PROCEEDINGS OF SCIENCE

Few-Nucleon Scattering Experiments to Explore the Three-Nucleon Forces

Yuko Saito[a,*]

[a] *Department of Physics, Tohoku University,*
6-3 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8578, Japan

E-mail: yuko.saito.q1@dc.tohoku.ac.jp

In pursuit of establishing a high-precision three-nucleon force (3*N*F) potential within the framework of chiral effective field theory (χEFT), we plan to acquire new data on the spin correlation coefficients in deuteron-proton (d-p) elastic scattering at 100 MeV/nucleon. We have developed a solid-state polarized proton target and the KuJyaku detector system for this purpose, whose performances were evaluated in the deuteron-polarized proton (d-$\vec{p}$) scattering experiment at the RIKEN RI Beam Factory in January 2024. The angular distributions of the preliminary differential cross-section and proton analyzing power results exhibit close agreement with existing data, suggesting successful identification of d-p elastic events using the KuJyaku system. However, the extracted polarization of the new target system was at 3%, and efforts are currently underway to increase this polarization aiming to achieve high precision in the forthcoming spin correlation coefficient measurements.

The 11th International Workshop on Chiral Dynamics (CD2024)
26-30 August 2024
Ruhr University Bochum, Germany

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0) All rights for text and data mining, AI training, and similar technologies for commercial purposes, are reserved. ISSN 1824-8039 . Published by SISSA Medialab.

PoS(CD2024)096

1. Introduction

The necessity of the three-nucleon forces ($3N$Fs) has become evident in various nuclear phenomena, such as the binding energies of nuclei [1], the saturation density of nuclear matter [2], and the existence limit of neutron-rich nuclei [3]. With numerically exact solutions to the Faddeev equations using both $2N$- and $3N$-forces now attainable for nucleon-deuteron (Nd) scattering observables, detailed insights into the $3N$Fs can be extracted by directly comparing high-precision data from Nd scattering experiments with theoretical predictions. Multiple deuteron-proton (d-p) elastic scattering experiments performed at 70–300 MeV/nucleon have revealed clear signatures of $3N$F effects in the differential cross-sections below 135 MeV/nucleon, whereas data of the spin observables and differential cross-sections at 250 MeV/nucleon and above have indicated deficiencies in the spin-dependent components and high-momentum transfer regions of some $3N$F models [4–7].

In pursuit of establishing a high-precision $3N$F potential within the evolving framework of chiral effective field theory (χEFT), we aim to determine the 13 low-energy constants c_{E_i} at the fifth-order (N^{4}LO) of the $3N$F sector, using few-nucleon scattering data at incident energies of 100 MeV/nucleon or below. This energy range allows for reduction of the truncation uncertainties in χEFT. It has been theoretically suggested that the spin observables in d-p elastic scattering are particularly effective in determining the 11 c_{E_i} that belong to the iso-spin channel $T = 1/2$ [8–10]. In this respect, experimental data of spin observables in d-p elastic scattering at 100 MeV/nucleon or below are in high demand, yet data remain scarce for certain observables. Notably, only two measurements have been conducted for the spin correlation coefficients at higher incident energies [11]. Given this context, we plan to measure the spin correlation coefficients in d-p elastic scattering at 100 MeV/nucleon.

Measurements of the spin correlation coefficients will be conducted at the RIKEN RI Beam Factory, utilizing the polarized deuteron beam provided by the polarized ion source [12], in conjunction with (a) the polarized proton solid-state target and (b) the KuJyaku detector system, both specifically designed and constructed for this study. The two newly developed systems were employed in the deuteron-polarized proton (d-$\vec{p}$) scattering experiment in January 2024. The experiment aimed (1) to confirm particle identification of the d-p elastic events detected by the KuJyaku through differential cross-section and proton analyzing power measurements, and (2) to verify the proton target's polarization. Note that the polarized deuteron beam was not utilized in this experiment, as the polarized ion source was under maintenance at the time.

This proceedings paper presents an overview on the d-$\vec{p}$ scattering experiment and its preliminary analysis results.

2. d-$\vec{p}$ Scattering Experiment

The deuteron-polarized proton (d-$\vec{p}$) scattering experiment was conducted at 135 MeV/nucleon at the RIKEN RI Beam Factory. Note that this experiment marks the first deuteron acceleration at RIKEN in 9 years, and 135 MeV/nucleon was selected based on previous experience at this energy. The experiment was designed to measure the differential cross-section and proton analyzing power in d-p elastic scattering at $\theta_{\mathrm{CM}} = 68.8°$–$150.3°$ in the center-of-mass frame, as well as the

PoS(CD2024)096

proton target's polarization. The unpolarized deuteron beam provided by the electron cyclotron resonance (ECR) ion source was accelerated to 7 MeV/nucleon by the azimuthally varying field (AVF) cyclotron and to 135 MeV/nucleon by the RIKEN Ring Cyclotron (RRC). The beam was then transported to the E3A course in the E3 experimental hall, where the polarized proton target and the KuJyaku system were installed.

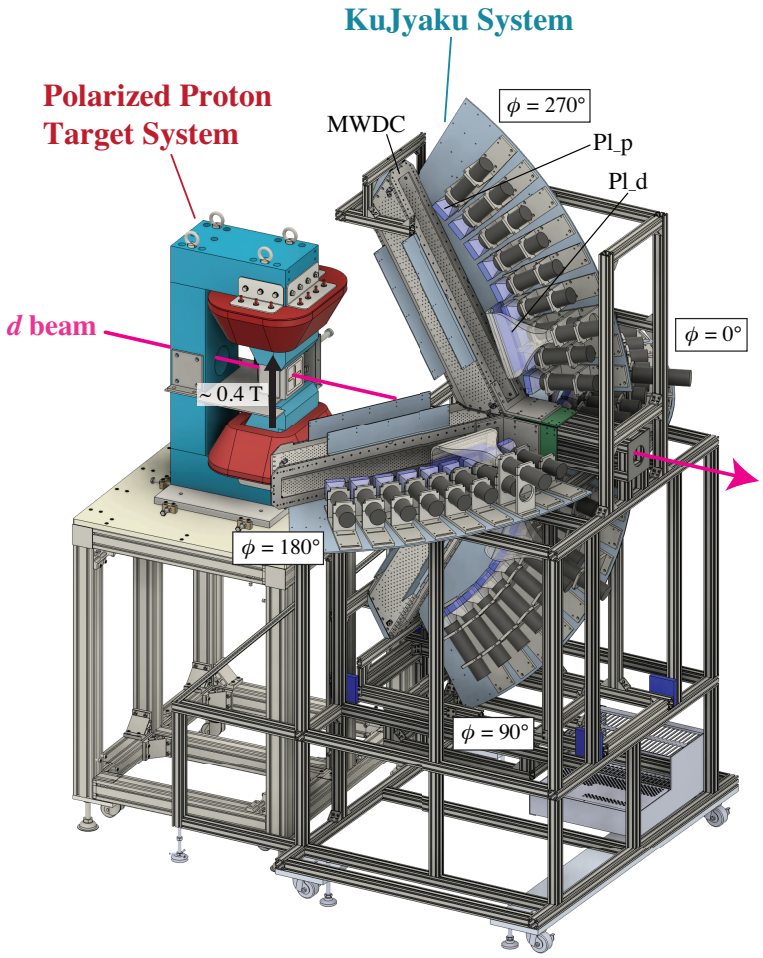

Figure 1: Schematic view of the polarized proton target and KuJyaku system during the d-$\vec{p}$ experiment.

A schematic view of the polarized proton target and the KuJyaku system during the d-$\vec{p}$ experiment is as shown in Figure 1. The solid-state polarized proton target, based on the triplet dynamic nuclear polarization method [13], provides an adequate luminosity ($\sim 10^{29}$ cm^{-2} s^{-1}) when paired with the polarized or unpolarized deuteron beam at RIKEN (≤ 0.1 nA). A 2.5 mm-thick p-terphenyl ($C_{18}H_{14}$) single crystal, doped with 0.005 mol% deuterated pentacene ($C_{22}D_{14}$, pentacene–d_{14}), was used as target material. The target system operates under relaxed conditions (room temperature with a magnetic field of ~ 0.4 T), allowing for the detection of scattered deuterons and recoil protons with relatively low kinetic energies over a wide angular range ($|\theta_{lab}| \leq 60°$ in the laboratory frame). Placed downstream of the target, the KuJyaku detector system covers a similarly broad angular range, including the cross-section minimum angles in d-p elastic scattering

PoS(CD2024)096

at $\theta_{\mathrm{CM}} = 70°$–$150°$ ($\theta_{lab} = 14°$–$54°$), while also enabling detection at the azimuthal angles $\phi = 0°, 180°, 270°$, and $90°$, corresponding to left, right, up, and down directions relative to the beam. It identifies the d-p elastic events in kinematic coincidence via the plastic scintillators for protons (Pl_p detectors) and deuterons (Pl_d detectors), thereby reducing background events. It is also equipped with multi-wire drift chambers (MWDCs) to determine the scattering angles of d-p elastic events whose trajectories are affected by the magnetic field on the polarized proton target.

3. Analysis Results

The d-p elastic events detected by the KuJyaku were identified using the energy deposit and the time-of-flight difference between the scattered deuterons and the recoiled protons collected by the plastic scintillators, together with the trajectory data acquired by the MWDCs. Figure 2(i) presents a typical two-dimensional light output spectrum obtained in kinematical coincidence using the Pl_p and Pl_d detectors, along with the time difference spectrum shown in Figure 2(ii). The loci of the d-p elastic events are clearly visible in the spectra, together with background events mainly from carbon and deuteron breakup reactions.

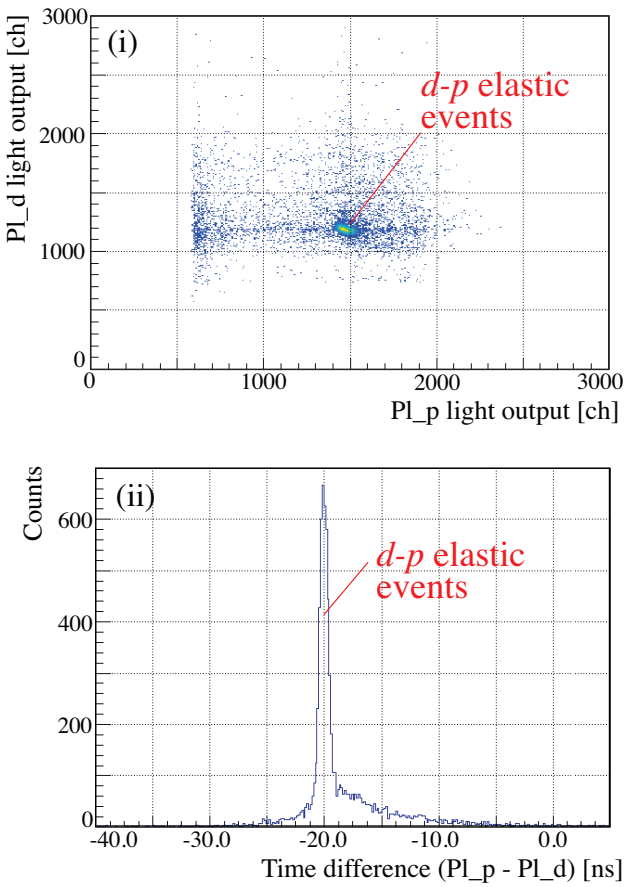

Figure 2: (i) Two-dimensional light output spectrum obtained in kinematical coincidence using the Pl_p and Pl_d detectors. (ii) Time difference spectrum between the Pl_p and Pl_d detectors.

PoS(CD2024)096

The identified d-p elastic events were used to extract the relative value of the differential cross-section and the proton analyzing power. Figure 3 presents the preliminary results together with the statistical errors, alongside existing data [4, 5, 14]. As for the determination of the differential cross section, d-p elastic events collected by the detectors in up and down directions of the KuJyaku were used to extract luminosity based on data from Refs. [4, 5]. This luminosity was then used to obtain the differential cross section values using data taken by the detectors on left and right side of the KuJyaku. The angular distributions of the preliminary differential cross-section and proton analyzing power show good agreement with the existing data[1]. These results indicate successful identification of d–p elastic events using the KuJyaku, a conclusion that will be further investigated in subsequent analyses. However, while the polarized proton target confirmed to maintain stable polarization under beam irradiations up to 10^8 cps in the experiment, the extracted polarization value was found to be at 3%. It is crucial to raise this polarization to at least 10% to achieve sufficient precision (≤ 0.03 for statistical uncertainty) in the upcoming measurements of the spin correlation coefficients. To address this issue, we are currently developing new target materials and modifying the laser system.

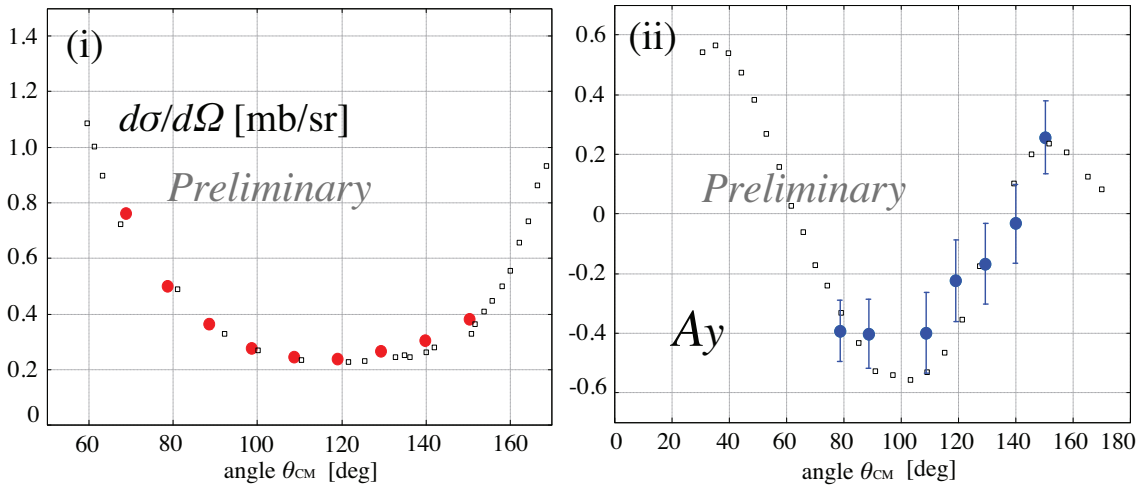

Figure 3: Preliminary results of (i) the differential cross-section and (ii) proton analyzing power in d-p elastic scattering at 135 MeV/nucleon. Only the statistical uncertainties are shown. Existing data are shown in black squares, from Ref. [4, 5] for the differential cross-section and Ref. [14] for the proton analyzing power.

4. Summary and Future Prospects

To determine the 11 out of 13 low-energy constants c_{E_i} at N^{4}LO of the 3NF sector in χEFT, we plan to acquire new data on the spin correlation coefficients in d-p elastic scattering at 100 MeV/nucleon at the RIKEN RI Beam Factory. To realize this measurement, we have developed a solid-state polarized proton target and the KuJyaku detector system, whose performances were evaluated in the d-$\vec{p}$ scattering experiment conducted in January 2024. The preliminary results

[1]The differential cross-section was also normalized to data from Ref. [15], where the angular distributions of the preliminary results and data from Ref. [15] are also found to be in agreement.

PoS(CD2024)096

of the differential cross-section and proton analyzing power show angular distributions in close agreement with existing data, indicating successful identification of d-p elastic events using the KuJyaku system. The extracted polarization of the new target system was at 3%, and ongoing efforts aim to increase it to at least 10% to achieve high precision in the forthcoming measurements of the spin correlation coefficients.

References

[1] S. C. Pieper *et al.*, Phys. Rev. C **64**, 014001 (2001).

[2] A. Akmal, V. R. Pandharipande, and D. G. Ravenhall, Phys. Rev. C **58**, 1804 (1998).

[3] T. Otsuka *et al.*, Phys. Rev. Lett. **105**, 032501 (2010).

[4] K. Sekiguchi *et al.*, Phys. Rev. C **65**, 034003 (2002).

[5] K. Sekiguchi *et al.*, Phys. Rev. Lett. **95**, 0162301 (2005).

[6] Y. Maeda *et al.*, Phys. Rev. C **76**, 014004 (2007).

[7] K. Sekiguchi *et al.*, Phys. Rev. C **83**, 061001 (2011).

[8] E. Epelbaum *et al.*, Eur. Phys. J. A **56**, 92 (2020).

[9] L. Girlanda, A. Kievsky, and M. Viviani, Phys. Rev. C **84**, 014001 (2011).

[10] L. Girlanda, A. Kievsky, and M. Viviani, Phys. Rev. C **102**, 019903 (2020).

[11] B. v. Przewoski *et al.*, Phys. Rev. C **74**, 064003 (2006).

[12] H. Okamura *et al.*, AIP Conf. Proc. **293**, 84 (1994).

[13] K. Tateishi, M. Negoro, S. Nishida, A. Kagawa, Y. Morita, and M. Kitagawa, Proc. Nat. Acad. Sci. **111**, 7527 (2014).

[14] K. Ermisch *et al.*, Phys. Rev. Lett. **86**, 5862 (2001).

[15] K. Ermisch *et al.*, Phys. Rev. C **71**, 064004 (2005).

PoS(CD2024)096