PROCEEDINGS OF SCIENCE

Metastability Exchange Optical Pumping to Polarize ^{3}He at High Magnetic Fields

Pushpa Pandey,[a,*] **Hao Lu,**[c] **James Brock,**[b] **Christopher Keith,**[b] **Xiaqing Li,**[d] **James Maxwell,**[b] **Richard Milner**[a] **and Dien Nguyen**[c]

[a] *Massachusetts Institute of Technology, Cambridge, MA, USA*
[b] *Thomas Jefferson National Accelerator Facility, Newport News, VA, USA*
[c] *University of Tennessee, Knoxville, TN, USA*
[d] *Shandong University, Jinan, China*

E-mail: ppandey@mit.edu

Recent advancements in Metastability Exchange Optical Pumping (MEOP) techniques have enabled the investigation of ^{3}He nuclear spin polarization under high magnetic fields and varying gas pressures. At Jefferson Lab, we are employing MEOP of ^{3}He nuclei at varying pressures using a fillable cell under magnetic fields ranging from 2 to 5 T. The current development focuses on creating a double-cell, cryogenic polarized ^{3}He target for CLAS12 in Hall B at JLab, featuring a central solenoid that generates a magnetic field of 5T. We will present the current progress in polarizing ^{3}He using MEOP at JLab, and outline the preliminary design of the double cell target.

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*Speaker

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1. Introduction

^{3}He consists of two protons and one neutron, where the protons pair with opposite spins, effectively canceling each other's contributions to the total nuclear spin. Consequently, the nuclear spin of polarized ^{3}He is primarily determined by the unpaired neutron, making it function as a "polarized neutron target." This unique characteristic allows polarized ^{3}He to be used in scattering experiments, offering valuable insights into the neutron's spin-dependent structure functions. Over the past 30 years, spin-polarized ^{3}He gas targets have been developed using optical pumping techniques [1] and successfully utilized in scattering experiments at MIT-Bates, SLAC, DESY, Mainz, HIGS, and JLab, [2–7] contributing to our understanding of the quark and gluon dynamics inside nucleons and nuclei.

Metastability Exchange Optical Pumping (MEOP) enables the high polarization of ^{3}He gas nuclei within a uniform magnetic field using circularly polarized light. An RF discharge excites a small fraction of the atoms into the metastable 2^3S_1 state, where transitions to the 2^3P_0 state are driven by 1083 nm laser light. The laser selectively changes the magnetic quantum number by ± 1, depending on the light's circular polarization. This induced polarization in the metastable atoms is subsequently transferred to the ground state atoms via metastability exchange collisions, leading to bulk nuclear polarization. Although MEOP techniques have generally achieved high polarization within a restricted pressure range, typically near 1 Torr, their rapid polarization rate and the absence of impurities from the exchange of gases or alkali vapors as in Spin-Exchange Optical Pumping (SEOP) make them well-suited for this application. The double-cell polarized ^{3}He target, designed and constructed by Caltech [8], was the first MEOP target developed specifically for electron scattering experiments. It was utilized in the MIT-Bates 88-02 experiment, marking the inaugural measurement of spin-dependent electron scattering from the ^{3}He nucleus. In this setup, ^{3}He was polarized at low magnetic fields using the MEOP technique within a room-temperature pumping cell and subsequently diffused into a cold target cell (operating below 20 K) to increase gas density, facilitating MEOP in the low-pressure regime of a few mbar.

Traditional polarized ^{3}He targets perform effectively in low magnetic fields (approximately 10^{-3} T); however, their behavior and performance in high magnetic field environments have not been thoroughly investigated. Recent breakthroughs in high-field MEOP for ^{3}He [9–11] have paved the way for broader use of polarized ^{3}He targets in experiments that require strong magnetic fields, such as those conducted with the Electron Beam Ion Source (EBIS) at Brookhaven National Laboratory (BNL) and the CLAS12 spectrometer at Jefferson Lab (JLab). A BNL-MIT collaboration is actively developing a polarized ^{3}He ion source within the 5 T solenoid of EBIS, which is a critical component for future Electron-Ion Collider applications [12]. At Jefferson Lab, our effort to develop an innovative polarized ^{3}He target for the CLAS12 spectrometer has been motivated by the success of the MIT-Bates target and recent high-field MEOP studies conducted at BNL [13]. The conceptual design of the CLAS12 polarized ^{3}He target integrates the double-cell cryogenic design of the MIT-Bates target with the newly developed high-field MEOP technique [14]. This approach aims to achieve polarized ^{3}He within the 5 T solenoid of CLAS12 while maintaining a target thickness comparable to traditional low-field polarized ^{3}He targets. This would allow the CLAS12 detector to operate fully for spin-dependent electron scattering measurements across the entire kinematic range, including elastic, quasielastic, resonance, deep inelastic, and deeply virtual

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exclusive scattering.

As an initial step toward developing a polarized ^{3}He target for CLAS12, systematic studies on metastability exchange optical pumping (MEOP) of ^{3}He nuclei have been conducted at Jefferson Lab using a 1-Torr sealed cell under magnetic fields ranging from 2 to 4 T [15]. These studies have explored the impact of discharge intensity, pump laser power, and various pumping transition schemes on the achievable nuclear polarization and pumping rate. A maximum steady-state nuclear polarization of approximately 75% has been achieved. With a similar purpose, but with the use of a fillable cell, in contrast to the sealed cell, we are employing MEOP on ^{3}He nuclei at varying pressures of 0.6, 1, 50, and 60 mbar under magnetic fields ranging from 2 to 5 T.

1.1 MEOP at High Field

In traditional low-field MEOP applications, the C_8 or C_9 transitions are used to optically pump the ^{3}He atoms by exciting the 2^3S_1 spin 1/2 and 3/2 states into the 2^3P_0 state, see Ref. [16], and the nuclear polarization of ^{3}He can be measured by observing the circular polarization of the 668-nm light emitted by the discharge. However, as the magnetic field increases, the energy levels of 2^3S_1 and 2^3P_0 states undergo significant splitting due to the Zeeman effect, which breaks the degeneracy of the states. This leads to the emergence of new lines in the absorption spectra, complicating the optical pumping process. For the 2^3S_1–2^3P_0 transitions in ^{3}He, the most effective optical pumping schemes are denoted as $f_4{}^{\pm}$ and $f_2{}^{\pm}$, where the subscripts "2" and "4" indicate the number of closely-spaced unresolved optical frequency lines involved. The ± symbols correspond to the use of either left-handed or right-handed circularly polarized 1083 nm laser light, as described in Ref. [9].

At high magnetic fields, the f_4 and f_2 transitions are distinctly separated from other lines [13]. By scanning the probe laser frequency, two specific 2^3S sublevels can be monitored, providing a measure of ground-state polarization. A separate pair of well-resolved transition lines (the probe doublet) is employed for optical polarimetry, ensuring that the 2^3S_1 sublevels are not addressed by the pumping lines. Although these lines appear faint in the spectrum, they are clearly resolved by the probe laser, minimizing interference with the substantial population shifts caused by the pumping laser. An absolute measure of the nuclear polarization M of the ground states can be determined from the change in the ratio $r = \frac{a_2}{a_1}$, where a_1 and a_2 are the absorption signal amplitudes for these sublevels and r_0 is their ratio when pump laser is off. They satisfy the relation

$$\frac{a_2/a_1}{a_2{}^0/a_1{}^0} = \frac{1+M}{1-M}, \tag{1}$$

which yields the nuclear polarization as

$$M = \frac{\frac{r}{r_0} - 1}{\frac{r}{r_0} + 1}. \tag{2}$$

2. Apparatus setup

Tests of metastability exchange optical pumping (MEOP) at magnetic fields up to 5 T were conducted at Jefferson Lab using a superconducting solenoid magnet from the FROST experiment.

Figure 1 illustrates the schematic layout of the experimental setup for MEOP. The ^{3}He gas cell (see figure 2) and all optical components are housed within a laser-tight rectangular enclosure measuring 59 cm in length, 43 cm in width, and 33 cm in height, featuring a cylindrical extension that is 62 cm long and 10 cm in diameter. High-field MEOP experiments typically require superconducting

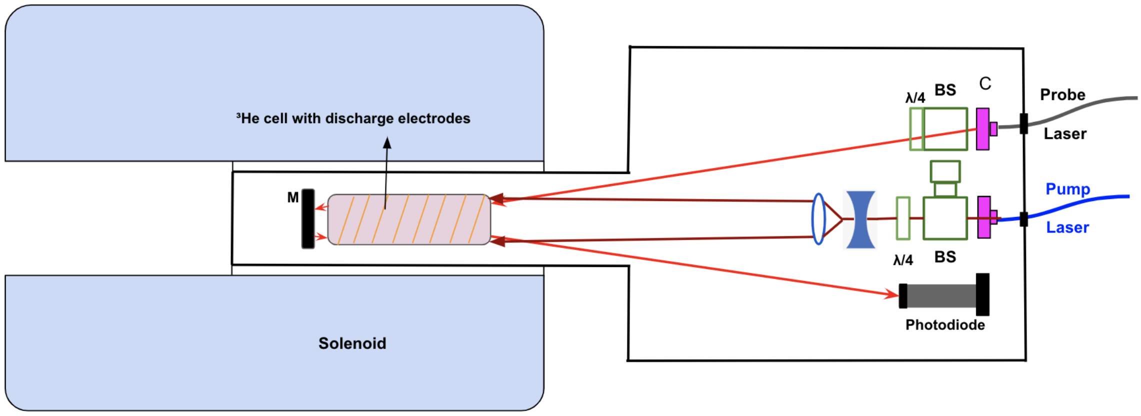

Figure 1: The schematic of the experimental apparatus details the configuration of the optical pumping system and probe polarimeter. Key optical components include a rotatable fiber collimator (R), a polarizing beamsplitter cube (B), a quarter-wave plate ($\lambda/4$), a lens (L), a fiber collimator paired with an iris diaphragm (I), and a mirror (M).

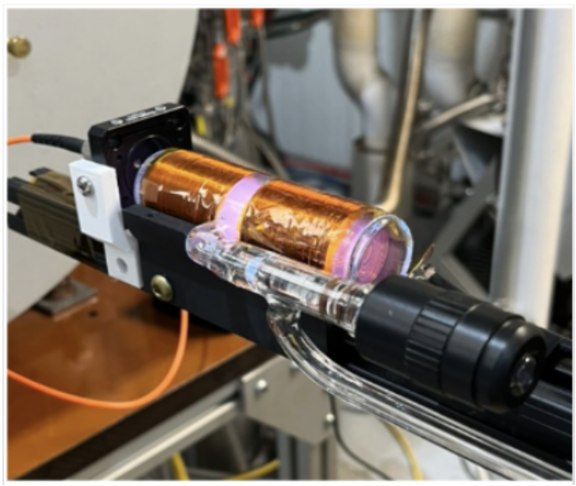

Figure 2: Fillable cell wrapped around with inductive coil RF electrode.

magnets to create stable, high magnetic fields (2 - 5 T). These magnets need to operate at cryogenic temperatures (often around 4 K) and are usually cooled with liquid helium. By capturing helium boil-off and re-liquefying it through advanced cryo-cooler technologies, such as pulse tube cryo-coolers, the liquefier ensures a continuous supply of liquid helium, significantly reducing helium consumption and operational costs.

The setup consists of two main components: **(i) the optical pumping system**, which includes the magnetic field, the ^{3}He gas cell, RF electrodes for discharge plasma generation in ^{3}He gas, and the pump laser with its optics; and (ii) **the optical polarimeter**, comprising the probe laser, a mirror, and a photodiode.

2.1 Pumping laser

A continuous-wave Ytterbium-fiber laser delivers 1083 nm pumping light at power levels of up to 10 W, featuring a nominal linewidth of 2 GHz and the capability to tune the wavelength over a range of 100 GHz. For better broadening of the signal to accommodate the peaks with better visibility, we used an Azurlight pumping laser system. There are three modules in the Azurlight pumping laser system, a low-power seed laser, a broadener to expand the laser line wavelength to cover our pumping lines, and an amplifier to increase the power of the broadened laser light to anywhere from 0.1 to 10 W. The broadener is an optional component sold with our system to optimize it for MEOP pumping. The seed laser and amplifier share 1 power supply, and the broadener has a separate one. A polarization-maintaining optical fiber channels the light to a polarizing cube, which guarantees complete linear polarization. Following this, a zero-order $\lambda/4$ wave plate converts the linear polarization into circular polarization. The pump light is subsequently expanded and collimated to uniformly illuminate the entire gas cell volume.

2.2 Fillable cell

The fillable cell used for this work is a cylindrical borosilicate glass, and has an outer diameter of 31 mm and a length of 10.1 cm. The cell was produced by a glass blower company through a series of steps, including repeated baking under a vacuum, and purging with clean ^{4}He gas. The cleanliness of the cell and the purity of the gas can be monitored at various stages of the process by alternately observing the spectrum of light emitted during a plasma discharge for the expected helium lines and used getter to pump out mostly hydrogen. The getter, which is also a pump, was activated first time at 400°C for ~ 45 minutes with set point 4 A, which corresponds to 16 W power. The getter must be reactivated every time we see impurities in the ^{3}He spectrum, at 350°C for ~ 30 minutes, until it reaches the 9 W power limit. The ^{3}He glass cell has a transfer valve that can be opened to fill up the ^{3}He gas pressure that we wanted and close it for operation, see figure 2. It is positioned at the end of the cylindrical volume, and inserted into the warm bore of a superconducting magnet. For the polarization tests, the superconducting magnet generates a uniform magnetic field of up to 5 T in the central region of its warm bore, which measures 76 cm in length and 13 cm in diameter. A plasma discharge through radio frequency voltage applied to electrodes on the outside of the cell is induced to create metastable populations in the gas. As the magnetic field strength rises, the charged plasma becomes more concentrated around the edges of the cell and less dense toward the center. An SRS generator produces an RF signal which is amplified using an RF amplifier, which is tuned with a radio transformer before being sent to the electrodes of the cell. The discharge amplitude is modulated from a signal generator and is taken as a reference by the lock-in amplifier. The output from the lock-in amplifier is read using Python software where the measured spectrum for the probe doublet is fitted.

2.3 Probe laser and fitting software

The probe laser light is supplied by a Toptica laser system (DFB pro L-33508) that operates within a tunable wavelength range of 1080.6–1084.2 nm, providing an output power of 70 mW. The laser frequency is controlled by adjusting the diode's temperature or operating current. Scanning the diode temperature covers the full frequency range, capturing an absorption spectrum that includes all relevant pump and probe peaks. To suppress undesired absorption peaks and ensure a clean

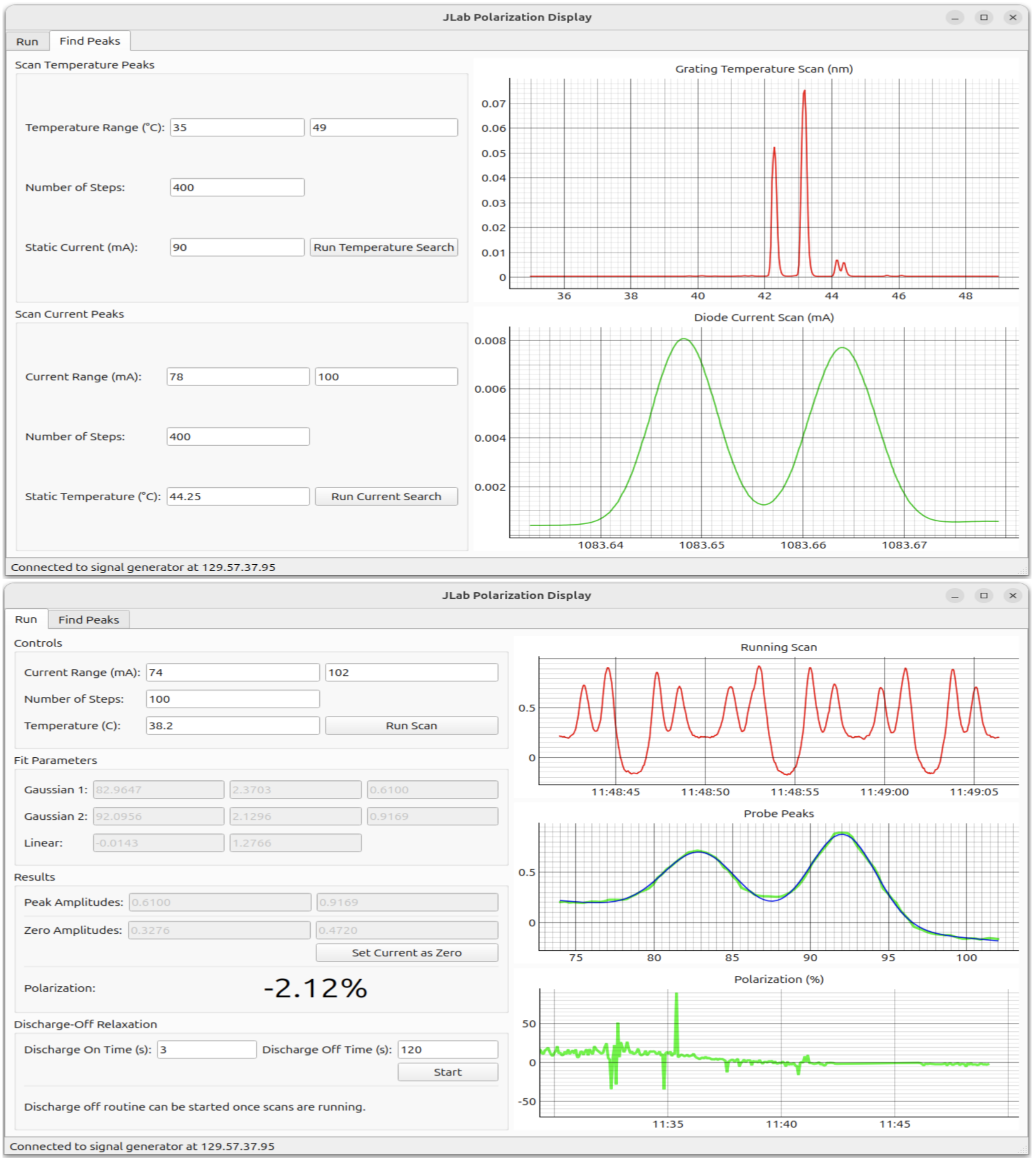

Figure 3: Top: Absorption spectrum showing the key pump and probe peaks (red). Scanning over a narrower frequency range to map the two absorption probe peaks (green). Bottom: The lineshape fit includes two adjacent Gaussian peaks, combined with a linear function to account for background from the pump laser light and the gradual variation in probe laser power due to frequency sweeps.

polarization signal, we made slight modifications to the polarimeter design in [15], including the addition of a $\lambda/4$ waveplate paired with a beam splitter (BS) cube to select either the σ^+ or σ^- components based on the quarter waveplate's orientation, see figure 1. After tuning, the current is adjusted over a narrower frequency range to map the two probe absorption peaks (see figure 3 top) [13]. The lineshape fit incorporates two adjacent Gaussian peaks, overlaid on a linear function to account for any background from the pump laser light and the gradual change in probe laser power resulting from frequency sweeps (see figure 3 bottom). The absorption signal amplitudes a_1 and a_2 for the two probe peaks are extracted as the fitted amplitudes of the two Gaussian functions. Calibration is performed by recording the unpolarized peak amplitudes, ${a_1}^0$ and ${a_2}^0$, before activating the pump laser to calculate the nuclear polarization using Eq. 2.

3. Results

Figure 4 shows the measurement cycle of optical pumping at 1 mbar fillable cell pressure, using the ${f_4}^-$ scheme and discharge-on relaxation at 2 T. Solid curves represent fits to the optical pumping and relaxation data. The pump laser is activated at 80 s, initiating the exponential build-up

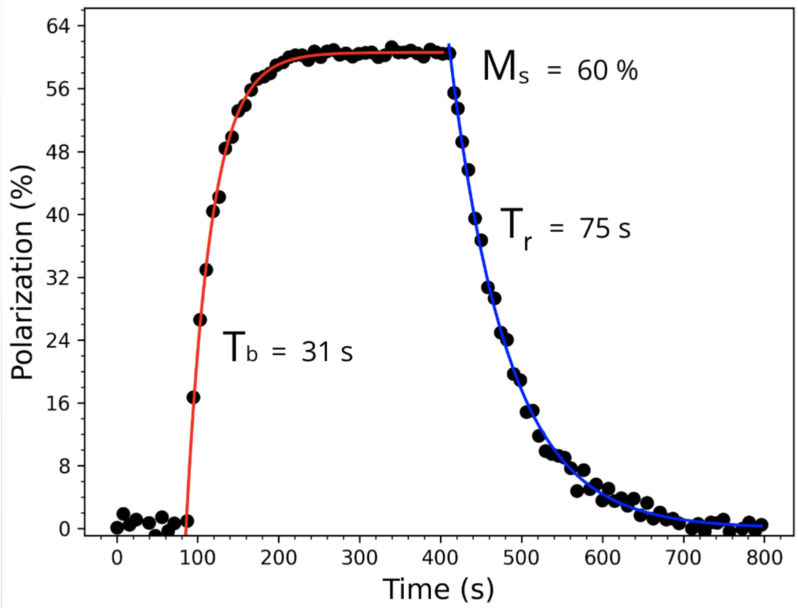

Figure 4: Typical cycle of optical pumping and relaxation at 2 T, illustrating the exponential build-up time T_b during active pumping and the relaxation time T_r after the pump laser is blocked at 430 s.

of ^{3}He nuclear polarization over time.

$$M(t) = M_s(1 - e^{\frac{-t}{T_b}}), \tag{3}$$

where M_s denotes the steady-state polarization, and T_b represents the build-up time constant. The pump laser is turned off at 430 s, and relaxation time T_r is determined as the exponential decay constant from data beyond this point. Measurements of M_s, T_b, and T_r were conducted across magnetic fields of 2, 3, 4, and 5 T to examine the influence of discharge intensity, pump laser power, and various optical pumping transition schemes on high-field MEOP performance.

3.1 Field variance

Figure 5 shows the maximum steady-state polarization achieved with the three different optical pumping transition schemes at magnetic field of 2 to 5 T, at a pressure of 0.6 mbar. The results for all four magnetic fields consistently show that the $f_4^{\pm}$ schemes yield considerably higher nuclear polarization than the f_2^{-} scheme. The full results, including the extracted pumping rate and relaxation time, are presented in Table 1.

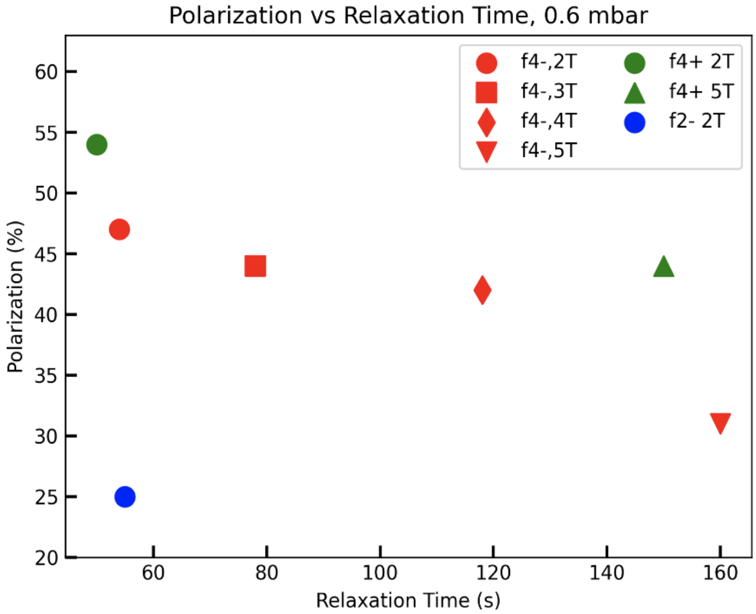

Figure 5: Maximum steady-state nuclear polarization measured with various discharge intensity levels (characterized by the relaxation time) at 2 T (circles), 3 T (squares), 4 T (diamond), and 5 T (triangles), using different pumping schemes and a pump laser output power of 3W.

3.2 Pressure Variance

Figure 6 shows the maximum polarization achieved with f_4^{-} peak at 2 T magnetic field, at cell pressures of 0.6, 1, 50, and 60 mbar. At lower pressures, we observed considerable polarization at the preliminary test stage for fillable cell. At higher pressure, on top of a higher field (2 T is much higher as compared to a few gausses pressure), the discharge gets pushed towards the edge of the cell, which makes the probe beam's absorption minimal, giving us low polarization. Hence, the configuration of the optical setup has to be changed to obtain a better match between metastable atoms and the laser path, as in figure 7. This requires an addition of a pair of axicons which mainly changes the Gaussian beam into the annular form, and hence the pump laser can align with the discharge at the edge of the cell. In addition to that, 3 mirrors M1, M2, and M3 have to be added for the probe laser path to ensure optimal absorption.

4. Double Cell Target

The goal of our investigation into ^{3}He MEOP performance at high magnetic field is the creation of a polarized ^{3}He target for the CLAS12 detector, located in Hall B at JLab. In electron scattering experiments, attaining high luminosity requires a ^{3}He gas target with a substantial polarization and number density product. In Hall A spectrometers, with minimal constraints on magnetic

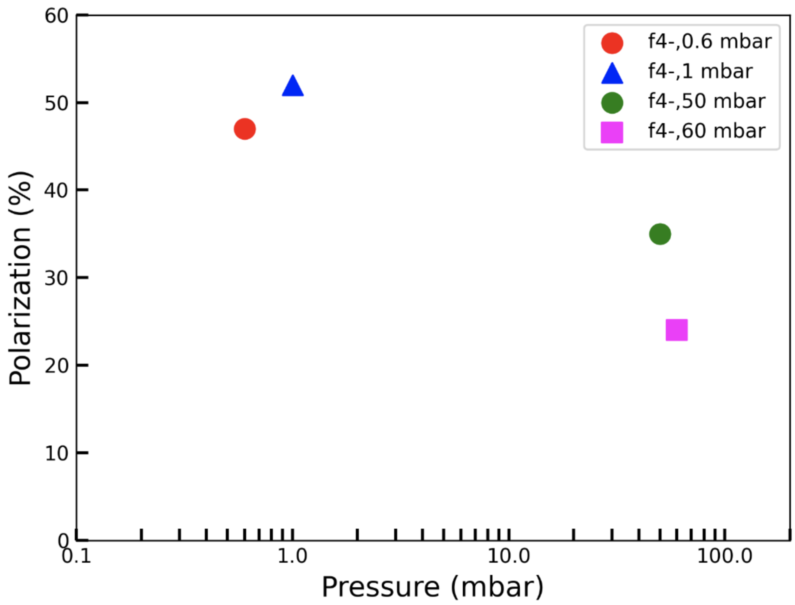

Figure 6: Maximum steady-state nuclear polarization was measured at 2T for different cell pressures: 0.6 mbar (red circle), 1 mbar (blue triangle), 50 mbar (green circle), and 60 mbar (magenta square). The measurements were performed using the f4⁻ pumping peak for comparison.

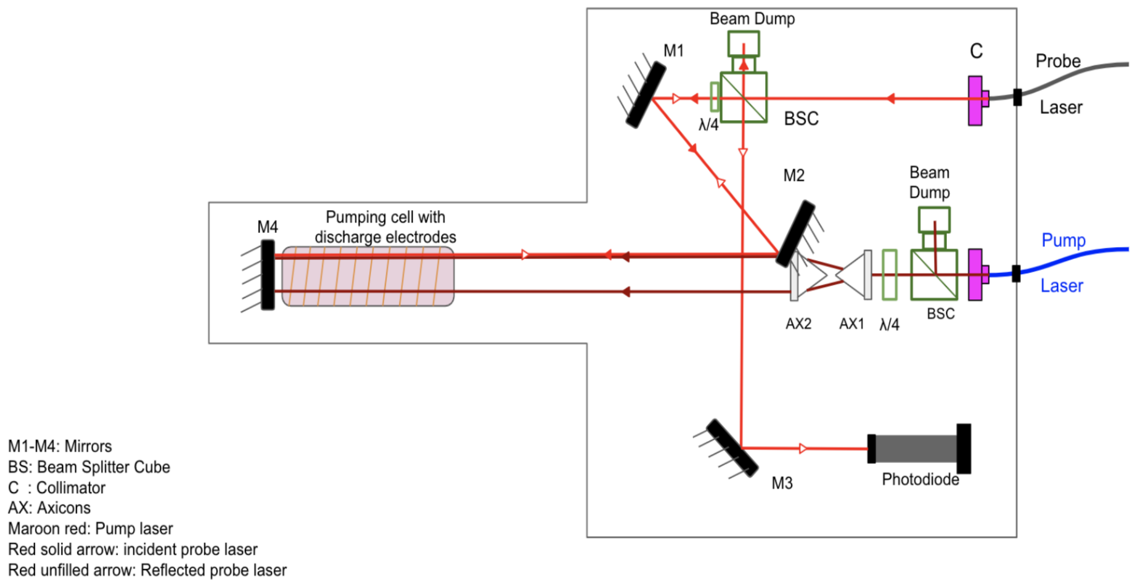

Figure 7: The optical setup for polarization tests at high cell pressure includes a pair of axicons positioned along the pump laser path to reshape the Gaussian beam into a ring, ensuring the beam profile aligns with the discharge distribution. On the probe laser path, three mirrors are incorporated. The probe laser first passes through a beam-splitter (BSC), then through a quarter-wave plate ($\lambda/4$), and strikes mirror M1. M1 reflects the beam towards M2, and from M2, it is directed to M4. The beam reflected from M4 returns to M2, which then reflects it to M1. The beam then travels to the BSC, reflects off it to M3, and finally reaches the photodiode.

Table 1: Steady-state nuclear polarization (M_s), build-up time (T_b), and discharge-on relaxation time (T_r) measured at 2, 3, 4, and 5 T using three optical pumping schemes.

Field (T)	Transition Scheme	M_s (%)	T_b	T_r
0.6 mbar				
2	f_4^-	47%	30	54
2	f_4^+	54%	31	50
2	f_2^-	25%	-	55
3	f_4^-	44%	62	78
4	f_4^-	42%	92	118
5	f_4^-	31%	134	160
5	f_4^+	44%	120	150
1 mbar				
2	f_4^-	52%	-	70
2	f_4^+	60%	25	62
2	f_2^-	36%	-	65
50 mbar				
2	f_4^-	35%	-	-
60 mbar				
2	f_4^-	24%	127	163
2	f_4^+	20%	136	234
3	f_4^-	20%	112	328

field conditions, Spin Exchange Optical Pumping (SEOP) has proven effective for generating high-density cells under low magnetic fields. In contrast, with the central solenoid of the CLAS12 detector possessing a 5 Tesla magnetic field, conventional SEOP methods become unfeasible. However, high-field MEOP can function under these conditions, despite the constraint that the conventional MEOP cell operates at a standard pressure of 1 Torr or 1.3 mBar, which is 10^4 times lower than the usual SEOP cell deployed at JLab. Even with the innovation of a high-pressure MEOP cell at 100 mBar, the pressure remains 100 times lower. Therefore, we will implement a cryogenically cooled double-cell configuration, which aims to increase the density of the target cell. This is achieved by transferring polarized ^{3}He gas from a cell at room temperature into a target cell maintained at temperatures below 5 K. This approach results in a condensation of the density ^{3}He approximately 100 times, providing a polarization-number density product comparable to the SEOP method.

4.1 Double Cell Design

The design of the double cell is influenced by the cells implemented in the MIT-Bates 88-02 experiment [8], where a Pyrex pumping cell maintained at 2.6 mbar and ambient temperature was positioned above a copper target cell. This copper cell was chilled to 20 K to enable a polarized gas target with a density increased by a factor of 15. Leveraging advancements in high-field MEOP polarization techniques, we intend to employ a pumping cell at a higher pressure of 100 mbar polarized at 5 Tesla, yielding nearly a 250-fold improvement compared to the BATES cell. For an in-depth comparison between our proposed cell and the BATES experiment, see [14].

Figure 8 presents an initial illustration of the double cell system inspired by the concept introduced in [14]. Constructed from aluminum, the target cell is cooled by the Hall B Cryotarget to temperatures under 5 K. A glass-metal transition is necessary to connect the Pyrex pumping cell with the target cell.

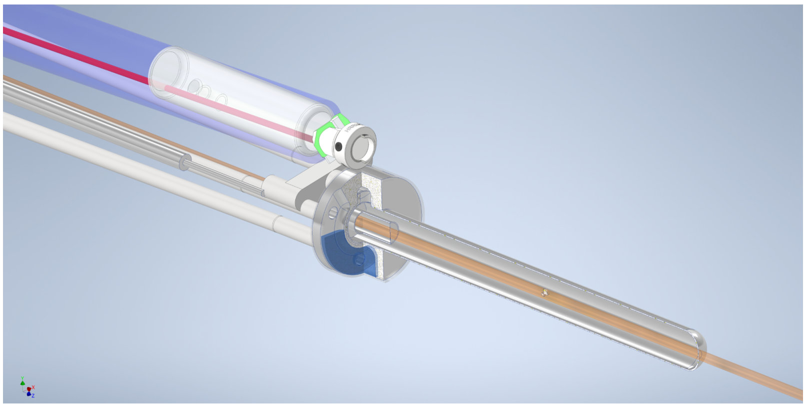

Figure 8: Preliminary 3-D CAD drawing of the double cell target mounted at the end of Hall-B Cryotarget Module. Polarized ^{3}He in the glass pumping cell (off-beam line) is diffusely transferred to the aluminum target cell.

4.2 Relaxation in Double Cell System

The primary factors influencing the efficiency of the target include ^{3}He polarization relaxation caused by wall relaxation from the metal cell, magnetic field gradients in the target and pumping cell areas, and depolarization from electron beams. The relaxation effect due to the metal wall was thoroughly examined in [18], demonstrating that a molecular H_2 coating can result in a relaxation time exceeding 1000 minutes. Given that T_1 is also highly sensitive to transverse B-field gradients, we propose situating the target cell in a region of extremely high uniformity, while maintaining the pumping cell in an area with a substantially large T_1. We intend to evaluate the depolarization effect from the beam before commissioning the target.

5. Conclusions

We report on the second series of tests conducted at JLab on MEOP for polarized ^{3}He in high magnetic fields. These experiments have identified the optimal optical pumping strategies for different cell pressures and magnetic fields using a fillable cell.

6. Acknowledgments

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