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# Development of a polarized proton target for spin-correlation coefficient measurements

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We report a newly developed polarized proton target for the measurement of spin-correlation coefficients. The polarized target is based on dynamical nuclear polarization using photo-excited triplet electron spins and is operated in moderate environments, 0.3 T and 100 K. Naphthalene single crystal doped with 0.003 mol% deuterated pentacene is used as a target material. We have performed the build up and spin relaxation measurements as a performance test and have succeeded to obtain a long spin-lattice relaxation time of 24.1 ± 0.2 h.

**KEYWORDS:** nuclear force, few-nucleon scattering, polarized proton target, dynamic nuclear polarization

## 1. Introduction

Understanding nuclear properties from bare nuclear forces is one of the main interests in nuclear physics. Establishment of high-precision realistic nucleon-nucleon (NN) potentials [1–3] and theoretical progress based on *ab initio* calculations have revealed as three-nucleon forces (3NFs) to be essentially important for various nuclear phenomena such as few-nucleon scattering [4], binding energies of light mass nuclei [5], and nuclear matter properties [6]. Few-nucleon scattering is a good probe to investigate dynamical aspects (momentum, spin and isospin dependence) of 3NFs. Direct comparison between precise data and rigorous numerical calculations enables us to study the nature of nuclear interactions.

Nucleon-deuteron ($Nd$) elastic scattering at intermediate energies (larger than ~60 MeV/nucleon) has provided a solid basis to explore 3NFs. RIKEN group has performed the measurements of deuteron-proton ($dp$) elastic scattering with a polarized deuteron beam, providing precise data set of differential cross sections [7–10], deuteron analyzing powers [7–9, 11–13], and polarization transfer coefficients [14]. Sizable discrepancies between the data and rigorous numerical calculations based on realistic NN potentials are found in these observables. For the differential cross section at 70 and 135 MeV/nucleon, theoretical predictions with the $2\pi$ exchange 3NF models (Tucson-Melbourne'99 [15], Urbana IX [16]) successfully remove these discrepancies. However, at a higher energy of 250 MeV/nucleon, the differences appear between the data and the calculation even including the 3NFs. As for spin observables the data are not always reproduced by the 3NF effects, indicating the defects in some spin dependent components of 3NFs.

In recent years, the revolutionary nuclear potential based on chiral effective field theory (EFT) has been available with the same accuracy as a realistic nuclear potentials [17]. Chiral EFT provides consistent two-, three- and many nucleon forces in the same footing order by order in chiral expansion. The first non-vanishing 3NF diagrams appear at the third expansion order, so called next-nextleading order (N2LO) including the $2\pi$ exchange 3NF [18]. At higher orders, there are various spin and iso-spin dependent terms of 3NFs as well as short-range interaction terms [19]. These short-range interactions involve unknown low energy constants (LECs) to be determined from experimental data. It has been suggested that the data of $dp$ elastic scattering at intermediate energies provide strong constraints to the determination of LECs [20]. Thus, to determine the LECs at the higher order 3NFs, the rich data set of 3N scattering is highly demanded.

Considering the above mentioned situation, we plan the measurement of spin-correlation coefficients for elastic $dp$ scattering at 100 MeV/nucleon and below for which high precision data set is scarce. The experiment will be performed at RIKEN RI Beam Factory (RIBF) using a polarized deuteron beam in conjunction with a polarized proton target. In this paper, we present the newly developed polarized proton target system for the spin-correlation coefficient measurements.

## 2. Polarized Proton Target

The polarization method for our newly developed polarized proton target was based on triplet dynamic nuclear polarization (triplet DNP) [21]. This method utilizes electron polarization in triplet states of photo-excited aromatic molecules. High proton polarization of 25% has been achieved under relatively low magnetic field of 0.35 T and at high temperature of 90 K with triplet DNP, because the distribution of optically excited electrons is independent of filed strength and temperature [22]. Naphthalene single crystal doped with a small amount of deuterated pentacene (0.003 mol%) was used as the target material. The crystal was shaped into a disk with a diameter of 10 mm and a thickness of 3 mm. In the first step of triplet DNP, hyperpolaized electrons are generated by pulsed laser irradiation. Laser irradiation at 589 nm induces transition from singlet grand state to first triplet state via first singlet excited state. Population difference in the triplet electrons is spontaneously produced, resulting in a high electron polarization. In the second step, the electron polarization is transferred to nearby protons of naphthalene by integrated solid effect (ISE) [21]. In the ISE process, microwave irradiation and magnetic field sweep are applied simultaneously, enabling the inhomogeneously broadened electron spin packets to be swept adiabatically. The polarization transfer occurs when the Rabi frequency of electron spins matches the Larmor frequency of proton spins during the process. After the ISE process, proton polarization localized around pentacene diffuses to the whole naphthalene crystal. Proton polarization can be accumulated by repeating the cycle of triplet DNP.

Figure 1 shows a photograph and a schematic view of the polarized proton target system. The target system was originally constructed for RI beam experiments at RIKEN [23–25], and was modified to cover a wide angular range ($\theta_{\mathrm{lab.}} = 60^\circ$–$120^\circ$ in the laboratory system (lab.)) for the measurement of spin-correlation coefficients. The target crystal was mounted in a dual-walled target chamber and was cooled to 100 K by blowing cold nitrogen gas. Inner chamber was thermally isolated from the room temperature by vacuuming an outer chamber. Each chamber has entrance and exit windows with thin Kapton foils (100 $\mu$m). The target chamber was inserted into a C-type electromagnet applying a 0.3 T magnetic field. Pulsed laser with a power of 9 W was irradiated to the target crystal through optical windows mounted these chambers. Pulse width and repetition rate of the laser were 180 ns and 4.5 kHz, respectively. Relative proton polarization was monitored with a pulse NMR method.

## 3. Target Performance

In this section, we present the performance test of the newly developed polarized proton target. Time evolution of the target polarization $P$ is expressed as [26],

$$\frac{dP}{dt} = \frac{1}{T_{\mathrm{B}}}(P_e - P) - \frac{1}{T_{\mathrm{L}}}(P - P_{\mathrm{TE}}), \tag{1}$$

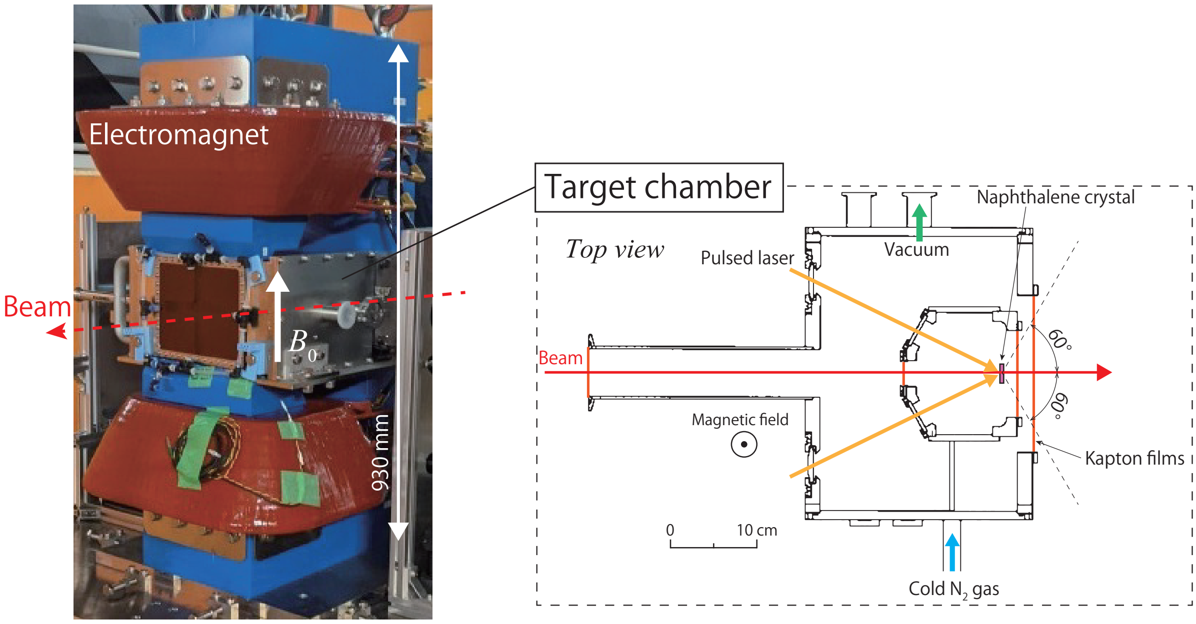


**Fig. 1.** Newly developed polarized proton target system. Dual-walled target chamber was inserted into a C-type electromagnet. Right figure shows a schematic view of a dual-walled target chamber.

where $P_e$ and $P_{\mathrm{TE}}$ are the polarizations of electron spins and proton polarization in thermal equilibrium, respectively. $T_{\mathrm{B}}$ is the build up time constant. $T_{\mathrm{L}}$ is the spin relaxation time with laser irradiation. Build up of the target polarization is obtained as the solution of Eq. (1):

$$P = \frac{P_e}{1 + \frac{T_{\mathrm{B}}}{T_{\mathrm{L}}}} \left\{ 1 - \exp\left[ -\left( \frac{1}{T_{\mathrm{B}}} + \frac{1}{T_{\mathrm{L}}} \right) t \right] \right\}. \tag{2}$$

Here, $P_{\mathrm{TE}}$ is negligibly small ($\sim 10^{-6}$) in our condition. Turning off the microwaves and laser irradiation, the proton polarization decreases following an exponential function:

$$P = P_0 \exp\left( -\frac{t}{T_1} \right), \tag{3}$$

where $P_0$ is the initial polarization at $t = 0$, and $T_1$ is the spin-lattice relaxation time.

Figure 2 shows the build up and spin relaxation curves of the relative target polarization measured with the pulse NMR method. As a result of fitting to the build up data, the time constant $\tau$ is obtained as,

$$\tau \equiv \left( \frac{1}{T_{\mathrm{B}}} + \frac{1}{T_{\mathrm{L}}} \right)^{-1} = 4.5 \pm 0.1 \text{ h}. \tag{4}$$

Similarly, the spin-lattice relaxation time $T_1$ is deduced from fitting to the spin relaxation data using Eq. (3):

$$T_1 = 24.1 \pm 0.2 \text{ h}. \tag{5}$$

Finally, we achieved a long spin relaxation time more than 20 hours. In order to estimate the achievable proton polarization by using Eq. (2), the spin relaxation time $T_{\mathrm{L}}$ will be obtained from the spin relaxation measurement under laser irradiation.

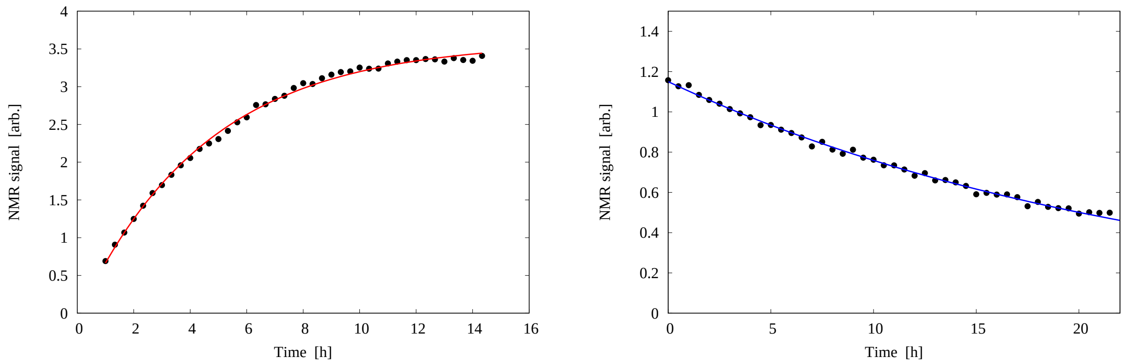


**Fig. 2.** Typical results of the performance test. Left (right) figure shows a build up (spin relaxation) of relative proton polarization. Solid lines are fitting results.

## 4. Summary

One of the main topic of nuclear physics is understanding nuclear properties from bare nuclear forces. It has suggested that 3NFs are essentially important to establish this topic. With the aim of determining the 3NFs based on chiral EFT, we plan the measurement of spin-correlation coefficients for $dp$ elastic scattering at 100 MeV/nucleon and below. In this paper, we have reported the polarized proton target system developed for the experiment.

Polarized proton target is based on the triplet DNP method which can be operated in a moderate environment of $< 1$ T and $\sim$ 100 K. The target is a naphthalene single crystal shaped in a size of $\phi 10 \times 3$ mm and doped with 0.003 mol% deuterated pentacene. The target crystal is placed inside a dual-walled chamber and cooled to 100 K. The chamber is inserted into a C-type electromagnet where a static magnetic field of 0.3 T is applied. Proton polarization is produced by the triplet DNP method with the simultaneous irradiations of pulsed laser, microwave, and field sweep. Relative proton polarization is monitored with a pulse NMR method.

We have performed the build up and spin relaxation measurements as a performance test of the newly developed polarized proton target. As a result, the build-up time constant and spin-lattice relaxation time are obtained to be 4.5 ± 0.1 h and 24.1 ± 0.2 h, respectively. We plan to evaluate the absolute target polarization by the measurement of scattering asymmetry for $pp$ elastic scattering where analyzing powers are well known.

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