

Proton-³He elastic scattering at intermediate energies

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We present a precise measurement of the cross section, proton and ³He analyzing powers, and spin correlation coefficient $C_{y,y}$ for p -³He elastic scattering near 65 MeV, and a comparison with rigorous four-nucleon scattering calculations based on realistic nuclear potentials and a model with Δ -isobar excitation. Clear discrepancies are seen in some of the measured observables in the regime around the cross section minimum. Theoretical predictions using scaling relations between the calculated cross section and the ³He binding energy are not successful in reproducing the data. Large sensitivity to the NN potentials and rather small Δ -isobar effects in the calculated cross section are noticed as different features from those in the deuteron-proton elastic scattering. The results obtained above indicate that p -³He scattering at intermediate energies is an excellent tool to explore nuclear interactions not accessible by three-nucleon scattering.

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I. INTRODUCTION

One of the open questions in nuclear physics nowadays is a complete knowledge of the interactions acting among nucleons. Modern nucleon-nucleon (NN) potentials reproducing the NN observables up to 350 MeV with very high precision do not describe that well various nuclear phenomena, e.g., some few-nucleon scattering observables, nuclear binding energies, and nuclear matter properties [1,2]. The three-nucleon forces ($3NF$ s), arising naturally in the standard meson-exchange picture [3] as well as in the chiral effective field theory (χ EFT) [4,5], have been suggested as possible candidates to improve the situation. Few-nucleon reactions offer good opportunities to investigate the nature of the nuclear interactions since rigorous numerical calculations with two-

nucleon ($2N$) and $3N$ forces and high-precision experiments are feasible.

Nucleon-deuteron (Nd) elastic scattering at energies above ≈ 60 MeV/nucleon has been considered as a solid basis to explore the nuclear interactions focusing on the $3NF$ s. Sizable discrepancies between the data and rigorous numerical calculations with realistic NN potentials were found in the cross section minimum [6]. They were successfully explained by inclusion of the two- π exchange $3NF$ models that reproduce the binding energies of ³H and ³He [7–9], or substantially reduced by calculations in an extended Hilbert space which allow the explicit excitation of a nucleon to a Δ isobar, yielding an effective $3NF$ [10,11]. It has been recently reported that the deuteron-proton (d - p) elastic cross section at 70 MeV/nucleon [12] constrains low-energy constants of $3NF$ s in χ EFT [13].

The four-nucleon ($4N$) system has also become a test field for modern nuclear forces. It is the simplest system of investigating the nuclear interactions in $3N$ subsystems with the total isospin $T = 3/2$, whose importance is suggested in

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asymmetric nuclear systems, e.g., neutron-rich nuclei [14] and pure neutron matter [15,16]. In recent years remarkable theoretical studies in solving the $4N$ scattering problem with realistic Hamiltonians have been reported [17–19] even above the $4N$ breakup threshold [20,21], opening new possibilities for nuclear force study in the $4N$ system at intermediate energies.

Thanks to developments in technology for high quality polarized and unpolarized proton beams together with sophisticated techniques for the polarized ^3He target system, p - ^3He scattering has an experimental advantage that allows high precision measurements of the cross section and a variety of spin observables. Indeed, at proton energy below 50 MeV rich data sets for p - ^3He elastic scattering are available, covering the cross section [22–33], proton analyzing power [26,29,32–37], ^3He analyzing power [34,37–40], and spin-correlation coefficients [34,37,40]. However, the existing data basis is rather poor at higher energies, mostly limited to the cross section [41–44] and the proton analyzing power [43]. Few data exist for the ^3He analyzing power and the spin correlation coefficients [45].

As for the theoretical descriptions of p - ^3He elastic scattering, calculations taking into account the $2N$ and $3N$ forces are reported in the framework of the Kohn variational approach up to 5.54 MeV (below $3N$ breakup threshold) [19]. At these lower energies, the data are well explained by the calculations with the $2N$ interactions. The exception is the proton analyzing power A_y , for which the so-called A_y puzzle exists as seen in the Nd elastic scattering. At higher energies, calculations in the framework of the Alt-Grassberger-Sandhas (AGS) equation are presented using various realistic NN potentials up to 35 MeV [20,21]. Although calculations including $3NF$ s have not been done for energies above the breakup threshold so far, these works performed coupled-channel calculations with the Δ -isobar degree of freedom as an alternative source of $3N$ and $4N$ forces. At incident energies above 20 MeV, the calculations with realistic NN potentials underpredict the cross section data in the minimum, as observed also in the Nd elastic scattering but at higher center-of-mass energy. The Δ -isobar effects slightly improve the agreement with the data for the cross section. In line with this feature it would be interesting to see how the theoretical calculations based on realistic nuclear potentials explain the data for p - ^3He elastic scattering at intermediate energies.

In this paper we present the first precise data set for p - ^3He elastic scattering at intermediate energies, the cross section $d\sigma/d\Omega$ and the proton analyzing power A_y at 65 MeV, and the ^3He analyzing power A_{0y} at 70 MeV spanning a wide angular range. In addition, we present the spin correlation coefficient $C_{y,y}$ at 65 MeV at the angles of 46.6° , 89.0° , 133.2° in the center-of-mass system. The data are compared with rigorous numerical calculations for $4N$ -scattering based on various realistic NN potentials as well as with the Δ -isobar excitation, in order to explore possibilities of p - ^3He elastic scattering as a tool to study nuclear interactions. However, the Coulomb force is omitted this time, thus the theoretical predictions of the present work in fact refer to the mirror reaction n - ^3H .

In Sec. II, we describe the experimental procedure and the data analysis. Section III presents a comparison between the

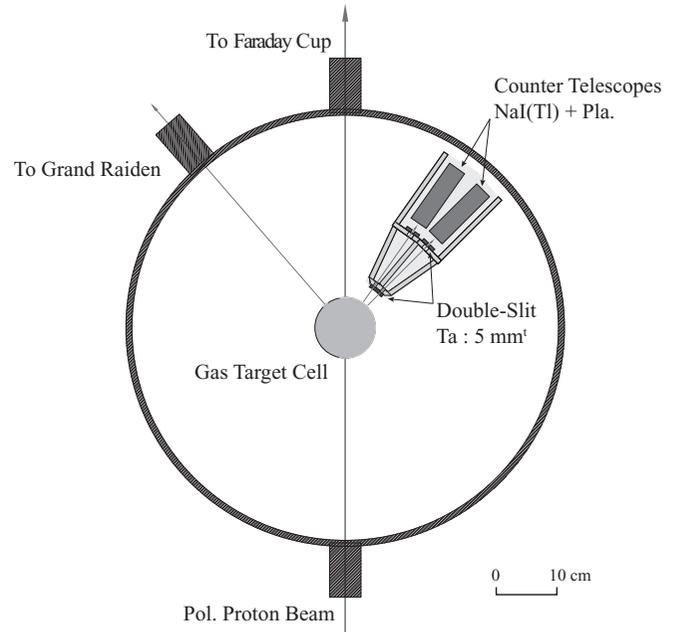


FIG. 1. Schematic layout of the experimental setup for the measurement of the cross section and the proton analyzing power A_y .

experimental data and the theoretical predictions, and discussion follows in Sec. IV. Finally, we summarize and conclude in Sec. V.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

A. Measurement of the cross section and the proton analyzing power A_y at 65 MeV

The measurement of the cross section $d\sigma/d\Omega$ and the proton analyzing power A_y was performed with a 65 MeV polarized proton beam in the West Experimental Hall at the Research Center for Nuclear Physics (RCNP), Osaka University. The measured angles were $\theta_{\text{lab.}} = 20.0^\circ$ – 165.0° in the laboratory system which corresponds to $\theta_{\text{c.m.}} = 26.9^\circ$ – 170.1° in the center-of-mass system. Figure 1 shows the schematic layout of the experimental setup around the ^3He target. The polarized proton beam provided by an atomic beam type polarized ion source [46] was accelerated up to 65 MeV by the AVF cyclotron. The beam was transported [47] to the ^3He gas target at the center of the scattering chamber of the magnetic spectrometer Grand Raiden [48] that was used to monitor the luminosity by observing the p - ^3He elastic scattering events at a laboratory angle of 41° . The beam was stopped in a Faraday cup located downstream of the scattering chamber. The beam intensity was 20–100 nA. The beam polarization was monitored with a beamline polarimeter of the West Experimental Hall by using p - ^{12}C elastic scattering [49]. During the measurement, the beam polarization was typically 53%. The ^3He gas target was contained in the cell of a cylinder of 99 mm diameter with a $50\text{-}\mu\text{m}$ -thick Al window with a pressure of 1 atm at room temperature. The absolute gas density was determined with uncertainty of less than 0.8% by continuously monitoring the pressure as well as the

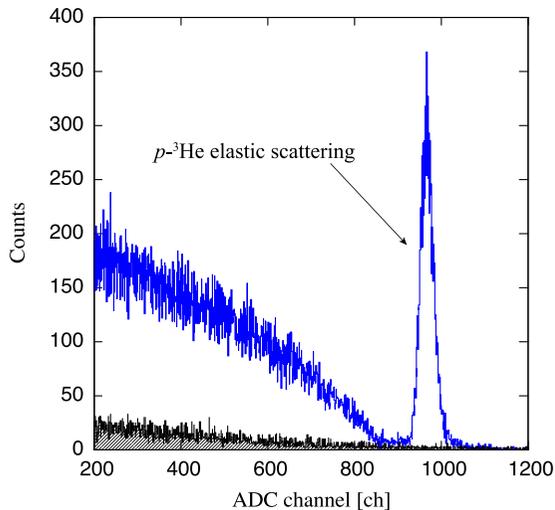


FIG. 2. Light output spectrum of scattered protons obtained by the NaI(Tl) scintillator at $\theta_{\text{lab.}} = 75^\circ$. The hatched region indicates events obtained with the empty target cell.

temperature during the measurement. Scattered protons from the ³He target were detected with two sets of counter telescopes which were placed in the scattering chamber and positioned 20 cm away from the center of the target cell. Each counter telescope consisted of a NaI(Tl) scintillator with dimensions 50 mm (thickness) \times 31 mm (width) \times 31 mm (height) and a 0.5-mm-thick plastic scintillator. A double-slit system was used to define the target volume and the solid angle. Each slit was made of 5-mm-thick Ta. The effective target thickness and the solid angle were calculated by Monte Carlo simulations. Elastically scattered protons from the ³He target were identified using the correlation between energy loss of a plastic scintillator and the remaining energy deposited in a NaI(Tl) scintillator. Figure 2 shows the light output spectrum for the scattered protons obtained by a NaI(Tl) scintillator at the laboratory angle of 70° ($\theta_{\text{c.m.}} = 89.0^\circ$). The peak corresponding to protons elastically scattered from ³He was well separated from the inelastic scattering events. The background events obtained with the empty target cell showed a nearly flat distribution. After subtracting the background contributions the yields of the p -³He elastic scattering were extracted by fitting with skewed Gaussians. The effects of nuclear reactions in the NaI(Tl) scintillators were interpolated from the published results [50,51]. The absolute values of the cross section for the p -³He elastic scattering were deduced by normalizing the data to the p - p scattering cross section as given by the phase-shift analysis program SAID [52]. The normalization factors were obtained from the measurement for the p - p scattering with hydrogen gas by using the same detection system for the p -³He scattering. The statistical error of $d\sigma/d\Omega$ for the p -³He elastic scattering is better than $\pm 2\%$. The systematic uncertainty, which is the quadratic sum of the uncertainty in the normalization factor, the uncertainty in the background contamination, the fluctuation in the luminosity, and the uncertainty in the beam polarization, is estimated to be 3%. For A_y , the statistical error is 0.02 or less and the systematic uncertainty is estimated to be 0.02.

B. Measurement of the ³He analyzing power A_{0y} at 70 MeV

The measurement of the ³He analyzing power A_{0y} was performed with a 70 MeV proton beam in conjunction with the polarized ³He target at the Cyclotron Radioisotope Center (CYRIC), Tohoku University. The experiment consisted of several separate measurements by using two different polarized ³He target cells. The experimental setup around the target is shown in Fig. 3. A proton beam with an intensity of 5–10 nA bombarded the polarized ³He target and it was stopped in a Faraday cup. Relative beam intensity was monitored by a beam monitoring system installed in the vacuum chamber, by which scattered protons from a polyethylene film with a thickness of 20 μm were detected. The polarized ³He target and the detector system for the p -³He scattering were operated in atmosphere. The vacuum was separated by a Kapton film with thickness of 50 μm which was attached to an aluminum made beam pipe connected to the vacuum chamber. Scattered protons from the ³He target were detected using sets of counter telescopes which were positioned 73 cm away from the center of the target cell symmetrically on each side of the beam axis at laboratory angles of 35.0° – 125.0° ($\theta_{\text{c.m.}} = 46.6^\circ$ – 141.4°). Each counter telescope consisted of a NaI(Tl) scintillator and a plastic scintillator. The NaI(Tl) scintillator was the same type as was used for the cross section measurement. For the plastic scintillators, different thicknesses, namely 0.2, 0.5, and 1.0 mm, were used depending on the measured angles. A double-slit collimator, which was made of 20-mm-thick Al for the front part and 15-mm-thick brass for the rear part, was used to define the target volume and the solid angle for each counter telescope. The method to polarize a ³He nucleus was based on the principle of spin-exchange optical pumping (SEOP) [53,54]. A target cell was one-piece GE180 glassware which consisted of a pumping chamber and a target chamber, connected by a thin transfer tube. This design prevented the depolarization of alkali-metal atoms due to the incident beam [55]. In addition to this, undesirable energy loss of the scattered protons passing through a material, which is used to heat the target cell for SEOP, can be avoided. The target cell contained ³He gas with a pressure of 3 atm at room temperature, a small amount of N₂ gas (0.1 atm), and a mixture of Rb and K alkali metals. The pumping chamber was heated up to about 500 K to provide sufficient high alkali-metal vapor density and maintain the ³He polarization. Circularly polarized laser light at 794.7 nm polarized Rb atoms in the pumping chamber. ³He nuclei were polarized through spin exchange interactions in the pumping chamber and then diffused into the target chamber. A 12 G magnetic field, provided by a pair of Helmholtz coils 100 cm in diameter, defined the direction of the ³He nuclear polarization. The target chamber of the target cell had a diameter of 4 cm and was 15 cm long along the beam path. The entrance and exit windows were made as thin as 0.4 mm, and the thickness of the side surfaces where scattered protons passed was about 1 mm. During the measurement the target polarization was measured by the adiabatic fast passage nuclear magnetic resonance (NMR) method, which was calibrated using the electron paramagnetic resonance technique [56]. Additionally, the absolute values of the target polarization were measured by the thermal neutron

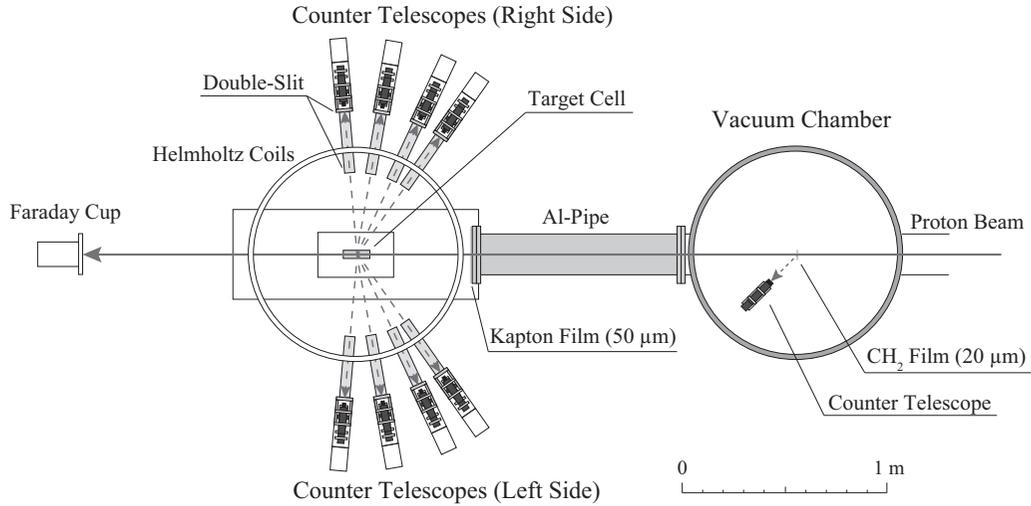


FIG. 3. Schematic layout of the experimental setup for the measurement of the ${}^3\text{He}$ analyzing power A_{0y} .

transmission using the RIKEN Accelerator-Driven Compact Neutron Source (RANS) [57]. The typical target polarization was 40% with an uncertainty of 2%. A more detailed description of the target system is found in Ref. [58]. The statistical error of the A_{0y} is 0.02 or less. The systematic uncertainty which mainly came from the uncertainty of the target polarization is 0.02 or less. The data taken independently with the different target setups at the same angles are consistent each other within the estimated uncertainty.

C. Measurement of the spin correlation coefficient $C_{y,y}$ at 65 MeV

The measurement was extended to the spin correlation coefficient $C_{y,y}$. The experiment was performed in the East Experimental Hall at RCNP. A 65 MeV polarized proton beam with an intensity of 10 nA bombarded the polarized ${}^3\text{He}$ target installed at the ENN beam line [58]. The beam polarizations monitored by using the proton-deuteron elastic scattering [59] were 50% for spin-up and 20% for spin-down, respectively. The same polarized ${}^3\text{He}$ target system and the same detection system as those for the ${}^3\text{He}$ analyzing power measurement at CYRIC were applied. The target polarization was 40% during the measurement. The measured angles were $\theta_{\text{lab.}} = 35.0^\circ$, 70.0° , and 115.0° ($\theta_{\text{c.m.}} = 46.6^\circ$, 89.0° , and 133.2°). The statistical error of the $C_{y,y}$ varies 0.03–0.06 depending on the measured angles, and the systematic error does not exceed the statistical one.

III. COMPARISON OF DATA WITH THEORETICAL CALCULATIONS

The measured cross section $d\sigma/d\Omega$, the proton analyzing power A_y , the ${}^3\text{He}$ analyzing power A_{0y} , and the spin correlation coefficient $C_{y,y}$ are shown in Fig. 4 as a function of the center-of-mass (c.m.) scattering angle $\theta_{\text{c.m.}}$ together with the theoretical calculations. The observables for the p - ${}^3\text{He}$ elastic scattering were calculated from the solutions of exact AGS equations as given in Refs. [20,21] using a number of NN

potentials: the Argonne v_{18} (AV18) [60], the CD Bonn [61], and the INOY04 [62]. The calculations based on two semilocal momentum space regularized chiral NN potentials of the fifth order ($N^4\text{LO}$) with the cutoff parameters $\Lambda = 400$ MeV/ c (SMS400) and $\Lambda = 500$ MeV/ c (SMS500) [63] are also presented. In addition, to test the importance of $3N$ and $4N$ forces in the p - ${}^3\text{He}$ elastic scattering, the calculations based on the CD Bonn+ Δ model [11], which allows an excitation of a nucleon to a Δ isobar and thereby yields effective $3NF$ s and $4NF$ s, are presented.

The AGS equations for $4N$ transition operators are solved in the momentum-space partial wave representation [20] including NN waves with total angular momentum below 4. Since the rigorous treatment of the Coulomb force requires the inclusion of much higher partial waves, the Coulomb force is omitted in the present study. Given relatively high energy, it is expected to be significant at small angles up to $\theta_{\text{c.m.}} \sim 40^\circ$ only.

As shown in Fig. 4, the calculations with the NN forces underestimate $d\sigma/d\Omega$ at the backward angles $\theta_{\text{c.m.}} \gtrsim 80^\circ$. It is also found that there is a large sensitivity of the calculations to the input NN forces at the minimum region. INOY04, which is fitted to reproduce the ${}^3\text{He}$ binding energy, provides a better description of the data, but it still underestimates the data. In addition, Δ -isobar contributions in the p - ${}^3\text{He}$ elastic scattering, which are estimated by the difference between the CD Bonn+ Δ and CD Bonn calculations, are clearly seen to the limited angles $\theta_{\text{c.m.}} \lesssim 110^\circ$. In the Nd elastic scattering, the Δ -isobar effects increase $d\sigma/d\Omega$ to reduce the discrepancy from the data over all angles [11].

The calculated A_y has a relatively small sensitivity to NN forces, and the description of A_y is moderate. Small but visible effects of the Δ isobar are predicted by CD Bonn+ Δ , which leads to a better agreement with the data depending on the measured angles.

As for A_{0y} , the calculations based on the NN potentials are close to each other. The A_{0y} data deviate largely from the NN force calculations at the minimum $\theta_{\text{c.m.}} \sim 90^\circ$ as well as the maximum $\theta_{\text{c.m.}} \sim 140^\circ$, which was not seen at lower

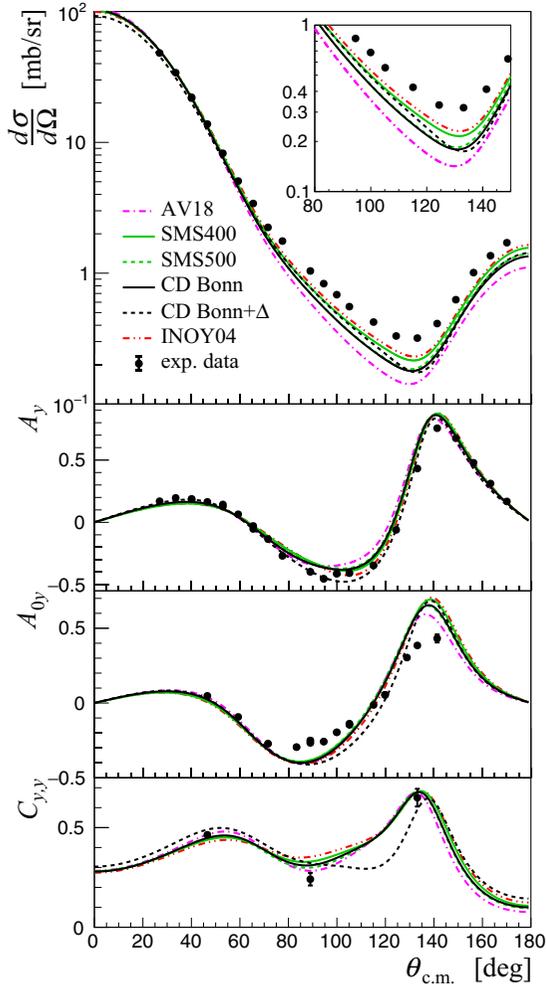


FIG. 4. Angular distributions of $d\sigma/d\Omega$ as well as A_y at 65 MeV, A_{0y} at 70 MeV, and $C_{y,y}$ at 65 MeV for p - ${}^3\text{He}$ elastic scattering. Experimental data (solid circles) are compared with the calculations from the solutions of exact AGS equations. Only statistical errors are indicated. Calculations based on the NN potentials are shown with magenta dash-dotted (AV18), black solid (CD Bonn), red dot-dot-dashed (INOY04), green solid (SMS400), and green dashed (SMS500) lines. Black dashed lines are calculations based on the CD Bonn+ Δ potential.

energies [19–21]. The Δ -isobar effects shift the calculated results slightly but in the wrong direction at $\theta_{c.m.} \sim 100^\circ$.

For $C_{y,y}$, the angular dependence looks quite different from that at lower energies [19–21], and large Δ -isobar effects are predicted at the angles $\theta_{c.m.} = 100^\circ$ – 140° . The data at the limited angles have moderate agreements to all the calculations with no definite conclusions for the Δ -isobar effects.

IV. DISCUSSION

In Refs. [20,21], it was found that $d\sigma/d\Omega$ for the p - ${}^3\text{He}$ elastic scattering calculated with the AV18, CD Bonn, and INOY04 NN potentials at lower energies of 7–35 MeV scale with the binding energy (B.E.) of ${}^3\text{He}$. Inspired by this fact we investigate the scaling relation between B.E.(${}^3\text{He}$) and the

cross section at 65 MeV in panels (a)–(c) of Fig. 5. In the minimum region of angles $\theta_{c.m.} = 80^\circ$ – 150° the calculated $d\sigma/d\Omega$, normalized by the corresponding experimental data, are plotted as a function of B.E.(${}^3\text{He}$). Linear correlations, shown as red straight lines in the figure, exist for the calculations based on the NN potentials including the two chiral NN potentials, i.e., SMS400 and SMS500. From the correlation lines one can predict the $d\sigma/d\Omega$ corresponding to the NN potential that reproduces the experimental B.E.(${}^3\text{He}$), which almost coincides with the INOY04 result. As shown in the figure, the predictions underestimate the experimental $d\sigma/d\Omega$ by 20–30%. Note that the calculations with CD Bonn+ Δ , that will be discussed later, are not included in the fitting of the correlation lines.

In panels (d)–(f) of Fig. 5, we also demonstrate the scaling relation between B.E.(${}^3\text{H}$) and the cross section for the deuteron-proton (d - p) elastic scattering at 70 MeV/nucleon. The calculated $d\sigma/d\Omega$ at 70 MeV/nucleon, normalized by the experimental data of the d - p elastic scattering [12], are plotted as a function of B.E.(${}^3\text{H}$) [64,65]; the Coulomb interaction is not taken into account. A similar scaling also exists in the d - p elastic scattering as seen in the p - ${}^3\text{He}$ scattering. The red straight lines are obtained by fitting the calculations with NN potentials: AV18, CD Bonn, Nijmegen I, II [66], and INOY04. These lines, as in the case of the p - ${}^3\text{He}$ scattering, allow us to predict $d\sigma/d\Omega$ with a NN potential that reproduces the experimental B.E.(${}^3\text{H}$). The panels (d)–(f) of Fig. 5 show that the predictions underestimate the experimental $d\sigma/d\Omega$ by 10–20%. In the figure, the calculations taking into account the Tucson-Melbourne '99 2π -exchange $3NF$ (TM99- $3NF$) [67] in which the cutoff parameter is fitted to reproduce the experimental B.E.(${}^3\text{H}$) for each combined NN potential, i.e., AV18, CD Bonn, Nijmegen I and II, are presented [65,68]. In addition, calculations including an irreducible $3N$ potential contribution to CD Bonn+ Δ which reproduces the experimental B.E.(${}^3\text{H}$), the model U2 of Ref. [69], are also shown. The calculated results provide good agreements with the experimental data, indicating strong evidence for the need to include the $3NF$ s. The discrepancy between the data and the predictions with a NN potential that reproduces the experimental B.E.($3N$) for the p - ${}^3\text{He}$ elastic scattering at the cross section minimum angles is similar in size or even larger than that for the d - p elastic scattering at a similar incident energy. It should be interesting to see whether the combinations of $2N$ and $3N$ forces, that give good descriptions of the d - p scattering cross section, explain the data for the p - ${}^3\text{He}$ scattering.

An interesting feature found in the above mentioned correlations is that dependence of the calculated $d\sigma/d\Omega$ on B.E.($3N$) for the d - p scattering is smaller than that for the p - ${}^3\text{He}$ scattering. It is quantified by the gradients of the correlation lines: $\sim 0.1/\text{MeV}$ for the d - p scattering and $\sim 0.3/\text{MeV}$ for the p - ${}^3\text{He}$ scattering. There is a speculation that a weaker sensitivity for the d - p elastic cross section is related to dominance of the total $3N$ spin $S = 3/2$ state (quartet state) in the nucleon-deuteron elastic scattering [70]. As for the neutron-deuteron s -wave scattering length, the quartet state is insensitive to the difference of NN potentials because of the Pauli principle, which prevents two neutrons getting close to each other [65,71]. Therefore it is expected that relatively

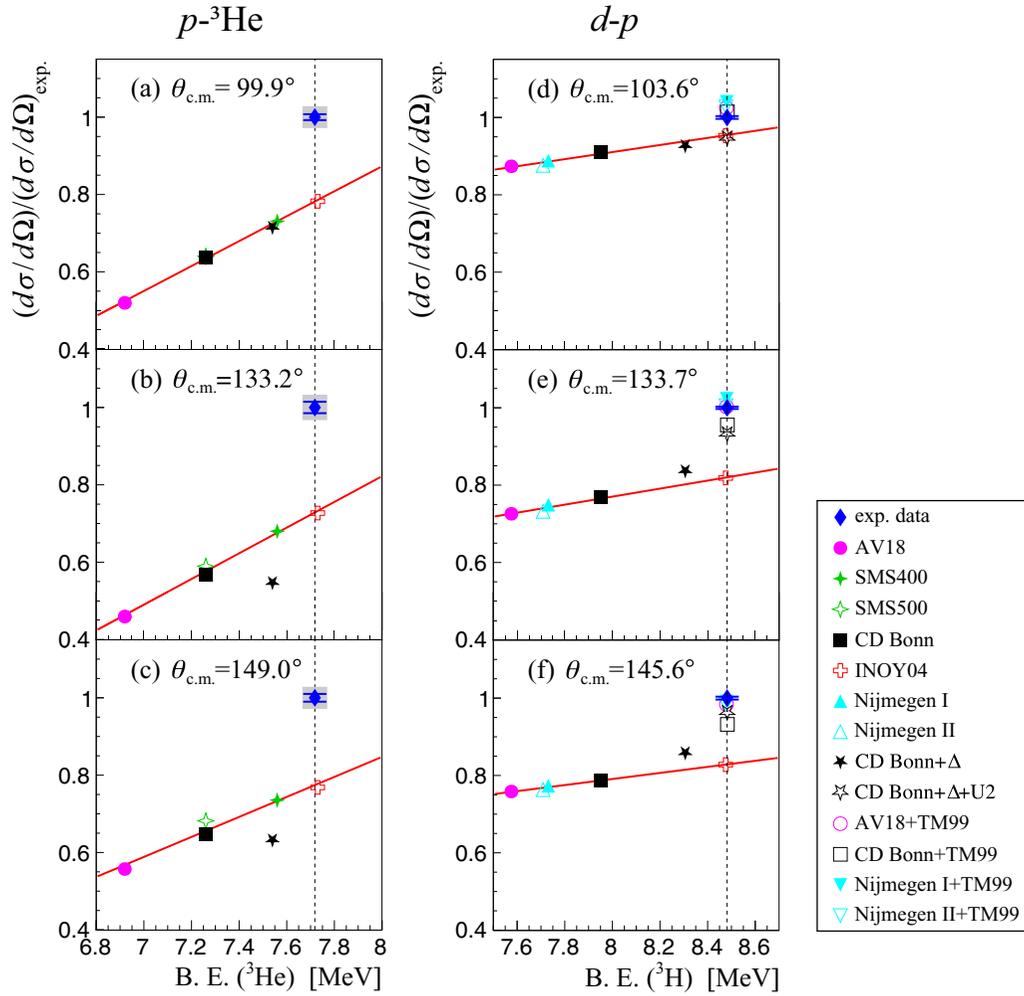


FIG. 5. Relation between the ${}^3\text{He}$ binding energy and the cross section for p - ${}^3\text{He}$ elastic scattering at around 65 MeV in panels (a), (b), and (c); and that between the ${}^3\text{H}$ binding energy and the cross section for d - p elastic scattering at 70 MeV/nucleon in panels (d), (e), and (f). The result of the cross section for each nuclear potential is shown as a ratio to the corresponding experimental data. The dashed vertical straight lines denote the experimental binding energy of the ${}^3\text{He}$ in panels (a)–(c) and that of ${}^3\text{H}$ in panels (d)–(f). For the scattering data the statistical (systematic) errors are shown with bars (bands). Correlation lines obtained with the results of the NN potentials are shown with red lines.

large dependence seen in the p - ${}^3\text{He}$ elastic cross sections is a reflection of medium- and short-range details of the nuclear interactions including $3NF$ s.

In the following, we discuss the Δ -isobar effects. As shown in panels (a)–(c) of Fig. 5, the calculations of the CD Bonn+ Δ model for the p - ${}^3\text{He}$ elastic scattering are off from the correlation lines at backward angles and move in a direction opposite to the experimental data. Thus, the Δ -isobar effects do not improve the agreement with the data. Meanwhile, as shown in panels (d)–(f) of Fig. 5, the calculations of the CD Bonn+ Δ model for the Nd elastic scattering are off from the correlation lines, but the Δ -isobar effects provide a better agreement with the data.

It is known that effective $3N$ and $4N$ forces due to the excitation of a nucleon to a Δ isobar are often partially canceled by Δ -isobar effects of $2N$ nature, the so-called $2N$ dispersion [10,11,72,73]. To study Δ -isobar effects more in detail, the effects of the $2N$ dispersion, and those of $3N$ and $4N$ forces, are singled out separately as in Ref. [17,72]. The results for the

cross sections are shown in Fig. 6(a) as a ratio to the calculation based on the CD Bonn potential. At the minimum angles, large contributions of the Δ -generated $3N$ and $4N$ forces increase the cross section values. However, together with this, there is a strong dispersive Δ -isobar effect, which is opposite to the $3NF$ and $4NF$ effects. As a result, the net effects of the Δ isobar are small, and their effects are even reversed at $\theta_{c.m.} \approx 140^\circ$. In the Nd elastic scattering the dispersive Δ -isobar effect is smaller than that of the Δ -generated $3NF$ s, and then the net contributions of the Δ isobar increase the cross section [10,73]. Since the calculated $3N$ binding energy with CD Bonn+ Δ is still smaller than the experimental value by about 0.2 MeV [11,72], further attractive effects attributed to the irreducible $3NF$ s in NNN - $NN\Delta$ model space [69] should be considered. It will be interesting to study in the future how such attractive contributions affect the cross sections for the p - ${}^3\text{He}$ scattering.

Regarding the spin observables, large Δ -isobar effects are predicted for the spin correlation coefficient $C_{y,y}$ (see Fig. 4).

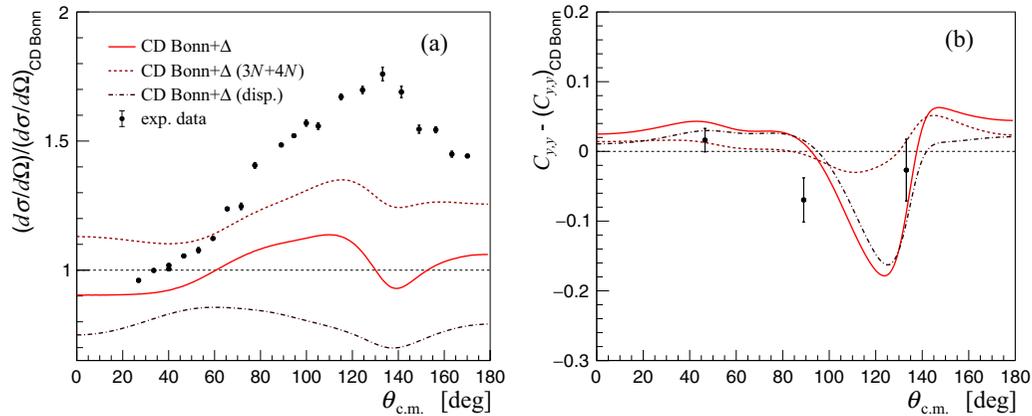


FIG. 6. Effects of the 2N dispersion (dash-dotted lines), those of 3N- and 4N-forces (dotted lines), and the total Δ -isobar effects (solid lines) in the p - ^3He elastic scattering at 65 MeV are shown as a function of the c.m. scattering angle for the cross section in panel (a) and the spin correlation coefficient $C_{y,y}$ in panel (b). For the cross section, the result of each contribution is shown as a ratio to the calculation based on the CD Bonn potential. For the spin correlation coefficient $C_{y,y}$, the differences from the calculation of the CD Bonn potential are presented.

Interestingly, Fig. 6(b) shows that the predicted Δ -isobar effects are mainly due to the 2N dispersion. Experimental data of the spin correlation coefficient $C_{y,y}$ in a wide angular range are needed for a detailed discussion of the Δ -isobar effects.

V. SUMMARY AND CONCLUSION

We have reported the precise data set for p - ^3He elastic scattering at intermediate energies: $d\sigma/d\Omega$ and the proton analyzing power A_y taken at 65 MeV in the angular regime $\theta_{c.m.} = 26.9^\circ$ – 170.1° ; the ^3He analyzing power A_{0y} at 70 MeV in the angular regime $\theta_{c.m.} = 46.6^\circ$ – 141.4° , and the spin correlation coefficient $C_{y,y}$ at 65 MeV for $\theta_{c.m.} = 46.6^\circ$, 89.0° , and 133.2° .

For the cross section the statistical error is better than $\pm 2\%$ and the systematic uncertainties are estimated to be 3%. The absolute values of the cross section were deduced by normalizing the data to the p - p scattering cross section given by the phase-shift analysis program SAID. For the proton and ^3He analyzing powers the statistical uncertainties are less than 0.02. They are 0.03–0.06 for the spin correlation coefficient $C_{y,y}$. The systematic uncertainties for all the measured spin observables do not exceed the statistical ones.

The data are compared with rigorous 4N-scattering calculations based on various realistic NN nuclear potentials without the Coulomb force. Clear discrepancies have been found for some of the measured observables, especially in the angular regime around the $d\sigma/d\Omega$ minimum. Linear correlations exist between the calculations of the ^3He binding energy and those of $d\sigma/d\Omega$, which enables us to evaluate $d\sigma/d\Omega$ with a NN potential that reproduces B.E.(^3He). Predicted values of $d\sigma/d\Omega$ in the minimum region clearly underestimate the data. A similar tendency is obtained in the Nd elastic scattering, where discrepancies are largely resolved by incorporating 3NFs. The NN potential dependence for the cross section in the p - ^3He scattering is found to be larger than that in the d - p elastic scattering, which could allow us to antic-

ipate a wealth of information on the nuclear interactions from further investigation of the p - ^3He scattering at these energies.

The Δ -isobar effects in the p - ^3He observables are estimated by the $NN+N\Delta$ coupled-channel approach. They do not always remedy the difference between the data and the calculations based on the NN potentials. In the case of $d\sigma/d\Omega$, large contributions of the effective 3N and 4N forces are largely canceled by the dispersive Δ -isobar effect, that leads to a rather small total Δ -isobar effect. The results are in contrast to those in the d - p scattering, where the cancellation is less pronounced. Since this approach still misses the 3N binding energies, its extensions, e.g., the irreducible 3N potential combined with the $NN+\Delta$ model [69], are needed. Together with this, large dispersive Δ -isobar effects predicted in the spin correlation coefficient $C_{y,y}$ should be investigated experimentally in the future.

From these obtained results we conclude that p - ^3He elastic scattering at intermediate energies is an excellent tool to explore the nuclear interactions including 3NFs that could not be accessible in 3N scattering. Recent study of the χEFT nuclear potentials intends to use the d - p scattering data at intermediate energies to derive the higher-order 3NFs [74]. It would be interesting to see how the predictions with such 3NFs explain the data for the p - ^3He elastic scattering, which will enable us to perform detailed discussions of the effects of 3NFs including the $T = 3/2$ isospin channels.

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