Electrical heating for SEOP-based polarized $^3\text{He}$ system

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Abstract. Development of neutron spin filters based on polarized $^3\text{He}$ is underway at Spallation Neutron Source (SNS). We report the progress of electrical heating tests in polarized $^3\text{He}$ based on Spin-Exchange Optical Pumping (SEOP) method. We first test the system performance based on electrical heating via non-inductance heating pads. We observe a contribution of 955 hours to the relaxation time $T_1$ from the heating pads. We then test the electrical heating SEOP pumping system at the SNS beamline Magnetic Reflectometer. We currently obtain 73% $^3\text{He}$ polarization in a cell with 820 cm$^3$ in volume.

1. Introduction

Polarized $^3\text{He}$ neutron spin filters have been used both as neutron polarizers and polarization analyzers in various polarized neutron scattering experiments [1, 2]. We have been developing the use of $^3\text{He}$ based on the Spin-Exchange Optical Pumping (SEOP) method [3]. During the SEOP pumping process, the gaseous $^3\text{He}$ cell is heated between 160$^\circ$C to 210$^\circ$C in order to create enough alkali vapor pressure for the spin-exchange process. The conventional way to heat the oven which contains the $^3\text{He}$ cell is to blow hot air in through silicone, teflon or copper tubes. This is simple to implement in an offline SEOP setup. However, constraints of space, heating, cooling and noise at a neutron scattering instrument make it cumbersome to use a hot air oven for in situ polarized $^3\text{He}$ based polarizers and analyzers [4]. To solve the problem we propose a new approach of heating source – none-inductive electrical heater pads. The heating pads are resistive heaters made of a printed circuit where the current path is laid out to enclose only a very small area, which might interfere with all the coils that are wound around the cell.

Our tests focused on comparing the system performance of using non-inductive electrical heating pads to hot air in the same oven in our laboratory based $^3\text{He}$ polarizing system. We find that both methods can reach the same range of temperature in the oven. Using the free induction decay (FID) nuclear magnetic resonance (NMR) method to monitor the $^3\text{He}$ polarization, we found a small but acceptable reduction of the $^3\text{He}$ polarization relaxation time $T_1$ with the heating pads energized. There exists little change of the final polarization that the cell can reach under both situations, which is insignificant. We also measure the impact of the heater pads toward using adiabatic fast passage (AFP) method to flip the $^3\text{He}$ polarization and find little interference. Another test is also carried out in our in situ $^3\text{He}$ polarizing system to find
out its polarizing ability. The system with heating pads installed successfully polarize $^3$He to 73%. We will report the details of these tests.

2. Laboratory based test

![Figure 1](image1.png)

(a) The frame  
(b) The oven

**Figure 1.** (a), The lab based SEOP system, laser optics excluded; (b), $^3$He cell sits on teflon stands which are placed in the oven. Two heating pads wrap around the oven wall to provide uniform heating.

The laboratory based $^3$He polarizing system with the oven is shown in Fig. 1. The system sits on an 80-20 frame. A pair of Helmholtz coils of 16” apart provide a field of 13.5 G at the center of the coils. A teflon based oven is placed at the center of the coils. The oven wall is 2” thick of teflon, two double-sided sapphire window are placed on each side for better heat insulation. The $^3$He cell, Bordeaux, is a hybrid cell containing gaseous $^3$He, rubidium and potassium, is made at National Institute of Standards and Technology (NIST). Two pieces of Mica heating pads [5] are curved and placed inside the oven 5 cm far from the cell to provide a uniform heating to the oven. Both heating pads have the same dimension of 4” x 6” and each of them have a resistance of 12.6 Ohms. An Agilent power supply sends in about 200 W power to the heating pads which heats up the cell to 190°C. Optical pumping is then performed by a 150 W diode laser shining from one side of the oven. One should be aware that the heating from Laser is comparable to the heating pads. In our setup the laser can heat the cell up to 90°C. A 150-turn 18 AWG coil is placed at the top of the $^3$He cell for FID polarization measurement. Because this test is carried out in the lab, the FID signal, which is proportional to $^3$He polarization, is our only monitor for $^3$He polarization.

The cell is first polarized till its polarization saturates. The measured pump up time constant is about 33 hours. Then we turn off the laser and monitor the FID signal continuously to extract the $^3$He polarization relaxation time $T_1$. We first get the data for the normal condition, by turning off the heating pads. We haven’t started to take data until the oven reaches room temperature due to the fact that the relaxation contribution from the rubidium vapor is too high and high temperature. Also, the FID signals change by temperature, which may bring systematic errors to our result. After we gather all the relaxation FID signals, we fit the data using Eq. (1).

$$P(t) = P_0exp(-t/T_1) \tag{1}$$

where $P(t)$ is the $^3$He polarization at time $t$ from the start time, $P_0$ is the initial $^3$He polarization from the start time, and $T_1$ is the relaxation time.
After the $T_1$ is determined, we re-pump the cell till its polarization saturates. Then we measure the cell relaxation data while the heating pads are on. In order to provide the same temperature condition as when we turn off the heating pads, we blow 80 PSI compressed air into the oven to cool it down to the room temperature. We then fit the data to get a second $T_1$. Both fits are plotted in Fig. 2. Although the cell orientation is not changed for the re-pump process, the measured relaxation time might be slightly different from the first measured relaxation time [6]. Unfortunately we don’t have the time to finish this measurement at that point.

As we can see from Fig. 2, when the heating pad is turned off, the fitted $T_1$ is $76.7 \pm 0.3$ hours; when the heating pad is on, the fitted $T_1$ is $71.0 \pm 0.8$ hours. We find less than 10% of relaxation time loss caused by the electrical heating pads. Yet this loss does little harm to the final saturation polarization.

We also test the impact that the heating pads bring to the AFP process. A 600 mV $V_{pp}$ radiofrequency (RF) signal sweeping from 30 kHz to 120 kHz in 1.5 seconds is sent into a RF amplifier which amplifies the signal by 100. The output signal is then sent into the AFP coils wound outside of the oven. Each AFP flip takes less than 2 seconds to complete. Because for each AFP flip the $^3$He polarization loss is very low ($< 0.1\%$), the FID signal loss is too little to be measured. Thus we take one FID signal measurement after 20 continuous AFP flips. 15 FID signal data points are taken. We then fit the data and find that with heating pad on, the fitted AFP loss per flip is $0.061 \pm 0.002\%$; with heating pad turned off, the fitted AFP loss per flip is $0.055 \pm 0.002\%$. The impact is obviously negligible.

3. In situ test

After we test the heating pads in the lab, we move the oven to our in situ SEOP pumping system and install the system at the SNS beamline 4A - magnetic refractometer. Our setup consists of two levels of equipments sitting on an 80-20 frame. The upper level is the laser and optics level. Two 150 W diode lasers are circularly polarized by liquid crystals. Laser lights are then reflected from two dielectric mirrors into the cell to optical pump the $^3$He. The lower level contains the magnetic shielding and the oven. The cell Barbera was made at NIST and it contains 1.52 bar $^3$He with a cell length of 8 cm. The heating pads heat the oven to around 200°C.
We start the test by extracting the cell thickness from two neutron transmission runs [7]. The transmissions are related in Eq. (2).

$$T_0(\lambda) = T_E \exp(-n\sigma_0 \lambda l)$$ (2)

where $T_0$ is the neutron transmission through unpolarized $^3$He cell, and $T_E$ is the transmission contributed from the sapphire windows of the oven and the dielectric mirrors. The cell thickness is then defined by $n\sigma_0 l$, where $n$ is the number density of the $^3$He, $\sigma_0 = 29,662$ b/nm, $\lambda$ is the neutron wavelength in nanometers, and $l$ is the cell length [8]. The fitted thickness is $8.35 \text{ nm}^{-1}$, which agrees with the value from NIST.

For an unpolarized neutron beam transmitting through a $^3$He cell, the transmitted neutron polarization of $P_n(\lambda)$ is given by Eq. (3).

$$P_n(\lambda) = \tanh(P_{He} n\sigma_0 \lambda l)$$ (3)

Thus by fitting the outgoing neutron polarization versus the neutron wavelength, we are able to extract the $^3$He polarization to be 73% ± 0.1%. A plot of above fitting is shown in Fig. 3.

4. Conclusion

We have tested an alternative heating method, electrical heating, for the SEOP pumping method for polarized $^3$He. The non-inductive heating pads installed in the oven provide enough heating for the spin exchange pumping process. At our lab based SEOP pumping setup, we have tested the relaxation time based on two situations: with the heating pads energized and with the pads off. Compressed air is blown into the oven to maintain the same temperature condition. The $T_1$ are $71.0 \pm 0.8$ hours and $76.7 \pm 0.3$ hours for heating pads on and off, accordingly. We have also tested the heating pads’ impact on the AFP flip loss. The AFP loss per flip is 0.061% with heating pads on comparing to 0.055% with heating pads off. From these lab based tests, we conclude that the negative impact that the electrical heating pads bring to the SEOP process
negligible. We have also tested the heating pads’ performance on our \textit{in situ} pumping system. The final $^3\text{He}$ polarization is 73\%, indicating that heating pads are a good alternative to the hot air heating.

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\textbf{References}

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