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A High-Field Polarized ^{3}He Target for Jefferson Lab's CLAS12 Spectrometer

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Polarized ^{3}He nuclear targets are invaluable surrogates for polarized neutron targets in spin-dependent scattering studies of the structure of matter. Traditional polarized ^{3}He targets have seen steady improvements and active use over the last three decades, however they have been limited to operation in low magnetic fields. This has precluded their use in spectrometers that utilize high-magnetic-field tracking systems, such as Jefferson Lab's CLAS12 spectrometer. Developments in high-magnetic-field metastability exchange optical pumping of ^{3}He, recently incorporated into the design of a polarized ^{3}He ion source for RHIC and the EIC, could enable a new, polarized ^{3}He fixed target to operate within high fields. Combining high-field techniques with the double-cell cryogenic target design used for the MIT-Bates 88-02 experiment, polarization and target density comparable to traditional polarized ^{3}He targets could be reached while within a high magnetic field environment. We discuss the conceptual design for such a target, show our progress in this target's development, and outline plans for in-beams tests in Jefferson Lab's Hall B.

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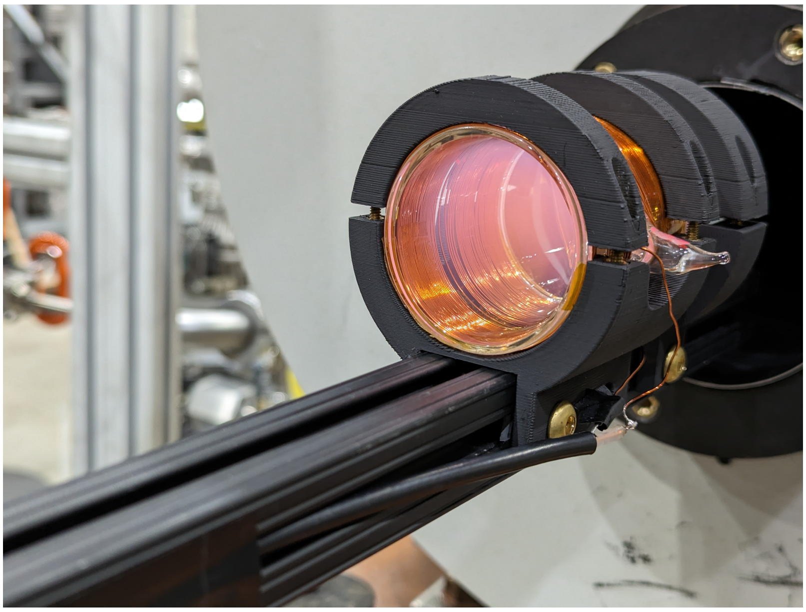

Figure 1: Photograph of a sealed helium cell under plasma discharge.

1. Introduction

The polarization of ^{3}He gas targets via optical pumping has provided an invaluable proxy for polarized neutron targets in spin-dependent scattering studies of the quark and gluon structure of matter [1]. Laser-driven optical pumping has been used to produce polarized ^{3}He for targets through two techniques: the pumping of metastable atoms produced in the gas via a plasma discharge (known as metastability exchange optical pumping or MEOP), and the pumping of gaseous alkali metals evaporated into the ^{3}He (known as spin exchange optical pumping or SEOP). The most important difference between these techniques is the gas pressure at which they can be performed: MEOP has historically been limited to near 1 mbar, while SEOP can effectively polarize at as high as 13 bar. SEOP has been the technique of choice for high luminosity scattering experiments for this reason, and SEOP targets have been used for 15 experiments at Jefferson Lab over the past three decades, with 5 more already approved to run in the future.

However, the prevalence of high magnetic fields in high energy and nuclear physics detector packages highlights a key limitation of SEOP targets. Large acceptance spectrometers such as JLab's CLAS12 [2] use magnetic fields around the interaction region as integral detector elements, bending charged particles for discrimination or rejection. Increasing wall relaxation at high field reduces the efficiency of SEOP [3], excluding commonly used polarized ^{3}He targets from such environments.

While MEOP has been limited to polarization at low pressures, this disadvantage has historically been countered by compression with specialized pumps or by increasing gas density using low temperatures. In the late 1980's, a double-cell, cryogenic target was developed [4, 5] at Caltech for Bates experiment 88-02. It utilized MEOP in a room-temperature, glass pumping cell, then transferred the polarized gas by diffusion into a copper target cell held at 13 K, increasing the gas

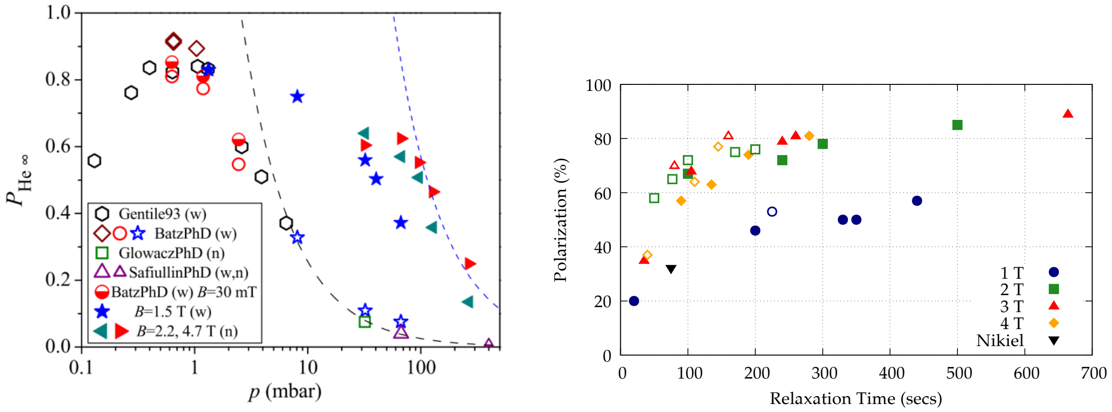

Figure 2: At left, the variation with pressure of highest steady-state polarizations achieved by various groups at low fields (open symbols) and high fields (filled) from [1]. At right, polarization achieved versus relaxation time (adjusted via discharge intensity) at various fields in 1.3 mbar sealed cells from [9].

density over 20 times.

1.1 High-field Optical Pumping

In the last 20 years, developments in polarization of ^{3}He for medical imaging have greatly expanded the capabilities of traditional MEOP through the use of high magnetic fields. Research at the Kastler-Brossel Lab at ENS Paris (LKB) has shown that increasing the holding field beyond 1 T greatly improves the efficiency of MEOP at higher gas pressures [6, 7]. Figure 2 shows steady-state polarization at fields of 1.5, 2.2 and 4.7 T in shaded points, compared to low-field polarization in open points. The ability to polarize to roughly 60% near 100 mbar and above 2 T would be particularly attractive for a polarized target application, and the ability to polarize within high fields is already being applied for a polarized ^{3}He ion source for the Electron Ion Collider [8, 9].

MEOP takes advantage of a population of meta-stable atoms in the 2^3S_1 state created in a plasma discharge. Laser light at 1038 nm will drive electronic transitions from the 2^3S_1 to the 2^3P_0 level, and if this light is circularly polarized, it will alter the total angular momentum m_F by one. As atoms decay to the metastable state, m_F changes by -1, 0 , or 1 with equal probability, but the net result of optical pumping is the polarization of the metastable population. Metastability exchange collisions of the metastable population with ground state atoms transfer this polarization to the entire population.

At low magnetic field, the possible 2^3S_1 to 2^3P_0 transitions result in an absorption spectrum of nine mostly degenerate peaks, as seen at top of Figure 3. Two of these transitions, C_8 and C_9 are cleanly resolved and typically used for optical pumping. C_9 is highlighted in the figure. By choosing the right (σ_+) or left (σ_-) handedness of the circular polarization, the direction of the polarization with respect to the holding field is selected.

As the magnetic field increases, Zeeman splitting drives the energy sublevels apart, breaking the degeneracy and creating a very different absorption spectra, as seen at the bottom of Figure 3. One effect of this peak separation is the creation of pairs of peaks which may be monitored to allow a measure of the polarization of the gas [10]. One such pair are highlighted as "probe peaks" in the

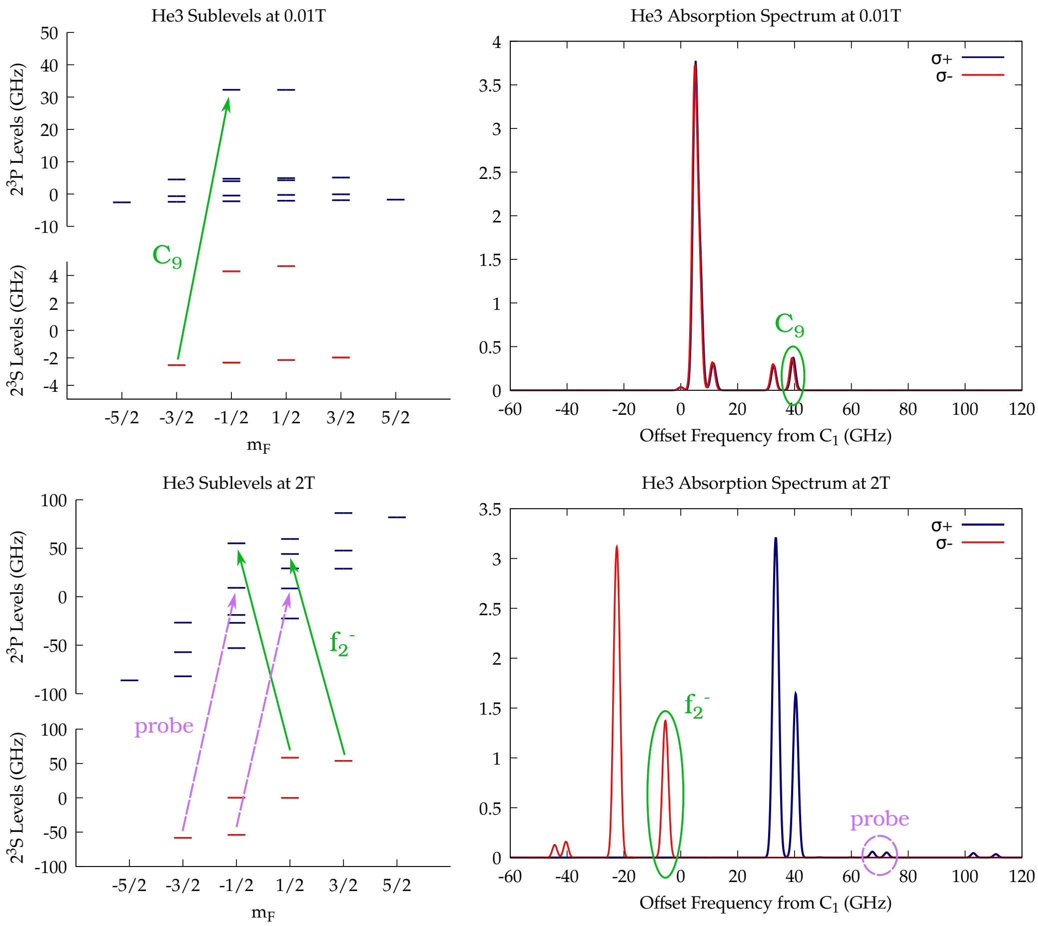

Figure 3: Optical pumping transitions at low (top) and high (bottom) magnetic fields. At left are the separations of the ^{3}He sublevels, with example pumping transitions C_9 and f_2^-. At right are the corresponding peaks in the absorption spectrum. Based on figures from [6, 7], calculated using code from P.J. Nacher.

figure. Another side effect is that the laser light need not be circularly polarized, as the σ_+ and σ_- peaks are distinct enough to address via a change in wavelength without hitting another peak.

2. Proposed Target Design

Combining double-cell cryogenic target techniques with the pressure increases allowed by MEOP at high magnetic fields will permit a new type of polarized target for high luminosity scattering experiments [11]. Where the Bates 88-02 target achieved 40% polarization near 2 mbar with a 13 K target cell, our new design aims to reach 60% at 100 mbar with a 5 K target cell. Although the density of such a target, at 5.4 amg, would not surpass the 9 amg typical of SEOP targets used at low fields with room temperature target cells, it would allow operation within high magnetic fields to enable new applications of polarized ^{3}He targets. We have begun development of such a target for use in Jefferson Lab's CLAS12 spectrometer in support of a conditionally approved program of spin-dependent electron scattering from polarized ^{3}He [12] in Hall B.

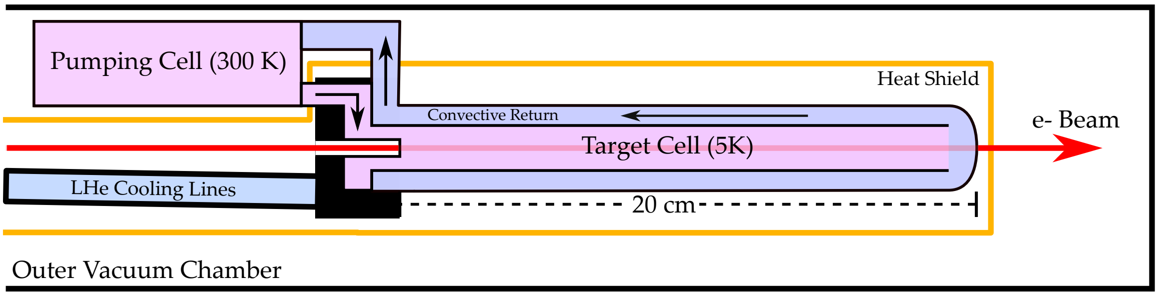

Figure 4: Schematic layout of the two-cell polarized ^{3}He target concept for CLAS12, from [11].

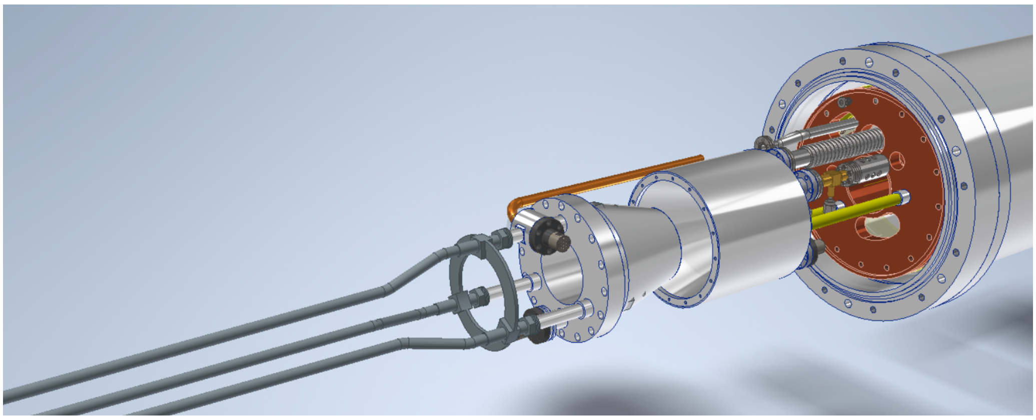

Figure 5: Modular, conical heat-exchanger of the Hall B cryotarget. The coolant loop on the right cools the concave conical mount to below 4 K with Joule-Thomson cooling of liquid helium. Extending to the left is the target loop which will support and cool our gas cells. The experimental beam passes through the center bore of the refrigerator.

As shown in Figure 4 this new design will include two cells, following the layout of Bates 88-02 target, with both cells held within the CLAS12 solenoid's magnetic field. The pumping cell will be typical of many MEOP setups: glass with optically clear ends to allow pumping laser light, coupled to electrodes to induce an RF discharge, and held at room temperature to avoid the rapid drop of metastablility-exchange collision cross sections with decreasing temperature [1]. The target cell will be aluminum, with thin windows to allow the passage of the experimental beam, and held at 5 K by a liquid helium heat exchanger. Should it be necessary, we could induce the convective flow of gas between the cells, using a thin-walled flow diverter to direct polarized gas down the full length of the 20 cm cell.

To cool the target cell to roughly 5 K, we plan to take advantage of a new cryotarget system which provides liquid hydrogen and helium targets in Hall B. This system incorporates a modular, conical refrigerant block, seen in Figure 5, allowing us to remove the liquid target cell loop and mount our gas cells. Taking advantage of liquid helium from the CEBAF end station refrigerator, this design will provide sufficient cooling power to maintain 5 K in the target cell and 300 K in the nearby pumping cell.

Measurements of the polarization will be performed using a probe laser to monitor the populations of Zeeman-separated energy levels [7] in the RF-induced plasma. Because it is performed within the RF discharge, these measurements will only be possible within the glass pumping cell. However, following methods used for the Bates 88-02 target, we plan to infer the polarization in the target cell using the measured polarization in the pumping cell and measurements of polarization relaxation and transfer time.

2.1 Depolarization Effects

Understanding and reducing possible sources of depolarization are crucial for the design of a successful target. Polarization relaxation can be expected from wall interactions, transverse magnetic field gradients, and ionization in the beam. To avoid depolarization on the aluminum cell walls, all metal surfaces will be cooled to cryogenic temperatures and coated with a thin layer of solid H_2, which has been shown to yield days-long relaxation times below 6 K [13]. Based on field maps of the CLAS12 solenoid, we expect the transverse gradients will be acceptable in the region where the cells can reside [11].

Jefferson Lab's 12 GeV polarized electron beam will induce depolarization through the production of molecular ^{3}He$_2^+$ ions. For Bates 88-02, this effect was found to create a 2000 second relaxation time in 2.6 mbar gas under a 5 μA beam current. While the molecular production increases with density, increasing the magnetic field reduces the depolarization rate due to diatomic molecules as the rotational angular momentum is decoupled from the total molecular-ion spin [14]. The relative strengths of these effects is unknown at these pressures and fields, so measuring the polarization relaxation in an ionizing beam in 100 mbar gas at magnetic fields above 2 T will be central to proof-of-concept tests of our target system.

3. Progress

We are focusing on two key questions in the development of a final target: what is the optimal gas pressure and magnetic field at which to polarize, and how much polarization relaxation should we expect at those conditions while in the experimental electron beam. Once we know the relaxation to expect, we can determine if the target can reach an attractive polarization, and how much communication between the pumping and target cell is necessary to maintain it.

To this end, we have begun tests of optical pumping at high fields at Jefferson Lab. Our MEOP tests began with low-field tests at 30 G, and have advanced to a high-field MEOP test stand shown in Figure 6. This stand includes 1083 nm pumping and probing laser systems, a laser wavelength meter, an amplifier and source to produce an RF discharge, and an enclosure which extends into the warm bore of a 5 T superconducting magnet.

As seen in the schematic in Figure 7 from [15], the ^{3}He cell is held within the center of the solenoid, and is illuminated by pump and probe lasers. The RF discharge is created using inductive electrodes coupled to an amplifier, which is driven by a signal near 10 MHz and amplitude modulated at 1 kHz. The probe laser is reflected back through the cell by a mirror and collected by a photodiode whose photocurrent is sent to a low-noise amplifier. The 1 kHz portion of the photodiode signal due to the absorption of the probe laser in the discharge is extracted using a lock-in amplifier. By sweeping the distributed feedback probe laser through the wavelength range of the two probe peaks from Figure 3, their relative intensities are determined, giving a measure of the gas polarization.

Figure 6: Photograph of the laser enclosure (in black) extending into the warm-bore magnet at left, and the supporting electronics rack on the right.

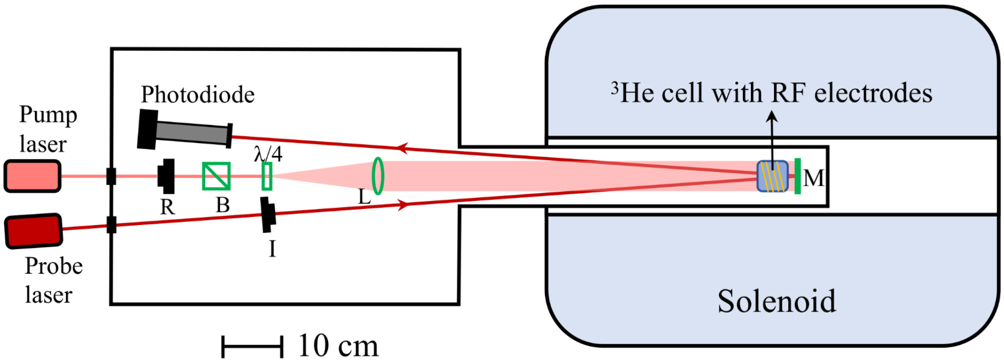

Figure 7: Schematic layout of our MEOP test apparatus, from [15].

We have published some initial tests of our system with a sealed helium cell, covering magnetic fields from 2 to 4 T, and reaching polarizations around 77% [15], as seen in Figure 8. This is somewhat lower than similar tests done with this sealed cell at Brookhaven [9], but the discrepancy is likely explained by field uniformity differences between the superconducting magnets used.

We have recently acquired two new pumping lasers with a larger 300 GHz wavelength tuning range, which will allow us to reach the pumping lines when they are shifted outward by a higher 5 T field. Hall B's nominal solenoid field is 5 T, so tests there will be of great interest.

Our next tests will investigate the polarization achievable at a range of gas pressures. Based on the LKB results, we should see roughly 60% around 100 mbar, however an accurate map of polarization versus pressure and field will be important for selecting the operating conditions for a

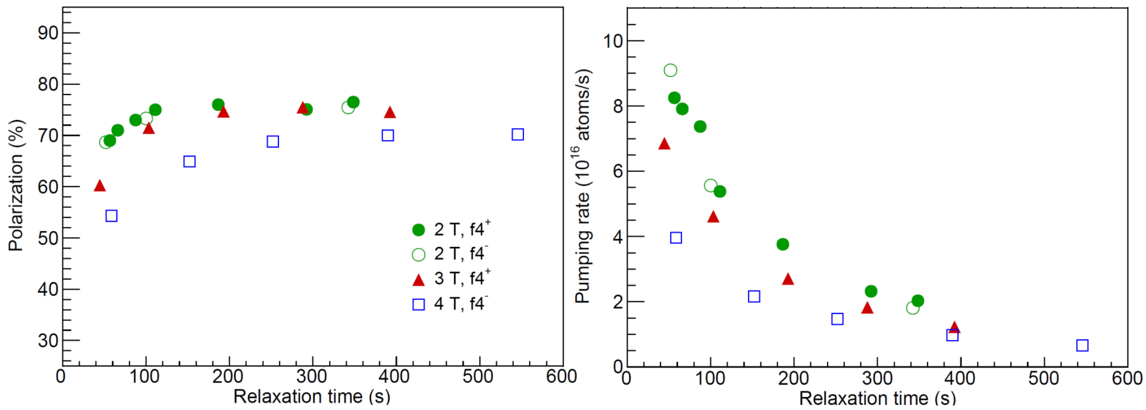

Figure 8: At left, the steady-state polarization achieved at JLab from 2 to 4 T with a 1.3 mbar sealed gas cell versus the discharge-on relaxation time with the laser off, and at right the corresponding pump up time with the laser on.

scattering experiment. We have produced new pumping cells for use in our polarizer stand which will allow cleaning and baking the system, as well as filling helium at varied pressures. This system includes a glass cell with a glass valve leading to a gas handling system with a sorption getter, diaphragm pump backed turbopump, capacitance manometer, and heater equipment to allow the system to be baked. The cleanliness of the system will be monitored using an optical spectrometer to observe discharge peaks in ^{4}He before filling with ^{3}He.

3.1 Beam Test Plans

While we continue tests with our system to reproduce the polarization results of the LKB, we are preparing for tests of gas depolarization in the experimental beam. Because our system is designed to be a module supported by the existing Hall B cryotarget, the most straight-forward and efficient tests would be done using the CEBAF beam inside Hall B. We are pursuing commissioning tests of the new polarized target to be scheduled directly before an experimental run utilizing the cryotarget. In this way, we can prepare the new target system during an accelerator maintenance period, running tests of polarization performance without beam, and then install the operational system into Hall B for the run. When experimental beam returns, a few days of tests should be sufficient to observe the rate of gas depolarization, and the cryotarget module can be restored to liquid for the regular run within another two days. This scheme must be reviewed and assessed for readiness before installation, but Hall B leadership has thus far been supportive.

We are currently finalizing the in-beam test design, and will soon move on to its construction and testing. Preparatory tests may be performed using the existing cryotarget refrigerator transferred from Hall B to the Target Group laboratory, or using an identical conical cooling block attached to a pulse-tube cryocooler. In both cases, our 5 T warm bore magnet could provide the holding field, albeit with a very different uniform field region than the CLAS12 solenoid.

4. Conclusion

We are undertaking development of a novel polarized target with the aim of providing 60% polarized gas at 100 mbar and 5 K to support a program of spin-dependent electron scattering from polarized ^{3}He in Jefferson Lab's Hall B. Tests of high-field metastability exchange optical pumping at JLab are proceeding well, and we are finalizing the design of a polarized ^{3}He module to interface with the existing Hall B cryotarget system. We aim to be ready for in-beam tests to prove the target feasibility next year.

Acknowledgments

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