A high-pressure polarized $^3$He gas target for nuclear-physics experiments using a polarized photon beam

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Abstract. Following the first experiment on three-body photodisintegration of polarized $^3$He utilizing circularly polarized photons from High-Intensity Gamma Source (HI$^3$S) at Duke Free Electron Laser Laboratory (DFELL), a new high-pressure polarized $^3$He target cell made of pyrex glass coated with a thin layer of sol-gel doped with aluminum nitrate nonahydrate has been built in order to reduce the photon beam-induced background. The target is based on the technique of spin exchange optical pumping of hybrid rubidium and potassium and the highest polarization achieved is $\sim 62\%$ determined from both NMR-AFP and EPR polarimetreis. The phenomenological parameter that reflects the additional unknown spin relaxation processes, $X$, is estimated to be $\sim 0.10$ and the performance of the target is in good agreement with theoretical predictions. We also present beam test results from this new target cell and the comparison with the GE180 $^3$He target cell used previously at HI$^3$S. This is the first time that the sol-gel coating technique has been used in a polarized $^3$He target for nuclear-physics experiments.

1 Introduction

Quantum chromodynamics (QCD) is the theory of strong interaction in terms of quark and gluon degrees of freedom. While QCD has been well tested in the high-energy regime where perturbative calculations can be carried out, it is still unsolved in the low-energy, non-perturbative regime. Understanding the structure of the nucleon from the underlying theory of QCD, a fundamental and challenging task in nuclear and particle physics, remains an area of active research. With developments in polarized beam, recoil polarimetry, and polarized target technologies, polarization experiments have provided new observables on quantities related to the nucleon structure.

The High-Intensity Gamma Source (HI$^3$S) at the Duke Free Electron Laser Laboratory (DFELL) opens a new window to studies of fundamental quantities related to the structure of the nucleon through polarized Compton scattering from polarized targets [1]. Such measurements allow access to nucleon spin polarizabilities, which describe the response of a spin-aligned nucleon to a quasistatic external electromagnetic field. Since there are no stable free neutron targets, effective neutron targets, such as deuteron and $^3$He, are commonly used. A polarized $^3$He target is an effective polarized neutron target [2,3] due to the fact that the neutron is $\sim 90\%$ polarized in a polarized $^3$He nucleus. There have been extensive studies employing polarized $^3$He targets to extract the neutron electromagnetic form factors [4–11], and neutron spin structure functions [12–17]. To extract information on neutron using a polarized $^3$He target, nuclear corrections need to be applied which rely on the state-of-the-art calculations of three-body systems.

The HI$^3$S facility also provides unique opportunities to test the three-body calculations. In 2008, a first measurement of double polarized three-body photodisintegration of $^3$He was carried out at HI$^3$S [18] with an incident gamma beam energy of 11.4 MeV. In addition to providing tests of three-body calculations, three-body photodisintegration of $^3$He is of further importance to experimental tests of the Gerasimov-Drell-Hearn (GDH) sum rule [19,20]. In this experiment, a high-pressure, longitudinally polarized $^3$He gas target [21] and a circularly polarized photon beam were employed. Seven liquid-scintillator detectors were placed around the $^3$He target to detect the neutrons from the three-body breakup channel. The $^3$He gas target cell was made of aluminosilicate (GE180) glass. This type of glass has fewer magnetic impurities and is less permeable to $^3$He atoms than regular pyrex glass. However, the rich concentration of barium in the GE180 glass produced a large amount of background events in the neutron detectors. To reduce the background
for future measurements at HI\textsubscript{7}S, a new high-pressure $^3\text{He}$ cell made of sol-gel-coated pyrex glass has been developed and tested.

The coating technique was developed by doping sol-gel with aluminum nitrate nonahydrate ($\text{Al(NO}_3\text{)}_3 \cdot 9\text{H}_2\text{O}$) [22,23]. This method produces a glass with better homogeneity and higher purity via a chemical route. Single sealed pyrex cells produced using the sol-gel coating technique have yielded longer relaxation times than those from cells without the coating [22]. This is the first time that this technique has been applied to a high-pressure $^3\text{He}$ target, a double-cell system for nuclear-physics experiments. The smooth paramagnetic-free aluminosilicate glass-coated surface reduces the probability of $^3\text{He}$ de-polarization from the wall. Its low $^3\text{He}$ permeability helps to prevent the loss of $^3\text{He}$ atoms. This allows a long-term operation at temperatures typical of the spin exchange optical pumping process (185°C for Rb-only cells and 238°C for Rb-K hybrid cells). The target cell “BOLT” was coated at the University of Virginia and filled at the College of William and Mary. A photon beam test of BOLT at HI\textsubscript{7}S was carried out in May, 2009. The rest of the paper is organized as follows. Section 2 describes the experimental apparatus and procedure. The target performance and a comparison between theoretical calculations and experimental results are presented in sect. 3. The in-beam test results of this new target are reported in sect. 4.

2 Experimental apparatus and procedure

A schematic of the experimental apparatus is shown in fig. 1. It consists of a pair of Helmholtz coils with a diameter of 173 cm to provide a magnetic holding field with a typical value of 21 G. BOLT is a pyrex glass cell coated with aluminosilicate and contains a mixture of Rb-K. It consists of a spherical pumping chamber with a radius of 4.3 cm and a target chamber with a length and a diameter of 38.7 cm and 3.1 cm, respectively. The chambers are connected by a tube that is 9 cm long with a diameter of 1.3 cm. The cell is installed in the center of the Helmholtz coils with the pumping chamber in an oven.

The $^3\text{He}$ polarization is measured using both the NMR-adiabatic fast passage (AFP) method [24] and the electron paramagnetic resonance (EPR) technique [25]. The AFP system includes two $\sim$79 cm diameter RF coils with a separation of 39.5 cm placed horizontally above and below the cell and a pair of rectangular pickup coils located on both sides of the target chamber. The pickup coils are perpendicular to both the holding field and the RF field. The EPR system includes a 5.1 cm diameter EPR coil inside the oven close to the pumping chamber and a photo diode to monitor the EPR signal. Details of the polarimetry systems can be found in [21]. The $^3\text{He}$ nuclei are polarized through spin exchange optical pumping. Limits of alkali polarization have been observed for the broadband laser light [26] and a spectrally narrowed laser is added to the experimental setup. Three lasers with three separate sets of optics are used to produce circularly polarized laser light. After the optics, the net output power of the two Coherent DUO-FAP broad-band lasers is $\sim$78 W and the third spectra physics narrowed laser has a net power output of 23 W.

Before the $^3\text{He}$ nuclei are polarized, the cell is heated to 120°C in a separate oven and a tunable laser is used to probe the line shape of the Rb $D_1$ transition. Collisions between Rb and $^3\text{He}$ can broaden the resonance lines of rubidium so that the width is proportional to the density of $^3\text{He}$ in the cell [27]. By measuring the width of the $D_1$ line, the density of $^3\text{He}$ is determined to be $5.16\pm0.29$ amagats. To polarize the $^3\text{He}$ nuclei, the pumping chamber is heated up in the oven by air flowing through three heaters. The pressure inside the cell is $\sim 7.66$ atm with the pumping chamber at (238 ± 0.5)°C and the target chamber at (60 ± 0.5)°C. The Rb atoms in the pumping chamber are polarized through the optical pumping process and then transfer the angular momentum to the K atoms. The spin exchange collisions between K and $^3\text{He}$ and between Rb and $^3\text{He}$ subsequently polarize the $^3\text{He}$ nuclei [28]. The time to reach the maximum polarization for such a Rb-K hybrid cell is much faster than a Rb-only cell due to the higher efficiency for polarizing $^3\text{He}$ by K [29].

The $^3\text{He}$ polarization measured by the NMR-AFP method is recorded every three hours during the polarization accumulation period ("pump-up" period). After the polarization has reached a maximum, EPR measurements are carried out to measure the absolute $^3\text{He}$ polarization, which can be compared to the value from the NMR signal after water calibration [24]. With the lasers off and the alkali no longer in vapor form, AFP measurements are continued in order to measure the spin-lattice relaxation time, $T_1$, in the cell at room temperature.

The systematic error of the relaxation time is dominated by the uncertainty in the determination of the AFP losses, which is derived by fitting $n$ consecutive AFP measurements to $A_0(1 - L)^n$, where $L$ is the AFP inefficiency.