First Use of a Longitudinally Polarized Target with CLAS12

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Run Group C comprises eight experiments utilizing the CLAS12 detector system in Hall B at Jefferson Lab to study the multidimensional partonic structure of nucleons. The experiments scatter electrons from polarized protons and neutrons in samples of solid NH_3 and ND_3, dynamically polarized at a temperature of 1 K in a 5 T magnetic field. After a brief description of the target system, the current status of the target and preliminary results of its performance in the experiment are presented.

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1. Introduction

Run Group C (RGC) is a collection of eight experiments taking place in Hall B at Jefferson Lab that began in June, 2022. These experiments explore the spin structure of nucleons using multiple scattering processes: deep inelastic scattering (DIS) for measuring spin structure functions, semi-inclusive DIS to access Transverse Momentum Distributions, and exclusive Deeply Virtual Compton Scattering (DVCS) to access Generalized Parton Distributions. Common to all experiments is the scattering of 10.6 GeV polarized electrons from longitudinally polarized protons and neutrons in 5 cm long samples of solid NH_3 and ND_3, respectively. The ammonia samples are dynamically polarized at a temperature of 1 K in a 5 T magnetic field using a new polarized target system constructed by a collaboration between Christopher Newport University, Old Dominion University, the University of Virginia, and the Jefferson Lab Target Group.

The Run Group C experiments utilize two detector configurations. Exclusive measurements are performed with the CLAS12 Forward Tracker in place (FT-In), while the inclusive and semi-inclusive measurements are done without the FT (FT-Out). In both cases the electron beam is rastered over the face of the polarized target sample to reduce polarization loss due beam heating and radiation damage. However, the rates in the FT become unacceptably high when the beam raster exceeds a radius of about 0.7 cm, and so the exclusive measurements are performed with 1.5 cm diameter target cells, a 1.4 cm raster diameter, and a 4 nA beam current. All other measurements are performed with a 2.0 cm target cell, a 1.9 cm raster, and a 8 nA beam current.

In these proceedings we provide a brief description of the target design and report preliminary results of its performance during the first months of the experimental run.

2. Description

A side view of the target installed in Hall B is shown in Fig. 1. It is specifically designed to operate inside the 12 GEV CEBAF Large Acceptance Spectrometer (CLAS12) [1] and uses the spectrometer's 5 T solenoid magnet [2] for the dynamic nuclear polarization (DNP) process. In order to reach the center of the solenoid and avoid interference with the CLAS12 Central Detector and its electronics, the target cryostat must be approximately 3 m long. The target is inserted into the spectrometer using a rail-mounted cart that also supports a 140 GHz microwave system for DNP at 5 T, NMR electronics for measuring the polarization, a roots pumping set for the horizontal ^{4}He evaporation refrigerator, and all other electronic equipment for monitoring and controlling the system. The compact, self-contained nature of the target system was chosen so that it could be fully assembled and tested in the JLab Target Group laboratory and installed in the experimental hall in only two weeks.

The horizontal 1 K evaporation refrigerator is patterned on a design by Roubeau [3]. Liquid helium at 4.2 K is siphoned from a nearby 500 l dewar using a bespoke, low-loss transfer line into the separator, a ~1 l cylindrical vessel where the gas fraction is removed by a small diaphragm pump. The dewar is continuously replenished with liquid helium from JLab's End Station Refrigeration (ESR) facility. The 4 K gas pumped from the top of the separator is used to cool a series of copper baffles located at the upstream (warm) end of the refrigerator. is used to fill the target bath, a rectangular PTFE container, open at the top, where the target samples are placed (Fig. 2).
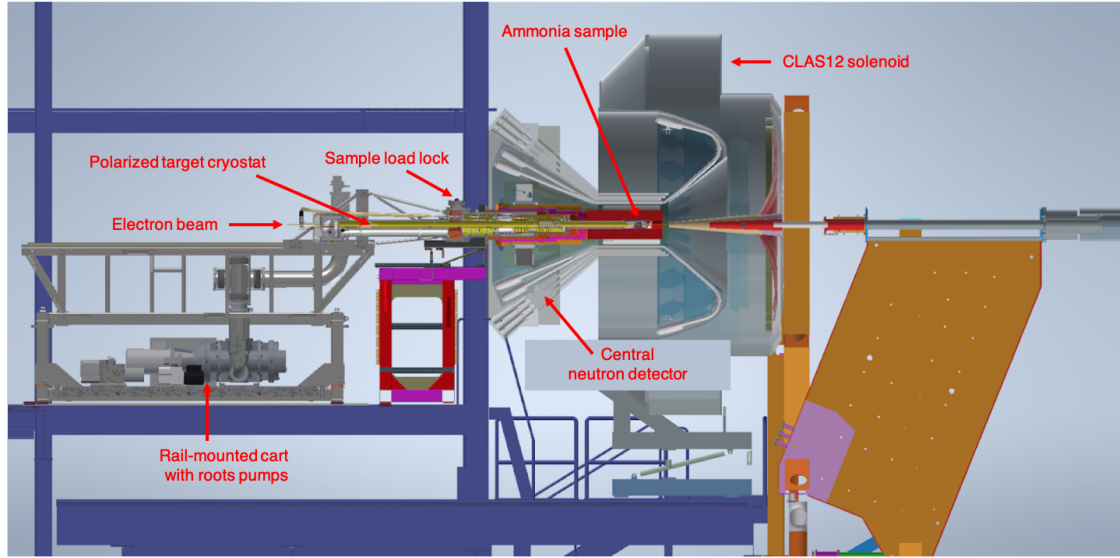
Figure 1: Side view of the polarized target installed in Hall B. The electron beam transverses the target from left to right in this view. Only a few elements of the CLAS12 spectrometer are visible. For more details on CLAS12, the reader is referred to Burkert et al. [1].

A 6000 m^3/h roots system pumps the liquid in the bath to a base temperature of 0.9 K and provides a cooling power of 1 K at approximately 1.1 K. The liquid flowing to the bath is cooled below 2 K by heat exchange with the helium vapor pumped from the bath and metered by a miniature needle valve. A second, coarser needle valve bypasses both the separator and liquid-vapor heat exchanger and is used for rapidly cooling the bath after a target sample is loaded. Both needle valves are actuated by computer-controlled stepper motors. A capacitance based level probe is located in the target bath and can be used in a feedback loop with the fine needle valve to maintain the bath level with a precision better than 1 mm. All refrigerator components are contained within a 2.5 m long pumping tube composed of G-10 fiberglass and aluminum that confines the low pressure gas evaporating from the target bath and guides it to the roots pumps. The pumping tube is in turn surrounded by a stainless steel and carbon fiber vacuum chamber that insulates all interior cryogenic components. A copper and aluminum heat shield is located between the pumping tube and vacuum chamber and is cooled by cold gas pumped from the separator. All helium gas pumped from both the separator and the target bath is returned to ESR for liquefaction. Cooling the refrigerator from room temperature to 1 K requires 6–8 hours. The distributed control software system EPICS (Experimental Physics and Industrial Control System) is used to monitor and control all aspects of the refrigerator operation.

Polarized target samples consist of 2-3 mm sized granules of frozen ammonia (^{14}NH$_3$ and ^{14}ND$_3$) prepared with paramagnetic radicals by irradiation in liquid argon using a 14 MeV electron beam to a dose of approximately 0.9×10^{17} e/cm^2. These irradiations were performed months or even years prior to the present experiments and stored under liquid nitrogen. For Run Group C, multiple samples were loaded into 5 cm long, perforated PCTFE containers ("target cells") with aluminum foils for beam entrance and exit windows. The cells are stored under liquid argon until placed in the beam. As explained in the Introduction, the cells are 2.0 cm in diameter except for the
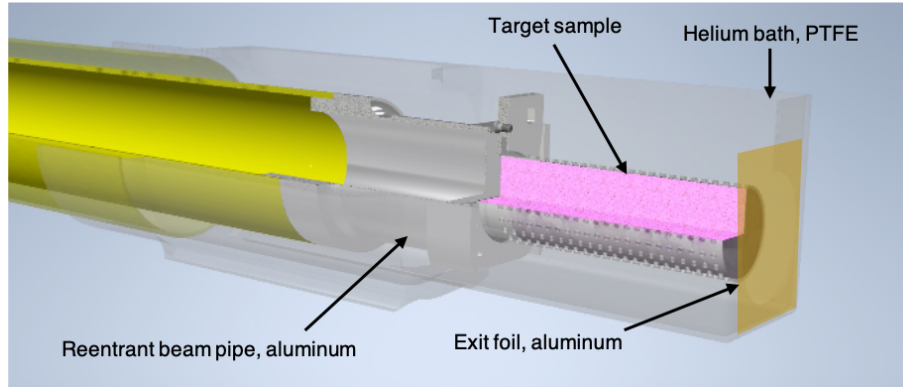
Figure 2: Cutaway drawing of the superfluid bath containing a target sample. A 2.5 cm hole in the downstream side of the bath is covered by an aluminum foil for the electron beam. The beam transverses left to right in this view.

exclusive measurements in which 1.5 cm diameter cells are used. In addition to ammonia, RGC also utilizes empty target cells and cells filled with carbon, polyethylene (C_2H_4), and deuterated polyethylene (C_2D_4) for background and dilution studies. A fixture attached to the bath's reentrant beam pipe locates the cells inside bath (see Fig 2).

Due to radiation damage from the electron beam, the ammonia samples need to be replaced or annealed every 2–3 days. It is also desirable to make frequent measurements on the polyethylene and carbon samples to minimize potential systematic uncertainties from changing detector efficiencies and target dilution factors. Unfortunately, the horizontal geometry of the CLAS12 detector (and by extension, the polarized target) only allows one target sample inside the cryostat at a given time. We have therefore implemented a novel method for loading and replacing target samples in the 1 K refrigerator that does not require disassembly of any portion of the electron beam line. In our system, the superfluid bath is attached to a set of recirculating, cryogenic bearings and can be retracted along the central axis of the refrigerator from its in-beam position at the center of the CLAS12 solenoid to a load-lock position about 2.5 m upstream. Here, the sample can be removed from the bath using a special tool and a new sample loaded into the bath in less than one minute. The bath is then transported back to the in-beam location and cooled to 1 K in about 30 minutes. Because we do not have to disassemble and reassemble any beam line components (beam pipe, focussing magnets, beam-position monitors, etc.), we can accomplish 3–4 target changes per week with only a few hours of lost beam time. We estimate the new system will save almost one month of beam time over the entire length of the RGC experiments.

Microwaves for the DNP process are produced by a 140 GHz extended interaction oscillator (EIO) with a tuning range of approximately 2 GHz and an output power of about 20 W. They are transmitted to the target through rectangular waveguide outside the cryostat and oversized (4.3 mm) circular waveguide inside. The waveguide terminates with a thin aluminum structure under the target bath that reflects the microwaves onto the target sample. After attenuation approximately 0.5–1 W of microwaves are provided to the sample. Coarse tuning of the frequency is performed using a computer-controlled DC motor that adjusts the length of the oscillator cavity, while fine tuning is accomplished by applying a DC bias to the cathode.
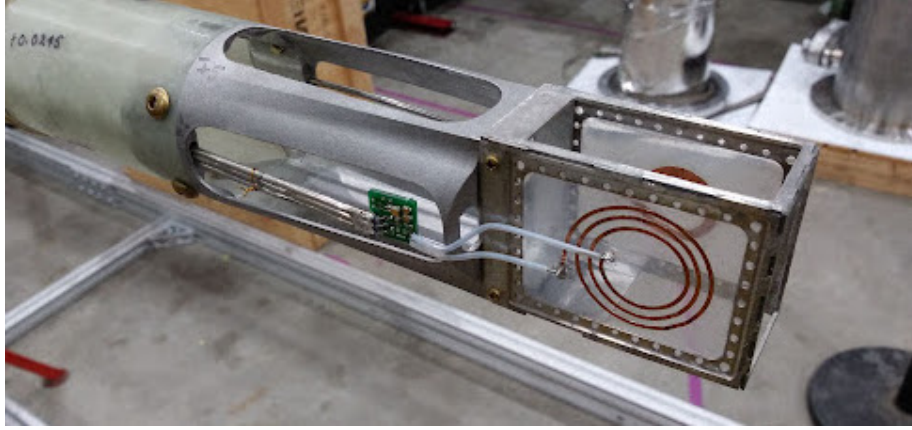
Figure 3: NMR coil for measuring the deuteron polarization at 32.7 MHz. The circuit board containing the tunable varactor diode is visible to the left of the coil. The helium bath (Fig. 2) slides into the metal frame for the in-beam position. The proton NMR coil can be seen on the opposite side of the frame.

The polarization is measured by CW-NMR using series-tuned Q-meters recently developed at Jefferson Lab [4]. There is one Q-meter used for proton NMR at 212.9 MHz and one for deuteron NMR at 32.7 MHz. The two NMR coils are fabricated from 25 μm thick copper foil and laminated between sheets of fluorinated ethylene propylene (FEP). These are attached to a low-density magnesium alloy structure inside the cryostat that also centers the target bath when it is moved into the in-beam position (Fig. 3). For the deuteron circuit, the tuning capacitor is placed next to the NMR coil which eliminates the need for a resonant $n\lambda/2$ cable and reduces the depth of the associated background Q-curve [5]. Rather than a fixed capacitor, we utilize a cryogenically-compatible, tunable varactor diode which gives a tuning range of approximately 22–36 MHz. Figure 4 compares deuteron NMR signals taken with the cold tuning varactor and non-resonant cable and with the traditional room temperature capacitor and $n\lambda/2$ resonant cable.

For optimum deuteron polarization, the CLAS12 solenoid is designed to provide a field uniformity of 100 ppm over the volume of the polarized target sample, but field mapping measurements indicate the uniformity is perhaps closer to 300 mm. We have therefore included four small, superconducting shim coils inside the target cryostat to improve the uniformity to ≤ 100 ppm [6].

3. Performance

At the time of this writing, Run Group C has completed approximately 90% of its scheduled 240 calendar days, although more than 50 days have been lost due to a failure of the CLAS12 solenoid's power supply. The reliability of the target system has thus far been better than 95%, losing a total of five days for repairs and maintenance. This does not include approximately 12 hours per week required to change and polarize targets, as this was included as overhead in the initial experimental plan. Data is typically acquired for two to three days on a polarized ammonia sample, either NH_3 or ND_3, after which time the polarization has decayed to an unacceptably low value due to radiation damage. That sample is then replaced for one or more days by a background target such as carbon and stored in liquid argon. In this way the ammonia sample is annealed at 87 K for
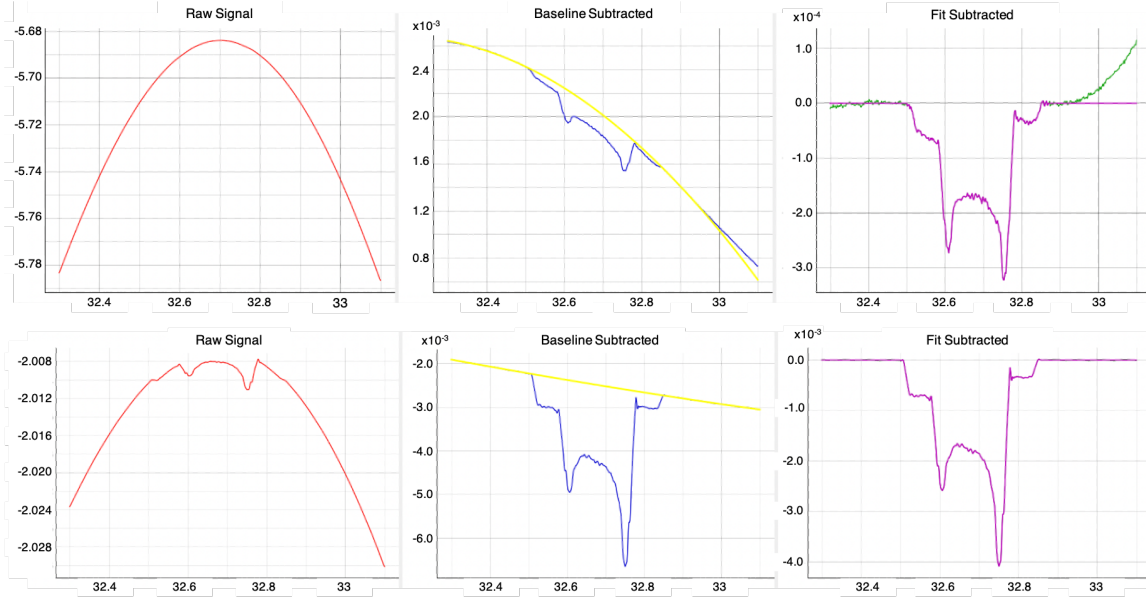
Figure 4: Comparison of the ND$_3$ NMR signals utilizing the traditional Q-meter circuit with the tuning capacitor at room temperature and connected to the NMR coil using a resonant nλ/2 cable (top) and with a cold tuning capacitor located near the NMR coil (bottom). The left plot is the raw signal from the Q-meter. The center plot has the background Q-curve subtracted, and the right plot is after subtracting a polynomial correction that compensates for drifts in the Q-curve.

many hours and usually obtains the original or even higher polarization when it is returned to the beam. The new loading mechanism has been utilized several dozen times, with no failures.

Because the load lock door features a borosilicate glass window, we are able to view the irradiated target samples before they are removed from the target cryostat and have observed luminescence in both the solid ammonia and polyethylene samples (Fig. 5). Although we have not yet made a careful, quantitative study of the phenomena, it may be useful as monitor of the annealing process in future polarized target experiments with solid ammonia.

Figure 5: Luminescence in a sample of solid ND$_3$ after a beam exposure of 2.6×10^{15} e$^-$cm^{-2}.

Initial proton and deuteron polarizations in our target system were approximately 60% and 25%, respectively. The proton polarization was lower than anticipated based on preliminary tests with samples of TEMPO-doped butanol. This, along with slow polarizing times, may indicate a lower-than-optimal concentration of paramagnetic radicals. With subsequent irradiation at 1 K using the 11 GeV beam, polarizations have increased to better than 80%. On the other hand, the low

initial deuteron polarization was expected and is the typical DNP performance for warm-irradiated ND_3 at 1 K and 5 T [7]. In this case, subsequent 1 K irradiation, followed by annealing in liquid argon, has yielded deuteron polarizations exceeding 50%.

The location of both the proton and deuteron NMR coils, outside the target cell, was chosen in order not to reduce the dilution factor. However this has negative consequences. First, the NMR signals are naturally smaller, and the calibration of the signal against the thermal equilibrium polarization at 1.5 K requires more signal averaging to achieve a precise result. Second, the sensitivity to polarization gradients within the sample is reduced. Third, the signal is dominated by the polarization of material at the periphery of the target cell, which is not exposed to the electron beam and experiences less radiation damage. For these reasons, the NMR is only intended as a *monitor* for the polarization, and offline analysis of elastic scattering asymmetries will ultimately be used to determine the absolute polarization. Although they are not known with great accuracy, we do compare the NMR with quasi-elastic scattering asymmetries to monitor the depolarization of the target. Preliminary results indicate that the NMR scans provide a reasonable indication of the polarization despite reduced sensitivity to the radiation-damaged portion of the target sample (Fig. 6).
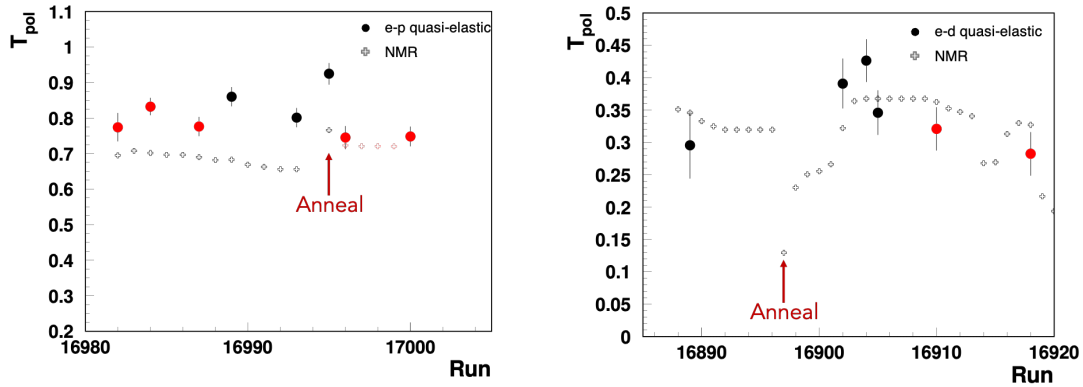

Figure 6: Comparison of target polarization (T_{pol}) determined by NMR and by quasi-elastic scattering. Results for the proton are shown in the left plot and for deuterons in the right plot. Each run is about four hours in length.

4. Summary

We have described the design, operation, and performance of a new longitudinally polarized solid-state target of NH_3 and ND_3. The target was constructed for operation inside the CLAS12 spectrometer in Hall B at Jefferson Lab and is currently being utilized for the Run Group C experiments which examine the partonic structure of protons and neutrons using the deep inelastic, semi-inclusive deep inelastic, and deeply virtual compton scattering of 11 GeV electrons. The various target samples (NH_3, ND_3, C, C_2H_4, C_2D_4) can be rapidly exchanged inside the restrictive CLAS12 geometry using a novel method developed for this target. Polarizations of 80% and 50% have been observed for the proton and deuteron, respectively, using new CW-NMR Q-meters designed and built at Jefferson Lab. We have also observed for the first time (we believe) luminescence in irradiated samples of polarized NH_3 and ND_3.

5. Acknowledgments

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