PROCEEDINGS OF SCIENCE

A High-Magnetic-Field Polarized ^{3}He Target for the CLAS12 Spectrometer

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We are developing a polarized ^{3}He target for use in high luminosity electron scattering experiments within the high magnetic field environment of Jefferson Lab's CLAS12 spectrometer. By combining recent advancements in metastability exchange optical pumping (MEOP) of ^{3}He with cryogenic, double-cell target methods as used for the MIT-Bates 88-02 experiment, a target with polarization and gas density comparable to traditional, low-field polarized ^{3}He targets can be reached within high magnetic field environments. We have begun polarizing sealed ^{3}He cells at fields up to 5 T at Jefferson Lab, and are preparing for our first tests exploring polarization performance versus magnetic field and gas pressure in a single cell before we move to the construction of a full, cryogenic, double-cell prototype target. A key focus of our research is the determination of polarization relaxation under the irradiation of an ionizing particle beam within high magnetic fields.

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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 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 14 experiments at Jefferson Lab over the past three decades, with 6 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], and this has precluded 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 density over 20 times.

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 ENS Paris has shown that by increasing the holding field beyond 1 T, MEOP efficiency was greatly improved at higher gas pressures [6, 7]. Figure 1 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 ability to polarize within high fields is already being applied for a polarized ^{3}He ion source for the Electron Ion Collider [8, 9].

2. Proposed Target Design

Combining double-cell cryogenic target techniques with the pressure increases allowed by MEOP at high magnetic fields will make possible a new type of polarized target for high luminosity scattering experiments [10]. 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

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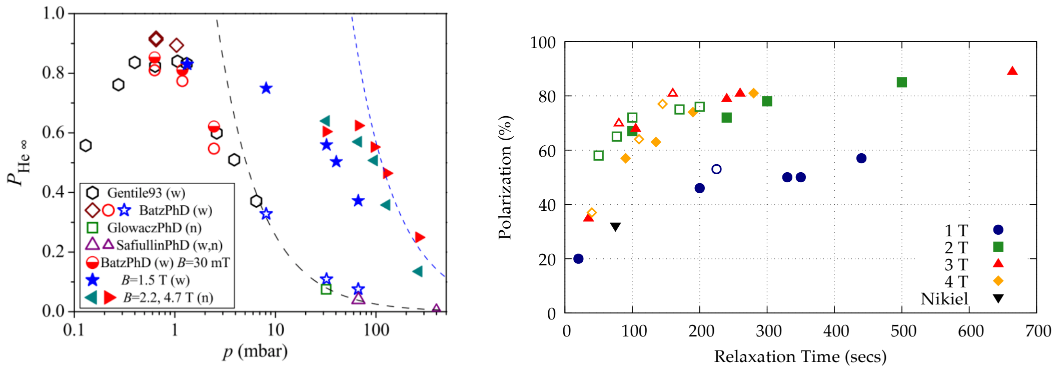

Figure 1: At left, the variation with pressure of highest steady-state polarizations achieved by various groups at low fields (open symbols, 1 to 3 mT) and high fields (filled symbols, see the legend) from [1]. At right, polarization achieved versus relaxation time (adjusted via discharge intensity) at various fields in 1.3 mbar sealed cells from [9], with one point at 4.7 T from [7].

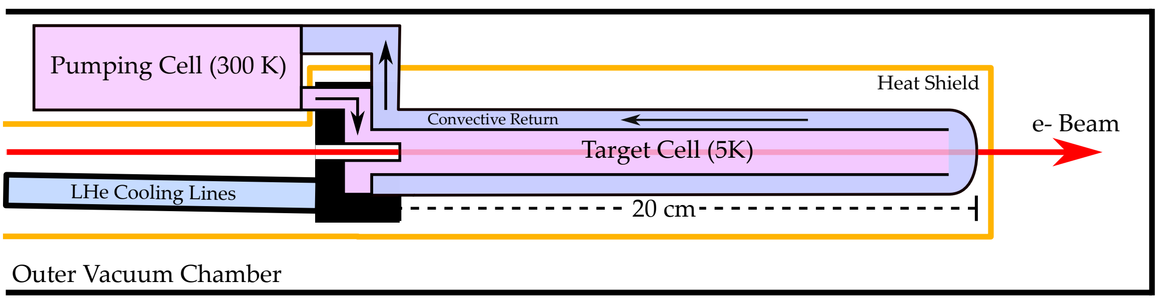

Figure 2: Schematic layout of the two-cell polarized ^{3}He target concept for CLAS12.

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 [11] in Hall B.

As shown in Figure 2 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.

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

The high field performance of MEOP polarization has been demonstrated at ENS, which means the focus of our study will be understanding and reducing depolarizing effects in our application. The main sources of polarization relaxation are expected to be wall interactions, transverse magnetic field gradients, and ionization in the beam. To avoid depolarization on the aluminum target cell walls, all metal surface will be kept cold to allow a coating of cryogenic H_2, which has been shown to yield days long relaxation times between 2 and 6 K [12]. The field within the CLAS12 solenoid has been analyzed to show that the transverse gradients will be acceptable in the region where the cells can reside [10].

Jefferson Lab's 12 GeV polarized electron beam will induce depolarization through the creation of molecular $^3He_2$ 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 from to diatomic molecules as the rotational angular momentum is decoupled from the total molecular-ion spin [13]. 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. Once a prototype target is built, we plan to take advantage of Jefferson Lab's injector test facilities to undertake this measurement.

3. Progress and Outlook

The first task in the development and design of a prototype is confirmation of the ENS results of polarization versus pressure and field, to determine the optimal conditions for our target. We have built a MEOP polarization stand at Jefferson Lab, seen in Figure 3, to begin this development. The laser path and gas cell are enclosed and interlocked to allow the system to be transported to a warm bore superconducting magnet for high field tests. The stand includes a 10 W pumping laser, 70 mW distributed-feedback probe laser, 25 W RF amplifier, laser wavelength meter, and lock-in amplifier to measure the probe laser absorption in the amplitude-modulated RF discharge via an amplified photodiode. To assess the operation of our pumping laser, we have performed initial low-field tests of MEOP polarization at 30 G, producing 70% in a sealed, 1.3 mbar ^{3}He cell.

The high magnetic field is provided by a 5-inch warm-bore superconducting solenoid, capable of reaching 5 T. To facilitate testing while avoiding delays and expense that come with liquid helium deliveries, we have adapted a Cryomech liquifier system to cool and maintain cryogens within the magnet's liquid reservoir. We have begun tests at high field to observe polarization performance at 2, 3 and 4 T in a 1.3 mbar sealed cell. While these tests proceed, we are preparing a valved pumping cell system to allow cleaning and filling with ^{3}He gas at varied pressure.

With tests of polarization versus field and pressure complete, we plan to take advantage of existing equipment to hasten the production of a proof-of-concept prototype. A pulse-tube cryocooler stand will be adapted to cool cryogens within a vacuum chamber extending inside the warm bore of our magnet. This vacuum chamber will be designed to permit the passage of an ionizing beam onto a prototype double-cell polarizer, which will be held in the magnet's uniform field region. We are aiming to have this system ready for in-beam tests in early 2024.

Figure 3: Photo of the polarization stand. The laser enclosure in black extends into the warm-bore of the superconducting solenoid to hold the pumping cell in the uniform field region.

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