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Operation of a Longitudinally Polarized Solid Nuclear Target in CLAS12

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A suite of experiments measuring spin observables in electron-nucleon scattering (dubbed Run Group C) was recently executed in Jefferson Lab. These experiments involved the scattering of a polarized 11 GeV electron beam from longitudinally polarized nucleon targets located within the CLAS12 spectrometer in Hall B. The dynamically polarized target used in these experiments was designed and constructed exclusively for operation inside CLAS12 and further optimized for the requirements of Run Group C. We report on the complete target setup, operational experience with the target, the benchmarks achieved using various polarizable and unpolarized materials as well as the preliminary target polarization analysis.

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1. Introduction

In nuclear and particle scattering experiments, a polarized target denotes a target system wherein the nuclear spins of its constituent particles are predominantly aligned in a specific direction. The distribution of scattered particles, depending on the orientation of the target and beam spin, provides valuable data to study the spin-dependent aspects of nuclear interactions, enabling precision measurements of the fundamental properties of nuclei and particles. Over the past decades, the utilization of solid polarized targets has emerged as a highly beneficial tool in nuclear and high-energy physics. This article describes the development of a new dynamically polarized solid nuclear target for Hall B at Jefferson Lab, the techniques used to polarize the target samples of NH_3 and ND_3, and its operational performance during the recent Run Group C experiments.

2. Run Group C Experiments

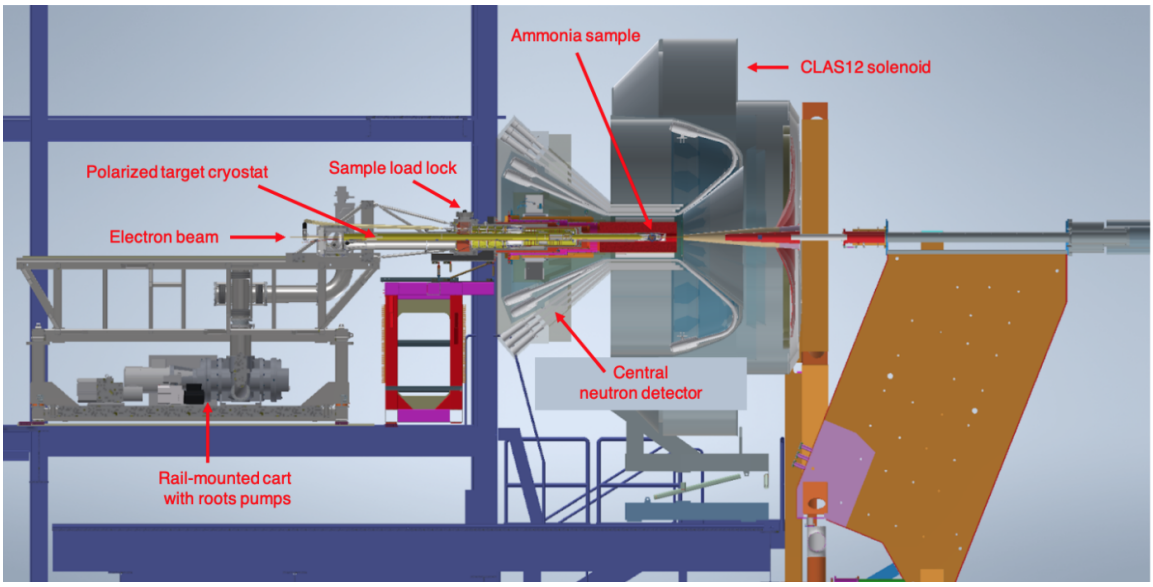

Figure 1: Incorporation of the APOLLO target into the CLAS12 detector system. For clarity, several CLAS12 components are omitted. [1]

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The RGC experiments mainly explore the spin structure functions of protons and deuterons for DIS inclusive, the spin- and transverse momentum-dependent (TMD) PDFs for (SIDIS), and the target single and beam/target double spin asymmetries in proton and neutron DVCS to access Generalized Parton Distributions (GPDs) [2]. The experimental setup for the RGC is shown in Fig 1. These experiments made use of two different detector configurations, with a Forward Tagger (FT) in place for the exclusive measurements and an FT out for higher statistics for the inclusive and semi-inclusive measurements. When the FT was out, a new lead tungsten shield was incorporated to protect the detectors from radiation damage caused by Moller-scattered electrons. Exclusive measurements with FT were carried out using 1.5 cm diameter target cells, a 1.4 cm raster diameter, and a 4 nA beam current. In contrast, all other measurements were conducted with a 2.0 cm target

cell, a 1.9 cm raster, and an 8 nA beam current. RGC was scheduled initially for 9 calendar months, and data were collected for 190 days, out of these 9 months from June 11, 2022, to March 20, 2023, corresponding to 80% of allotted beam time. The remainder of the beam time was lost due to a main power supply failure of the Hall B central solenoid, and also for configuration changes.

3. The RGC Polarized Target: APOLLO

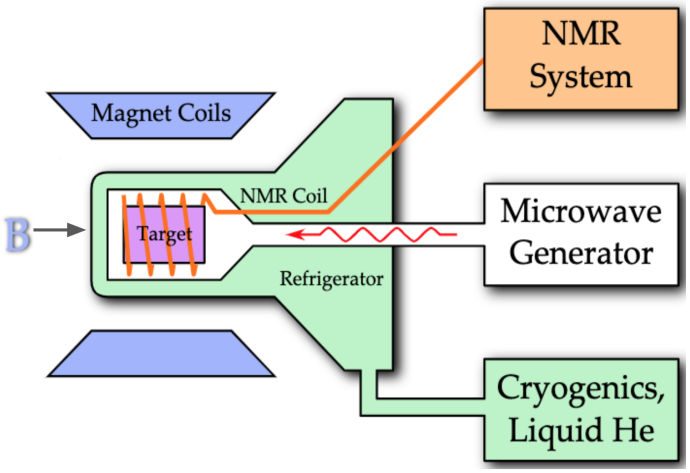

Figure 2: Basic illustration of a Dynamic Nuclear Polarization (DNP) apparatus.

The RGC experiments employed a new dynamically polarized target (APOLLO, Ammonia POLarized LOngitudinally) developed explicitly for operation within the CLAS12 detector. The target was constructed by a collaboration between Christopher Newport University, Old Dominion University, the University of Virginia, and the Jefferson Lab Target Group. A schematic for the various components of a generic dynamically polarized target is shown in Fig. 2, and those for the APOLLO target are described below. Importantly, the geometry of CLAS12 imposed severe constraints on the target design, resulting in a horizontal cryostat nearly 4 m long. It also motivated a novel method for loading and unloading the scattering samples to and from the cryostat, described in Sec. 4.

A magnetic field of 5 T was provided by the existing CLAS12 solenoid magnet. The uniformity of this field was specified to be $\Delta B/B \leq 10^{-4}$ over the volume of the polarized sample, but initial field maps indicated it may be somewhat worse. At uniformities of 10^{-3}, proton and deuteron polarizations are expected to degrade by relative values of about 20% and 50%, respectively. To guarantee optimum polarization, internal corrective magnetic shim coils were incorporated into the APOLLO design [3]. These four, thin superconducting coils were positioned immediately around the sample volume and were powered independently of one another to allow for a high degree of manipulation and fine-tuning of the local field. The currents to the coils (a few A) were supplied through a compact series of high-temperature superconducting (HTC) leads to reduce the heat leak to the refrigerator.

Microwaves for the Dynamic Nuclear Polarization (DNP) process were generated by a 140 GHz Extended Interaction Oscillator (EIO) with a tuning range of around 2 GHz and an output power of approximately 20 W. The microwaves were attenuated to approximately 1 W and transmitted into the target cryostat through an oversized circular waveguide (4.5 mm inner diameter) and reflected onto the target sample using an aluminum structure directly under the sample. Frequency modulation at 1 kHz was employed on the EIO throughout most of the Run Group C experiments, although the observed effect on the polarization was small – a few percent for ND_3 and no discernible effect for NH_3.

The target samples were cooled to 1 K using a horizontal ^{4}He evaporation refrigerator similar to the design described by Roubeau [4]. An annotated photograph of the major refrigerator components is shown in Fig. 3. Briefly, the target cryostat received 4.2 K liquid helium from a dewar positioned a few meters away and continually replenished by the JLab End Station Refrigerator facility. Liquid from this dewar was delivered to a liquid-vapor phase separator located inside the target cryostat. Vapor pumped from the separator was used to cool a series of radiation baffles located in the warm, upstream end of the refrigerator, as well as a conically-shaped heat exchanger for the 20 K thermal shield surrounding the low-temperature end. Liquid from the separator was expanded through a miniature Joule-Thomson (JT) valve and delivered to a small, rectangular bath containing the target sample. The bath was fabricated from PTFE and featured thin aluminum windows at the upstream and downstream ends for beam passage. Liquid collected in the bath was pumped by a 6000 $m^3\ h^{-1}$ pumping system to a vapor pressure of approximately 13 Pa, corresponding to a temperature of 1 K. A capacitive probe in the bath measured the liquid level with a resolution better than 1 mm and was used to always maintain the level slightly above the target sample via a PID feedback loop with the JT valve [5]. A heat exchanger, stamped from C101 copper plates, utilized the vapor pumped from the bath to cool the liquid to approximately 2 K before expansion.

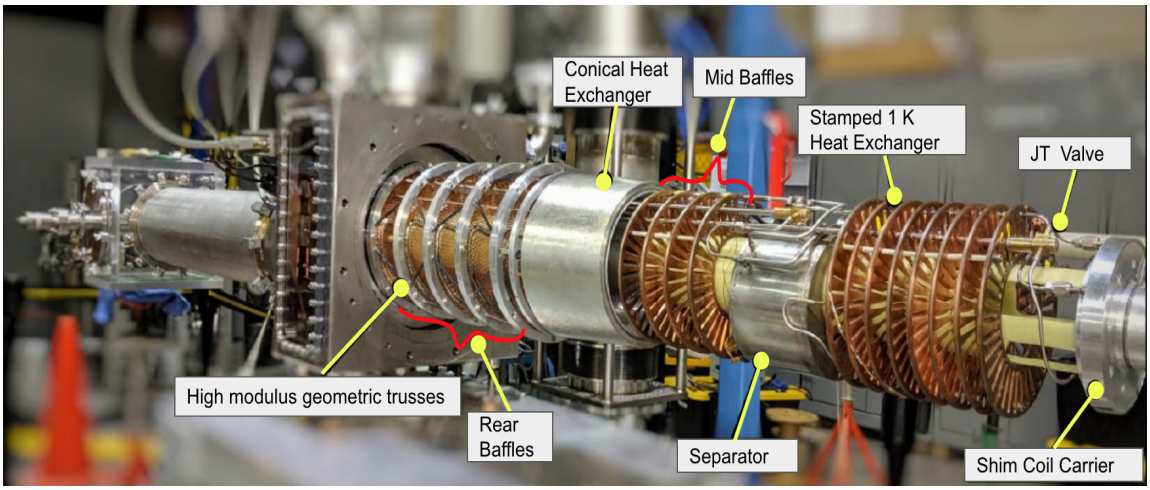

Figure 3: The 1 K evaporation refrigerator featuring the majority of its key components.

The sample polarization was measured using continuous-wave NMR with a new Q-meter recently developed by a collaboration between the Jefferson Lab Target and Fast Electronic Groups [6]. The new instrument replaces the Liverpool Q-meter which is no longer commercially available [7].

Compared to the Liverpool Q-meter, it provides a somewhat better signal-to-noise ratio and features ergonomic improvements such as remote, electronic tuning for both the diode and phase channels. The JLab design is also highly modular, which should make for easier modifications and upgrades in the future. New python-based software that incorporates NMR control, data acquisition, and data analysis into a single package was developed to accompany the new Q-meter. Screenshots for both proton and deuteron signals using the new software are shown in Fig. 4.

The proton polarizations were determined by measuring the area under the NMR signal. These were calibrated against measurements made with the microwaves off and the spins in thermal equilibrium (TE) with the helium bath at 1.5 K and 5 T. In the case of deuterons, the corresponding TE signals were too small to be measured with useful accuracy, and the polarizations were extracted from an analysis of the deuteron NMR line shape [8]. Two NMR coils were used, both positioned outside the target bath and connected to Q-meters using semi-rigid coaxial lines. The first was tuned at 213 MHz for proton detection, and the second at 32 MHz for deuterons. This location of the coils was chosen to maximize the dilution factor of the samples, but it reduced the sensitivity of the NMR measurements to the depolarization caused by the electron beam. As a result, the proton and deuteron polarizations in the Run Group C experiments will ultimately be determined from elastic and quasi-elastic scattering asymmetries.

4. Target cells/materials

Seven different materials, contained within 5 cm long containers ("cells"), were utilized as scattering targets during the RGC experiments. NH_3 and ND_3 were used for polarized asymmetry measurements. Carbon, CH_2, CD_2, and empty cells were used for dilution studies, and tungsten-wire targets were used for beam position and optics measurements. The materials were changed frequently to minimize systematic uncertainties caused by drifts in detector efficiency. To facilitate their rapid interchange without disturbing other beam line elements such as focusing magnets and beam position monitors, the superfluid bath for the target samples was not permanently fixed at the low-temperature end of the refrigerator. Instead, it could be retracted through the central axis of the refrigerator from its in-beam position at the center of the CLAS12 solenoid to an easily accessible load lock approximately 2 m upstream [9]. Here, under a strong purge of helium gas, one sample could be removed from the bath and replaced with another using a bespoke insertion tool. The pumping system for the 1 K refrigerator was shut off during this procedure, and the bath typically warmed to 80–90 K when retracted to the load lock. However, the refrigerator and sample could be cooled back to 1 K in about 15 minutes. From start to finish, a sample exchange could be performed in as little as 30 minutes, and a total of 75 such exchanges were performed through the entirety of the RGC experiments.

Like the sample bath, a fluorocarbon (PCTFE) was chosen for the ammonia sample cells as it does not produce a proton or deuteron NMR signal. Torlon (polyamide-imide) cells were used for all other target samples. In all cases, the cells had 0.5 mm thick perforated walls and 20 μm thick aluminum beam windows glued at the ends. The ammonia was prepared with the paramagnetic radicals needed for DNP by irradiation at liquid argon temperatures using a low energy ($\sim$ 15 MeV) electron beam prior to the experiment, transferred into target cells, and stored in liquid nitrogen until placed in beam. An ammonia sample was typically used for 2–3 days, during which time

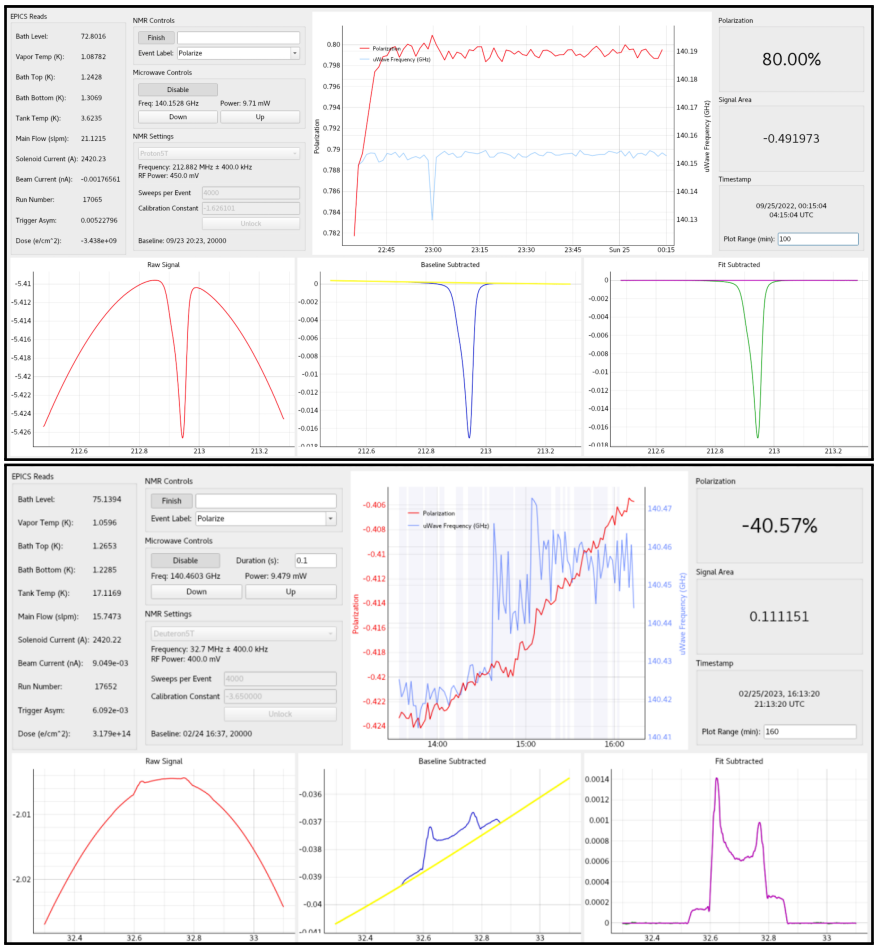

Figure 4: Online NMR display showing positive polarization for the proton (top) and negative polarization for the deuteron (bottom). In both cases, the upper graph shows the polarization as a function of time, and the three graphs at the bottom indicate the NMR signal at different stages of analysis. The left graph is the raw signal from the Q-meter, which includes both the NMR signal and the inherent voltage-versus-frequency response of the circuit ("Q-curve"). In the middle, the Q-curve (measured with the magnetic field off-resonance) has been subtracted. The right graph shows the signal following a polynomial correction designed to offset any drifts in the Q-curve.

its polarization decayed due to beam-induced radiation damage, the accumulation of excessive DNP radicals and/or radical species that are detrimental to the DNP process. At this point, it was exchanged for a different sample and stored in liquid argon at 87 K for a few days. This proved warm enough to repair most of the radiation damage and return the sample to its previous state.

5. Target Polarization Analysis and Results

Proton polarizations in excess of 80% and deuteron polarizations greater than 50% were observed during the Run Group C experiments. However, the proton results at the beginning of RGC were significantly lower than this value but consistently increased as the samples were irradiated at 1 K with the 11 GeV CEBAF beam and subsequently annealed at 87 K. This behavior,

along with very slow polarizing times, hints that the initial concentration of paramagnetic radicals in the sample was too low. This may indicate an insufficient irradiation with low-energy electrons prior to RGC or that the samples were exposed to temperatures greater than 100 K after the irradiation. Similar results were observed for deuterons, but this behavior was expected. Dynamic polarization of ND_3 at 1 K and 5 K does not exceed about 25% until the sample receives some irradiation at very low temperatures [10].

Offline analyses of the NMR results are currently in progress. In the case of the proton, where the NMR signals were routinely calibrated against the thermal equilibrium (TE) polarization, the online and offline results compare well (Fig. 5). As previously described however, TE polarization measurements were not made for the deuteron, and the polarization was instead extracted from the NMR line shape. In this case, deviations between the online and offline results are observed, especially for the early exclusive measurements. For technical reasons beyond this scope of these proceedings, the deuteron NMR signal was abnormally small and prone to distortion during this time period, thus making reliable analysis of the line shape difficult. In the offline analysis, only signals with minimal distortion are selected. The area under these signals is then used to estimate the polarization of the distorted signals based on those signal areas.

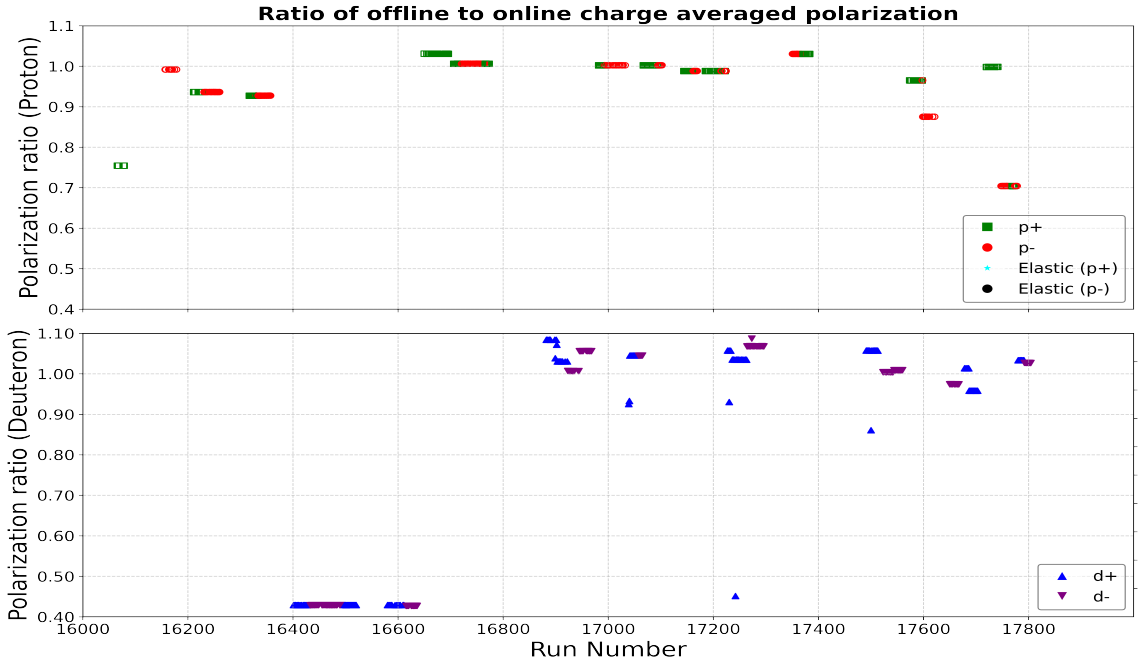

Figure 5: The ratio of charge-averaged offline to online polarization for protons (top) and deuterons (bottom).

6. Conclusion

We provided details on the construction, functionality, and effectiveness of a new longitudinally polarized solid target utilizing NH_3 and ND_3. This target was specifically designed for operation within the CLAS12 spectrometer at Jefferson Lab's Hall B and was employed in the Run Group C experiments. These experiments investigated the partonic structure of protons and neutrons

through deep inelastic, semi-inclusive deep inelastic, and deeply virtual Compton scattering of 11 GeV electrons. A unique method was developed for the rapid exchange of various target samples within the confined geometry of CLAS12. Proton and deuteron polarizations of 80% and 50%, respectively, were demonstrated in the new target. Offline analyses of the NMR results are currently underway.

7. Acknowledgments

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