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Polarized ^{3}He Target for JLab 12 GeV Era

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Since most of the ^{3}He spin is carried by the unpaired neutron, polarized ^{3}He targets have been widely used as a effective polarized neutron target in electron scattering experiments to study the spin structure of neutron. Over the past a couple of decades, polarized ^{3}He targets had been successfully utilized in thirteen electron scattering experiments during JLab 6 GeV era. At JLab, a technique called Spin-Exchange Optical Pumping (SEOP) is used to polarized the ^{3}He target. For the past decade, several developments including Rb-K hybrid alkali system and high power narrow line-width diode lasers were implemented to the polarized ^{3}He target in order to reach higher ^{3}He polarization with world record luminosity. As JLab completed 12 GeV upgrade in 2017, there are seven upcoming approved polarized ^{3}He target experiments. Upgrade of the target with convection cell and Pulse Nulear Magnetic Resonance (PNMR) polarimetry were completed for the first upcoming 12 GeV era experiment A_1^n (E12-06-110) with collaboration of d_2^n (E12-06-121) in JLab Hall C. For typical 10^{22}/cm^2 high-density target used in this collaboration experiments, the maximum polarization reached over 50% under 30 uA electron beam, thus the luminosity of 10^{36}/cm^2/s will be achieved.

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1. Introduction

Polarized targets has been widely used for experiments to study the nucleon inner structure. Since free neutron has short life time of 880.2 seconds [1]. There is no free neutron target for electron scattering experiments. The ground state of ^{3}He nucleus wave function is dominated by the S-state which the two proton spins cancel and the nuclear spin resides entirely on the single unpaired neutron [2]. Thus the unpaired neutron carries the majority of the ^{3}He nucleus polarization, and we could use polarized ^{3}He as the effective neutron target to study the neutron spin structure.

In order to polarize the high-density ^{3}He gas in target cell to reach high luminosity, we use the technique called Spin Exchange Optical Pumping (SEOP) [3]. With external B field, we polarize vaporized Rb atoms using circularly polarized laser and the alkali atoms can reach up to 95% polarization [3]. Then polarized Rb atoms transfer its polarization to ^{3}He nucleus by spin-exchange process which is dominated by binary collisions [3].

Over the past a couple of decades, polarized ^{3}He targets had been successfully utilized at SALC and utilized in thirteen electron scattering experiments during JLab 6 GeV era [4]. The performance of ^{3}He target cell was improved through out experiments. One of the improvements was the usage of hybrid alkali with addition of K [5]. This technique increased the efficiency of spin exchange. Another major improvements was the usage of high power and narrow bend diode lasers (COMET) instead of broad-width diode lasers (Coherent) [6]. The usage of narrow bend laser modules further increased optical pumping efficiency. With above improvements, the typical 10^{22}/cm^2 high-density target reached 60% polarization under 15 uA electron beam and achieved world record luminosity of 10^{36}/cm^2/s [4].

2. Target cell upgrade for 12 GeV Era

2.1 Convection Cell

For approved JLab 12 GeV Era experiments, Gordon's group at UVa finished the design and test of convection cell, see Figure 1 [7]. For upcoming A_1^n/d_2^n experiments, the desired luminosity is 10^{36}/cm^2/s where the 10^{22}/cm^2 high-density target cell reach over 50% polarization under 30 uA beam. Figure 2 shows the how the convection cell is installed in Hall C. The convection is needed to reduce the ^{3}He polarization gradient between pumping chamber and target chamber. For diffusion cell, the polarization gradient is about 5%-10%; while convection cell can reduce polarization gradient to 1% [8]. As shown in Figure 3, convection condition is established by adding a convection Kapton heater (polyimide film) on one of the transfer tube. By sending radio-frequency (RF) signal with Larmor frequency at PNMR Coil, we create depolarization at 1-inch sphere region. Then we could measure the depolarization dip of NMR-AFP signal amplitude through out the target chamber with upstream and down stream NMR pick-up coils. As shown in Figure 4, with known distance between upstream and down stream NMR pick-up coils, we could estimate the convection speed from the dip time difference for upstream pick-up coils and downstream pick-up coils. Under normal convection condition, the typical convection speed along the target chamber is around 5 cm/min.

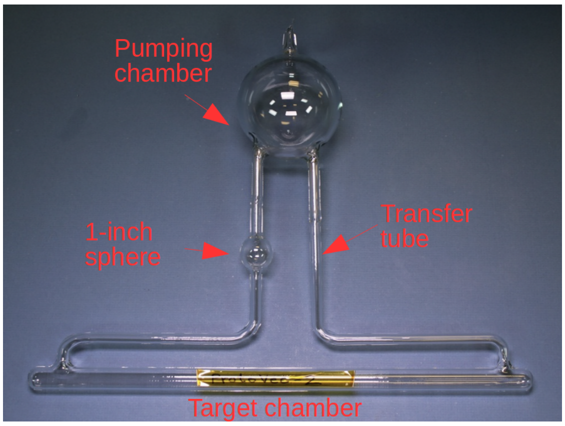


Figure 1: The convection design of polarized ^{3}He target cell.

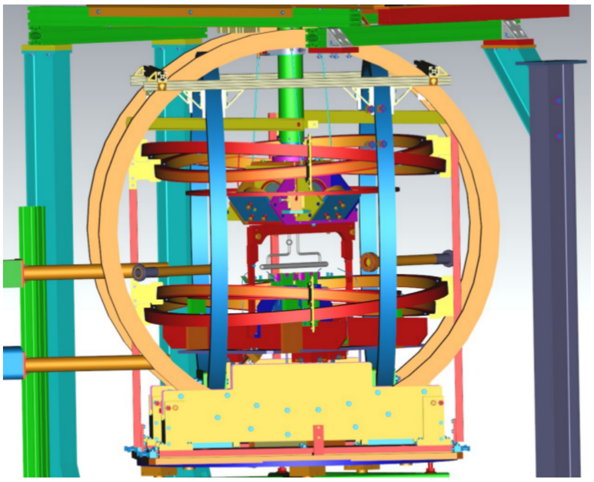


Figure 2: The mechanical design of polarized ^{3}He target cell installed in JLab Hall C.

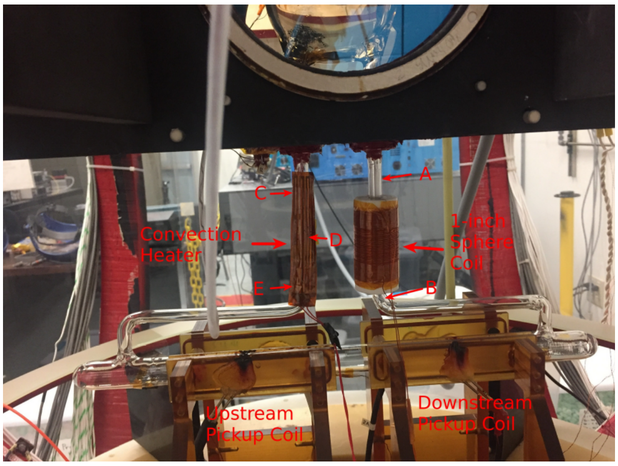


Figure 3: Convection cell setup for convection speed test. Convection flow direction is from down stream to upstream with transfer tube temperature gradient ~+30 °C between point C and point A.

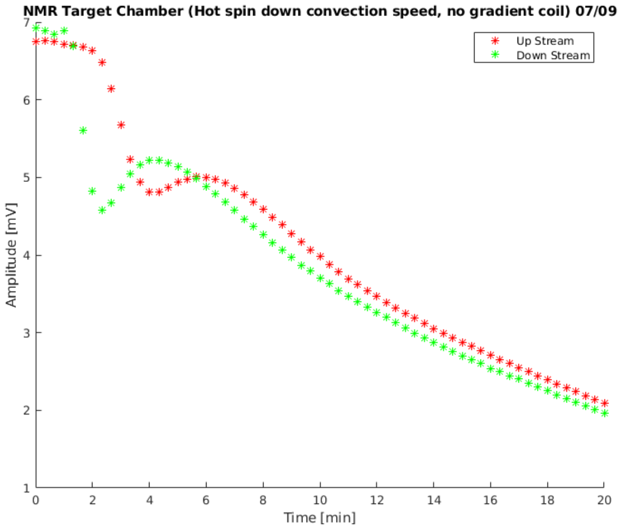


Figure 4: Convection speed test results. The green curve is target chamber downstream NMR signal amplitude, while the red curve is target chamber upstream NMR signal amplitude. The measured convection speed is ~5 cm/min.

2.2 PNMR Polarimetry

For JLab 6 GeV era experiments, Adiabatic Fast Passage Nuclear Magnetic Resonance (AFP-NMR) and Electron Paramagnetic Resonance (EPR) were developed to measured the ^{3}He polarization inside the target chamber. The absolute EPR measurement at pumping chamber was used to provide the calibration constant for the relative AFP-NMR measurement at target chamber to obtain the ^{3}He polarization. For JLab 12 GeV Upgrade, while keeping using AFP-NMR and EPR for target cell polarimetry, we developed the Pulse NMR (PNMR) system which will be a new polarimetry for polarized ^{3}He target cell. A PNMR measurement is preformed by sending a RF pulse at Larmor frequency of ^{3}He to the PNMR coil. This RF pulse will create a RF magnetic field at PNMR coil with amplitude H_1 orthogonal to the holding field axis. Thus the RF pulse will tip the ^{3}He spin near the PNMR coil away from holding field axis [9]:

$$\theta_{tip} = \frac{1}{2} \gamma H_1 t_{pulse}$$

where γ is the gyro-magnetic ratio, and t_{pulse} is the duration of RF pulse. When RF pulse ends, the spin precesses back to its initial state and experience free induction decay (FID). This FID signal is picked up by the PNMR coil. The amplitude of FID signal envelope will measure the transverse component of magnetic moment proportional to ^{3}He polarization [9]:

$$S(t) \propto M_z \sin\theta_{tip} \cos(\omega t + \phi_0) e^{\left(\frac{-t}{T_2}\right)}$$

The newly developed PNMR has several advantages. First, a PNMR measurement will take shorter time to complete and will cause less depolarization compare to AFP-NMR. In addition, for future metallic end cells, since the metallic ends will attenuate RF signal at target chamber, PNMR will provide local polarimetry at transfer tube [8]. For the PNMR system R&D work, the former graduate students have developed a prototype PNMR with radio-frequency (RF) mixer and oscilloscope [8]. By replacing the RF mixer and oscilloscope with a lock-in amplifier and a fast DAQ card, I was able to finalized the PNMR system with smaller resolution uncertainty and better tracking of smaller PNMR signals, see Figure 5. At current stage, by calibrating PNMR signal amplitude with NMR peak height, I have reached measurement precision to about 3% as in Figure 6.

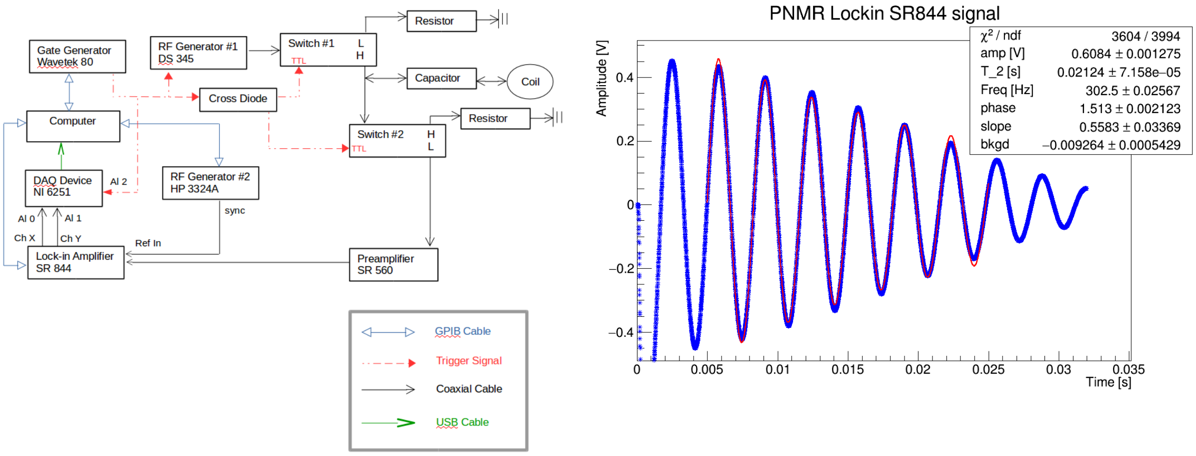


Figure 5: (left) PNMR system with Lock-in amplifier and fast DAQ card set up. (right) Typical PNMR FID signal.

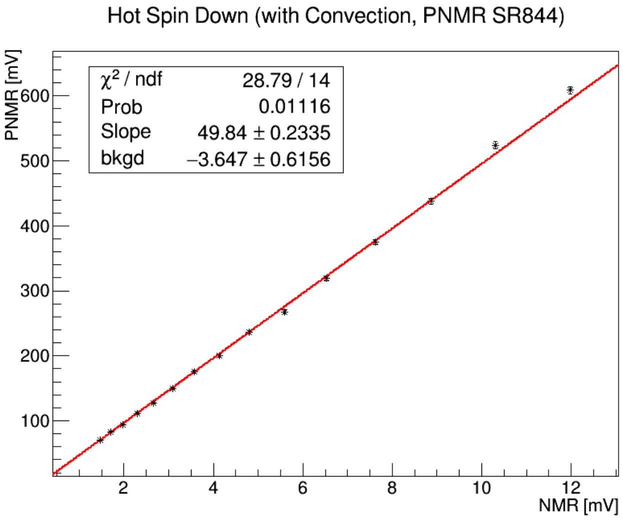


Figure 6: PNMR vs. NMR signal amplitude calibration with linear fit.

3. Typical Production Cell Performance

At JLab, we give names to all the polarized ^{3}He target cells in order to easily distinguish them. For example, cell “Fulla” is a typical cell that will be used for A_1^n/d_2^n experiments. At target lab, we characterize the cell performance by measuring the cell max polarization and life time, see Figure 7. Due to the limitations of current glass fractionation technique, different target cell are made with slightly different pumping chamber shape. Therefore, when we use target oven to heat up the pumping chamber, the amount of alkali vapor that will be released is different for different target cell. In another words, for different target cell the optimal SEOP condition is different. Thus fine tune of the oven temperature and incident laser power for each target cell is needed to ensure all the incident laser is absorbed by right amount of alkali vapor.

Under the optimal condition, the target cell is optically pumped to its maximum polarization. For tracking the spin up curve during SEOP, we used EPR to make absolute measurements of target polarization at pumping chamber. However, Masing effect (coupling of ^{3}He spin and pick-up coils) during EPR measurements reduced the max ^{3}He polarization. Here we waited for around 10 hours for no measurement and the next EPR gave max ^{3}He polarization for "Fulla" to be ~54%. As for target cell life time, it was measured by AFP-NMR during target cold spin down (oven was off). As shown in Figure 8, life time for cell "Fulla" is about 14 hours.

For A_1^n/d_2^n experiments, the production cells were fabricated and filled by Gordon's group at UVa, Professor Todd Averett at W&M also helped to fill some of the cells. Table 1 is a summary of all the production cell performance.

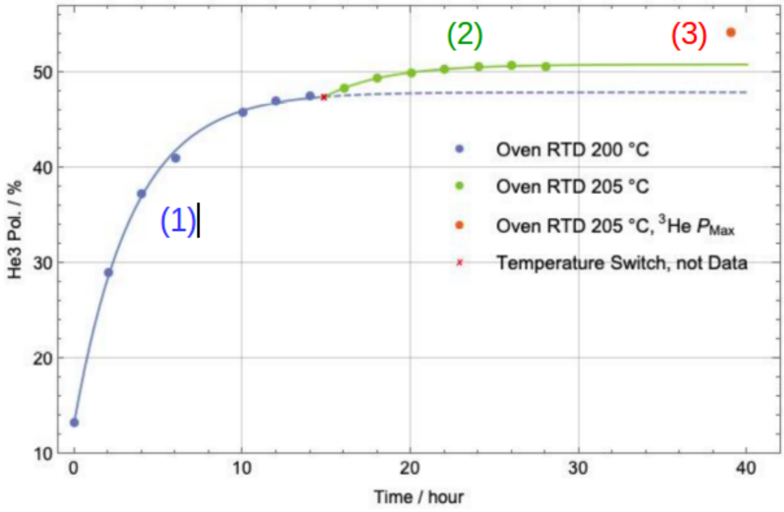
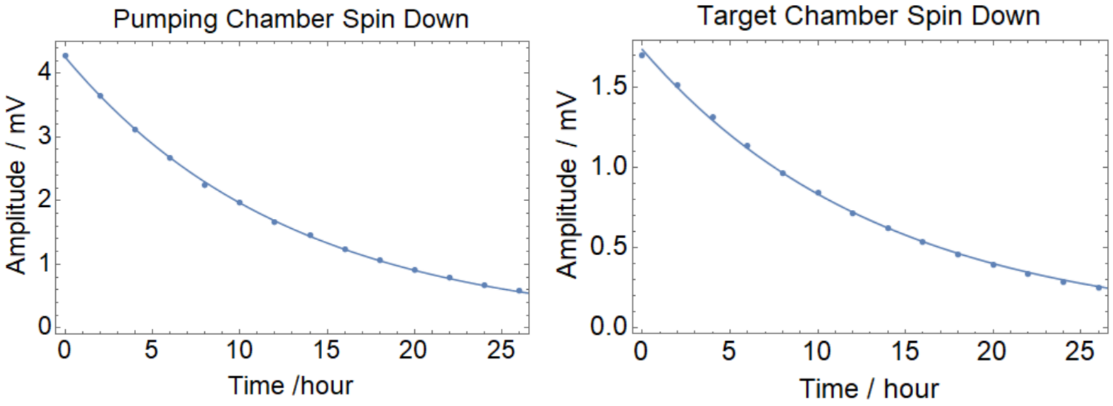
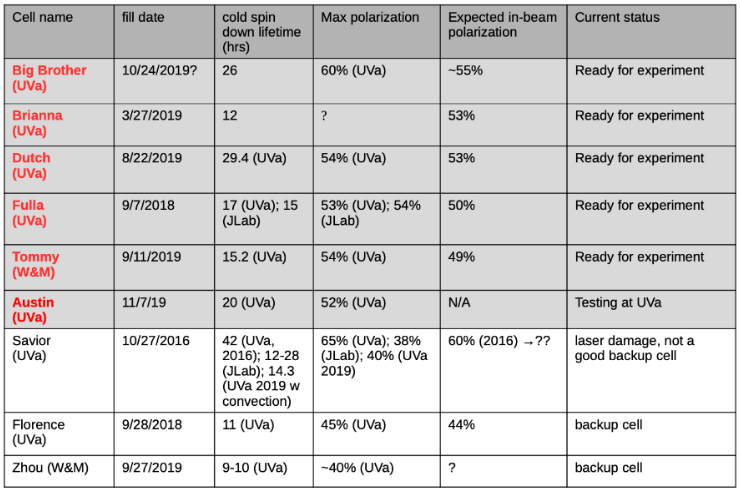


Figure 7: (1) EPR measurements of hot spin up curve at pumping chamber.
(2) Optimize the SEOP conditions to get higher ^{3}He polarization. (for laser power 90 W)
(3) Masing effect during EPR measurements reduce the max ^{3}He polarization. Wait ~10 hrs for no measurement and the next EPR gives max ^{3}He polarization for "Fulla" to be ~54%.



	Spin Down / h	AFP Loss per sweep
Pumping Chamber	14.23	0.8%
Target Chamber	13.92	0.13%

Figure 8: "Fulla" lifetime measurement by cold spin down AFP-NMR.



Cell name	fill date	cold spin down lifetime (hrs)	Max polarization	Expected in-beam polarization	Current status
Big Brother (UVa)	10/24/2019?	26	60% (UVa)	~55%	Ready for experiment
Brianna (UVa)	3/27/2019	12	?	53%	Ready for experiment
Dutch (UVa)	8/22/2019	29.4 (UVa)	54% (UVa)	53%	Ready for experiment
Fulla (UVa)	9/7/2018	17 (UVa); 15 (JLab)	53% (UVa); 54% (JLab)	50%	Ready for experiment
Tommy (W&M)	9/11/2019	15.2 (UVa)	54% (UVa)	49%	Ready for experiment
Austin (UVa)	11/7/19	20 (UVa)	52% (UVa)	N/A	Testing at UVa
Savior (UVa)	10/27/2016	42 (UVa, 2016); 12-28 (JLab); 14.3 (UVa 2019 w convection)	65% (UVa); 38% (JLab); 40% (UVa 2019)	60% (2016) → ??	laser damage, not a good backup cell
Florence (UVa)	9/28/2018	11 (UVa)	45% (UVa)	44%	backup cell
Zhou (W&M)	9/27/2019	9-10 (UVa)	~40% (UVa)	?	backup cell

Table 1: Current Production Cells Performance. Production cells are fabricated and filled by Gordon's group at UVa. Professor Todd Averett at W&M helped to fill some of the cells.

4. Summary

During JLab 6 GeV era, the polarized ^{3}He target system was successfully implemented in to multiple electron scattering experiments with world-record luminosity. As JLab upgraded to 12 GeV, the upgrades of convection cell and Pulse Nulear Magnetic Resonance polarimetry were done and the target system is ready for the upcoming A_1^n/d_2^n collaboration experiments in Hall C which were started in November, 2019 and they will keep running until May, 2020.

References

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