EPJ Web of Conferences **3**, 05022 (2010)
DOI:10.1051/epjconf/20100305022

Measurement of ^{2}H(p, pp)n cross sections at E_p = 250 MeV

S. Kuroita[1,a], K. Sagara[1], Y. Eguchi[1], K. Yashima[1], T. Yabe[1], T. Shishido[1], M. Dozono[1], Y. Yamada[1], T. Wakasa[1], T. Noro[1], H. Matsubara[2], J. Zenihiro[2], A. Tamii[2], H. Okamura[2], K. Hatanaka[2], T. Saito[3], Y. Maeda[3], H. Kamada[4], and Y. Tameshige[5]

[1] Department of Physics, Kyushu University, Hakozaki, Fukuoka, 812-8581, Japan
[2] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, 567-0047, Japan
[3] Department of Applied Physics, University of Miyazaki, Miyzaki, Miyazaki, 889-2192, Japan
[4] Department of Physics, Faculty of Engineering, Kyushu Institute of Technology, Kitakyushu, 804-8550, Japan
[5] National Institute of Radiological Sciences, Anagawa, Chiba, 263-8555, Japan

Abstract. In our previous inclusive experiment on pd breakup at E_p = 247 MeV, we found experimental cross section is about twice larger than $3N$ calculation with $\pi\pi$3NF at forward angle. Therefore we made exclusive measurement of ^{2}H($p, p_1 p_2$)n cross section at the same 247 MeV. Preliminary data indicate that the cross section enhancement appears at forward angles of θ_1 and θ_2. We made also inclusive experiment again and confirmed the previous data.

1 Introduction

Realistic nucleon-nucleon (NN) potentials have been obtained based on meson-exchange theory or phenomenological approaches [1,2], and existing experimental data on NN systems up to 350 MeV are well reproduced using these NN potentials. Some experimental data on $3N$ systems, however, can not be well reproduced by these NN potentials. The disagreement between $3N$ data and $3N$ Faddeev calculations using NN potentials seems to indicate effects of three nucleon forces (3NF).

Existence of 3NF was predicted by Fujita-Miyazawa in 1957 [3]. Many attempts were made to search for Fujita-Miyazawa type $\pi\pi$-exchange 3NF ($\pi\pi$3NF). Because 3NF effects are small compared to 2NF effects, identification of 3NF effects out of 2NF effects is difficult. Accurate and systematic experiments and rigorous calculations are necessary to find 3NF effects.

In 1998, after 41 years from Fujita-Miyazawa prediction, strength of $\pi\pi$3NF was first determined from two kinds of disagreements between experiments and calculations with 2NF on ^{3}H binding energy [4] and on cross section minima of pd elastic scattering [5]. Both disagreements were excellently eliminated by introducing the same $\pi\pi$3NF. Nowadays, $\pi\pi$3NF models, for example, Tucson-Melbourne (TM3NF) [6] and Urbana IX [7] are widely used, and biding energies of $3N$ systems as well as cross section of Nd elastic scattering below 140 MeV are well reproduced.

After $\pi\pi$3NF has been introduced in $3N$ calculations, there still remain many disagreements in observables of $3N$ reactions, that is, in cross sections and in polarization observables of analyzing powers, spin-transfer coefficients, and spin-correlation coefficients [8–10]. We guess that disagreements at higher energy may have some relations with short-range 3NF (SR3NF) which have not been introduced yet. Typical SR3NF are $\pi\rho$-exchange 3NF ($\pi\rho$3NF) and $\rho\rho$-exchange 3NF ($\rho\rho$3NF). Our next step is to identify effects of SR3NF and to determine strengths of SR3NF one by one.

We investigate first the disagreements in $3N$ cross section at higher energy, because scalar observable is basic quantity and has influences on vector and tensor observables. So far, two kinds of disagreements have been found in $3N$ cross section at higher energy.

(a) One is in Nd elastic scattering cross section.
(b) The other is in pd breakup cross section.

Typical example in (a) can be seen in Nd elastic scattering cross section at E_N = 250 MeV. Experimental cross section at backward is about 2 times larger than $3N$calculations [8,11]. Inclusion of 2π3NF increases cross section only a little and the disagreement is almost unchanged. Relativistic effects have been investigated, and the effects are expected to be small, below several percents. Therefore, effects of SR3NF are expected to be large in (a). Disagreement in backward scattering cross section begins to appear at around E_N = 140 MeV [12] and becomes larger monotonically with energy.

Example in (b) was found in our ^{2}H(p, p)pn experiment at 250 MeV [13,14]. Only one proton among three nucleons from pd breakup reaction was detected (inclusive experiment), and energy spectra of pd breakup cross section were obtained as shown in Fig. 1. Measured cross section is up to twice larger than $3N$ calculated one. Inclusion of $\pi\pi$3NF reduces the disagreement, but larger part of

[a] e-mail: kuroita@phys.kyushu-u.ac.jp

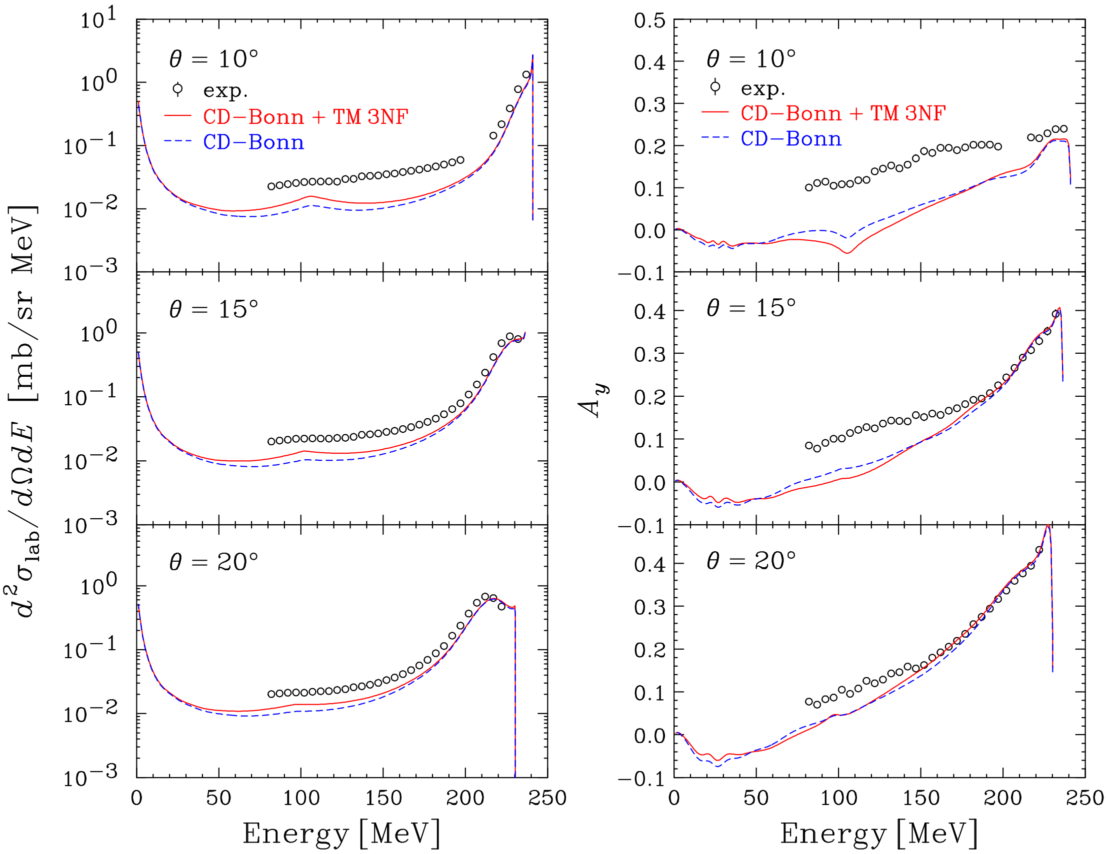

Fig. 1. Open circles represent cross sections (left) and analyzing power A_y (right) of ^{2}H($\vec{p}$, p)pn reaction at 247 MeV. Red solid and blue dashed curves stand for 3N calculations [15] using CD-Bonn potential with and without TM3NF, respectively.

the disagreement remains. The disagreement in *pd* breakup cross section becomes larger at forward proton angle. At 250 MeV, total *Nd* breakup cross section is about 10 times larger than total *Nd* elastic scattering cross section [16]. The disagreement in *pd* breakup cross section, therefore, should be investigated in detail. Fig. 1 shows that also A_y is not reproduced. We will investigate A_y problem after we solve the cross section problem.

To investigate further the disagreement found in our inclusive experiment for *pd* breakup, we made an exclusive experiment of ^{2}H(p, pp)n cross section at 250 MeV, by detecting two protons from the *pd* breakup reaction. Exclusive measurement needs much time and we should select angle pairs where the measurement is made. Details are described at next section.

2 Experiment procedure

Experiments on *pd* breakup cross section was made at the Research Center for Nuclear Physics (RCNP), Osaka University using a 250 MeV proton beam from ring cyclotron[17]. Protons from *pd* breakup were detected two magnetic spectrometers, Grand Raiden which is the high resolution spectrometer [18] and LAS which is the second arm large acceptance spectrometer [19].

To measure ^{2}H(p, p_1p_2)n cross section, angle of p_1 and p_2 should be determined. Fig. 1 shows that disagreement increases as angle (θ_1) goes to forward. Therefore, the p_1-counter was placed at an as forward angle as possible, at $\theta_1 = 15°$. The other counter for p_2 was placed at several angles at 35°, 50°, 65° and 80°, to see angular dependence of the disagreement.

Calculation of ^{2}H(p, p_1p_2)n cross section at angle (θ_1, θ_2, ϕ_{12}) was made prior to the experiment by H. Kamada [20], where ϕ_{12} is relative azimuth angle between p_1 and p_2 with respect to polar axis of the beam direction ($\phi_{12} = \phi_1 - \phi_2$). The calculation predicts that the *pd* breakup cross section at the same (θ_1, θ_2) takes the maximum value at $\phi_{12} = 180°$, and monotonically decreases as ϕ_{12} decreases to 0°. We decided to measure the maximum cross section, and detected p_1 and p_2 on the opposite (left and right) sides of the beam.

At an angle pair (θ_1, θ_2, ϕ_{12}), energies of protons from ^{2}H(p, p_1p_2)n reaction, E_1 and E_2, varies from 0 to about 247 MeV. Our counters for p_1 (Grand Raiden) and p_2 (LAS) can detect particles in restricted momentum range ±2.5% and ±15%, respectively. Therefore, we had to choose energy region to be measured. We chose E_1 to be around 150 MeV, because disagreement becomes largest around 150 MeV (Fig. 1). Another energy E_2 is determined uniquely by kinematics.

As shown in Fig. 2, the beam was stopped on a Faraday cup in a scattering chamber of 70 mm in diameter. A liquid target was set at the center of the chamber. Two protons p_1 and p_2 were detected by vertical drift chambers (VDCs) and trigger scintillators of Grand Raiden and LAS, respectively. During the experiment, product of the target thickness and the beam current was monitored by measuring *pd* elastic scattering using two counters of plastic scintillators.

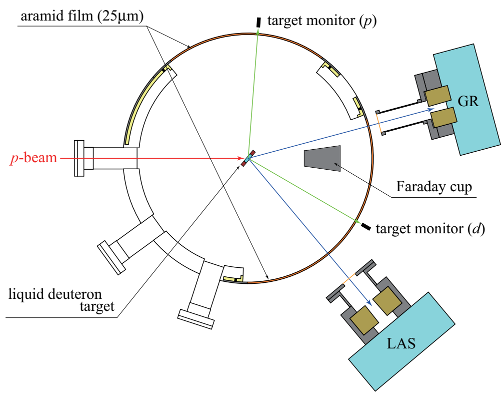

Fig. 2. Experimental setup inside scattering chamber.

2.1 Improved scattering chamber

Ordinarily, Grand Raiden and LAS are connected to the scattering chamber in vacuum by sliding membrane systems. When Grand Raiden or LAS counter rotates around the chamber to change its angle, stainless steel (SUS) membranes of 0.5 mm in thickness on both sides of the counter slide together on o-ring surfaces keeping the chamber in vacuum. The membrane rolling systems need space.

We replaced the membrane systems with fixed windows sealed by 25μm thick aramid foil. Protons from the target went out of the vacuum chamber through the window foil, ran about 50 mm in air, then entered the counter duct in vacuum through another window foil. The protons have energy higher than 70 MeV and can pass through foils and air with small angular spread. By this replacement, dynamic angular range of Grand Raiden and LAS was increased and we could place, for example, Grand Raiden at 15° and LAS at 35° for coincidence measurement.

2.2 Target

Cross sections of exclusive *pd* breakup reaction ^{2}H(p, pp)n were measured using a liquid deuterium (Liq.D_2) target with thickness of about 220 mg/cm^2. Because the thickness of a Liq.D_2 target change corresponding to temperature and pressure, we monitored the thickness by measuring *pd* elastic scattering under measurement of cross section for ^{2}H(p, pp)n. The thickness of a Liq.D_2 target have been decided by comparing counts of *pd* elastic scattering from liquid deuteron target and deuterated polyethylene foil which thickness was understood.

The target of Liq.D_2 [21], whose thickness was about 10 mm, that is, about 140 mg/cm^2, was used for this experiment. Thin aramid foil of 6μm in thickness was used for windows of the target cell. Compared with a CD_2 target of the same thickness, D-contents was 4 times increased, and number of impurity atoms (C and others) was decreased to 1/250. A low-background, thick-target experiment was made.

Schematic view of the target system is in Fig. 3. The target cell was connected through a pipe to a D_2 gas reservoir in the atmosphere. The target cell was cooled down below 20 K by a cryogenic refrigerator and D_2 was liquefied. When D_2 freeze in the pipe and D_2 gas can not escape, the window foil is exploded. When temperature of Liq.D_2 varied 1°C, its density varies 1-2%. Therefore temperature was measured using Si diode sensors (2 places) and was kept constant using a heater. The refrigerator was powerful and the heater power was 6 W normally.

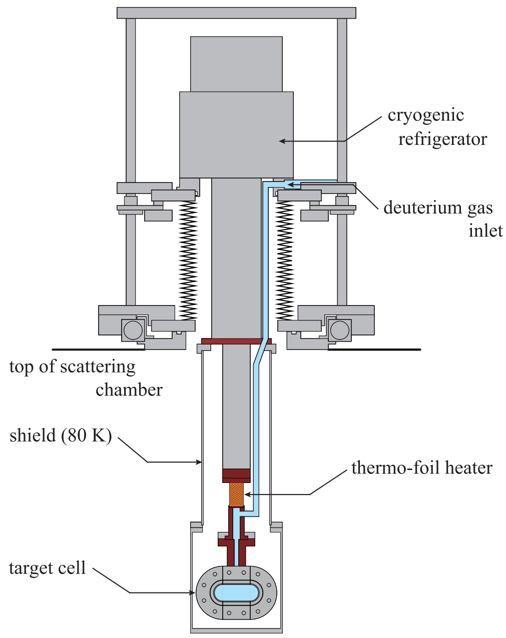

Fig. 3. Schematic view of the Liq.D_2 target.

The target cell and a cold head of the cryogenic refrigerator were covered by an Aluminum heat-shield of about 80 K, to cut radiation heat and to avoid adsorption of residual gases on the target windows.

As seen in Fig. 2, we detected p_1 at 15° on the left side, and detected p_2 at 35°-80° on the right side. Besides, monitor detectors were set at 85.6° on the left and at 30.1° on the right. Therefore, the target plane was 45° inclined with respect to the beam axis. Since the target has thickness of 10 mm, it needs enough horizontal length, as seen in Fig. 3. After the window shape was determined, the limiting pressure of the window foil was measured to be 0.8 atmospheres on the average.

To evaluate thickness of the Liq.D_2 target, we used a CD_2 foil target of about 13.5 mg/cm^2. We solved CD_2 powder by xylene and heated the solvent on a hot flat-glass

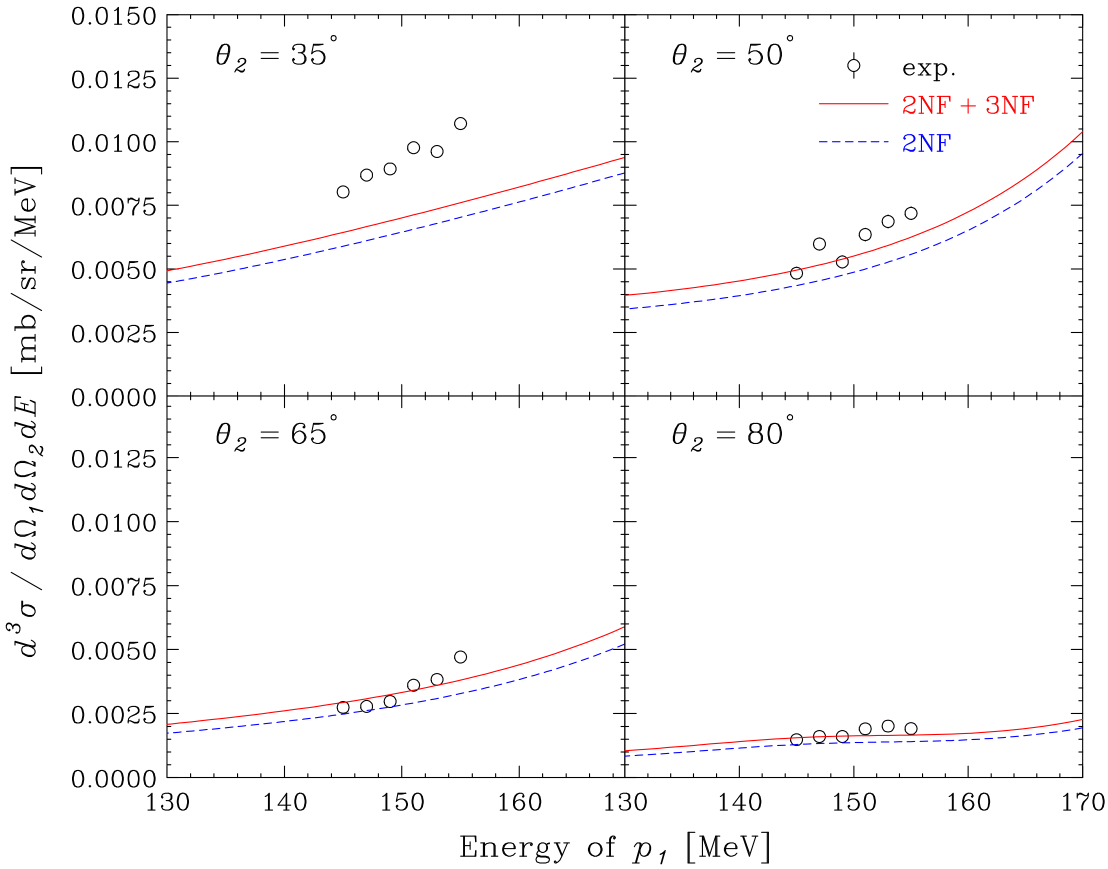

Fig. 4. Open circles represent preliminary cross sections of ^{2}H($p, p_1 p_2$)n reaction at 250 MeV. The cross sections measured, when $\theta_{p_1} = 15^\circ$ and $E_{p_1} = 150$ MeV were fixed. Red solid and blue dashed curves stand for 3N calculations [20] using CD-Bonn potential with and without TM3NF, respectively.

plate to polymerize CD_2. Since the solvent was a lot to make 13.5 mg/cm^2 thick polymer, a ring-glass was used on the flat-glass as a dam.

Using a 250 MeV proton beam and the target monitor system, ratio of the liquid D_2 target thickness and the CD_2 foil thickness was measured. Absolute thickness of the CD_2 target was measured at Kyushu University tandem accelerator laboratory (KUTL) using a 12 MeV proton beam from tandem accelerator [22] and using accurate and systematic data on pd elastic scattering cross section taken at KUTL [23].

3 Experimental results

The present exclusive experiment of ^{2}H($p, p_1 p_2$)n cross section at $E_p = 250$ MeV was made in May 2009, and preliminary experimental results are shown in Fig. 4. Statistical errors in Fig. 4 are typically ±3%. Errors in scale (in absolute values) are about 10% at present, and will be reduced to a few percentage after detailed data analysis is completed. Main error sources come from the target thickness and from the detection efficiencies of the Grand Raiden and LAS counters.

In Fig. 4, disagreement between the experiment and calculation increases as θ_2 goes forward (θ_1 is fixed at 15°). Absolute value of the cross section also increases as θ_2 goes forward. That means, the main contribution to the disagreement may be produced at forward angle region where the cross section is large. Inclusion of $\pi\pi$3NF pushes up the cross section and reduces the disagreement, but effects of $\pi\pi$3NF are not sufficient. Experimental data indicate existence of origin(s) other than $\pi\pi$3NF.

From dependence of the disagreement seen in Fig. 4, one wishes to make further measurement at forward θ_2. Unfortunately, two big counters, Grand Raiden and LAS, can not come to each other closer than 48°, and ($\theta_1 = 15^\circ, \theta_2 = 35^\circ$) is the practical limit at present.

In the same beam time, we measured also inclusive ^{2}H(p, p_1)$p_2 n$ cross section in the angular range of 10° < 35°. At $\theta_1 = 15^\circ$, our previous data and the new data agree well within experimental errors, that is, the experimental data are confirmed to be about twice larger than calculations.

4 Summary

In our previous experiment on ^{2}H(p, p_1)p_2n cross section at E_p = 247 MeV, experimental cross section is larger than calculation. Inclusion of $\pi\pi$3NF increases cross section a little and the disagreement between the experiment and calculation still remains. The disagreement increases as θ_1 becomes forward.

In the present experiment, cross section of ^{2}H(p, p_1p_2)n reaction at E_p = 250 MeV was measured at $\theta_1 = 15°$ and $\theta_2 = 35°, 50°, 65°$ and $80°$, around E_1 = 150 MeV. Preliminary experimental cross section agrees with calculation at backward, and gradually overwhelms calculation as θ_2 becomes forward. In the same experiment, inclusive ^{2}H(p, p_1)p_2n cross section was measured again in wider angular range, and disagreement was confirmed.

We found that cross section of pd breakup at 250 MeV overwhelms calculation at forward angles. Inclusion of $\pi\pi$3NF enhances cross section a little, but several times more enhancement is necessary to reproduce experiment at forward angles. Short range 3NF (SR3NF), such as $\pi\rho$3NF and $\rho\rho$3NF, are candidates for origin(s) of the enhancement. Theoretical investigations are required.

In Nd elastic scattering at the same 250 MeV, experimental cross section at backward was found to be larger than calculation. The disagreement in Nd scattering is similar magnitude as that in pd breakup. It is natural to imagine both disagreements have common origin(s). We hope challenging calculations using SR3NF.

References

1. R.B. Wiringa, V.G.J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, (1995) 38.
2. R. Machleidt, F. Sammarruca, and Y. Song, Phys. Rev. C **53**, (1996) R1483.
3. J. Fujita and H. Miyazawa, Prog. Theor. Phys. **17**, (1957) 360.
4. A. Nogga *et al.*, Phys. Lett. B **409**, (1997) 19.
5. H. Witała *et al.*, Phys. Rev. Lett. **81**, (1998) 1183.
6. S.A. Coon *et al.*, Nucl. Phys. **A317**, (1979) 242.
7. B.S. Pudliner *et al.*, Phys. Rev. C **56**, (1997) 1720.
8. K. Hatanaka *et al.*, Phys. Rev. C **66**, (2002) 044002.
9. K. Sekiguchi *et al.*, Phys. Rev. C **65**, (2002) 034003.
10. R.V Cadman *et al.*, Phys. Rev. Lett. **86**, (2001) 967.
11. Y. Maeda *et al.*, Phys. Rev. C **76**, (2007) 014004.
12. K. Ermisch *et al.*, Phys. Rev. C **71**, (2005) 064004.
13. S. Kuroita *et al.*, Few-body Syst. **44**, (2008) 53.
14. S. Kuroita *et al.*, Mod. Phys. Lett. A **24**, (2009) 823.
15. H. Witała, private communication.
16. J. Kuroś-Żołnierczuk *et al.*, Phys. Rev. C **66**, (2002) 024003.
17. I. Miura *et al.*, in *Proceedings of the 13th International Conference on Cyclotrons and their Applications, Vancouver, 1992*, edited by G. Dutto and M.K. Craddock, (World Scientific, Singapore, 1993), p3.
18. M. Fujiwara *et al.*, Nucl. Instrum. Methods Phys. Res. A **422**, (1999) 484
19. N. Matsuoka *et al.*, RCNP report, (1992)
20. H. Kamada, private communication.
21. K. Sagara *et al.*, RCNP Anual Report, (1995) 158.
22. A. Isoya *et al.*, KUTL report **1**, (1985) 3.
23. K. Sagara *et al.*, Phys. Rev. C **50**, (1994) 576.