattering experiment with high efficiency, we developed a liquid $^4$He (LHe) target system shown in Fig. 15. The LHe target was also used as a scintillation counter.

LHe target was contained in a cell of 25 mm in diameter and 50 mm in height. Target LHe was kept in super-fluid state, by evacuating LHe using a rotary vacuum pump. The LHe reservoir tanks were completely surrounded by walls at liquid nitrogen temperature. Walls of the LHe target system were made thin so as to reduce the scattering of neutrons by the walls.
3.4 Experimental Results

The meta-stable states of the $\vec{d}$-beam were switched cyclically in time as $m = 1, 0, -1$. That is, the $\vec{d}$-beam vector polarization was switched as $p_x, 0, -p_x$, and the tensor polarization as $p_{yy}, -2p_{yy},$ and $p_{yy}$. For each of the three states, neutrons from $^4\text{He}(\vec{n}, n)^4\text{He}$ scattering were detected both on the left and right sides of the beam axis at 4 angles. Typical energy (light output) spectra in the left and right counters (NE213) at the same angle $112^\circ$ are shown in Fig. 16. Large asymmetry between spin-up ($m = 1$) and spin-down ($m = -1$) events can be seen, and the asymmetries in the left and right counters are of opposite sign.

We denote $L^m$ for $n$-counts from $n-^3\text{He}$ scattering per $m$-state $d$-beam charge in a left $n$-counter. The experimental asymmetry in the left counter, $p_{ny}A(\theta)$, was obtained as,

$$p_{ny}A(\theta) = \frac{L^1 - L^{-1}}{L^1 + L^0 + L^{-1}}$$

The experimental asymmetry was obtained also from the right counter, and the left and right values were averaged.

The experimental asymmetry is related to $\vec{d}$-beam polarizations $p_{x}$ and $p_{yy}$ as

$$p_{ny}A(\theta) = \frac{(3/2)p_{y}K_{x}^{y}(0^o)A_{x}(\theta)}/[1 - A_{zz}(0^o)p_{yy}/4]$$

In order to know $p_{ny}$ from $p_{x}$ and $p_{yy}$, we need to determine $K_{x}^{y}(0^o)$ and $A_{zz}(0^o)$ of $^3\text{He}(\vec{d}, \vec{n})$ reaction. We obtained $A_{zz}(0^o)$ from the left counts using the relation

$$p_{yy}A_{zz}(0^o) = \frac{2(2L^0 - L^1 - L^{-1})}{(L^1 + L^0 + L^{-1})}$$
Experimental Investigations of Discrepancies in Three-Nucleon Reactions

Fig. 17 Curve is $A_y$ of $n-^4$He scattering at 12 MeV calculated using phase shifts by Bond et al. Our data for asymmetry $p_{ny}A_y(\theta)$ were scaled to fit the curve, and the $\vec{n}$-beam polarization $p_{ny}$ was determined from the common scaling factor.

Fig. 18 Polarization transfer coefficient $K_y(0^\circ)$ of $^2$H($\vec{d}, n$)$^3$He reaction. Solid circles are the present data.

Also from the right counts $A_{zz}(0^\circ)$ was obtained, and the two values were averaged.

In order to determine $K_y(0^\circ)$, we extracted $p_{ny}$ from $p_{ny}A(\theta)$ by estimating $A(\theta)$ from existing phase shift analyses. There are several phase shift analyses for $\vec{n}+^4$He scattering [22–25]. It is known that $\vec{n}+^4$He$A_y(\theta)$ takes the theoretical maximum $A_y=1.0$ at around $E_{\vec{n}}=12$ MeV and around $112^\circ$, and all the phase shift sets have the $A_y=1$ point in the region [21].

Our data for $p_{ny}A_y(\theta)$ at 4 angles were most excellently reproduced by prediction by the phase shifts of Bond et al., if the common parameter $p_{ny}$ was properly chosen, as shown in Fig. 17. We therefore determined $p_{ny}$ in this experiment using phase shifts of Bond et al. Then using the determined $p_{ny}$ and $A_{zz}(0^\circ)$ value, and the measured $p_y$ and $p_{yy}$, $K_y(0^\circ)$ of $^2$H($\vec{d}, n$)$^3$He reaction was determined.

Our data for $K_y(0^\circ)$ of $^2$H($\vec{d}, n$)$^3$He reaction at $E_{\vec{d}}=8.92$ MeV ($E_{\vec{n}}=12$ MeV) and at $E_{\vec{d}}=13.15$ MeV ($E_{\vec{n}}=16$ MeV) are plotted in Fig. 18 together with existing data [26–29]. Our $K_y(0^\circ)$ data were about 4% higher than other data. Our $A_{zz}(0^\circ)$ agreed with other data.

3.5 Experiments of $\vec{n}d A_y$

3.5.1 Experimental Procedure

After a long-time preparing for the polarized $\vec{n}$-beam production and determination of the $\vec{n}$-beam polarization, we measured $A_y(\theta)$ of $^4$He($\vec{n}, n$) scattering at $E_{\vec{n}}=12$ and 16 MeV. The experiments were done at RIKEN using a high-intensity polarized $\vec{d}$-beam of typically 2 $\mu$A.
Fig. 19 Present data for $A_y$ of $\vec{n}d$ scattering at 12 MeV (rectangle) and TUNL data (cross)

Fig. 20 Present $\vec{n}d$ $A_y$ data at 12 MeV and Faddeev calculation with Paris potential. A large discrepancy ($A_y$ puzzle) was confirmed

Backgrounds from Ta($\vec{d}, n$)X were about an order of magnitude more in the experiment at 16 MeV than in the experiment at 12 MeV. To reduce background neutron flux we increased the Pb shields.

3.5.2 Experimental Results

In Fig. 19, the present $\vec{n}d$ $A_y$ data at 12 MeV are compared with TUNL data at the same energy [19]. Both data agree with each other within experimental errors. As was seen in Fig. 18, our $K_y^{\vec{y}}(0^\circ)$ value at 12 MeV was about 4% higher than TUNL value. If the same $K_y^{\vec{y}}(0^\circ)$ value was adopted, both $\vec{n}d$ $A_y$ values would become closer. The present data are compared with calculation by Takemiya using Paris potential in Fig. 20. Experimental $A_y$ peak value is about 27% higher than calculated value, confirming $A_y$ puzzle.

Present data for $ndA_y$ at 16 MeV are shown in Fig. 21. At this energy there were no other $A_y$ data. Fitted $A_y$ peak value was 0.19 at 12 MeV, and 0.25 at 16 MeV.

3.5.3 Difference Between $\vec{n}d$ $A_y$ and $\vec{p}d$ $A_y$

The purpose of our first $\vec{n}d$ $A_y$ measurement at 12 MeV was to confirm the existence of $A_y$ puzzle without Coulomb force. Our present $\vec{n}d$ $A_y$ data coincided with existing TUNL $A_y$ data, and both data largely disagreed
Experimental Investigations of Discrepancies in Three-Nucleon Reactions

Fig. 21 Present data for $A_y$ of $\bar{n}d$ scattering at 16 MeV and Faddeev calculation with Paris potential

Fig. 22 Comparison of $\bar{n}d$ $A_y$ peak value and $\bar{p}d$ $A_y$ peak value

with the calculated $\bar{n}d$ $A_y$. $A_y$ puzzle at 12 MeV was completely confirmed through two experiments made at different laboratories.

Our second $\bar{n}d$ $A_y$ measurement at 16 MeV had two purposes: one was to accumulate evidences for $A_y$ puzzle, and the other was to examine a slow-down hypothesis [30]. The slow-down hypothesis is as follows. When $p$ and $d$ approach each other before they collide, repulsive Coulomb force ‘slowed-down’ the relative velocity between $p$ and $d$. As a result, $p$ and $d$ collide at a relative velocity that is a little slower than the relative velocity they had before they felt Coulomb repulsion. Therefore, $\bar{p}d$ scattering at $E_{\bar{p}d}$ is similar to $\bar{n}d$ scattering at $E_{\bar{n}d} = E_{\bar{p}d} - \Delta E_{SD}$, with $E_{SD}$ being about 0.6 MeV.

In Fig. 22, peak values at around 120° of $\bar{n}d$ $A_y$ and $\bar{p}d$ $A_y$ are plotted against $E_\bar{n}$ and $E_{\bar{p}}$. When $\bar{p}d$ $A_y$ peaks were fitted and the fitted curve was shifted to the left by 0.6 MeV, the shifted curve well reproduced $\bar{n}d$ $A_y$ data below $E_\bar{n} = 12$ MeV. The slow-down hypothesis seemed to work well below 12 MeV.

Our precise $\bar{n}d$ $A_y$ data at 16 MeV, however, apparently off the shifted curve as seen in Fig. 22. That fact indicates that the slow-down hypothesis does not hold. Large difference between $\bar{n}d$ $A_y$ and $\bar{p}d$ $A_y$ at 16 MeV is considered to be caused by nuclear forces. Why such large difference (i.e., charge asymmetry) is caused by nuclear forces, is a big problem to be investigated in the future.

In summary, we have two big problems on $NdA_y$ at low energy;

(a) $A_y$ puzzle in both $\bar{n}d$ $A_y$ and $\bar{p}d$ $A_y$
(b) Charge asymmetry between $\bar{n}d$ $A_y$ and $\bar{p}d$ $A_y$

It is an interesting task to examine problems (a) and (b) more accurately using recent reliable $\bar{p}d$ calculations and to search for their origin(s) based on challenging ideas.
4 pd Capture

4.1 Selection of Strategy

We measured analyzing powers and cross section of $p + d$ scattering at 2–18 MeV in 1988–1994, and we measured $n + d A_y$ at 12–16 MeV in 1994–1997. Precise datasets were obtained. Fortunately from the cross section data, existence of $2\pi 3NF$ was confirmed and strength of $2\pi 3NF$ was determined. Unfortunately, $A_y$ puzzle was not solved (even now).

What should we do next? We had two choices: one was to begin a new experiment different from $3N$ experiments, and the other was to continue $3N$ experiments but on different subjects. As a results, we did both.

Our new experiment was in astrophysics, on $^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} + \gamma$ reaction below $E_{\text{c.m.}} = 2.4$ MeV to investigate the helium burning process in stars. Our next $3N$ experiment was on pd capture, $p + d \rightarrow ^3\text{He} + \gamma$.

4.2 Why We Selected pd Capture?

There are three kinds of reactions induced by $p + d$ collision;

1. $p + d \rightarrow p + d$ (pd scattering)
2. $p + d \rightarrow p + p + n$ (pd breakup)
3. $p + d \rightarrow ^3\text{He} + \gamma$ (pd capture)

To find 3NF effects, pd breakup is considered to be more suitable than pd scattering, because there are many different kinematical configurations in $3N$ breakup and some configurations may be sensitive to 3NF. However, we do not know at present what configuration is the best to study 3NF.

On the other hand, pd capture has small number of observables, cross section and analyzing powers. In pd capture, $p + d$ scattering state transforms to $^3\text{He}$ ground state with high momentum transfer. The high momentum transfer and the compact structure of $^3\text{He}$ may be advantageous to study 3NF. Furthermore, Ishikawa predicted that $A_{zz}$ of pd capture seemed to be sensitive to 3NF [41].

We therefore made pd capture experiments at $E_d = 17.5$ MeV at KUTL, at $E_d = 197$ MeV twice at RCNP, and at $E_d = 137$ MeV at RCNP. These experiments are described below. Cross section of pd capture is very small, less than 1 $\mu$b. Hence special care was taken to increase detection efficiency and to reduce backgrounds.

4.3 pd Capture Experiment at $E_d = 17.5$ MeV

4.3.1 $\vec{d}$-Beam

A 17.5 MeV polarized $\vec{d}$-beam from Kyushu University tandem accelerator was used in this experiment. Tensor analyzing powers, $A_{xx}$, $A_{yy}$ and $A_{zz}$ of pd capture were measured. The $\vec{d}$-beam was tensor polarized in x, y or z direction, with z-axis being the beam direction, and y-axis being the vertical direction. Tensor polarization of the $\vec{d}$-beam, $p_{xx}$, $p_{yy}$ or $p_{zz}$ was measured always during the experiment using $^{12}\text{C}(\vec{d}, d)$ scattering. Before pd capture experiment, we measured analyzing powers $A_{xx}(\theta)$, $A_{yy}(\theta)$ and $A_{zz}(\theta)$ of $^{12}\text{C}$(d, d) elastic scattering at 17.5 MeV in an angular range of $96^\circ < \theta < 110^\circ$, where all the $A_{xx}$, $A_{yy}$ and $A_{zz}$ take the maximum values in magnitude, as shown in Fig. 23. The experimental setup is illustrated in Fig. 24.

4.3.2 Target

We used H$_2$ gas as the target, because CH$_2$ foil target was easily melted by $\vec{d}$-beam at about 200 nA at the present energy. Ordinarily, metal foils are used for the gas target windows, because metal foils can endure the beam heat. In the present detection of $^3\text{He}$ (true) events from

$$H \ (\text{target}) + \vec{d} \ (\text{beam}) \rightarrow ^3\text{He} \ (\text{true}) + \gamma \quad (9)$$

we had to remove the $^3\text{He}$ backgrounds, $^3\text{He}$ (BG) coming from

$$\text{Window (target)} + \vec{d} \ (\text{beam}) \rightarrow ^3\text{He} \ (\text{BG}) + \gamma \quad (10)$$
Fig. 23 Tensor analyzing powers of $^{12}$C($\vec{d}, \vec{d}$) elastic scattering at 17.5 MeV. The data were used for $\vec{d}$-beam polarimeter.

Counts of $^3$He(BG) are significantly larger than the counts of $^3$He(true), because (a) the cross section of (9) is less than 1 µb and the cross section of (10) is about 1–10 mb, and (b) the particle number in the gas target is 2–4 orders of magnitude lower than that in the window foils. Therefore the backgrounds $^3$He from (10) are several orders in number more than true $^3$He from (9). What material should we use for the window foil?

We chose carbon foils. Of course $^{12}$C and $^{13}$C cause ($d$, $^3$He) reactions, however, both $^{12}$C($d$, $^3$He) and $^{13}$C($d$, $^3$He) reactions have high negative $Q$-values. Therefore $^3$He(BG) produced in carbon foils have enough lower energy than $^3$He(true). All other foil materials produce $^3$He(BG) having higher energy than $^3$He(true). Higher energy $^3$He(BG) have lower energy tail which are harmful for detection of $^3$He(true) which are small in number.

To our knowledge, the use of a carbon foil for a gas target window was the first try in the world. Carbon foils are hard and easily broken. Besides, carbon foils of enough thickness (>0.1 mg/cm$^2$) are difficult to make.

We manufactured carbon foils of 0.36 mg/cm$^2$ in thickness by evaporating carbon onto glass plates by electric discharge in vacuum. Since only a little amount was evaporated in one discharge and a cooling time of about 5 s was necessary, we evaporated 6,000 times over 10 h to obtain carbon foils of 0.36 mg/cm$^2$ in thickness.

The thick carbon foils were pasted using an epoxy resin on the cylindrical inner walls of the gas target cell, as seen in Fig. 25. If a foil is pasted on a flat window and the foil is not elastic, tension of the foil produced by inner gas pressure is infinitely large and the foil is easily broken. By pasting the carbon foils on cylindrical
inner surfaces, we could contain the target gas of 0.8 atm in the target cell, and we could make \( pd \) capture experiment at 17.5 MeV.

4.3.3 \(^3\)He Detection

In the \( H(\vec{d}, \vec{H}e)\gamma \) experiment with a 17.5 MeV \( \vec{d} \)-beam and a hydrogen target, \(^3\)He recoils come out with energy from 10.6 MeV to 12.7 MeV at forward angles within \( \pm 2.6^\circ \) (the beam direction is 0\(^\circ\)). As illustrated in Fig. 24, \(^3\)He recoils were analyzed in momentum by a dipole magnet and were detected by a Si-SSD.

In a magnetic field of strength \( B \), a particle of mass \( m \), energy \( E \) and electric charge \( q \) is bent with the radius of the curvature \( \rho \) as

\[
B\rho = \sqrt{\frac{2mE}{q}} \tag{11}
\]

The field \( B \) is common for all the particles, and particles having the same \( \rho \) come to the detector. Huge background deuterons having the same \( \rho \) as \(^3\)He \((E_d = (3/8)E_{3He})\) came to the detector. The low energy deuterons were hallow-components of the \( \vec{d} \)-beam. They could be separated from true \(^3\)He in energy, but the counting rate of the backgrounds was too high and the detection system could not work.

We reduced the beam-hallow components by using a 4\(^\circ\)-deflecting magnet before the target, as shown in Fig. 24. The counting rate of the backgrounds in detector was 2–3 orders of magnitude decreased, and we were able to detect true \(^3\)He events.

A horizontal slit was placed in front of the Si-detector. Energy and position of \(^3\)He recoils on the detector plane are plotted in Fig. 26. The detector had 12 strips. Each strip detected higher-energy \(^3\)He and lower-energy \(^3\)He, as indicated in Fig. 26. Typical energy spectrum in one detector strip is shown in Fig. 27.

As indicated in Fig. 26, we detected \(^3\)He recoils at 12 \( \times \) 2 = 24 angles. As 6 points on the upper locus and 6 points on the lower locus had almost the same c.m. angles, they were averaged out to obtain 6 data points. Finally, we attained 18 data points in the range of \( \theta_{\text{c.m.}} = 23.1^\circ \text{–} 150.6^\circ \).

4.3.4 Experimental Results

We measured \( A_{xx}, A_{yy}, A_{zz} \) and \( A_y \) of \( p + d \rightarrow \vec{3He} + \gamma \) at \( E_d = 17.5 \) MeV. In Fig. 28, experimental results for \( A_{xx} + A_{yy} + A_{zz} \) are shown. We confirmed that our data satisfied the equality relation \( A_{xx} + A_{yy} + A_{zz} = 0 \) within experimental errors.

Next, our data were compared to Faddeev calculations by Golak et al. [31] using AV18 2NF and Tucson-Melbourne type \( 2\pi \) 3NF with the meson-exchange currents being taken into account. From Fig. 29, we concluded as follows,

(a) \( A_{xx} \) data agree well with 3NF calculation. \( A_{yy} \) data disagree, and \( A_{zz} \) data disagree a little with 3NF calculation.
Fig. 26 Vertical position ($x$) of 12-strips of Si detector and energy (high and low) of incoming $^3$He particles

Fig. 27 Energy spectrum of $^3$He detected by a detector strip

Fig. 28 Measured $A_{xx} + A_{yy} + A_{zz}$ of $pd$ capture at $E_d = 17.5$ MeV

(b) $A_y$ data agree well with 3NF calculation.
(c) Effects of $2\pi$3NF are relatively large in the tensor analyzing powers of $A_{xx}$, $A_{yy}$ and $A_{zz}$. 3NF effects are small in the vector analyzing power $A_y$. 
In Fig. 29, $A_{yy}$ and $A_{zz}$ data disagree with the calculation with $2\pi$ 3NF. As $2\pi$ 3NF is an established force, we should always include $2\pi$ 3NF in 3N calculations, and compare experimental data to calculations with $2\pi$ 3NF. The disagreement in Fig. 29 indicates that $2\pi$ 3NF+additional forces may be necessary to reproduce the data.

4.3.5 Discussion

We examined the energy dependence of $A_{yy}(90^\circ)$ and $A_{zz}(90^\circ)$ by collecting experimental data below $E_d = 45$ MeV [42–45]. Disagreement between experiment and 3NF calculation seemed to exist. However, the absolute values of $A_{yy}$ and $A_{zz}$ in this energy region are below 0.1, which are considerably small considering the range of $-2 \leq A_{ii} \leq 1$. The disagreement is therefore small.

To search for effects of short-range 3NF other than $2\pi$ 3NF, we decided to make $pd$ capture experiments at higher energy, where momentum transfer between the initial $p+d$ scattering state to the final $^3$He ground state is large, and short-range forces may play important roles. Absolute values of the tensor analyzing powers gradually increase up to about 0.5 at 200 MeV.

Experimental study on $p+d \rightarrow ^3$He + $\gamma$ reaction at $E_d = 17.5$ MeV was described in some detail in reference [32]. The experimental methods of recoiled-particle detection from a capture $\gamma$ reaction were succeeded to our another experiment of $^{12}$C + $^4$He $\rightarrow ^{16}$O + $\gamma$ reaction at KUTL to investigate the helium burning process in stars.

4.4 $pd$ Capture Experiment at $E_d = 196$ MeV

4.4.1 $\vec{d}$-Beam

Next we performed a $pd$ capture experiment using a 196 MeV polarized $\vec{d}$-beam from RCNP ring cyclotron. The beam polarization was set in the vertical (y) direction. Horizontal components of the beam polarization are rotated when the beam is bent in a magnetic field of a cyclotron. The polarization (spin) rotation angle $\theta_{pol}$ in a magnetic field is different from the beam bending angle $\theta_{beam}$, as $\theta_{pol} = g \theta_{beam}$, with $g = 0.857$ for a $\vec{d}$-beam and $g = 2.9$ for a $\vec{p}$ beam. The beam is $N$ times circulated during acceleration and is extracted from a cyclotron, then we have $\theta_{pol} = g \theta_{beam} = g(2\pi N)$, where $N$ is very large, for example about $10^4$. A beam extracted from AVF cyclotron is usually accompanied by $N \pm 1, N \pm 2$ components.

In a ring cyclotron (different from AVF cyclotron), $N$ can be determined uniquely in principle, and we can obtain a beam which is polarized in a direction in the horizontal plane. To obtain a single-turn beam of $N$ turns for a long time is difficult in practice, and impurity beams of $N \pm 1$ turns sometimes come together...
and deteriorate the polarization. In order to make a reliable polarization experiment, we decided to use only a vertically polarized \( \vec{d} \) beam.

### 4.4.2 Determination of \( \vec{d} \)-Beam Polarization

To determine the beam polarization, a beam polarimeter is necessary and we have to calibrate the effective analyzing power of the beam polarimeter. We chose \( \vec{d} + p \) scattering for the \( \vec{d} \)-beam polarimeter. A \( \vec{d} \)-beam passed through a thin CH\(_2\) foil of about 1.3 mg/cm\(^2\) in thickness was placed in the beam line, and elastically scattered \( p \) and \( d \) were detected in coincidence by two plastic scintillators to reduce huge backgrounds. In our polarimeter calibration, we used \( ^{12}\text{C}(\vec{d},\alpha)^{10}\text{B}(2^+)_\text{at}\) reaction at 0°, whose analyzing power is theoretically known as \( A_{yy} = -1/2 \) (i.e., \( A_{zz} = 1 \)) from spin-selection rule. Experimental setup is shown in Fig. 30.

The measured \( \vec{d} \)-beam polarization was very low as about a half of the value expected from the ion source operation. We made the second calibration after a few months, and got the same results. In our third experiment, we finally found the cause.

A polarized beam and an unpolarized beam were cyclically produced by changing ion-source operation. Polarized data and unpolarized data were separately stored into different memories. The beam charge was accumulated in a Faraday cup, and the accumulated amount was measured in discharging process in a current integration circuit.

The beam polarization was quickly changed. We stopped data-accumulation during the changing process, and restarted data-accumulation after the change was completed. The interval, during which data-accumulation was stopped, was set to be 0.01 s at RCNP for a long time. In our third experiment, however, we found that the interval of 0.3 s was necessary to completely discharge the accumulated charge in a current integrator. If the interval was short, beam discharge was not completed, and the remaining beam charge was treated as the charge of the next differently-polarized beam. As a result, beam charges were mixed and averaged.

The unpolarized \( d \)-beam had about 1.3 times higher beam intensity than the polarized beam, but the measured intensity was only 1.1–1.2 times higher. Therefore, the calculated beam polarization was low. In the third calibration experiment, we found this failure by chance. We changed the stopping interval from 0.01 to 1.0 s, and the beam polarization was correctly measured. Finally, we calibrated effective analyzing power of our \( \vec{d} \)-beam polarimeter using \( \vec{d} + p \) scattering as,

\[
\begin{align*}
A_y(30^\circ) &= 0.341 \pm 0.006, \quad A_{yy}(30^\circ) = 0.615 \pm 0.011 \\
A_y(36^\circ) &= 0.437 \pm 0.008, \quad A_{yy}(30^\circ) = 0.568 \pm 0.010
\end{align*}
\]

where angles in parentheses are those of protons scattered in the laboratory frame. We measured vector and tensor polarization of the \( \vec{d} \)-beam always during the experiment using two pairs of scintillation counters.
The stopping interval of 0.01 s had been used for a long time before our experiment. In polarized $\vec{p}$-beam experiments, the short interval was not so harmful because the $\vec{p}$-beam intensities in spin-up and spin-down modes were almost the same.

4.4.3 Liquid Hydrogen Target

In our $pd$ capture experiment at $E_\vec{d} = 17.5$ MeV, we used a gas H$_2$ target confined by carbon foil windows. In the present experiment at 196 MeV, we needed a thicker hydrogen target having thin window foils, because the $pd$ capture cross section decreased and backgrounds from window foils increased with energy.

We first developed a liquid nitrogen (LN$_2$) cooled H$_2$ gas target of 6 atm $\times$ 10 mm in length confined by Mylar window foils of 25 $\mu$m in thickness. With this target, backgrounds were found to be an order of magnitude higher in number than the true $^3$He events from $pd$ capture. We gave up trying with gas target.

Next, we developed a liquid hydrogen (LH$_2$) target contained in Aramide foil windows of 4.4 $\mu$m in thickness. Aramide foil is made up of polyimide and has high tensile strength. Figure 31 shows our LH$_2$ target system. A reservoir tank for H$_2$ gas was placed in the atmosphere, and was connected through a flexible pipe to the LH$_2$ target cell in a vacuum scattering chamber. The target cell was cooled down to about 17 K to liquefy hydrogen. The LH$_2$ target was almost completely shielded by walls at LN$_2$ temperature to cut radiation heat from walls at the room temperature.

The thickness of the LH$_2$ target was rather thin at about 1.5 mm ($\approx 10$ mg/cm$^2$), in order to reduce the energy loss of $^3$He recoils in the target, for example, a 100 MeV $^3$He loses about 1.3 MeV in 1.5 mm thick LH$_2$. Compared to our cooled H$_2$ gas target, our LH$_2$ target had 70 times more H-content, and window foils of 1/4 thickness. As a result, the background level was reduced to 1/280, and we were able to clearly detect $^3$He recoils from $pd$ capture.

As seen in Fig. 31, the LH$_2$ target could be raised about 10 cm, and foil targets, such as a beam viewer and a CH$_2$ foil, could be utilized. It was a helpful function.

The temperature of LH$_2$ target was kept constant using a heater and two thermometers made of Si diodes. The density of LH$_2$ varies 1–2% in 1 degree. When H$_2$ become solid by over-cooling and the window foils were broken, a half day was necessary to re-change the LH$_2$ target.

By heating the target, LH$_2$ target easily become H$_2$ gas target and the gas could be evacuated by a vacuum pump. We frequently used the empty target to measure backgrounds.

4.4.4 $^3$He Detection

An experimental setup for $pd$ capture is illustrated in Fig. 32. The $\vec{d}$-beam was incident on LH$_2$ target, and the recoiled $^3$He and the $\vec{d}$-beam were bent by a magnetic spectrograph called LAS (large acceptance spectrograph). Recoiled $^3$He were momentum-analyzed by LAS, and detected by vertical drift chambers (VDC) and a
Experimental Investigations of Discrepancies in Three-Nucleon Reactions

Fig. 32 Setup for $p\bar{d}$ capture experiment using LAS (large acceptance spectrograph) at RCNP

Fig. 33 a Energy and laboratory angle of $^3$He from $pd$ capture at $E_d = 196$ MeV. b Vertical slit for LAS at $0^\circ$ to measure $A_{xx}$. c Horizontal slit for LAS at $3^\circ$ to measure $A_{yy}$ and $A_y$

plastic scintillator. When LAS was placed at $0^\circ$ as seen in Fig. 32, the beam entered into LAS and was stopped by a Faraday cup. When LAS was placed at $3^\circ$, the beam was stopped by a Faraday cup in the scattering chamber.

In the laboratory system, $^3$He recoils from the $pd$ capture were ejected within a cone of a half angle of $4.7^\circ$, as indicated in Fig. 33a. LAS has vertical acceptance of $\pm 5.7^\circ$ and horizontal acceptance of $\pm 3.4^\circ$. We used a vertical slit in Fig. 33b to measure $A_{xx}$ with the beam polarization being in the vertical direction. A horizontal slit in Fig. 33c was used to measure $A_{yy}$ and $A_y$ with LAS placed at $3^\circ$. $^3$He recoils at $1.5^\circ \leq \theta_{\text{lab}} \leq 4.7^\circ$. 
(about \(20^\circ \leq \theta_{\text{c.m.}} \leq 160^\circ\)) were allowed to pass through the slits, and were detected by counters. The angular distribution of \(^3\text{He}\) in \(20^\circ \leq \theta_{\text{c.m.}} \leq 160^\circ\) was simultaneously measured in one shot.

We obtained the following information for each event:

(a) time of flight from the target to the scintillator
(b) energy loss in the scintillator
(c) direction and position of particle ray at VDC1 and VDC2.

Using the above information, we were able to identify \(^3\text{He}\) events. A typical spectrum for \(A_{xx}\) measurement (LAS at \(0^\circ\)) is shown in Fig. 34, where the \(^3\text{He}\) events through the vertical slit were clearly seen. The horizontal position \((X)\) corresponds to the \(^3\text{He}\) momentum, thereby, to \(\theta_{\text{c.m.}}\). Higher-\(Y\) or lower-\(Y\) events correspond respectively to the \(^3\text{He}\) recoils passed through the upper or lower vertical slits in Fig. 33a. Pure backgrounds spectra were obtained using an empty target.

The data in a band from \(X_1\) to \(X_2\) were projected onto a \(Y\)-axis. In Fig. 34, the projected spectrum is displayed with normalized background spectrum. From the spectrum, the background subtraction was made, and we obtained data for \(A_{xx}\).

In Fig. 35, the typical spectrum for \(A_{yy}\) measurement (LAS at \(3^\circ\)) is shown. The projected spectrum in the lower part of Fig. 35 indicates that backgrounds were well estimated also in the measurement of \(A_{yy}\).
Experimental Investigations of Discrepancies in Three-Nucleon Reactions

4.4.5 Experimental Results

Experimental results for $A_{xx}$, $A_{yy}$, $A_y$ and cross section of $pd$ capture at $E_d = 196$ MeV are shown in Fig. 36, together with MEC calculation by Witała and Golak (Private Communication) with 2NF alone (dashed lines) and with 2NF + 2π 3NF (solid lines). Systematic error of the measured cross section data was about ±7%.

$A_{xx}$ and $A_y$ were well reproduced by calculation with 2π 3NF. $A_{yy}$ data agreed fairly well with the calculation. However, $A_{xx}$ data strikingly disagreed with the calculation. Inclusion of 3NF decreased $A_{xx}$ a little, but the discrepancy between the experiment and the calculation in $A_{xx}$ was several times larger than the 2π 3NF effects.

$A_{xx}$ data were measured in the vertical plane, and two kinds of data were obtained, one through the upper slit and the other through the lower slit. The two kinds of $A_{xx}$ data agreed well with each other. The beam polarization was nearly the same in both $A_{xx}$ and $A_{yy}$ measurements. Therefore $A_{xx}$ data were reliable.

4.4.6 Discussions

The present data for $pd$ capture have an interesting feature. Experimentally, a relation of $A_{xx} \approx A_{yy}$ holds, although theoretically $A_{xx} \neq A_{yy}$. The relationship $A_{xx} = A_{yy}$ indicates a symmetry with respect to z-axis (the beam axis).

A deuteron has a prorate shape. If a deuteron-induced reaction takes place in a nuclear peripheral region, $A_{xx} \neq A_{yy}$ is expected to appear. Indeed, in most of deuteron-induced reactions other than the $dp$ capture, the relation $A_{xx} = -A_{yy}$ approximately holds. When a $d$-beam polarized in the $x$ direction enhances the reaction, a $d$-beam polarized in the $y$ direction suppresses the reaction. There are many such examples of $A_{xx} \approx -A_{yy}$ in $(d, d)$, $(d, ^3\text{He})$, $(d, ^4\text{He})$ reactions and even in the $d + p$ scattering.

It is very interesting to investigate whether the $A_{xx} \approx A_{yy}$ relation (axial symmetry) in $pd$ capture is caused by short-range 3NF such as $\pi\rho$ 3NF and $\rho\rho$ 3NF, or not.

So far as we know, there have been no reports nor discussions on the $A_{xx} \approx A_{yy}$ relation, not only in $pd$ capture but also in other reactions. Before we investigate the origin(s) of the $A_{xx} \approx A_{yy}$ relation in $pd$ capture, we should confirm the relation in a wider energy region. Therefore, next we measured $A_{xx}$ and $A_{yy}$ of $pd$ capture of $E_d = 137$ MeV. The experiment is described below.

4.5 Experiment on $pd$ Capture at $E_d = 137$ MeV

4.5.1 Why 137 MeV?

In most $pd$ capture experiments, $A_y$ and $A_{yy}$ were measured, but $A_{xx}$ and $A_{zz}$ were scarcely measured. A $\vec{d}$-beam from a cyclotron is difficult to polarize in a horizontal ($xy$) plane, and the measurement was...
generally made using a vertically (y) polarized \( \vec{d} \)-beam and by detecting the reaction products in the horizontal plane. \( A_y \) and \( A_{yy} \) were measured in this method. We did measurement of \( A_{xx} \) of \( pd \) capture at \( E_d = 196 \text{ MeV} \) using a vertically polarized \( \vec{d} \)-beam and by detecting \( ^3\text{He} \) recoils in the vertical plane. We found the \( A_{xx} \approx A_{yy} \) relation in \( pd \) capture at \( E_d = 196 \text{ MeV} \). Our previous experiment at \( E_d = 17.5 \text{ MeV} \) also support \( A_{xx} \approx A_{yy} \) relation. At 17.5 MeV, values of \( A_{xx} \) and \( A_{yy} \) are small as about +/-0.03, and both \( A_{xx} \) and \( A_{yy} \) roughly agree with calculations. Calculations predict \( A_{xx} \approx A_{yy} \) below \( E_d = 20 \text{ MeV} \). Above \( E_d = 100 \text{ MeV} \), predicted \( A_{xx} \) and \( A_{yy} \) are largely different to each other.

We decided, therefore, to measure \( A_{xx} \) and \( A_{yy} \) of \( pd \) capture at \( E_d = 137 \text{ MeV} \), where the analyzing powers of \( p + \vec{d} \) scattering had been measured \cite{33} and the data could be used for a \( \vec{d} \)-beam polarimeter.

**4.5.2 Experimental Procedure**

Experimental setups for \( pd \) capture at \( E_d = 137 \text{ MeV} \) were almost the same as those at \( E_d = 196 \text{ MeV} \). As the energy of the \( ^3\text{He} \) recoils decreased, we tried to make a thinner LH2 target, however, it proved impossible because the thin window foils swelled out in a vacuum scattering chamber by inner pressure of the target. As a result, the thickness of the LH2 target was the same as before, 1.5 mm (\( \approx 10 \text{ mg/cm}^2 \)).

Polarizations \( p_y \) and \( p_{yy} \) of the \( \vec{d} \)-beam at 137 MeV were measured using \( p + \vec{d} \) scattering in the same manner as before. We used the analyzing powers of \( A_y \) and \( A_{yy} \) of \( pd \) scattering measured at \( E_d = 140 \text{ MeV} \) \cite{33}.

The \( \vec{d} \)-beam was polarized in the vertical direction, and \( A_{xx}(\theta) \) and \( A_{yy}(\theta) \) of \( pd \) capture at \( E_d = 137 \text{ MeV} \) were measured in the vertical plane and in the horizontal plane, respectively. Compared to the previous experiment at 196 MeV, background levels were high, probably due to an increased multiple scattering in the target and in the exit window foil of LAS where Kevlar mesh was used. Therefore, analysis of the data was difficult and took a lot of time.

**4.5.3 Experiment Results**

The experimental results are shown in Fig. 37. First we made data-analysis by the single-cluster method, which was used also in the analysis of 196 MeV data. The analysis of 137 MeV data was not succeeded due to background problems and low detection efficiency. Therefore, we gave up the single-cluster method and developed a new multi-cluster II method, which will be described in Sect. 4.7.2. The results in Fig. 37 were obtained by the new multi-cluster II method.

As shown in Fig. 37, the relation \( A_{xx} \approx A_{yy} \) was also confirmed at \( E_d = 137 \text{ MeV} \). A large discrepancy in \( A_{xx} \) between the experiment and the calculation was also observed at 137 MeV. \( A_{yy} \) data agreed well with MEC calculations by Witala and Golak (Private Communication). The effects of 2\( \pi \) 3NF were small in both \( A_{xx} \) and \( A_{yy} \). The same three characteristics were recognized both at 137 MeV and at 196 MeV.
4.6 Experiments of \(pd\) Capture at KVI

At KVI, \(A_{yy}\) and \(A_{zz}\) of \(pd\) capture were measured at \(E_d = 133\) MeV and at 180 MeV [46]. Their \(A_{yy}\) and \(A_{zz}\) data fairly well agreed with calculations. From the identical relation \(A_{xx} + A_{yy} + A_{zz} = 0\), their \(A_{xx}\) also fairly well agreed with calculations.

On the contrary, our data on \(A_{xx}\) (and \(A_{zz}\)) at \(E_d = 137\) MeV and 196 MeV noticeably disagreed with calculations. What was the cause of the contradiction? There were two different points between the experiments at KVI and at RCNP. The detection systems were largely different, and the selected reaction plane was different. In both experiments, the \(d\)-beam was polarized in the vertical direction.

In our experiment at RCNP, the \(^3\)He recoils were momentum-analyzed by a magnetic dipole LAS, and detected by four VDCs and one scintillator in coincidence. For each event, we measured \(\Delta E\) in scintillator, time-of-flight (TOF) from the target to the scintillator, and positions at VDCs. From the measured positions at four VDCs, we defined the particle-ray (direction and position), and also obtained \(p/q\) (momentum/charge). Backgrounds were measured using an empty target and were subtracted carefully. \(A_{yy}\) was measured in the horizontal plane, and \(A_{xx}\) in the vertical plane.

In KVI experiment, they detected \(^3\)He recoils and \(\gamma\)-rays in coincidence. \(^3\)He recoils were momentum-analyzed by a dipole magnet and were detected by a scintillator, and \(\gamma\)-rays were detected by a scintillator array system around the target. The reaction planes were defined by \(\gamma\)-ray detectors, and the energy and TOF of the \(^3\)He recoils were measured. Background measurement was not made. \(A_{yy}\) was measured in the horizontal plane, and \(A_{zz}\) was measured in two \(x = \pm y\) planes which were inclined by \(\pm 45^\circ\) from the horizontal plane (\(xz\) plane) with respect to the beam axis (z-axis).

In both experiments, \(A_{yy}\) were measured in the same horizontal plane and agreed fairly well with each other. On the other hand, \(A_{xx}\) in RCNP and \(A_{zz}\) in KVI were measured in different planes, and they considerably disagreed with each other when we compared them using the equality relation of \(A_{xx} + A_{yy} + A_{zz} = 0\).

Therefore we decided to make a confirming experiment to measure \(A_{xx}\) in the vertical plane, \(A_{yy}\) in the horizontal plane, and \(A_{zz}\) in the \(\pm 45^\circ\) inclined plane. Consistency check could be made by comparing \(-A_{xx} - A_{yy}(= A_{zz})\) data with \(A_{zz}\) data obtained in the same experiment. The energy was selected as 196 MeV, because the absolute values of \(A_{ii}\) are about twice larger at 196 MeV than at 137 MeV.

4.7 Confirming Experiment at 196 MeV

4.7.1 Experimental Procedure

Setups for the new \(pd\) capture experiment at \(E_d = 196\) MeV were almost the same as those in the previous experiment at 196 MeV. The biggest difference was in that we made new \(A_{zz}\) measurement in addition to \(A_{xx}\) and \(A_{yy}\) measurements which were the same as before. Data acquisition speeds became several times faster than in the previous experiment. Although staff members remained almost the same, all the students were new.

We used three slits (see Fig. 38) to measure \(A_{xx}, A_{yy}\) and \(A_{zz}\). The raw data for the three measurements are shown in Fig. 39, together with the backgrounds taken using an empty target.
4.7.2 Data Analysis Method

Compared to our previous experiment at the same energy, the background levels in the new experiment were a few times higher, due to a higher beam intensity, remaining beam hallow, and thicker target window foils. When background particles passed near the true $^3$He ray in a VDC plane, the $^3$He signal in the VDC was deteriorated. In the conventional single-cluster method, such an incomplete $^3$He ray was discarded and $^3$He detection efficiency decreased. In the new experiment, the detection efficiency was very low as about 45\% when we used the single-cluster method.

A number of real events was estimated by dividing a number of analyzed events by the detection efficiency. The correction of $1/0.45$ was too big an amount, and yielded a large uncertainty in the estimation of real counts. Analyzing powers were obtained from a small difference between real counts of different spin-modes, and were greatly influenced by the error in real counts. To reduce the errors in analyzing powers, we needed to increase the detection efficiency.

We used a pair of VDCs to define a particle ray in one direction. Using two pairs of VDCs in different direction ($x$ and $y$, for example), we were able to define a complete ray.

In the conventional single-cluster method, each VDC should have only one cluster as seen in Fig. 40a, and the VDC events of two or more clusters as in (b) and (c) were discarded. The ray was easily defined, but lots of the events were discarded and the detection efficiency was low.

In the multi-cluster method, events having many clusters were analyzed and the most probable ray in various combinations between two clusters was adopted. When a background particle passed near the true particle in a VDC, the two clusters piled up. In the multi-cluster method, events including piled-up clusters were discarded.

We developed a new multi-II method. A pair of a normal cluster and a piled-up cluster was adopted when the pair formed the most probable ray. We could roughly define the ray direction from a complete cluster. If there was a piled-up cluster near the ray direction, we adopted the cluster pair as a ray. In multi-II method, a real ray was discarded when its clusters in both VDC’s were made as piled-up clusters by backgrounds. Such cases were rare, and the count loss in multi-II method was a few percent.
Fig. 40 Data analysis methods for a pair of X1 VDC and X1 VDC. a) Single-cluster method analyzed only a single cluster in one VDC. b) Multi-cluster method analyzed many but complete clusters in one VDC. c) Multi-II method analyzed even a ray composed of a complete cluster and a piled-up cluster, to decrease count loss.

Fig. 41 New $A_{xx}$ and $A_{yy}$ data from the confirming experiment using multi-II method (solid circle) and single-cluster method (open circle).

Our previous $A_{xx}$ and $A_{yy}$ data at 196 MeV were analyzed in the single cluster analysis. We re-analyzed the previous data in the multi-II method. Both of $A_{xx}$ and $A_{yy}$ results are compared in Fig. 41. Corresponded results in the multi-II are a little small in the absolute values. As seen in Fig. 41, $A_{xx}$ anomaly remained and $A_{yy}$ data agreed fairly well with calculations.

4.7.3 Experimental Results

In Fig. 42, new experimental results at 196 MeV for $A_{xx}$, $A_{yy}$ and $A_{zz}$ are shown. Our previous data which were re-analyzed in the multi-II are also shown in the same figure. Three kinds of $A_{zz}$ data are compared in Fig. 42.

1. previous $-A_{xx} - A_{yy} (= A_{zz})$ data,
2. present $-A_{xx} - A_{yy} (= A_{zz})$ data, and
3. present $A_{zz}$ data measured in $\pm45^\circ$ planes.

All three kinds of $A_{zz}$ data basically matched each other, through they scattered to some extent. That means that $A_{zz}$ data are about 1.5 times higher than the calculated value.
4.8 Summary

Although the present data of \(pd\) capture are not final ones, we conjecture the followings from the present data.

1. \(A_{xx}\) and \(A_{zz}\) of \(pd\) capture at 137 MeV and 196 MeV largely disagree with calculations, and \(A_{yy}\) of the same reactions agrees with calculations.

2. A relation \(A_{xx} \approx A_{yy}\) holds in \(pd\) capture in the energy range from \(E_{\vec{p}} = 17.5\) MeV to 196 MeV. KVI data at 133 MeV and 180 MeV also support the \(A_{xx} \approx A_{yy}\) relation within experimental errors, although KVI \(A_{zz}\) data disagree with ours.

3. Effects of \(2\pi\) 3NF are too small to reduce the large discrepancy in \(A_{xx}\) (and in \(A_{zz}\)) and to explain the \(A_{xx} \approx A_{yy}\) relation.

It is very interesting to investigate the origin(s) of (1–3). Short-range 3NF (SR3NF) other than \(2\pi\) 3NF may be candidates for the origin(s). We are awaiting calculations with various SR3NF.

5 Experiment on \(pd\) Breakup at \(E_{\vec{p}} = 247\) MeV

5.1 Motivation

Different from \(pd\) scattering and \(pd\) capture, \(pd\) breakup has a variety of reaction dynamics due to the presence of three outgoing particles in the final state. Nuclear force models of 2NF and 3NF can be examined in various situations in \(pd\) breakup reaction.

The cross section of \(pd\) breakup is smaller than that of \(pd\) scattering below about \(E_{\vec{p}} = 50\) MeV. Above 50 MeV, \(pd\) breakup becomes dominant, for example, the \(pd\) breakup cross section is about 10 times larger than that of \(pd\) scattering at 250 MeV. As the \(pd\) capture cross section is about 1/1000 of the total cross section, \(pd\) breakup is the main process in \(p + d\) reactions at high energy.

After we found \(2\pi\) 3NF, we have been searching for short-range 3NF (SR3NF). Effects of SR3NF are expected to become large at higher energy and can be seen also in \(pd\) breakup. The problems is how to find...
SR3NF effects in $pd$ breakup and what is the best way for us. Experiments of $pd$ breakup under various kinematical conditions need lots of time even if the breakup cross section is large.

We decided to make first an inclusive $D(p, p_1)p_2n$ measurement at $E_p = 247$ MeV so as to obtain a global feature, then to make exclusive $D(p, p_1p_2)n$ measurements at selected kinematical conditions at the same energy. In the inclusive measurement, only one outgoing proton which has continuum energy is detected, similar to the measurement of inelastic scattering, although proton detection over a wide energy range is necessary.

The incident energy of $E_p = 247$ MeV was selected referring to $pd$ elastic scattering experiments. Below $E_p = 140$ MeV, $pd$ scattering cross section was well reproduced by including $2\pi$ 3NF. Above 150 MeV, the experimental cross section of $pd$ scattering at backward angles was found to become larger than the calculation, even if $2\pi$ 3NF was included. In Fig. 43, the experiment/calculation ratio of $pd$ scattering cross section at $\theta_{c.m.} = 150^\circ$ is shown. The experiment/calculation ratio is 1.0 below 140 MeV, and gradually increases with energy above 150 MeV.

Around the $\pi$-threshold of 210 MeV, the ratio varies monotonically. The influence of $\pi$-channel seems to be small. We thought that an investigation of the anomalous experiment/calculation ratio could be performed well even above 210 MeV. At higher energy, the ratio becomes larger, but theoretical calculations becomes less reliable because lots of higher angular momentum states are taken into account. We decided, to make a $pd$ breakup experiment at $E_p = 247$ MeV, where measurement of $pd$ scattering was made at RCNP [40].

5.2 Experiment of $D(p, p_1)p_2n$ at 247 MeV

A polarized $\vec{p}$-beam of 247 MeV from the RCNP ring cyclotron was incident on a liquid $D_2$ target, and one of outgoing protons from $p + d \rightarrow p_1 + p_2 + n$ reaction was detected using a large acceptance spectrometer (LAS) which consisted of Q- and D-magnets with a set of drift chambers and a scintillation counter. To detect protons over a wide energy range from 70 to 250 MeV, LAS was used in four different magnetic fields. Proton detection by LAS was made at $7^\circ$, $10^\circ$, $15^\circ$ and $20^\circ$.

The $\vec{p}$-beam was polarized in the vertical direction, and the beam polarization was measured by a beam-line polarimeter which used $pp$ scattering. The beam intensity was measured by a Faraday cup in the scattering chamber.

There were two crucial points in this experiment; the background subtraction and the evaluation of absolute cross section. We used a liquid deuteron ($L_2$) target of about 10 mm in thickness (140 mg/cm$^2$). The beam entrance and exit windows of the liquid target were made of thin Aramide foils of 6 $\mu$m in thickness (0.9 mg/cm$^2$). This polymer foils produced background protons from $(p, p')$ reactions including elastic and inelastic scatterings.

Liquid $D_2$ becomes gas $D_2$ above 20 K, and the density is three orders of magnitude smaller in gaseous $D_2$ than in liquid $D_2$. By heating the target up to about 70 K, we measured backgrounds from the window foils. Background were nearly equal in number to the true protons from $L_2$ target around $E_p = 70$ MeV, and 1/10 at around 150 MeV, and about 1/100 at around 230 MeV. If we used a $C_2$ target instead of a $L_2$ target, the
background level might be about 200 times higher. Our LD$_2$ target was an almost pure D$_2$ target and was very effective to reduce backgrounds.

To evaluate the absolute cross section, we needed to know the target thickness, beam charge, solid angle of the detector, and the counting loss of the detection system, in addition to make background subtraction. Measurement of the liquid target thickness was made as follows.

The target window foils swelled out by the inner pressure when the target was placed in vacuum, and the target thickness was about 1–2 mm increased. We could not measure the target thickness in vacuum. Moreover, the density of LD$_2$ increases by a few % when the target temperature decreases by 1 degree. During the measurement of several hours, the temperature slowly drifted by about ±1 degree.

We therefore used a reference CD$_2$ foil target whose thickness was known. During the D$(p, p_1)p_2n$ experiment at 247 MeV using a LD$_2$ target, protons elastically scattered by the LD$_2$ target were always counted using a target monitor system consisting of two plastic scintillators. Using the same system, protons elastically scattered by the reference CD$_2$ target were also counted, and relative thickness of the two targets was determined.

The reference target was a CD$_2$ foil of about 10 mg/cm$^2$ in thickness. We fabricated the foil. The target foil thickness was measured accurately using a 12 MeV $p$-beam at KUTL and using the precise $pd$ scattering cross section at the same energy [6]. In other words, the absolute value of D$(p, p_1)p_2n$ cross section at 247 MeV was determined referring to the $pd$ scattering cross section at 12 MeV.

5.3 Results of D$(p, p_1)p_2n$ Experiment at 247 MeV

Results of D$(p, p_1)p_2n$ experiment at 247 MeV are shown in Fig. 44 with the D$(n, n_1)n_2p$ calculations by Wita (Private Communication). Both the measured cross section and $A_y$ disagreed with the calculations. The measured cross section is at the most twice the size of the calculations. Although $2\pi3NF$ increases the cross section, much more increase is necessary to reproduce the experimental data.

In general, analyzing powers are considerably influenced by the modification of the cross section, but the cross section is little influenced by modification of the analyzing powers. Our policy is as follows:

(a) If there is a dominant discrepancy in the cross section, the first thing we need to find is the origin(s) of this discrepancy.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig44}
\caption{Cross section (left) and $A_y$ (right) of D$(p, p_1)p_2n$ reaction at 247 MeV. Effects of $2\pi3NF$ increase the cross section (Witala, Private Communication), but are insufficient to reproduce the experimental data.}
\end{figure}
Fig. 45 Kinematic S-curve in $E_1 - E_2$ plane. Only the cross section in the region of $E_1 = (150 \pm 7.5)$ MeV was measured by the spectrograph GR.

(b) When the cross section is fairly well reproduced, then we can proceed in investigating remaining problems of analyzing powers.

We decided first to investigate the origin(s) of the large discrepancy in $pd$ breakup cross section in Fig. 44. There seems be one problem near FSI peak at around $E_p = 110$ MeV. Another problem may exist at around $E_p = 150$ MeV where the relative discrepancy takes on the largest value. At around 150 MeV, no characteristic reaction mechanisms are considered to occur.

We decided then to investigate first the discrepancy at around 150 MeV. At around 150 MeV, experimental cross section is about twice larger than the calculation at forward angles, and the discrepancy varies gradually with energy and angle. The origin of the discrepancy seems be simple in nature.

5.4 Measurement of $D(p, p_1 p_2)n$ Cross Section at 247 MeV

From the preceding kinematically incomplete $D(p, p_1) p_2 n$ experiment, we saw a global feature of the discrepancy in the cross section. Next we started a microscopic investigation of the discrepancy by a kinematically complete measurement of $D(p, p_1 p_2)n$ cross section. From the dependence of the discrepancy on angle pairs $(\theta_1, \theta_2, \phi_{12})$, we are able to see whether the discrepancy is distributed over a wide area or if it is concentrated to a special region.

Two protons from $D(p, p_1 p_2)n$ reaction were detected in coincidence using two big magnetic spectrometers, LAS and GR (Grand Raiden), at RCNP. GR was set at $\theta_1$ and LAS was set at $\theta_2$, on the left and right sides of the beam axis, respectively, in the horizontal plane. Therefore, $\phi_{12}$ was fixed at an angle of 180°. From the dynamic ranges of rotation of the two big counters, $\theta_1$ and $\theta_2$ should satisfy the following conditions; (a) $\theta_1 < 70^\circ$, (b) $\theta_2 < 90^\circ$, and (c) $\theta_1 + \theta_2 > 48^\circ$. The two big counters would collide to each other at $\theta_1 + \theta_2 = 48^\circ$.

Under the condition of $\phi_{12} = 180^\circ$, we chose four angle pairs as, $(\theta_1, \theta_2) = (15^\circ, 35^\circ)$, $(15^\circ, 50^\circ)$, $(15^\circ, 65^\circ)$, and $(15^\circ, 80^\circ)$. Measurement of $D(p, p_1 p_2)n$ cross section at 247 MeV was made only at the four angle pairs, due that kinematically complete measurement in high statistics need a lot of time.

At each angle pair, proton energies $E_1$ and $E_2$ vary from 0 MeV up to 245 MeV as seen in Fig. 45. GR and LAS were able to detect protons only in energy ranges of $E_0 \pm 0.05 E_0$ and $E_0 \pm 0.3 E_0$, respectively, when their magnetic fields were set to detect protons around $E_0$. Therefore, detecting protons in all the energy ranges was practically impossible. We chose only $E_1 = (150 \pm 7.5)$ MeV region at each angle pair, as indicated in Fig. 45, to achieve high statistic data in a limited beam time.

The procedure of $D(p, p_1 p_2)n$ experiment was similar to that of the previous $D(p, p_1) p_2 n$ experiment. A 247 MeV $p$-beam from RCNP cyclootron was guided onto a LD$_2$ target, and the $p$-beam was stopped in a Faraday cup in a scattering chamber. We used an unpolarized $p$-beam in this experiment and measured only the cross section. The thickness of the LD$_2$ target was monitored during the experiment by detecting $p$ and $d$ from $pd$ scattering in coincidence. A reference CD$_2$ target was used to evaluate the thickness of the LD$_2$ target.
Fig. 46 Measured cross section of D($p, p_1p_2$)n reaction at ($\theta_1 = 15^\circ, \theta_2 = 35–80^\circ, \phi_{12} = 180^\circ$). Inclusion of 2$\pi$3NF increases the cross section.

To detect two protons at $\theta_1 = 15^\circ$ and $\theta_2 = 35–80^\circ$ in coincidence in D($p, p_1p_2$)n experiment, we modified the standard scattering chamber at RCNP. The scattering chamber was equipped with two sliding membrane systems to connect in vacuum to two rotatable spectrometers, LAS and GR. The sliding membrane system needed a space, and measurement of D($p, p_1p_2$)n reaction at ($\theta_1 = 15^\circ, \theta_2 = 35^\circ$) could not be made.

We therefore removed the sliding membrane systems, and sealed the windows of the scattering chamber with Aramide foils of 25 $\mu$m in thickness. The scattering chamber and the two spectrometers were disconnected. Protons came out of the scattering chamber through the window foil, passed over a 5 cm distance in the air, and entered the vacuum spectrometer through a window of Aramide foil. Energy loss and angular spread of the protons through the foils and in the air were negligible because the proton energy was higher than 50 MeV.

5.5 Results of D($p, p_1p_2$)n Experiment at 247 MeV

Figure 46 shows the measured D($p, p_1p_2$)n cross section at four angle pairs at 247 MeV and D($n, n_1n_2$)p calculations with and without 2$\pi$3NF by Kamada (Private Communication). As $\theta_2$ goes to forward, the breakup cross section increases, and the measured cross section becomes larger than the calculated one. Effects of 2$\pi$3NF are not enough to explain the discrepancy in the cross section.

In Fig. 47, $\theta_2$ dependence of the discrepancy is shown. The discrepancy in D($p, p_1p_2$)n cross section around $E_1 = 150$ MeV at $\theta_1 = 15^\circ$ increases as $\theta_2$ goes forward. We know also that the discrepancy in D($p, p_1$)p2n cross section around $E_1 = 150$ MeV increases as $\theta_1$ goes forward. Therefore, the discrepancy around $E_1 = 150$ MeV seems to be concentrated at forward angle pairs. This information is important to make conjecture on the origin of the discrepancy in the breakup cross section.

Further measurement at forward angle pairs may be helpful for the investigation of the discrepancy. Measurement at $\theta_1 + \theta_2 < 48^\circ$ using the existing big spectrometers is impossible as described above. Measurement at $\theta_1 + \theta_2 < 48^\circ$ would be possible if we develop a new counter system.

In the same beam time for the D($p, p_1p_2$)n experiment, we measured again D($p, p_1$)p2n cross section using the same $p$-beam at 247 MeV. Data analysis is in progress. Preliminary data for the present D($p, p_1$)p2n experiment agreed with our previous data.
5.6 Discussion on Discrepancy in $pd$ Breakup Cross Section at High Energy

We call the discrepancy found in $pd$ breakup cross section at 247 MeV as high-energy $pd$ breakup discrepancy (HEBU discrepancy). HEBU discrepancy is different from Sagara discrepancy at $pd$ scattering cross section minimum, and also different from $pd$ space-star anomaly to be described in the next section. As seen in Fig. 47, HEBU discrepancy appears when cross section is locally large. On the contrary, the other two discrepancies appear when cross section is small. Besides, as seen in $D(p, p_1p_2)n$ data in Fig. 44, HEBU discrepancy appears over a wide proton energy range from 80 to 180 MeV. From the above characteristics, HEBU discrepancy seems to reflect fairly dominant reaction mechanism.

HEBU discrepancy appears at forward angle. On the contrary, high-energy discrepancy in $pd$ scattering cross section (HESC discrepancy) appears at backward angle. Whether HEBU discrepancy and HESC discrepancy have a common origin or not is a very interesting subject to study. More systematic experimental data on HEBU discrepancy may be helpful to find its origin(s). The present data for HEBU discrepancy, however, may be sufficient to start theoretical investigations. We hope various calculations are made based on challenging ideas.

6 $pd$ Breakup at Low Energy

6.1 Introduction

Historically, we first made experiments on $pd$ scattering and $nd$ scattering at low energy in order to study $A_y$ puzzle, and found a signature of $2\pi$3NF from the discrepancy in $pd$ scattering cross section. Next we made $pd$ capture experiments at from $E_d = 17.5$ MeV to 196 MeV to search for short-range 3NF (SR3NF) other than $2\pi$3NF, and we found $A_{xx}$ anomaly which might be a possible signature for SR3NF. Then we started experiments on $pd$ breakup at $E_p = 247$ MeV, and found a discrepancy in cross section which also seems to be a signature of SR3NF. Theoretical investigations are being made on the discrepancies in $pd$ capture and $pd$ breakup at high energy. In the near future, information on SR3NF will be obtained from the above data. We are surely getting close behind SR3NF.

On the other hand, $A_y$ puzzle at low energy remains unsolved, as already discussed in Sects. 2 and 3. At low energy, there is another big problem of Space Star anomaly (SS anomaly). Both $A_y$ puzzle and SS anomaly have little relation with 3NF, because they appear only at low energy.

We have possible candidates for origin(s) of $A_y$ puzzle. For SS anomaly, however, we have no candidates for its origin(s). SS anomaly is a discrepancy in $Nd$ breakup cross section which is a scalar quantity, and SS anomaly requires modification of scalar part of nuclear forces. The scalar part is basic in nuclear interactions, and modification of it causes influence on all the observables not only in 3N systems but also in 2N systems.

We thought that a systematic experiment on SS anomaly might be the remaining big task in our 3N study, and we started the experiment on $pd$ SS anomaly in 2000.
6.2 SS Configuration

We express $Nd$ breakup reaction as $1 + (2 + 3) \rightarrow 1 + 2 + 3$, where 1, 2, and 3 represent nucleons and $(2 + 3)$ stands for a deuteron. Let’s consider $1 + (2 + 3) \rightarrow 1 + 2 + 3$ reaction in the c.m. system. Outgoing three nucleons take various sets of momentum $(P_1, P_2, P_3)$ under the condition $P_1 + P_2 + P_3 = 0$.

When positions of three outgoing nucleons form an equilateral triangle, we call the configuration as ‘Star’. In Star, relations of $|P_1| = |P_2| = |P_3|$, and $|P_{12}| = |P_{23}| = |P_{31}|$ hold, where $P_{ij}$ is a relative momentum between $i$ and $j$ nucleons. When the equilateral triangle is perpendicular to the beam axis, as illustrated in Fig. 48, the configuration is called as Space Star.

In $1 + (2 + 3) \rightarrow 1 + 2 + 3$ breakup, there are two mechanisms which enhance the breakup cross section. One is the quasi-free scattering (QFS) and the other is the final state interaction (FSI).

QFS between 1 and 2 assumes that (a) the incident nucleon 1 causes scattering with 2, and (b) 3 acts as a spectator with its momentum unchanged. Therefore in the deuteron $(2 + 3)$ just before the breakup, 2 and 3 are assumed to have momenta $P_3$ and $P_3$, respectively, and consequently to have the relative momentum $P_{23} = -P_3$. The cross section of QFS between 1 and 2 is proportional to a product of the deuteron form factor and the cross section of elastic scattering between 1 and 2. The deuteron form factor $\phi_d(P_{23})$ takes its maximum value at $|P_{23}| = 0$. Therefore QFS cross section is enhanced at $|P_{23}| = 0$, i.e., at $|P_3| = 0$ or equivalently at $E_3 = 0$. The $3N$ breakup reaction is enhanced when QFS cross section is enhanced.

The breakup cross section is also enhanced by FSI which occurs when relative energy between two nucleons in the final state becomes small, down to 0. This is because NN (nucleon-nucleon) scattering cross section is small and varies slowly as if it were constant. Such conditions are advantageous to detect minor effects. We remember that $2\pi 3NF$ was found from the minimum of $pd$ scattering cross section, where effects of 2NF are small and $2\pi 3NF$ effects become relatively large.

6.3 Discovery of SS Anomaly in $nd$ Breakup

A large discrepancy in $nd$ breakup cross section between experiment and calculation was first found at $E_n = 13$ MeV and at 10.5 MeV [34]. An $n$-beam was produced by D(d, n)$^3$He reaction at $0^\circ$, and the $n$-beam was incident on a CD$_2$ target, and scattered neutrons were detected by liquid scintillators. The CD$_2$ target worked also as a scintillator for d-recoils. Measured $nd$ breakup cross section around SS was larger than calculated values by about 30% at $E_n = 13$ MeV and by about 15% at 10.3 MeV.

Experiments with a $n$-beam are much more difficult than those with a $p$-beam or $d$-beam. Moreover, precise measurement of the cross section is more difficult than measurement of analyzing powers. Therefore,
Fig. 49 Experiment/calculation ratio of \( \text{Nd} \) breakup cross section at Space Star. The ratio is higher than 1 for \( \text{nd} \) SS, and lower than 1 for \( \text{pd} \) SS.

Experiments on \( \text{nd} \)-SS cross section were performed at only a few laboratories, at Erlangen [34,39], Bochum [37], TUNL [35,36], and Bonn–Beijing [38].

Experimental results of SS cross section are illustrated in Fig. 49 in terms of the ratio of experiment to calculation. Experimental \( \text{nd} \) cross section is higher than calculated values. The ratio becomes largest at \( E_n = 13 \) MeV and gradually decreases to 1.0 as the energy increases.

Occurrence of \( \text{nd} \)-SS anomaly only in low energy region resembles the feature of \( A_y \) puzzle. \( A_y \) puzzle is prominent below \( E_N = 20 \) MeV and seems to fade out at above 30 MeV. The similarity between \( A_y \) puzzle and \( \text{nd} \)-SS anomaly does not directly mean that they have a common origin. \( A_y \) is vector, and SS anomaly is on the breakup cross section which is scalar.

To precisely investigate origin(s) of SS anomaly, further accumulation of the \( \text{nd} \)-SS cross section would be helpful. However, precise experiments on the \( \text{nd} \) cross section are very hard and to make experiments on \( \text{pd} \)-SS is much more advantageous if we have the \( \text{pd} \) breakup calculation in which Coulomb force is reliably treated.

6.4 Experiments on \( \text{pd} \) Breakup at SS

Before \( \text{pd} \) breakup calculations became available, only a few experiments on \( \text{pd} \)-SS were made and the \( \text{pd} \) data were compared with \( \text{nd} \) calculations. Typical experiments on \( \text{pd} \)-SS cross section before \( \text{pd} \) calculation were made at Kölín [47,48] and at Kyushu [50]. After calculation on \( \text{pd} \) breakup was succeeded by Deltuva et al. [52], we started our systematic measurement on \( \text{pd} \) SS cross section, and the measurement is still going on.

The ratios of the existing \( \text{pd} \) SS cross section data to \( \text{pd} \) calculations, together with the ratios for \( \text{nd} \) SS cross section, are displayed in Fig. 49. The ratio of experiment/calculation gradually becomes 1.0 as the energy increases in both \( \text{pd} \) breakup and \( \text{nd} \) breakup as seen in Fig. 49. \( A_y \) puzzle has the similar energy dependence.

Another feature of SS anomaly is a remarkable charge asymmetry. Experimental cross section at SS is lower than calculation in \( \text{pd} \) breakup, and higher than 1.0 in \( \text{nd} \) breakup as seen in Fig. 49. \( A_y \) puzzle does not have such a remarkable charge asymmetry.

SS anomaly is a very curious phenomenon. Our investigation on \( \text{pd} \) SS anomaly is described below.

6.5 Experiment on \( \text{pd} \) Breakup Around SS at \( E_p = 13 \) MeV

At \( E_n = 13 \) MeV, \( \text{nd} \)-SS anomaly seems to become largest as seen in Fig. 49. It is to be investigated whether 13 MeV is a special energy or not. We therefore chose \( E_p = 13 \) MeV and made a systematic measurement on \( \text{pd} \) breakup cross section around \( \text{pd} \)-SS configuration [50].

A 13 MeV \( \text{p} \)-beam from Kyushu University tandem accelerator was incident on a \( \text{CD}_2 \) foil target. Two protons from \( \text{p} + \text{d} \rightarrow \text{p}_1 + \text{p}_2 + \text{n} \) breakup reaction were detected in coincidence at 23 angle pairs of \( (\theta_1, \theta_2, \phi_{12} = 120^\circ) \), shown in Fig. 50 where \( \phi_{12} = (\phi_1 - \phi_2) \) is a relative azimuthally angle between two
**Fig. 50** Angle pairs \((\theta_1, \theta_2, \phi_{12} = 120^\circ)\) where \(D(p, p_1 p_2)n\) cross section at \(E_p = 13\ \text{MeV}\) was measured. A star mark indicates SS configuration.

**Fig. 51** Measured \(D(p, p_1 p_2)n\) cross section around SS at 13 MeV. Coulomb force decreases the cross section only a little and there remains a discrepancy between the \(pd\) experiment and the \(pd\) calculation.

Since the cross section is the same at \((\theta_1, \theta_2)\) and \((\theta_2, \theta_1)\), we obtained 15 independent cross section data at 7 angle pairs for \(\theta_1 = \theta_2\) and 8 pairs for \(\theta_1 \neq \theta_2\). At \((\theta_1, \theta_2, \phi_{12}) = (50.5^\circ, 50.5^\circ, 120^\circ)\), \(pd\)-SS appears.

Some of the measured data at \(\theta_1 = \theta_2\) are displayed in Fig. 51, with the recent \(pd\) calculation by Deltuva et al. [52]. At all the angle pairs, the measured \(pd\) breakup cross section is lower than the \(pd\) calculation. Coulomb effects are not large around \(pd\)-SS. Effects of \(2\pi\) 2NF are very small at this low energy.

To see a trend of \(pd\)-SS anomaly, several data around \(E_1 = E_2\) at each pair \((\theta_1, \theta_2, 120^\circ)\) were averaged and the average was compared with calculated average as shown in Fig. 52. Experiment is 10–15% lower than calculation in \(\theta_1 + \theta_2\) range of about \(\pm 15^\circ\) around SS. Outsides of \(\pm 15^\circ\) from SS, the experiment tends to become close to the calculation, although more data are necessary to confirm the phenomenon.

### 6.6 Off-Plane Star Anomaly at \(E_{\vec{d}} = 19\ \text{MeV}\)

A large anomaly at \(pd\) star apart from \(pd\)-SS was found by Köln group at \(E_{\vec{d}} = 19\ \text{MeV}\) in 2006 [51]. In their \(\vec{d} + p \rightarrow p_1 + p_2 + n\) experiment with a \(\vec{d}\)-beam, outgoing \(p_1, p_2\) and \(n\) formed a star (equilateral triangle), and the star plane was inclined from the horizontal plane by an angle from \(0^\circ\) to \(56^\circ\).
Let's define an inclined angle $\alpha$ of a star in the c.m. system as shown in Fig. 53. We always detect $p_1$ and $p_2$ at the same polar angle, $\theta_1 = \theta_2$. When $p_1$, $p_2$ and $n$ form a star and $\theta_1 = \theta_2$ is satisfied, we then define an inclined angle $\alpha$ as the angle between the proton momentum in the initial state $P_p$ and the momentum sum $P_1 + P_2$ in the final state, as in Fig. 53. When $\alpha = 90^\circ$, the inclined star is called as Space Star. When $\alpha = 0^\circ$ or $\alpha = 180^\circ$, the star is called as in-plane star, and otherwise the star is called as off-plane star.

At Köln University tandem laboratory, cross section and analyzing powers of $pd$ breakup at $E_d = 19$ MeV were measured at stars at $\alpha = 180^\circ$, 162.3$^\circ$, 144$^\circ$ and 124$^\circ$. Striking feature was seen in their experimental data. The $pd$ breakup cross section at the inclined star was about 25% lower than $pd$ calculation. The discrepancy was larger than that $pd$-SS anomaly which was about 15% at most.

Whether star anomaly is confined near SS, or star anomaly is spread over all $\alpha$ range, is a big problem. A confined anomaly is rather easy to think. We have to examine whether star anomaly appears over a wide angular range or not.

6.7 Systematic Measurement of $\alpha$-Dependence of $pd$ Star Cross Section

6.7.1 Plan for Experiment

Fortunately, a reliable calculation of $pd$ breakup was made available in 2005 by introducing a new screening method of Coulomb force by Deltuva et al. [52]. We are now able to compare precise $pd$ data with reliable $pd$ calculations, and can obtain concrete conclusions.

We have started, therefore, a systematic measurement of $p + d \rightarrow p_1 + p_2 + n$ cross section at $pd$ star in a wide angular region of $0^\circ \leq \alpha \leq 180^\circ$, first at $E_p = 13$ MeV ($E_d = 26$ MeV) and next at 9.5 MeV. A $p$-beam and a CD$_2$ target were used in $0^\circ \leq \alpha \leq 105^\circ$, and a $d$-beam and a CH$_2$ target were used in $120^\circ \leq \alpha \leq 180^\circ$, so as to detect higher-energy $p_1$ and $p_2$ in the laboratory frame. We used unpolarized beams in order to concentrate on reliable measurement of the cross section.

To save time, we made simultaneous measurements at three angle pairs using three pairs of Si-detectors placed on both left and right sides of the beam axis.
6.7.2 Evaluation of Cross Section

In addition, a beam-monitor Si detector was used to detect $p$ and $d$ from $pd$ elastic scattering. The absolute value of $pd$ breakup cross section was evaluated by comparing the breakup counts to the elastic scattering counts and using precise $p + d$ scattering cross section whose total errors are within about 1% [6]. The main source of systematic error came from the evaluation of solid angles of detectors. A typical aperture of a detector had a radius of $9.0 \pm 0.05$ mm in diameter and was $350 \pm 0.5$ mm from the target.

6.7.3 Rotary Foil Target

Also to save time, we developed a rotary foil target and increased the beam intensity by a few times. A polyethylene foil of CH$_2$ or CD$_2$ was melted when heated by a 13 MeV $p$-beam or a 26 MeV $d$-beam of about 200 nA. Therefore the beam intensity was limited to about 100 nA. Besides, D (H) content in the CD$_2$(CH$_2$) target foil decreased by a beam irradiation, even if the target foil did not melt. Decrease of D (H) content was roughly proportional for integrated beam charge. We assumed that the chemical bonds in CD$_2$ polymer were cut by a $p$-beam and D (or D$_2$) content might escape from the CD$_2$ target foil.

Our rotary foil target had a large diameter of 50 mm and the beam irradiated an area typically of 30 mm in diameter. The target was rotated in 20 rpm (rounds per minute). By rotating the foil target, an increase in foil temperature was reduced to about 1/10. A speed of 20 rpm was enough to reduce the foil temperature in our simulation. By the rotation at 30 mm in diameter, the rate of D-content reduction in CD$_2$ target foil was found to be decreased to about 1/100. For example, we injected a 200 nA $p$-beam on a 0.3 mg/cm$^2$ thick target CD$_2$ foil, and the reduction of D-content in CD$_2$ foil was about 5% per day. Usually, we used a beam of 250–400 nA on the rotary target. We saved the beam-time by a few times, or we used a thinner foil target so as to reduce energy loss of reaction products in the target. The rotary target proved to be a very useful apparatus for our low energy $p + d$ experiments.

6.7.4 Experimental Results

Examples of the measured cross section data of $p + d \rightarrow p + p + n$ at off-plane star are displayed in Fig. 54. At several angles of $\alpha$, we repeated the same experiments using our home machine at KUTL to confirm the results. Confirming experiments are very important to obtain reliable experimental data which are necessary for precise study of nuclear physics. Confirming experiments can be made easily in a home laboratory like KUTL, but such experiments are very difficult to make in big laboratories.

To see $\alpha$-dependence of star anomaly, we estimated the average cross section from a few data points around $pd$ star, and compared it to the calculation averaged in the same range as experimental data.

The ratio of the averaged experiment/calculation is shown in Fig. 55. Our previous data at 13 MeV at around $\alpha = 90^\circ$ [50] and K&ln data at 9.5 MeV ($E_d = 19$ MeV) at $124^\circ \leq \alpha \leq 180^\circ$ [51] are also included in Fig. 55. Error bars indicate only statistical errors. Systematical errors are 3–4%, except for at $\alpha \leq 30^\circ$ where data-analysis is still on-going and the systematical errors at present are about $\pm 7\%$. In Fig. 55, there are three kinds of possible anomalies, (a) at $70^\circ \leq \alpha \leq 110^\circ$, (b) at $\alpha \leq 30^\circ$, and (c) at $120^\circ \leq \alpha$ at 9.5 MeV ($E_d = 19$ MeV).
The anomaly (a) is SS anomaly. Figure 55 indicates that $pd$-SS anomaly (of about 15%) exists at $\alpha = 90^\circ$ and the anomaly decreases to zero in about $\pm 20^\circ$ range of $\alpha$. Our previous experiment around $pd$-SS at 13 MeV with conditions of $\theta_1 = \theta_2 = 120^\circ$ and $47.5^\circ \leq \theta_1 \leq 63^\circ$ ($\theta_1 = 50.5^\circ$ at SS) approximately correspond to off-plane star at $85^\circ \leq \alpha \leq 120^\circ$ within $\pm 15^\circ$ differences in $\phi_{12}$. SS anomaly in $pd$ breakup occurs only around $\alpha = 90^\circ$, and fades out at about $\alpha = 90^\circ \pm 20^\circ$. This characteristic feature is helpful in considering the origin(s) of SS anomaly. 3N breakup in a plane perpendicular to the beam axis is special. Anomaly occurs only in the perpendicular plane. It is a very suggestive characteristic, although further experimental confirmation is necessary.

An occurrence of a possible anomaly (b) at $\alpha \leq 30^\circ$ has not been confirmed yet. Further data analysis is necessary. Moreover, $pd$ star at $\alpha = 0^\circ$ is close to $pp$-QFS (quasi-free scattering). For example at $\alpha = 0^\circ$ at $E_p = 13$ MeV, the star occurs at $\theta_1 = \theta_2 = 33.3^\circ$, and QFS occurs at $\theta_1 = \theta_2 = 39.0^\circ$. At $\alpha \leq 30^\circ$, the $pd$ breakup cross section becomes large owing to QFS enhancement. The cross section of star at $\alpha = 0^\circ$ is about 5 times larger than that at $\alpha = 90^\circ$. Therefore, if there is an anomaly at $\alpha \leq 30^\circ$, it is not the star anomaly but QFS anomaly. Besides, even if a star anomaly exists at $\alpha \leq 30^\circ$, QFS enhancement overwhelms the star anomaly and we cannot detect the star anomaly at $\alpha \leq 30^\circ$.

A possible anomaly (c) at $120^\circ \leq \alpha$ at 9.5 MeV ($E_d = 19$ MeV) is a curious phenomenon. At 13 MeV ($E_d = 26$ MeV), no large anomaly occurred in our experiment at $120^\circ \leq \alpha$, but a 25% anomaly was found at 9.5 MeV. In general 3N reactions vary slowly with the incident energy. We believe that another experiment at $120^\circ \leq \alpha$ at $E_d = 19$ MeV is necessary to examine the possible anomaly (c). After the new experiment, we will discuss this particular anomaly (c).

### 6.8 QFS Anomaly at Low Energy

There have been several reports on a large discrepancy in cross section of QFS both in $nd$ breakup [53,54] and in $pd$ breakup [47–49,55]. For example, $nd$ QFS cross section around $E_n = 25$ MeV is 16–18% higher than the calculation, and $pd$ QFS cross section is lower than the calculation by about 20% at $E_p = 19$ MeV and about 10% at 10.5 MeV. Large charge asymmetry of QFS anomaly is similar to that of SS anomaly.

Leading reaction mechanisms in QFS and in SS are completely different. SS anomaly in $pd$ reaction has not been confirmed yet. Further data analysis is necessary. Moreover, $pd$ star at $\alpha = 0^\circ$ is close to $pp$-QFS (quasi-free scattering). For example at $\alpha = 0^\circ$ at $E_p = 13$ MeV, the star occurs at $\theta_1 = \theta_2 = 33.3^\circ$, and QFS occurs at $\theta_1 = \theta_2 = 39.0^\circ$. At $\alpha \leq 30^\circ$, the $pd$ breakup cross section becomes large owing to QFS enhancement. The cross section of star at $\alpha = 0^\circ$ is about 5 times larger than that at $\alpha = 90^\circ$. Therefore, if there is an anomaly at $\alpha \leq 30^\circ$, it is not the star anomaly but QFS anomaly. Besides, even if a star anomaly exists at $\alpha \leq 30^\circ$, QFS enhancement overwhelms the star anomaly and we cannot detect the star anomaly at $\alpha \leq 30^\circ$.

A possible anomaly (c) at $120^\circ \leq \alpha$ at 9.5 MeV ($E_d = 19$ MeV) is a curious phenomenon. At 13 MeV ($E_d = 26$ MeV), no large anomaly occurred in our experiment at $120^\circ \leq \alpha$, but a 25% anomaly was found at 9.5 MeV. In general 3N reactions vary slowly with the incident energy. We believe that another experiment at $120^\circ \leq \alpha$ at $E_d = 19$ MeV is necessary to examine the possible anomaly (c). After the new experiment, we will discuss this particular anomaly (c).
Angle pair \((\theta_1, \theta_2)\) for QFS at 13 MeV, together with \(\theta_1 = \theta_2\) line. Measurements were made at marked angle pairs.

Typical data for \(D(p, p_1p_2)n\) cross section at QFS at 13 MeV. \(E_n\) is plotted to indicate QFS condition.

Experiment/calculation ratio of \(D(p, p_1p_2)n\) cross section at QFS at 13 MeV. There is no anomaly at QFS at 13 MeV.

A cross section ratio of the experiment/calculation was obtained from averaged values around QFS peak, and illustrated in Fig. 58 as the function of \(\theta_1 - \theta_2\). Also, the energy dependence of the experiment/calculation ratio of QFS peak height at \(\theta_1 = \theta_2\) is shown in Fig. 59. From our new data and Köln data, we assume that there is no QFS anomaly in 9.5–13 MeV region. In \(pd\) breakup, there is only one possible QFS anomaly that occurs at \(E_p = 19\) MeV.

A confirming of the QFS experiment at \(E_p = 19\) MeV should be made in the future. If QFS anomaly is confirmed at 19 MeV, energy dependence of the QFS anomaly should be investigated at around 19 MeV. If there is no QFS anomaly at 19 MeV, then we will conclude that there is no QFS anomaly in \(pd\) breakup.
Experimental Investigations of Discrepancies in Three-Nucleon Reactions

Fig. 59 Experiment/calculation ratio of cross section for nd QFS and pd QFS. Further experiments at around 20 MeV are necessary.

Fig. 60 Discrepancies in 3N reactions and their possible origins

Experiments on QFS cross section in nd breakup are also necessary. After a conclusion on QFS anomaly in pd breakup is obtained, an experiment on nd QFS will be made, since precise measurement of the absolute cross section of nd breakup is extremely difficult.

7 Summary

Experiments on the following subjects have been described in this report:

(a) pd scattering at $E_p = 2$–18 MeV and $E_d = 5$–18 MeV for cross section, $A_y, iT_{11}, T_{20}, T_{21}$ and $T_{22}$,
(b) nd scattering at $E_n = 12$ and 16 MeV for $A_y$,
(c) pd capture at $E_d = 17.5, 137$ and 196 MeV for $A_y, A_{xx}, A_{yy}$ and $A_{zz}$,
(d) pd breakup at $E_p = 247$ MeV for cross section and $A_y$,
(e) pd breakup at $E_p = 9.5$ and 13 MeV, and $E_d = 26$ MeV.

We have made these experiments with purposes of

(A) to find 3NF effects and to determine the strengths of 3NF, and/or
(B) to solve low-energy problems, such as $A_y$ puzzle and Space-Star anomaly, which may be irrelevant to 3NF effects.

So far only $2\pi$ 3NF effects were found and the strength of $2\pi$ 3NF was determined from pd scattering cross section and 3N binding energy. Determination of short-range 3NF (SR3NF) such as $\pi\rho$ 3NF and $\rho\rho$ 3NF is still a big undertaking to be made. Low-energy problems (B) are still big challenges even after data accumulation of more than 20 years.

In Fig. 60, Discrepancies in 3N reactions are illustrated. Various kinds of discrepancies between experiment and calculation have been reported in Nd scattering, in pd capture, and in Nd breakup. Many experimental
data have been accumulated. We now have enough data sets to begin theoretical investigation for the origins of the discrepancies, although additional experiments are necessary to confirm quantitatively the discrepancy and to complete precise datasets.

From an experimentalist’s point of view, success in the reliable treatment of Coulomb force in \( pd \) scattering, \( pd \) capture and \( pd \) breakup was the greatest theoretical progress made in the last decade. All the precise and systematic \( pd \) data at low energy region can be used for precise study of discrepancies in 3\( N \) reactions. Acute characteristics in 3\( N \) system can be found and precisely investigated nowadays.

Discrepancies in 3\( N \) reactions in higher energy region may be caused more or less by SR3NF and by relativistic effects. Theoretical calculations with trial SR3NF and full relativistic effects will open the door to the next stage of 3\( N \) study. Existing experimental data are waiting for such calculations to be made extensively in the near future.

Discrepancies in 3\( N \) reactions in low energy region are waiting for new trial calculations based on challenging ideas. Systematic and precise dataset for \( A_y \) puzzle has been prepared, and the dataset is waiting for calculations based on various ideas. Solving low-energy discrepancies may be more difficult than solving higher energy ones, because we have now no candidates for the origins of low-energy discrepancies.

When we find an origin for a discrepancy and the origin is not peculiar to nuclear forces but, for example, is related to 3-particle dynamics, the discrepancy may also appear in other 3-particle systems other than 3-nucleon systems. Experiments can be made most precisely in 3\( N \) systems than in other 3-particle systems. 3\( N \) systems are rich fields for precise study of 3-particle problems.

Acknowledgments Experimental studies described in this report were made by many collaborators over about 25 years. The experimental collaborators were from Kyushu University, RCNP Osaka University, Kyoto University, University of Tokyo, RIKEN, Tohoku University, and Miyazaki University. In these experimental studies, six doctoral theses were written by S. Shimiizu (1992), N. Nishimori (1996), H. Akiyoshi (1997), T. Fujita (1999), T. Yagitaitai in 2002 and Y. Tameshige (2008), and S. Kuroita will finish his doctoral thesis in 2011. In addition to the above doctoral students, the following members have collaborated in the experimental studies; K. Hatanaka, A. Tamii, T. Wakasa, H. Okamura, H. Nakamura, T. Nakashima, K. Maeda, Y. Sakemi, T. Noro, T.P. Yoshida, Y. Maeda, K. Sekiguchi, J. Kamiya, Y. Shimizu, T. Kawabata, K. Fujita, M. Matsubara, H. Oguri, H. Ochihishi, S. Ueno, T. Miwa, T. Bussaki, K. Shigenaga, K. Ogata, K. Tachikawa, M. Kondo, S. Minami, T. Ishida, H. Ochi, S. Nozoe, M. Shiota, S. Shimomoto, T. Kudo, H. Ōhira, M. Tomiyama, T. Sugimoto, H. Shioda, T. Sueta, Y. Eguchi, K. Yashima and Y. Tabe. The author wishes to thank above members for their contributions in our 3\( N \) experiments at KUTL, RCNP and RIKEN. The author also wishes to thank the following collaborators for their theoretical calculations and discussions of 3\( N \) reactions; Y. Koike, N. Takemiya, S. Ishikawa, H. Kamada, H. Witala, W. Glöckle, J. Golak, A. Kienvsky, and A. Deltuva. Many progresses have been made from comparison of our experimental data to their calculations. The author also appreciate much technical staffs at KUTL. T. Maeda for preparing various electrical circuits, and Y. Koga for manufacturing many metal parts by machinery. The author thank to S. Kuroita, K. Yashima and T. Yabe for their help in preparation of the manuscript. The author would like to express his appreciation to the editors for the opportunity to present this report.

Open Access This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

1. Koike, Y., Heidenbauer, J.: The neutron-deuteron elastic scattering with the Paris potential. Nucl. Phys. A 463, 365c (1987)
2. Takemiya, N.: On the low energy \( n-d \) scattering. Prog. Theor. Phys. 74, 301 (1985)
3. Witala, H., Glocker, W., Cornelius, T.: Three-nucleon continuum calculations with realistic NN potentials. Few-Body Syst. 2, 555 (1987)
4. Witala, H., Glocker, W., Cornelius, T.: Rigorous Faddeev calculations for elastic neutron-deuteron scattering around 8 MeV c.m. energy. Nucl. Phys. A 491, 157 (1989)
5. Sagara, K., et al.: Polarization monitors for proton and deuteron beams below 20 MeV. Nucl. Instr. Methods A 270, 444 (1988)
6. Sagara, K., et al.: Energy dependence of analyzing power \( A_y \) and cross section for \( p+d \) scattering below 18 MeV. Phys. Rev. C 50, 576 (1994)
7. Shimizu, S., et al.: Analyzing powers of \( p+d \) scattering below the deuteron breakup threshold. Phys. Rev. C 52, 1193 (1995)
8. Koike, Y., Ishikawa, S.: Possible origin of Sagara discrepancy in the cross section minimum of \( p-d \) elastic scattering. Nucl. Phys. A 631, 683c (1998)
9. Sakamoto, N., et al.: Measurement of the vector and tensor analyzing powers for the \( d-p \) elastic scattering at \( E_d = 270 \) MeV. Phys. Lett. B 367, 60 (1996)
10. Witala, H., et al.: Cross section minima in elastic \( N\bar{d} \) scattering: possible evidence for three-nucleon force effects. Phys. Rev. Lett. 81, 1183 (1998)
11. Fujita, J., Miyazawa, H.: Pion theory of three-body forces. Prog. Theor. Phys. 17, 360 (1957)
12. Takemiya, N.: Analyzing powers in elastic nucleon-deuteron scattering. Prog. Theor. Phys. 86, 975 (1991)
13. Witala, H., Gloeckle, W.: The analysing power in elastic nucleon-deuteron scattering: information on two-nucleon $^3P_0$ forces? Nucl. Phys. A 528, 48 (1991)

14. Kiessky, A.: Phenomenological spin-orbit three-body force. Phys. Rev. C 60, 034001 (1999)

15. McNinch, J.E., et al.: Analyzing power in neutron-deuteron elastic scattering at $E_n = 3$ MeV. Phys. Rev. C 50, 589 (1994)

16. Tornow, W., et al.: The low-energy neutron-deuteron analyzing power and the $^3P_{0,1,2}$ interactions of nucleon-nucleon potentials. Phys. Lett. B 257, 273 (1991)

17. Tornow, W., et al.: Discrepancy between three-nucleon calculations and neutron-deuteron elastic analyzing power data at 8.5 MeV. Phys. Lett. B 203, 341 (1988)

18. Tornow, W., et al.: Analyzing power measurements for $(2H(\theta_{pol}, n)2H)$ scattering at 10 MeV compared to few-nucleon calculations and data for $(2H(p_{pol}, p)2H)$ scattering. Phys. Rev. Lett. 49, 312 (1982)

19. Howell, C., et al.: Rigorous calculations and measurements of $A_\theta(\theta)$ for $n + d$ elastic-scattering and breakup processes. Phys. Rev. Lett. 61, 1565 (1988)

20. Tornow, W., et al.: Measurements of analyzing power for $^2H(\vec{n}, n)^2H$ scattering at 14.1 MeV and comparisons to $^2H(\vec{d}, p)^2H$. Phys. Rev. C 27, 2439 (1983)

21. Plattner, G.R., Bacher, A.D.: Absolute calibration of spin image polarization. Phys. Lett. B 36, 211 (1971)

22. Bond, J.E., Firk, F.W.K.: Determination of $R$-function and physical-state parameters for $n^4$He elastic scattering below 21 MeV. Nucl. Phys. A 287, 317 (1977)

23. Satchler, G.R., et al.: An optical model for the scattering of nucleons from $^4$He at energies below 20 MeV. Nucl. Phys. A 112, 1 (1968)

24. Stammbach, T.H., Walter, R.L.: $R$-matrix formulation and phase shifts for $n^4$He and $p^4$He scattering for energies up to 20 MeV. Nucl. Phys. A 180, 225 (1972)

25. Arndt, R.A., Roper, L.D.: Nucleon-alpha elastic scattering analyses: (II). 0 to 21 MeV energy-dependent $n-\alpha$ analysis. Nucl. Phys. A 209, 447 (1973)

26. Simmons, J.E., et al.: Reaction $D(d, n)^3$He at $0^\circ$ with polarized beam: a new source of polarized neutrons from 7 to 18 MeV. Phys. Rev. Lett. 27, 113 (1971)

27. Salzman, G.C., et al.: Polarization and polarization transfer in the $2H(d, n)^3$He reaction at 10 MeV. Nucl. Phys. A 222, 512 (1974)

28. Lisowski, P.W., et al.: Polarization transfer in the $2H(\vec{d}, \vec{n})^3$He reaction at $\theta = \theta^\prime$. Nucl. Phys. A 242, 298 (1975)

29. von Witsch, W., et al.: Transverse polarization transfer in the $2H(d, \vec{n})^3$He reaction at $\theta = 0^\circ$. Phys. Rev. C 57, 2104 (1998)

30. Tornow, W., et al.: No evidence for large charge-symmetry breaking effects in the $^3P_0$ nucleon-nucleon interactions. Phys. Rev. C 55, 525 (1990)

31. Golak, J., et al.: Faddeev calculations of proton-deuteron radiative capture with exchange currents. Phys. Rev. C 62, 054005 (2000)

32. Akiyoshi, H., et al.: Measurement of analyzing powers of the $1H(d, ^3He)\gamma$ reaction at 17.5 MeV. Phys. Rev. C 64, 034001 (2001)

33. Sekiguchi, K., et al.: Complete set of precise deuteron analyzing powers at intermediate energies: comparison with modern nuclear force predictions. Phys. Rev. C 65, 034003 (2002)

34. Strate, J., et al.: Differential cross section of the $^2H(n, n\gamma)$-reaction at $E_n = 13$ MeV. Nucl. Phys. A 501, 51 (1989)

35. Setze, H.R., et al.: Minimal supersymmetric Higgs boson decay rate in $O(\alpha_2^2)$ perturbative QCD. Phys. Lett. B 338, 229 (1996)

36. Setze, H.R., et al.: Cross-section measurements of neutron-deuteron breakup at 13.0 MeV. Phys. Rev. C 71, 034006 (2005)

37. Stephan, M., et al.: Neutron-induced deuteron breakup cross section at 10.3 MeV. Phys. Rev. C 39, 2133 (1989)

38. Zhou, Z., et al.: The space-star anomaly in $n^4d$ breakup at 25 MeV. Nucl. Phys. A 684, 545 (2001)

39. Gebhardt, K., et al.: Experimental and theoretical investigation of the $^2H(n, n\gamma)$ reaction and of the neutron-deuteron scattering length. Nucl. Phys. A 561, 232 (1993)

40. Hatanaka, K., et al.: Cross section and complete set of proton spin observables in $p \to d$ elastic scattering at 250 MeV. Phys. Rev. C 66, 044002 (2002)

41. Ishikawa, S., Sasakawa, T.: $p + d \to ^3He + \gamma$ reaction with realistic three-nucleon wave functions. Phys. Rev. C 45, R1428 (1992)

42. Lourdan, J., et al.: $p - d$ Radiative capture and the $^3He$ D-state d. Nucl. Phys. A 453, 220 (1986)

43. Atkinson, I., et al.: Tensor analyzing power $A_{yy}$ of $d - p$ radiative capture. Nucl. Phys. A 636, 189 (1998)

44. Goeckner, F., et al.: Analyzing power measurements for $p - d$ radiative capture. Phys. Rev. C 45, R2536 (1992)

45. Schmid, G.I., et al.: 1996 $T=0$ measurements for $^1H(d, \gamma)^3He$ and the $P$-wave component of the nucleon-nucleon force. Phys. Rev. C 53, 35 (1996)

46. Mehndandoost-Khajeh-Dad, A.A., et al.: Spin observables in deuteron-proton radiative capture at intermediate energies. Phys. Lett. B 617, 18 (2005)

47. Rauprich, G., et al.: Study of the kinematically complete breakup reaction $2H(\vec{P}, pp)n$ at $E_p = 3$ MeV with polarized protons. Nucl. Phys. A 535, 313 (1991)

48. Grossmann, R., et al.: Low energy proton-deuteron versus neutron-deuteron breakup in four configurations: implications for Coulomb-force effects. Nucl. Phys. A 603, 161 (1996)

49. Patelberg, H., et al.: Deuteron breakup reaction $2H(p, pp)n$ induced by polarized protons at $E_p = 19.0$ MeV. Phys. Rev. C 53, 1497 (1996)

50. Ishida, T., et al.: Search for Space Star anomaly in $pd$ breakup reaction 13 MeV. Mod. Phys. Lett. A 18, 436 (2003)

51. Ley, J., et al.: Cross sections and tensor analyzing powers Ayy of the reaction $1H(d, pp)n$ in “symmetric constant relative energy” geometries at $E_d = 19$ MeV. Phys. Rev. C 73, 064001 (2006)

52. Deltuva, A., et al.: Momentum-space description of three-nucleon breakup reactions including the Coulomb interaction. Phys. Rev. C 72, 054004 (2005)
53. Siepe, A., et al.: Neutron-proton and neutron-neutron quasifree scattering in the $n - d$ breakup reaction at 26 MeV. Phys. Rev. C 65, 034010 (2002)
54. Ruan, X.C., et al.: Experimental study of neutron-neutron quasifree scattering in the $nd$ breakup reaction at 25 MeV. Phys. Rev. C 75, 057001 (2007)
55. Allet, M., et al.: Proton-induced deuteron breakup at $E_{\text{lab}} = 65$ MeV in quasi-free scattering configurations. Few-Body Syst. 20, 27 (1996)