Chapter 89
Experimental Analysis of Few-Body Physics

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Abstract The differential cross sections of the elastic *Nd* scattering at the energy below 150 MeV can be well reproduced by introducing 3NF in the Faddeev calculations based on modern nucleon-nucleon (NN) interactions. On the other hand, some spin-observables, and the differential cross sections of *Nd* elastic and inelastic scatterings at over 250 MeV show large discrepancies between the data and the Faddeev calculations with 3NF. It indicates the presence of the missing features of the three nucleon systems. For the systematic study about these large discrepancies at higher energy regions, we measured the differential cross sections and the vector analyzing power for the inclusive and exclusive breakup reaction at 170 and 250 MeV. The experiments were carried out at RCNP. The data were compared with the results of the Faddeev calculations with and without the 3NF.

89.1 Introduction

The study of three-nucleon force (3NF) effects is attracting attentions not only in the few-body studies but also in the studies of heavier system like neutron-rich nuclei and neutron star. Historically, the need for many-body interaction was suggested just after Yukawa's meson theory in 1939 [1]. Based on the meson exchange picture, the main component of the 3NF is considered to be Fujita-Miyazawa type, a 2π-exchange between three nucleons with a Δ isobar excitation as an intermediate state [2]. Firstly, the study of the 3NF effects was started through the bound states of few nucleon systems. The correct binding energies of 3N bound systems were reproduced by introducing the Tucson-Melbourne (TM) or Urbana-IX 3NFs, which showed the clear effects of 3NF in the nucleus.

The study of the 3N continuum states through the *Nd* scattering allows us to measure not only the cross sections but also the spin observables, which offer more details of 3NF properties. The recent progress in computational resources has made

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it possible to obtain rigorous numerical results of Faddeev calculations for the 3N scattering at intermediate energy region with using the realistic NN forces and 3N forces. In the experimental sides, highly precise measurements of the *dp* elastic scattering for the deuteron energies of E_d^{lab} = 140, 200 and 270 MeV have been performed [3, 4]. The calculations with NN forces only fail to reproduce the data of cross sections and vector analyzing powers at the angular range where the cross section takes minimum. These discrepancies are filled by adding 3NFs. These results mean that the *Nd* elastic scattering at intermediate energy is a good probe to study the 3NF effects.

Theoretically, 3NF effects are expected to be significant at higher energy. However, the Faddeev calculations with 3NF still underestimate the data for *nd* [5] and *pd* [6] elastic scattering at 250 MeV. The discrepancies between the data and the theory can not be explained by the relativistic corrections [7]. This is quite different to the results of the comparisons between the data and the theoretical predictions at 135 MeV/nucleon.

For the next step of the study of 3NF effects, the breakup reactions are expected to give us more information because the total cross sections of the breakup are predicted to become larger than elastic at higher energy region. So we performed measurements of both inclusive and exclusive breakup reactions at 170 and 250 MeV at Research Center for Nuclear Physics (RCNP), Osaka university.

89.2 Inclusive Breakup Reaction

We performed two different types of measurements of inclusive breakup reactions at RCNP. One was $\mathrm{D}(p,p)pn$ inclusive breakup reaction at $E_p = 250$ MeV [8]. In this experiment, polarized proton beam of 250 MeV was bombarded on the liquid deuterium target and scattered proton was analyzed by LAS spectrometer at θ_{LAB} = 10, 15, 20, 25, and 30°. In [8], the differential cross sections and vector analyzing powers are compared with the Faddeev calculations with and without 3NF. Concerning about the differential cross sections, only the half value of the data in the high energy transfer region were explained by the theory. This result is similar to that of elastic scattering at 250 MeV.

Another was $\mathrm{D}(p,n)pp$ inclusive breakup reaction at 170 MeV. Because this energy is lower than the π-threshold of 210 MeV, it would allows us explicit comparison between the data and the theory. In this experiment, we accelerated the polarized proton beam up to E_p = 170 MeV and transported it to the N0 experimental hall. We used the deuterated polyethylene (CD_2) sheets [9] as the deuteron targets. The thickness of them were 44 and 110 mg/cm^2. To subtract the contributions from the carbons in CD_2 targets, we also used a graphite target of 140 mg/cm^2.

The proton beam was injected to the targets in the vacuum scattering chamber and bent to the beam dump by the swinger magnet. The scattered neutrons passed through the vacuum window and ran through the 100 m time-of-flight (TOF) tunnel in the air then be detected by NPOL3 [10]. The efficiency of NPOL3 was determined

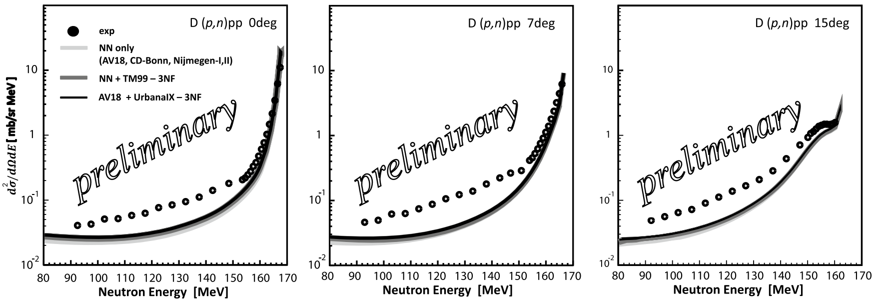

Fig. 89.1 The double differential cross sections for the D(p, n) breakup reactions at $\theta_{lab} = 0, 7, 15°$ as functions of the scattered neutron energy. The solid circles show the data with statistical errors only. The calculations including various NN forces only (light shaded band), various NN forces with TM99-3NF (dark shaded band) and AV18+UrbanaIX-3NF (solid line) are also shown

by measuring the ^{7}Li(p, n)^{7}Be(g.s. + 0.4 MeV) reaction, of which cross sections were measured over the wide energy range. In this work, the efficiency was deduced to be about 1.5%. The energy of a detected neutron was deduce by TOF method.

Preliminary results for the double differential cross sections at θ_{lab} = 0, 7, 15° are shown in Fig. 89.1 as functions of the scattered neutron energy. The data are compared with the Faddeev calculations [11]. The dark (light) shaded bands show the calculations based on the NN forces (CD-Bonn, AV18, Nijmegen-I&II) with (without) TM99-3NF. The solid lines represent the calculations based on AV18 and UrbanaIX-3NF.

We can see large discrepancies between the data and the calculations in the low neutron energy regions. In this regions, the calculations including 3NF can explain only about 50% of the data, which is similar to the results of the D(p, p) inclusive breakup reaction at 250 MeV. It may indicates the presence of the missing features of the three nucleon system at intermediate energy region, for instance $\pi - \rho$ or $\rho - \rho$ exchange type 3NF effects, which are not included in the present calculations. On the other hand, the energy dependence of discrepancies between the data and the theoretical calculations are rather small, which is different from the case of elastic scatterings. It suggests that more study of the inclusive breakup reactions in the different beam energies are important to explore the energy dependence of the 3NF effects.

Concerning about the analyzing powers of D(p, n)pp reacrions, the statistical errors of the data are large to discuss about the effects of 3NF. The data are almost consistent with the calculations within the error bars.

89.3 Exclusive Breakup Reactions

In the studies by using the exclusive breakup reactions, it is important to select kinematical configurations to measure because the three-nucleon final states are kinematically much more complicated than elastic and inclusive breakup reactions. To investigate the origin of large discrepancies in the differential cross sections of the elastic and inelastic scattering which were mentioned above, we performed the two different sets of measurements of $D(p, pp)n$ exclusive breakup reactions at 250 MeV at RCNP west experimental hall. The polarized proton beam of 250 MeV was bombarded to liquid deuterium target and scattered two protons (p_1 and p_2) were analyzed by double arm magnetic spectrometer LAS and Grand Raiden (GR), respectively.

In one set of measurements, we focused on the kinematical configurations that one proton p_1 was scattered into $\theta_{LAS} = 15°$, because the data of $D(p, p)pn$ inclusive measurement showed large disagreement with the theories at forward angular region [12]. Another proton p_2 was measured at $\theta_{GR} = 35$, 50, 65, and 80°. In [12], the comparison between the data of differential cross sections and the theoretical calculations show angular distribution: the data are well reproduced only in configurations with large θ_2.

In another set of measurements, we focused on the kinematical configurations, so-called final state interaction (FSI) geometry, because FSI configurations are predicted to be a good probe for not only the 3NF effects but also the difference between the 3NF models [13]. According to this theoretical prediction, we measured A_y and the differential cross sections of the following reaction $\overrightarrow{p} + d \rightarrow (p_1 n)_{FSI} + p_2$ at E_p = 250 MeV. We chose the configuration that the *np* pair is around FSI, because it is difficult to include the Coulomb force in the Faddeev calculations for the *pp* pair in FSI. The recoiled proton p_1 in FSI is detected by using LAS spectrometer at $\theta_{\rm LAB}$ = 40°. Another proton p_2 which scattered in the direction around $\theta_{\rm LAB}$ = 67°, which depends of the relative energy between proton p_1 and neutron, is detected by using GR spectrometer in coincidence with p_1. By using the momentum vectors of p_1 and p_2, we obtained the missing mass spectrum of neutrons with the energy resolutions of 1.2 MeV.

We obtained the preliminary results of the differential cross sections and the vector analyzing powers with the S-curve energy bin of the 7 MeV. The results are plotted in Fig. 89.2 by solid circles as a function of the energy of p_1. The statistical errors of the data are less than 1% and 0.02 for the differential cross sections and the vector analyzing powers, respectively. The peak corresponds to the FSI can be seen around $E_p = 65$ MeV.

The solid (dashed) lines represent the results of the Faddeev calculations [14] with (without) Tucson-Melbourne99 (TM99) 3NF based on the CDBonn potential. The dot-dashed (dotted) lines are the same predictions with solid (dashed) lines but integrated with the experimental solid angles. From Fig. 89.2, we can see that the experimental results are well reproduced by the calculations which integrated with the angular acceptance of the measurements. The data around FSI are well reproduced

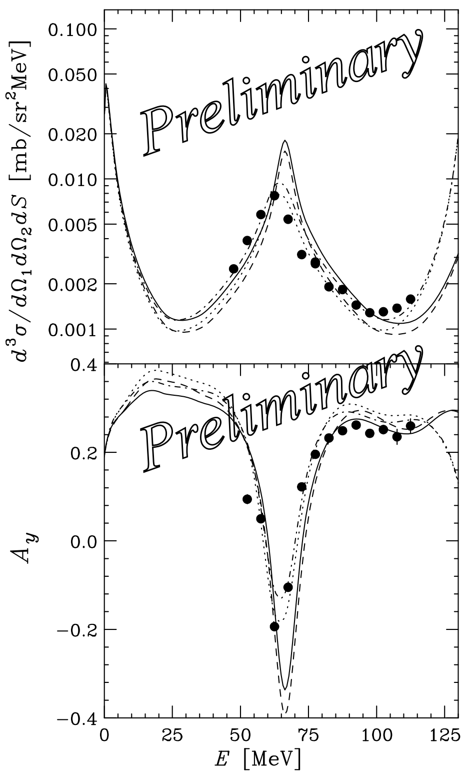

Fig. 89.2 The upper and the lower panel show the results of the differential cross sections and the vector analyzing powers for the *pd* break reactions at 250 MeV for $\theta_p = \theta_n = 40°$ in the laboratory system (solid circles). Only the statistical errors are represented. The predictions with CDBonn and TM99-3NF (solid line) and that with CDBonn only (dashed line) are shown simultaneously. The dot-dashed (dotted) lines are the theoretical results with (without) TM99-3NF which integrated with the angular acceptance of the measurements

by the calculations with CDBonn only but the data around the cross section minimum are well reproduced by that including TM99-3NF. This result is different from the case of elastic and inclusive breakup reactions. It would be interesting to compare the data with the theoretical predictions which include the relativistic corrections [7] or the Coulomb interaction effects [15].

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