Kenshi Sagara

Experimental Investigations of Discrepancies in Three-Nucleon Reactions

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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,

K. Sagara (✉)
Department of Physics, Kyushu University, Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan
E-mail: sagara@phys.kyushu-u.ac.jp

- (b) nd scattering at $E_n = 12$ and 16 MeV,
- (c) pd capture at $E_{\vec{d}} = 17.5, 137$ and 196 MeV,
- (d) pd breakup at $E_p = 247$ MeV,
- (e) pd breakup at $E_p = 9.5$ and 13 MeV, and $E_d = 26$ MeV.

These experiments were made at KUTL, at RCNP (Research Center for Nuclear Study, Osaka), and at RIKRN in Saitama. All the above experiments are described in this report.

We found a systematic discrepancy around the minimum of pd scattering cross section (Sagara discrepancy, 1994) [6,8]. From the discrepancy, the strength of 2π -exchange 3NF (2π 3NF) was determined in 1998 [10], 41 years after Fujita–Miyazawa original paper on 2π 3NF in 1957 [11].

We hope that searches for short-range 3NF such as $\pi\rho$ 3NF and $\rho\rho$ 3NF will be intensively made based on recent higher-energy systematic data including our data in this report. Also we hope that low-energy anomalies such as A_y puzzle and Space-Star anomaly will be investigated based on datasets including ours in this report.

We are still continuing 3N experiments in order to obtain complete datasets for discrepancies at low-energy as well as at higher energy. We hope that many challenging theoretical investigations will be made to reproduce rich datasets on 3N reactions, and that long-standing big problems in 3N reactions are solved in the near future. Our experiments over 22 years are described in the following sections. Sections 2, 3, 4, 5, and 6 correspond to the above experiments (a), (b), (c), (d), and (e), respectively.

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 $1.5\mu\text{A}$ 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

Fig. 1 Block diagram for Lamb-shift type polarized ion source at KUTL

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 $\mathbf{E}$ and a magnetic field $\mathbf{B}$ were applied perpendicularly to the beam axis to satisfy $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{0}$, with $\mathbf{v}$ being the beam velocity. The H^- beam passed through the spin processor without bending, but the beam spin ($\mathbf{s}$) was rotated by a force proportional to $\mathbf{s} \times \mathbf{B}$.

As the spin processor was rotatable with respect to the beam axis, we could choose the direction of $\mathbf{B}$ 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 θ is the polar angle between the beam axis and the beam spin axis, and ϕ 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.

Fig. 2 Set up for calibration of $\vec{p}$ -beam polarimeter ($\vec{d}$ -beam polarimeter)

Fig. 3 Set up for $\vec{p} + d$ scattering experiment with a D_2 gas target

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° . 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 ± 0.3 MeV and $112^\circ \pm 5^\circ$. At 12 MeV, we found that A_y took the maximum value at 113° . We presumed therefore $A_y = 1.000 \pm 0.003$ at 113° 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 $\theta_{\max}$, 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 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.

Fig. 4 Integration width W_i was changed to estimate a real value of analyzing power

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 μm 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_{up} , R_{up} , L_{down} and R_{down} which were normalized by solid angles and the beam charge. Experimental asymmetry was obtained in four ways,

$$(L_{\text{up}} - L_{\text{down}})/(L_{\text{up}} + L_{\text{down}}) \quad (1)$$

$$(R_{\text{up}} - R_{\text{down}})/(R_{\text{up}} + R_{\text{down}}) \quad (2)$$

$$(L_{\text{up}} - R_{\text{up}})/(L_{\text{up}} + R_{\text{up}}) \quad (3)$$

$$(L_{\text{down}} - R_{\text{down}})/(L_{\text{down}} + R_{\text{down}}) \quad (4)$$

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_{up} and L_{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_{up} and L_{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 ± 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, $(\text{calc-exp})/\text{exp}$ 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 $N+N A_y$ data. Therefore we thought that there might be other origin(s) of A_y puzzle.

Fig. 5 Examples of measured $\bar{p}d$ A_y (solid circle). Open circles are $\bar{p}d$ 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 $\bar{p}d$ A_y peak. Present $\bar{p}d$ A_y data were compared to pd calculation with Paris potential (solid circle), to pd calculation with LS modified potential (open circle). $\bar{n}d$ 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 ~ 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.

Table 1 List of measured cross section and analyzing powers of $p + d$ scattering

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

After our $p + dA_y$ measurement, we measured $n + dA_y$ at $E_n = 12$ MeV and $E_n = 16$ 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 $p + dA_y$ puzzle is now possible. Utilizing the precise and systematic $p + d$ dataset, $p + dA_y$ puzzle should be solved first, and the solution should be examined by $n + dA_y$ 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 $\vec{d}$ -beam at $E_{\vec{d}} = 5.0, 6.0, 8.0, 10.0, 14.0$ and 18.0 MeV. The center-of-mass energy $E_{c.m.}$ of $p + d$ system is $2E_{\vec{p}}/3$ in a $\vec{p}$ -beam experiment, and is $E_{\vec{d}}/3$ in a $\vec{d}$ -beam experiment. We measured the data listed in Table 1. Measurement on the $p + d$ scattering cross section is described in the next section.

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

We made three kinds of measurements on $p + d$ scattering with the $\vec{d}$ -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° from the beam axis. In each measurement, three magnetic sub-states of deuteron, $m_Z = 1, 0$, and -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 and A_{yy} , (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 $E_{\vec{d}} = 6.0$ MeV are shown in Fig. 7. The data have very small experimental errors. Also at $E_{\vec{d}} = 5.0, 8.0, 10.0, 14.0$ 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° .
- (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.

Fig. 7 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° 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 $\pm 20 \mu\text{m}$ 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. 8 Examples of measured cross section of $p + d$ scattering. Solid and dashed curves are pd and nd calculations, respectively by Takemiya. Coulomb force was treated in an approximate way

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 $\pm 1.1\%$ and statistical errors were typically $\pm 0.3\%$. 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

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 $E_d = 270$ MeV (equivalent to $E_p = 135$ 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 ${}^3\text{H}$ binding energy were simultaneously solved by using the same 2π 3NF [10]. It was known before 1998 that the ${}^3\text{He}$ binding energy could be reproduced by adjusting a cut-off parameter in 2π 3NF. Reproduction of only one observable by adjusting one parameter in 2π 3NF could not be evidence for 2π 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 2π 3NF. Therefore, existence of 2π 3NF was confirmed and the strength of 2π 3NF was determined. It was a landmark event as 41 years had passed since the first paper on 2π 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 2π 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 2π 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 ndA_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.

Fig. 11 Setup for measurement of relation between $\vec{d}$ -beam polarization and $\vec{n}$ -beam polarization

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 ${}^4\text{He}$ in Fig. 11 was replaced by a CD_2 target, we were able to measure $\vec{n}d$ A_y .

We adopted ${}^2\text{H}(\vec{d}, n){}^3\text{He}$ reaction at 0° for the $\vec{n}$ -beam production. For example, a 12 MeV $\vec{n}$ -beam was produced by ${}^2\text{H}(\vec{d}, n){}^3\text{He}$ reaction using a 8.92 MeV $\vec{d}$ -beam. Background neutrons were produced by ${}^2\text{H}(\vec{d}, n)pd$ 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-sessions.

3.2 Production of $\vec{n}$ -Beam

Figure 12 shows our $\vec{n}$ -beam production target. A 12 MeV $\vec{n}$ -beam was produced by $\text{D}(\vec{d}, n){}^3\text{He}$ reaction at $E_{\vec{d}} = 8.92$ MeV in the $\vec{d}$ -beam direction. This reaction is most efficient in order to produce polarized $\vec{n}$ -beams in the energy range of 10–20 MeV, because the cross section is high enough and $\vec{n}$ -beam polarization is nearly the same as the polarization of an initial $\vec{d}$ -beam.

The target D_2 gas of 3 atm $\times$ 2cm in thickness was confined in a cylindrical cell. A $\vec{d}$ -beam entered the D_2 target through a 3 μm -thick Ta foil window. To increase inner gas pressure endured by the window foil, the foil was pasted on a cylindrical wall.

In the production of a 12 MeV $\vec{n}$ -beam, the energy of the $\vec{d}$ -beam from an accelerator was 9.18 MeV, and the $\vec{d}$ -beam energy was decreased to 9.03 MeV by passing through the entrance Ta window. The beam energy was also decreased by the target D_2 gas to 8.81 MeV. Therefore, ${}^2\text{H}(\vec{d}, n){}^3\text{He}$ reaction occurred at 8.92 ± 0.11 MeV, and a $\vec{n}$ -beam of 12.00 ± 0.11 MeV was produced in the $\vec{d}$ -beam direction. When a 1 μA $\vec{d}$ -beam entered the D_2 target, 2.4×10^6 neutrons/s were produced within a solid angle of $\pm 1.5^\circ \times \pm 3.0^\circ$ in the $\vec{d}$ -beam direction.

Fig. 12 D_2 target for $\vec{n}$ -beam production and ^3He target for $\vec{d}$ -beam polarimeter. *Top view*

The $\vec{d}$ -beam, after passing through the D_2 target, entered into the ^3He gas target of 1.5 atm through a 3- μm thick Ta window foil. Polarization of the $\vec{d}$ -beam was then measured using $^3\text{He}(\vec{d}, p)^4\text{He}$ reaction which has large analyzing powers for both the vector and tensor polarized beams. The $^3\text{He}(\vec{d}, p)^4\text{He}$ 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 $^3\text{He}(\vec{d}, p)^4\text{He}$ 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 $^3\text{He}(\vec{d}, p)^4\text{He}$ polarimeter should be known. As described in Sect. 2, we had a $\vec{d}$ -beam polarimeter whose analyzing powers were calibrated using $^{16}\text{O}(\vec{d}, ^4\text{He})^{14}\text{N}$ 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 $^3\text{He}(\vec{d}, p)^4\text{He}$ reaction by measuring the $\vec{d}$ -beam polarization with the $\vec{d}$ -beam polarimeter. Proton detectors of the $^3\text{He}(\vec{d}, p)^4\text{He}$ 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 D_2 target and ^3He 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 $^2\text{H}(\vec{d}, n)^3\text{He}$ 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 $^3\text{He}(\vec{d}, p)$ reaction because p -detection is much easier than n -detection.

Fig. 13 Neutron counter composed of a liquid scintillation counter (NE213) and a photo-multiplier tube

The $\vec{n}$ -beam polarization p_{ny} has following relation with the $\vec{d}$ -beam polarizations p_y and p_{yy} as,

$$p_{ny} = (3/2)p_y K_y^y(0^\circ) / \{1 - p_{yy} A_{zz}(0^\circ)/4\} \quad (5)$$

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° .

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 $\vec{n}$ -beam polarization using $\vec{n} + ^4\text{He}$ scattering. Experimental setup is illustrated in Fig. 11.

Our next tasks were preparation of $\vec{n}$ -detectors equipped with fast $n - \gamma$ separation system, and development of a liquid ^4He 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 γ -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 γ -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 γ -rays were almost completely discriminate out. In a $\vec{n}d$ A_y experiment with a high-intensity beam, rejection of numerous background γ -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 μ -seconds and stored in a memory typically in 100 μ 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 μ s. A main memory accepted a signal from the ring memory in a constant speed of 100 μ s per signal. By use of the ring memory, dead time for one event was reduced from about 100 μ s to about 5 μ 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 γ -rays in the *left peak*

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

3.3.3 Liquid ${}^4\text{He}$ Target

To make $\bar{n} + {}^4\text{He}$ scattering experiment with high efficiency, we developed a liquid ${}^4\text{He}$ (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.

Fig. 16 Energy spectra of n -counters on the *left* and *right* sides of the $\vec{n}$ -beam axis. Spin up-down asymmetry in the spectrum was large and inverse between the *left* and *right* counters

We used LHe target also as a scintillator. A ^4He particle recoiled by a n -beam produced scintillation lights in LHe target. From the lights, we detected the time when $\vec{n} + ^4\text{He}$ scattering took place. The lights were reflected by reflector-painted inner walls of LHe target cell, and came out of the target cell through a quartz glass at the bottom. A vacuum seal between the stainless steel cell and the quartz glass was maintained by an Indium metal ring, that is, we sealed super-fluid helium in vacuum using an Indium packing.

The scintillation lights were guided to a photo-multiplier tube (PMT) and emitted electrons on the inner surface of the entrance window of PMT. In our first design, we cooled PMT down to LN_2 temperature, using special PMT that could work at low temperatures. The cooled PMT worked well for a low neutron flux. When neutron flux became higher, output from the PMT decreased to about 1/10. We did not investigate the origin because it would require too much time, so we replaced our design.

Our final design was placing PMT at the room temperature in the atmosphere, and guiding the scintillation lights over a 20 cm distance using a cylinder whose inner wall was coated with a reflector, as seen in Fig. 15. By using this method, we succeeded in stabling and detecting scintillation lights produced in a super-fluid He target. It was also a big step forward.

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 $p_y, 0, -p_y$, 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° 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 - ^4He 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,

$$p_{ny}A(\theta) = (L^1 - L^{-1}) / (L^1 + L^0 + L^{-1}) \quad (6)$$

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_y and p_{yy} as

$$p_{ny}A(\theta) = (3/2)p_y K_y^y(0^\circ) A_y(\theta) / \{1 - A_{zz}(0^\circ) p_{yy}/4\} \quad (7)$$

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

$$p_{yy}A_{zz}(0^\circ) = 2(L^0 - L^1 - L^{-1}) / (L^1 + L^0 + L^{-1}) \quad (8)$$

Fig. 17 Curve is A_y of n - ${}^4\text{He}$ 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 $\bar{n}$ -beam polarization p_{ny} was determined from the common scaling factor

Fig. 18 Polarization transfer coefficient $K_y^y(0^\circ)$ of ${}^2\text{H}(\vec{d}, n){}^3\text{He}$ 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 $K_y^y(0^\circ)$, 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 $\bar{n} + {}^4\text{He}$ scattering [22–25]. It is known that $\bar{n} + {}^4\text{He} A_y(\theta)$ takes the theoretical maximum $A_y = 1.0$ at around $E_{\bar{n}} = 12$ MeV and around 112° , 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} , $K_y^y(0^\circ)$ of ${}^2\text{H}(\vec{d}, n){}^3\text{He}$ reaction was determined.

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

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

3.5.1 Experimental Procedure

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

Fig. 19 Present data for A_y of $\bar{n}d$ scattering at 12 MeV (rectangle) and TUNL data (cross)

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

Backgrounds from $\text{Ta}(\bar{d}, n)\text{X}$ 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 $\bar{n}d$ 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 $K_y^y(0^\circ)$ value at 12 MeV was about 4% higher than TUNL value. If the same $K_y^y(0^\circ)$ value was adopted, both $\bar{n}d$ 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 $\bar{n}d A_y$ 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 $\bar{n}d$ A_y and $\bar{p}d$ A_y

The purpose of our first $\bar{n}d$ A_y measurement at 12 MeV was to confirm the existence of A_y puzzle without Coulomb force. Our present $\bar{n}d$ A_y data coincided with existing TUNL A_y data, and both data largely disagreed

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 $\vec{n} + d A_y$ 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 $E_{c.m.} = 2.4$ 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 ^3He ground state with high momentum transfer. The high momentum transfer and the compact structure of ^3He 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 μb . 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 $^{12}\text{C}(\vec{d}, d)$ 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 ^3He (true) events from

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

we had to remove the ^3He backgrounds, ^3He (BG) coming from

$$\text{Window (target)} + \vec{d} \text{ (beam)} \rightarrow ^3\text{He (BG)} + \gamma \quad (10)$$

Fig. 23 Tensor analyzing powers of $^{12}\text{C}(\vec{d}, d)$ elastic scattering at 17.5 MeV. The data were used for $\vec{d}$ -beam polarimeter

Fig. 24 Experimental setup for $\vec{d} + p \rightarrow {}^3\text{He} + \gamma$ reaction at 17.5 MeV

Counts of ${}^3\text{He}(\text{BG})$ are significantly larger than the counts of ${}^3\text{He}(\text{true})$, because (a) the cross section of (9) is less than $1 \mu\text{b}$ and the cross section of (10) is about $1\text{--}10 \text{ mb}$, 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 ${}^3\text{He}$ from (10) are several orders in number more than true ${}^3\text{He}$ from (9). What material should we use for the window foil?

We chose carbon foils. Of course ^{12}C and ^{13}C cause $(d, {}^3\text{He})$ reactions, however, both $^{12}\text{C}(d, {}^3\text{He})$ and $^{13}\text{C}(d, {}^3\text{He})$ reactions have high negative Q -values. Therefore ${}^3\text{He}(\text{BG})$ produced in carbon foils have enough lower energy than ${}^3\text{He}(\text{true})$. All other foil materials produce ${}^3\text{He}(\text{BG})$ having higher energy than ${}^3\text{He}(\text{true})$. Higher energy ${}^3\text{He}(\text{BG})$ have lower energy tail which are harmful for detection of ${}^3\text{He}(\text{true})$ 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 ($>0.1 \text{ mg/cm}^2$) 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

Fig. 25 H₂ gas target and $\bar{d}$ -beam polarimeter for $\bar{d} + p \rightarrow {}^3\text{He} + \gamma$ experiment

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 ${}^3\text{He}$ Detection

In the $H(\bar{d}, {}^3\text{He})\gamma$ experiment with a 17.5 MeV $\bar{d}$ -beam and a hydrogen target, ${}^3\text{He}$ 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°). As illustrated in Fig. 24, ${}^3\text{He}$ 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 ρ as

$$B\rho = \sqrt{2mE}/q \quad (11)$$

The field B is common for all the particles, and particles having the same ρ come to the detector. Huge background deuterons having the same ρ as ${}^3\text{He}$ ($E_d = (3/8)E_{{}^3\text{He}}$) came to the detector. The low energy deuterons were hallow-components of the $\bar{d}$ -beam. They could be separated from true ${}^3\text{He}$ 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° -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 ${}^3\text{He}$ events.

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

As indicated in Fig. 26, we detected ${}^3\text{He}$ 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 $p + d \rightarrow {}^3\text{He} + \gamma$ at $E_{\bar{d}} = 17.5$ 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 2π 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 ^3He particles

Fig. 27 Energy spectrum of ^3He 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 2π 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 .

Fig. 29 Measured analyzing powers of pd capture at $E_d = 17.5$ MeV. Curves are MEC calculations with (solid) and without (dashed) 2π 3NF [31]

In Fig. 29, A_{yy} and A_{zz} data disagree with the calculation with 2π 3NF. As 2π 3NF is an established force, we should always include 2π 3NF in 3N calculations, and compare experimental data to calculations with 2π 3NF. The disagreement in Fig. 29 indicates that 2π 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 2π 3NF, we decided to make pd capture experiments at higher energy, where momentum transfer between the initial $p + d$ scattering state to the final ${}^3\text{He}$ 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 $p + d \rightarrow {}^3\text{He} + \gamma$ 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 γ reaction were succeeded to our another experiment of ${}^{12}\text{C} + {}^4\text{He} \rightarrow {}^{16}\text{O} + \gamma$ reaction at KUTL to investigate the helium burning process in stars.

4.4 pd Capture Experiment at $E_{\vec{d}} = 196$ 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 θ_{pol} in a magnetic field is different from the beam bending angle θ_{beam} , as $\theta_{\text{pol}} = g \theta_{\text{beam}}$, 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 $\theta_{\text{pol}} = g \theta_{\text{beam}} = g(2\pi N)$, 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

Fig. 30 Calibration of a beam-line $\vec{d}$ -beam polarimeter using $^{12}\text{C}(\vec{d}, \alpha)^{10}\text{B}(2^+)$ reaction at 0°

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 $^{12}\text{C}(\vec{d}, \alpha)^{10}\text{B}(2^+)$ 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,

- $A_y(30^\circ) = 0.341 \pm 0.006$, $A_{yy}(30^\circ) = 0.615 \pm 0.011$
- $A_y(36^\circ) = 0.437 \pm 0.008$, $A_{yy}(30^\circ) = 0.568 \pm 0.010$

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.

Fig. 31 Liquid Helium target system

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 μ m in thickness. With this target, backgrounds were found to be an order of magnitude higher in number than the true 3He 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 μ 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 cell 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 (≈ 10 mg/cm²), in order to reduce the energy loss of 3He recoils in the target, for example, a 100 MeV 3He 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 3He 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 3He 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 3He and the $\vec{d}$ -beam were bent by a magnetic spectrograph called LAS (large acceptance spectrograph). Recoiled 3He were momentum-analyzed by LAS, and detected by vertical drift chambers (VDC) and a

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

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

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

In the laboratory system, ^3He recoils from the pd capture were ejected within a cone of a half angle of 4.7°, 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°. ^3He recoils at $1.5^\circ \leq \theta_{\text{lab.}} \leq 4.7^\circ$

Fig. 34 Raw data for $p\vec{d}$ capture A_{xx} (left), and a spectrum of data in a width of X projected on a Y -axis (right)

Fig. 35 Raw data for $p\vec{d}$ capture A_{yy} (left), and a spectrum of data in a width of θ projected on a X -axis (right)

(about $20^\circ \leq \theta_{c.m.} \leq 160^\circ$) were allowed to pass through the slits, and were detected by counters. The angular distribution of ^3He in $20^\circ \leq \theta_{c.m.} \leq 160^\circ$ 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 into the scintillator
- (c) direction and position of particle ray at VDC1 and VDC2.

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

Fig. 36 Experimental results for $\vec{p}\vec{d}$ capture at $E_d = 196$ MeV, analyzed by single-cluster method. Curves are MEC calculations with (solid) and without (dashed) $2\pi 3NF$

4.4.5 Experimental Results

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

Measured cross section and A_y were well reproduced by calculation with $2\pi 3NF$. 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 $2\pi 3NF$ 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 A_{xx} and A_{yy} 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 prolate 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 $(\vec{d}, d)$, $(\vec{d}, {}^3\text{He})$, $(\vec{d}, {}^4\text{He})$ reactions and even in the $\vec{d} + p$ 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 $E_{\vec{d}} = 137$ MeV. The experiment is described below.

4.5 Experiment on pd Capture at $E_{\vec{d}} = 137$ 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

Fig. 37 Experimental results for $p\bar{d}$ capture at $E_d = 137$ MeV, analyzed by multi-cluster II method. Curves are MEC calculations with (solid) and without (dashed) $2\pi 3NF$

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 $E_{\vec{d}} = 196$ 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 $E_{\vec{d}} = 196$ MeV. Our previous experiment at $E_{\vec{d}} = 17.5$ 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 $E_{\vec{d}} = 20$ MeV. Above $E_{\vec{d}} = 100$ 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 $E_{\vec{d}} = 137$ MeV, where the analyzing powers of $p + d$ scattering had been measured [33] and the data could be used for a $\vec{d}$ -beam polarimeter.

4.5.2 Experimental Procedure

Experimental setups for pd capture at $E_{\vec{d}} = 137$ MeV were almost the same as those at $E_{\vec{d}} = 196$ MeV. As the energy of the ${}^3\text{He}$ recoils decreased, we tried to make a thinner LH_2 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 LH_2 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 $E_{\vec{d}} = 140$ MeV [33].

The $\vec{d}$ -beam was polarized in the vertical direction, and $A_{xx}(\theta)$ and $A_{yy}(\theta)$ of pd capture at $E_{\vec{d}} = 137$ 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 $E_{\vec{d}} = 137$ 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 Witała 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.

Fig. 38 Slits for confirming $p\bar{d}$ capture experiment at 196 MeV, (a) for A_{xx} , (b) for A_{yy} , and (c) for A_{zz}

4.6 Experiments of pd Capture at KVI

At KVI, A_{yy} and A_{zz} of pd capture were measured at $E_{\bar{d}} = 133$ 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 $E_{\bar{d}} = 137$ 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 $\bar{d}$ -beam was polarized in the vertical direction.

In our experiment at RCNP, the ^3He recoils were momentum-analyzed by a magnetic dipole LAS, and detected by four VDCs and one scintillator in coincidence. For each event, we measured ΔE 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 ^3He recoils and γ -rays in coincidence. ^3He recoils were momentum-analyzed by a dipole magnet and were detected by a scintillator, and γ -rays were detected by a scintillator array system around the target. The reaction planes were defined by γ -ray detectors, and the energy and TOF of the ^3He 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 $E_{\bar{d}} = 196$ 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.

Fig. 39 Raw data for A_{xx} (left), for A_{yy} (center), and (c) for A_{zz} (left). Lower parts are background data obtained with the 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 ^3He ray in a VDC plane, the ^3He signal in the VDC was deteriorated. In the conventional single-cluster method, such an incomplete ^3He ray was discarded and ^3He 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 $\pm 45^\circ$ 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.

Fig. 42 A_{zz} of $\vec{p}\vec{d}$ capture at 196 MeV, obtained from (1) $-A_{xx} - A_{yy}$ in the previous experiment (solid circles), (2) $-A_{xx} - A_{yy}$ in the confirming experiment (open circles), and (3) A_{zz} in the confirming experiment using inclined slits (crosses). Curves are MEC calculations with (solid) and without (dashed) $2\pi 3NF$

All the data in Fig. 42 are not final ones. The data were analyzed by one of our group members. To obtain final data, we need make another independent data-analysis study by a different member. More time is needed to perform this task.

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 $E_{\vec{d}} = 17.5$ 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 $E_p = 50$ 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

Fig. 43 Ratio of experiment/calculation for the cross section of pd elastic scattering at 150°

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 $E_{\vec{p}} = 247$ 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 $E_{\vec{p}} = 247$ MeV was selected referring to pd elastic scattering experiments. Below $E_p = 140$ MeV, pd scattering cross section was well reproduced by including 2π 3NF. Above 150 MeV, the experimental cross section of pd scattering at backward angles was found to become larger than the calculation, even if 2π 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 π -threshold of 210 MeV, the ratio varies monotonically. The influence of π -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 become less reliable because lots of higher angular momentum states are taken into account. We decided, to make a pd breakup experiment at $E_{\vec{p}} = 247$ 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° , 10° , 15° and 20° .

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 (LD_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 $6 \mu\text{m}$ 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 LD_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 CD_2 target instead of a LD_2 target, the

Fig. 44 Cross section (*left*) and A_y (*right*) of $D(p, p_1)p_2n$ reaction at 247 MeV. Effects of $2\pi 3NF$ increase the cross section (Witala, Private Communication), but are insufficient to reproduce the experimental data

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 $2\pi 3NF$ 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.

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 to 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 to 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 $D(p, p_1)p_2n$ 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 θ_1 and LAS was set at θ_2 , on the left and right sides of the beam axis, respectively, in the horizontal plane. Therefore, ϕ_{12} was fixed at an angle of 180° . From the dynamic ranges of rotation of the two big counters, θ_1 and θ_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 to that kinematically complete measurement in high statistics needs 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 $E_0 \pm 0.05E_0$ and $E_0 \pm 0.3E_0$, 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 $D(p, p_1)p_2n$ experiment. A 247 MeV p -beam from RCNP cyclotron 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 $D(p, p_1 p_2)n$ 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 $D(p, p_1 p_2)n$ 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 $D(p, p_1 p_2)n$ 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 μm 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 $D(p, p_1 p_2)n$ Experiment at 247 MeV

Figure 46 shows the measured $D(p, p_1 p_2)n$ cross section at four angle pairs at 247 MeV and $D(n, n_1 n_2)p$ calculations with and without $2\pi 3NF$ by Kamada (Private Communication). As θ_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, θ_2 dependence of the discrepancy is shown. The discrepancy in $D(p, p_1 p_2)n$ cross section around $E_1 = 150$ MeV at $\theta_1 = 15^\circ$ increases as θ_2 goes forward. We know also that the discrepancy in $D(p, p_1)p_2n$ cross section around $E_1 = 150$ MeV increases as θ_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 $D(p, p_1 p_2)n$ experiment, we measured again $D(p, p_1)p_2n$ cross section using the same p -beam at 247 MeV. Data analysis is in progress. Preliminary data for the present $D(p, p_1)p_2n$ experiment agreed with our previous data.

Fig. 47 Dependence of $D(p, p_1 p_2)n$ cross section on θ_2

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 $D(p, p_1)p_2n$ 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 2π 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 2π 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.

Fig. 48 Configuration of Space Star in c.m. system. Outgoing three nucleons form an equilateral triangle

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 ($\mathbf{P}_1, \mathbf{P}_2, \mathbf{P}_3$) under the condition $\mathbf{P}_1 + \mathbf{P}_2 + \mathbf{P}_3 = 0$.

When positions of three outgoing nucleons form an equilateral triangle, we call the configuration as 'Star'. In Star, relations of $|\mathbf{P}_1| = |\mathbf{P}_2| = |\mathbf{P}_3|$, and $|\mathbf{P}_{12}| = |\mathbf{P}_{23}| = |\mathbf{P}_{31}|$ hold, where $\mathbf{P}_{ij}$ 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 $\mathbf{P}_3$ and $\mathbf{P}_3$, respectively, and consequently to have the relative momentum $\mathbf{P}_{23} = -\mathbf{P}_3$. 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 $\phi_d(\mathbf{P}_{23})$ takes its maximum value at $|\mathbf{P}_{23}| = 0$. Therefore QFS cross section is enhanced at $|\mathbf{P}_{23}| = 0$, i.e., at $|\mathbf{P}_3| = 0$ 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 increases when their relative energy decreases to 0. There are three FSIs between 1-2, 2-3, and 3-1.

Star configuration is most far from FSI configuration. In a star configuration, all relative energies are the same $E_{12} = E_{23} = E_{31} = E_r^{av}$. Off the star, at least one relative energies E_{ij} is smaller than E_r^{av} , and FSI_{ij} is stronger than FSI_{av} .

Space Star (SS) is also far from QFS. Consider pd breakup with a p -beam and a d -target. At pp -QFS, $E_n = 0$ (laboratory frame). At SS, $E_n = E_{p1} = E_{p2} = E_N^{av}$ which is far from 0.

Since SS is most far from FSI and considerably far from QFS, breakup cross section at SS is small. Around SS configuration, there are no mechanisms that enhance the breakup cross section. It means the breakup cross section is small and varies slowly as if it were constant. Such conditions are advantageous to detect minor effects. We remember that $2\pi 3\text{NF}$ was found from the minimum of pd scattering cross section, where effects of 2NF are small and $2\pi 3\text{NF}$ 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 $D(d, n)^3\text{He}$ reaction at 0° , 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 Nd breakup cross section at Space Star. The ratio is higher than 1 for nd SS, and lower than 1 for pd SS

experiments on 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 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 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 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 nd -SS cross section would be helpful. However, precise experiments on the nd cross section are very hard and to make experiments on pd -SS is much more advantageous if we have the pd breakup calculation in which Coulomb force is reliably treated.

6.4 Experiments on pd Breakup at SS

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

The ratios of the existing pd SS cross section data to pd calculations, together with the ratios for nd SS cross section, are displayed in Fig. 49. The ratio of experiment/calculation gradually becomes 1.0 as the energy increases in both pd breakup and 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 pd breakup, and higher than 1.0 in 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 pd SS anomaly is described below.

6.5 Experiment on pd Breakup Around SS at $E_p = 13$ MeV

At $E_n = 13$ MeV, 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 pd breakup cross section around pd -SS configuration [50].

A 13 MeV p -beam from Kyushu University tandem accelerator was incident on a CD_2 foil target. Two protons from $p + d \rightarrow p_1 + p_2 + n$ 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 $E_p = 13$ 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

protons. Since the cross section is the same at (θ_1, θ_2) and (θ_2, θ_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. Outsidess 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 $E_{\vec{d}} = 19$ MeV

A large anomaly at pd star apart from pd -SS was found by Köln group at $E_{\vec{d}} = 19$ 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° to 56° .

Fig. 52 Angular dependence of $D(p, p_1 p_2)n$ cross section around SS at 13 MeV

Fig. 53 Definition of an inclination angle α of Star

Let's define an inclined angle α 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 α as the angle between the proton momentum in the initial state $\mathbf{P}_p$ and the momentum sum $\mathbf{P}_1 + \mathbf{P}_2$ 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° . 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 α 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 α -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.

Fig. 54 Typical data of $D(p, p_1 p_2)n$ cross section at off-plane Star at 13 MeV

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 ± 0.05 mm in diameter and was 350 ± 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 $\text{CD}_2(\text{CH}_2)$ 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 α , 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 α -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 Köln 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).

Fig. 55 Off-plane Star anomaly as a function of α at 13 MeV and 9.5 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 α . Our previous experiment around pd -SS at 13 MeV with conditions of $\theta_1 = \theta_2$, $\phi_{12} = 120^\circ$ 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 ϕ_{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 breakup is well known and has been confirmed by repetitious experiments at KUTL and at Köln. On the contrary, there have been a few experiments on QFS anomaly. Accumulation of reliable experimental data on QFS anomaly is now highly required.

We have started a systematic measurement of pp -FSI cross section at $E_p = 9.5$ MeV and at 13 MeV, using a p -beam at KUTL. When a $p + d \rightarrow p_1 + p_2 + n$ experiment is made with a d -target and p_1 and p_2 are detected, QFS occurs at $E_n = 0$ MeV in the laboratory system. The QFS condition, $E_n = 0$ MeV, is satisfied at various combinations of (θ_1, θ_2) as shown in Fig. 56. So far QFS in pd breakup has been measured only at $\theta_1 = \theta_2$. The angle pairs of (θ_1, θ_2) at which we have made our measurements are indicated in Fig. 56.

Experimental procedure for QFS was the same as that for the off-plane star. The absolute value of QFS cross section was determined referring to our precise data on $p + d$ scattering cross section [6]. Examples of the measured QFS cross section are illustrated with pd calculations by Deltuva (Private Communication) in Fig. 57. Effects of Coulomb force and those of $2\pi 3NF$ influence cross section are small. Calculation with Coulomb force and $2\pi 3NF$ agrees fairly well with the measured cross section not only around QFS peak but also in the whole region.

Fig. 56 Angle pair (θ_1, θ_2) for QFS at 13 MeV, together with $\theta_1 = \theta_2$ line. Measurements were made at marked angle pairs

Fig. 57 Typical data for $D(p, p_1 p_2)n$ cross section at QFS at 13 MeV. E_n is plotted to indicate QFS condition

Fig. 58 Experiment/calculation ratio of $D(p, p_1 p_2)n$ 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.

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;

- pd* scattering at $E_{\vec{p}} = 2-18$ MeV and $E_{\vec{d}} = 5-18$ MeV for cross section, A_y , iT_{11} , T_{20} , T_{21} and T_{22} ,
- nd* scattering at $E_{\vec{n}} = 12$ and 16 MeV for A_y ,
- pd* capture at $E_{\vec{d}} = 17.5, 137$ and 196 MeV for A_y , A_{xx} , A_{yy} and A_{zz} ,
- pd* breakup at $E_{\vec{p}} = 247$ MeV for cross section and A_y ,
- pd* breakup at $E_{\vec{p}} = 9.5$ and 13 MeV, and $E_{\vec{d}} = 26$ MeV.

We have made these experiments with purposes of

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

So far only 2π 3NF effects were found and the strength of 2π 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 $3N$ reactions. Acute characteristics in $3N$ system can be found and precisely investigated nowadays.

Discrepancies in $3N$ 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 $3N$ study. Existing experimental data are waiting for such calculations to be made extensively in the near future.

Discrepancies in $3N$ 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 $3N$ systems than in other 3-particle systems. $3N$ systems are rich fields for precise study of 3-particle problems.

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