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A. Watanabe · S. Nakai · Y. Wada · K. Sekiguchi · T. Akieda · D. Etoh · M. Inoue · Y. Inoue · K. Kawahara · H. Kon · K. Miki · T. Mukai · D. Sakai · S. Shibuya · Y. Shiokawa · T. Taguchi · H. Umetsu · Y. Utsuki · M. Watanabe · S. Goto · K. Hatanaka · Y. Hirai · Y. Ikeda · T. Ino · D. Inomoto · S. Ishikawa · M. Itoh · H. Kanda · H. Kasahara · Y. Maeda · S. Mitsumoto · K. Nonaka · H. J. Ong · H. Oshiro · Y. Otake · H. Sakai · A. Taketani · D. T. Tran · T. Uesaka · T. Wakasa · Y. Wakabayashi · T. Wakui

Analyzing Power Measurement for p-^{3}He Elastic Scattering at Intermediate Energies

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Abstract We present a precise measurement of ^{3}He analyzing powers for p-^{3}He elastic scattering with the polarized ^{3}He target at 50, 65, 70, and 100 MeV. The data at 65 and 70 MeV are compared with the theoretical predictions based on the modern nucleon-nucleon potentials. Large discrepancies between the data and the

A. Watanabe (✉)· S. Nakai · Y. Wada · K. Sekiguchi · T. Akieda · D. Etoh · M. Inoue · Y. Inoue · K. Kawahara · H. Kon · K. Miki · T. Mukai · D. Sakai · S. Shibuya · Y. Shiokawa · T. Taguchi · H. Umetsu · Y. Utsuki · M. Watanabe
Department of Physics, Tohoku University, Sendai 980-8578, Japan
A. Watanabe
E-mail: watanabe@lambda.phys.tohoku.ac.jp

S. Nakai
Graduate Program on Physics for the Universe (GP-PU), Tohoku University, Sendai 980-8578, Japan

S. Goto · Y. Hirai · D. Inomoto · H. Kasahara · S. Mitsumoto · H. Oshiro · T. Wakasa
Department of Physics, Kyushu University, Fukuoka 819-0395, Japan

K. Hatanaka · H. Kanda · H. J. Ong · D. T. Tran
Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan

Y. Ikeda · Y. Otake · A. Taketani · Y. Wakabayashi
RIKEN Center for Advanced Photonics, Wako 351-0198, Japan

T. Ino
High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

S. Ishikawa
Science Research Center, Hosei University, Tokyo 102-8160, Japan

M. Itoh
Cyclotron and Radioisotope Center, Tohoku University, Sendai 980-8578, Japan

Y. Maeda · K. Nonaka
Faculty of Engineering, University of Miyazaki, Miyazaki 889-2192, Japan

predictions are clearly seen at the angles where the ^{3}He analyzing power takes the minimum and maximum values, which are not explained by Δ-isobar effects.

1 Introduction

Three-nucleon forces (3NFs) have an important role in the description of various nuclear phenomena: few-nucleon scattering [1], binding energies of light mass nuclei [2], and nuclear matter properties [3]. In order to understand nuclear properties based on bare nuclear forces, it is indispensable to consider the 3NF. Few-nucleon scattering is a good probe to investigate dynamical aspects of 3NFs such as momentum, spin and isospin dependences. Direct comparison between high-precision data and rigorous numerical calculations for few-nucleon scattering processes provide a quantitative discussion of 3NF properties.

Nucleon-deuteron (Nd) elastic scattering at intermediate energies (larger than about 60 MeV/nucleon) has provided a solid basis to explore the 3NFs. Large discrepancies between the data and rigorous numerical calculations based on realistic nucleon-nucleon (NN) potentials were found in the cross section minimum [4]. Theoretical predictions with the 2π exchange 3NF models (Tucson-Melbourne'99 [5] or Urbana IX [6]) successfully reproduced the data.

The four-nucleon ($4N$) scattering also offers good opportunities to investigate the total isospin $T = 3/2$ channel of 3NFs whose importance is suggested for understanding asymmetric nuclear systems, e.g., neutron-rich nuclei [2] and neutron matter properties [3]. The p-^{3}He scattering is one of the simplest systems in which the $T = 3/2$ component of 3NFs can be investigated. With the aim of pinning down 3NF effects in comparison with the rigorous numerical $4N$ calculations and then approaching to the $T = 3/2$ channel of 3NFs, we performed the measurement of p-^{3}He elastic scattering at intermediate energies. In this contribution we report the measurement of ^{3}He analyzing powers for p-^{3}He elastic scattering with the polarized ^{3}He target.

In this paper we present the measurement of ^{3}He analyzing power A_{0y} at 50, 65, 70, and 100 MeV. In Sect. 2, we describe the details of the polarized ^{3}He target system. Section 3 presents the experimental procedure, and results follow in Sect. 4. Summary and conclusion are finally described in Sect. 5.

2 Polarized ^{3}He Target

Figure 1 shows a schematic view of the polarized ^{3}He target system. The method to polarize a ^{3}He nucleus was based on the spin-exchange optical pumping (SEOP) [7,8]. A target cell was one-piece GE180 glassware which consisted of two cylindrical chambers (a target chamber and a pumping chamber). The target (pumping) chamber had a length and a diameter of 15 cm (4.5 cm) and 4 cm (6 cm), respectively. The two chambers were connected by a thin transfer tube. This design was suitable for a scattering experiment because the depolarization of alkali metals and undesirable energy loss of the scattered protons passing through materials used for SEOP could be avoided. The target cell contained ^{3}He gas with a pressure of 3 atm at room temperature, a small amount of N_2 gas, and a mixture of Rb and K. The pumping chamber was headed up to about 500 K by a hot air blower to obtain a sufficient amount of alkali-metal vapor density. Rb atoms in the pumping chamber were polarized by using a circularly polarized laser light at 794.7 nm. ^{3}He nuclei were polarized through spin exchange interactions with alkali metals and diffused into the target chamber. Main coils which were a pair of Helmholtz coils 100 cm in diameter provided a 12 G magnetic field to define the direction of the ^{3}He polarization.

We used three totally independent methods to measure the ^{3}He nuclear polarization: an adiabatic fast passage nuclear magnetic resonance (AFP-NMR), an electron paramagnetic resonance (EPR) [9], and a neutron transmission. The AFP-NMR system consisted of the main coils, drive coils, and pick-up coils. Sweeping a static magnetic field while applying a RF field provided by the drive coils under the AFP condition, we flipped the direction of ^{3}He spin. The induced NMR signals were detected by the pick-up coils. We obtained the absolute values of the ^{3}He polarization and calibrated the AFP-NMR by using the EPR method. This method utilizes the EPR frequency shift due to the magnetic field created by polarized ^{3}He nuclei. The EPR system

H. Sakai · T. Uesaka
RIKEN Nishina Center, Wako 351-0198, Japan

T. Wakui
National Institute of Radiological Science, Chiba 263-8555, Japan

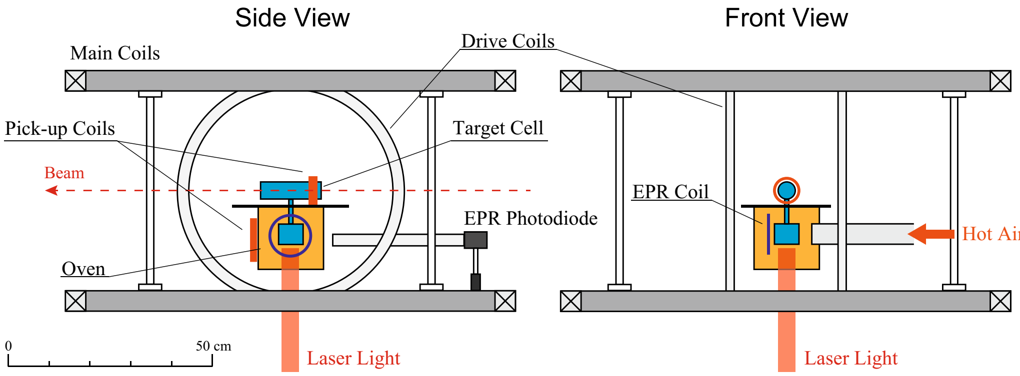

Fig. 1 A schematic view of the polarized ^{3}He target system

Table 1 Experimental conditions at CYRIC and RCNP

Facilities	CYRIC		RCNP	
Beam	Proton		Proton	
Target	^{3}He gas (2 mg/cm^2)		^{3}He gas (2 mg/cm^2)	
Energy	50 MeV	70 MeV	65 MeV	100 MeV
Beam intensity	3 nA	5–10 nA	10 nA	30 nA
Typical target polarization	50%	40%	45%	40%
Measured angles (θ_{cm})	47°–120°	46°–141°	47°–133°	47°–149°

consisted of a EPR coil to provide an RF magnetic field and a photodiode to detect a EPR signal. Additionally, we performed the neutron transmission measurement which offers direct measurement of the ^{3}He polarization in the target chamber at the RIKEN Accelerator-driven compact Neutron Source (RANS) [10]. The typical target ^{3}He polarization was 40–50% with an uncertainty of 2%. A more detailed description of the polarized ^{3}He target system can be found in Ref. [11].

3 Measurement of the ^{3}He Analyzing Power A_{0y}

The measurement of the ^{3}He analyzing power A_{0y} was performed with the polarized ^{3}He target at the Cyclotron Radioisotope Center (CYRIC), Tohoku University and the Research Center for Nuclear Physics (RCNP), Osaka University. The experiments at 50 and 70 MeV (65 and 100 MeV) were performed at CYRIC (RCNP). The experimental conditions are summarized in Table 1.

The same polarized ^{3}He target system and the same detection system were applied for the experiments at CYRIC and RCNP. An accelerated proton beam bombarded the polarized ^{3}He target and it was stopped in a Faraday cup which was used to charge collection of the beams. Scattered protons from the target were detected using sets of counter telescopes placed symmetrically on each side of the beam axis. The counter telescope consisted of a 50-mm-thick NaI(Tl) scintillator and a thin (0.2, 0.5, and 1.0 mm) plastic scintillator. A double-slit collimator was used to define the target volume and the solid angle for each counter telescope. During the experiment the AFP-NMR was used to monitor the target polarization and flip the direction of ^{3}He nuclear spin.

4 Experimental Results

The measured ^{3}He analyzing power A_{0y} is shown in Fig. 2 as a function of the center-of-mass (c.m.) scattering angle $\theta_{\text{c.m.}}$. The data are shown with the statistical errors as well as the systematic errors. The data at 65 and 70 MeV are compared with the theoretical calculations [12] based on the NN potentials: AV18 [13], CD Bonn [14], INOY04 [15], SMS400, and SMS500 [16]. The SMS400 (SMS500) is a semilocal momentum space regularized chiral NN potential of the fifth order (N^{4}LO) with the cutoff parameter $\Lambda = 400$ (500) MeV/c. In addition, we present the calculations based on the CD Bonn+Δ model [17] which allows the explicit excitation

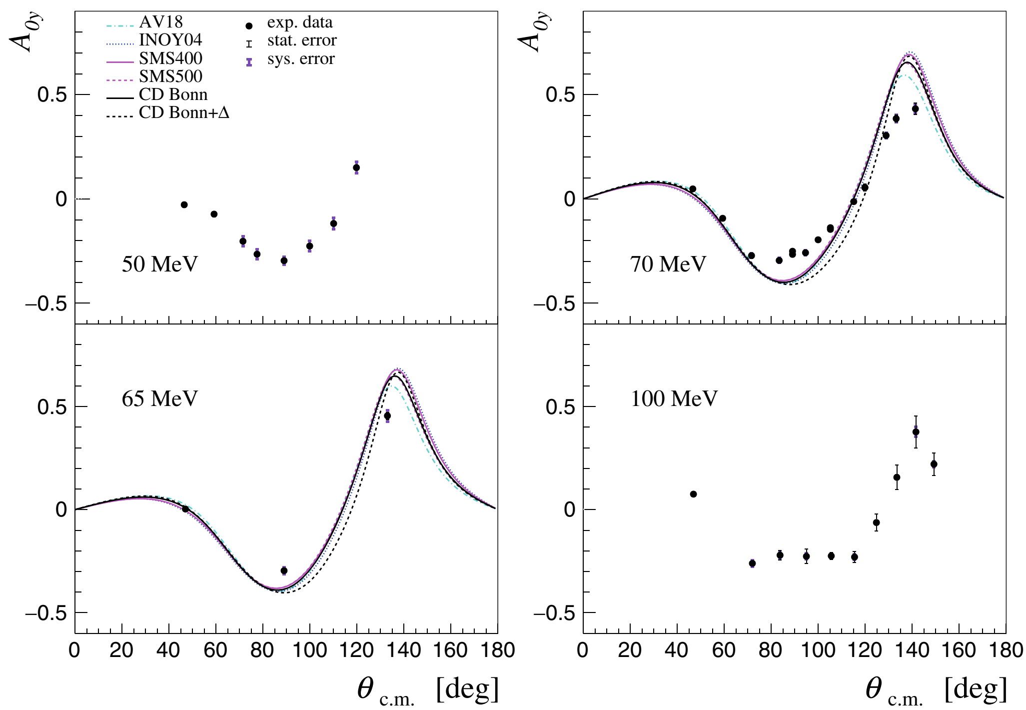

Fig. 2 (Color online) Angular distributions of ^{3}He analyzing power A_{0y} in p-^{3}He elastic scattering at 50, 65, 70, and 100 MeV. The theoretical calculations based on the AV18 (cyan dashed-dotted lines), CD Bonn (black solid lines) and INOY04 (blue dotted lines) NN potentials are shown. The magenta solid (dashed) lines are the calculation using the SMS400 (SMS500) potential. Black dashed lines are the calculations based on the CD-Bonn potentials with the Δ degrees of freedom

of a nucleon to a Δ-isobar and thereby provides effective 3NFs and 4NFs. The Coulomb force is omitted in the present study.

The theoretical calculations based on the NN potentials are close to each other. They clearly underestimate the data in the minimum region around $\theta_{\text{c.m.}} = 80°–100°$ and overestimate the data maximum region around $\theta_{\text{c.m.}} = 130°–140°$, which has not been seen at lower energies [18,19]. The Δ-isobar effects slightly shift the calculations but do not exclude the discrepancies between the data and the calculations. It is indicated that the irreducible 3NFs, such as the N^{2}LO or higher order 3NFs in the chiral effective field theory (EFT), should be considered.

5 Summary and Conclusion

We have performed the measurement of ^{3}He analyzing powers A_{0y} for p-^{3}He elastic scattering at 50, 65, 70, and 100 MeV with the polarized ^{3}He target. The experimental data at 65 and 70 MeV are compared with the rigorous numerical calculations based on the realistic NN potentials. Large discrepancies are found between the data and the calculations at around the angles where the A_{0y} takes minimum and maximum. The Δ-isobar effects do not remedy the difference between the data and the calculations. The obtained results indicate that some other components are missed in the theoretical predictions. It would be interesting to see how the predictions with the 3NFs such as the N^{2}LO or higher order 3NFs in the chiral EFT explain the data.

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