Measuring gas temperature during spin-exchange optical pumping process

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Abstract. The gas temperature inside a Spin-Exchange Optical Pumping (SEOP) laser-pumping polarized ³He cell has long been a mystery. Different experimental methods were employed to measure this temperature but all were based on either modelling or indirect measurement. To date there has not been any direct experimental measurement of this quantity. Here we present the first direct measurement using neutron transmission to accurately determine the number density of ³He, the temperature is obtained using the ideal gas law. Our result showed a surprisingly high gas temperature of 380 °C, compared to the 245 °C of the ³He cell wall temperature and 178 °C of the optical pumping oven temperature. This experiment result may be used to further investigate the unsolved puzzle of the "X-factor" in the SEOP process which places an upper bound to the ³He polarization that can be achieved. Additional spin relaxation mechanisms might exist due to the high gas temperature, which could explain the origin of the X-factor.

1. Introduction

Many neutron scattering facilities routinely use polarized ³He neutron spin filters as neutron polarizers or analyzers [1-5]. Two main methods to produce polarized ³He are metastability-exchange optical pumping (MEOP) and spin-exchange optical pumping (SEOP). Specifically in SEOP, alkali atoms, typically Rb and K in vapor form inside a glass cell (optical pumping cell) are first polarized through optical pumping. Then, via binary collisions between the alkali electrons and the ³He atoms, the polarization is transferred to ³He. However, optically-pumped alkali atoms can re-emit photons which can significantly reduce the polarization. To suppress this effect, a small amount of N₂ gas (50-100 torr) is added to the gas chamber to quench the excited alkali metal electrons non-radioactively back to the ground state by depositing the excitation energy to the rotational and vibrational states of the N₂ molecules [6, 7]. This energy can greatly increase the gas temperature inside the pumping cell which directly affects several key parameters in SEOP: the alkali metal vapor density, the alkali spin destruction rate and the alkali-³He spin-exchange rate. In a conventional setup, the temperature is measured by placing a resistance temperature detector (RTD) or a thermocouple (TC) on the OUTSIDE wall of the glass cell; hence giving a reading that may not be the gas temperature inside the cell. Thus, a precise measurement of the temperature INSIDE the pumping cell is called for. Previous attempts include Raman spectroscopy [8] and NMR measurements of ³He diffusion coefficient to determine the temperature inside the pumping cells [9]. These methods have shed light on temperature distribution and heat flow inside a pumping cell. However, none of these are direct measurements.

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Assumptions and models need to be made to calculate the temperature. In this proceeding, we report a direct temperature measurement of a $^3$He pumping cell under normal optical pumping conditions using a double-cell configuration and neutron transmission measurements. As far as we know, this is the first attempt to directly measure the temperature of the $^3$He gas inside polarizing cells.

2. Experimental technique, Design and Construction
The goal of this experiment is to determine the temperature inside the $^3$He cell being optically pumped. The idea is to use neutron transmission measurements to deduce the $^3$He number density which in turn gives the corresponding temperature if the $^3$He gas pressure is also known. The ideal gas law gives

$$P = n k_B T$$

where $P$ is the pressure, $n$ is the gas number density, $k_B$ is the Boltzmann constant and $T$ is the temperature. Once a $^3$He cell is filled and sealed, the $^3$He number density stays constant. For unpolarized neutrons passing through an unpolarized $^3$He cell, the transmission is given by

$$T_n = T_e e^{-n \sigma(\lambda)L}$$

where $T_n$ is the neutron transmission passing through $^3$He, $T_e$ is the neutron transmission through the container’s glass wall, $n$ is the $^3$He number density, $\sigma(\lambda)$ is the neutron absorption cross section which is a function of the neutron wavelength $\lambda$ and $L$ is the inner length of the $^3$He cell. From the neutron transmission, the $^3$He number density can be deduced. However, for a single sealed cell there is no direct way to accurately measure the pressure when the cell is being pumped by lasers. Therefore, a double-cell setup was constructed as shown in Figure 1a. Both the top and bottom cells are made of GE-180 glass. The bottom cell (3” outer diameter) was placed in an oven that controls the alkali vapour pressure and optically pumped, i.e. the cell is heated while the laser light shines from both sides. The top cell (2” outer diameter) is outside the oven and does not see any laser light. The two cells are connected by a 0.5 inch diameter glass tube. It is 5 inches in length to make sure that the top cell is well away from the oven. Neutron transmission measurements can independently be done on the top or bottom cell. A thermocouple was inserted and epoxied into the glass tube near the opening of the top cell to give a direct measurement of the temperature in the top cell (Figure 1b). The thermocouple was not placed in the middle of the top cell in order to avoid interference with the neutron transmission measurements. Two additional thermocouples were taped on the outer wall of the bottom cell and the glass tube to read the wall temperature. Because the thermocouple on the glass tube was away from the pumping laser, it was a good indicator of the overall oven temperature. With the double-cell configuration, the $^3$He number density can be determined for the top cell from the neutron transmission measurements. The temperature of the top cell can be measured with the inserted thermocouple. Then using Eq.1, the pressure of the top cell can be determined. To a good approximation, the pressure of the top cell should be equal to the pressure of the bottom cell at equilibrium. Therefore, once the number density of the bottom cell is determined by neutron transmission measurement, the temperature of the bottom cell can be calculated.
Figure 1. (a) Schematics of the double cell system; (b) the thermocouple inserted through the glass stem into the top cell.

The oven that houses the bottom cell is made of G7 (glass silicone laminate) which has a temperature rating up to 220°C. On the front and back side of the oven two 2” holes were cut and covered with sapphire windows for neutrons and laser light to pass through. Instead of using compressed air to heat up the oven, electrical heating pads were chosen for simplicity and convenience [10]. The heating pads are PID controlled which helps stabilize the final temperature reading. Figure 3a shows the oven with the double cell and the heating pads in place. The two solenoids used were identical and placed over the oven so that the stem of the double cell would safely fit. Each solenoid has an 8.5” x 8.5” cross section and is 6” in length. Each one consists of 150 turns of 18 AWG solid copper wire. Current passes through the coils in series to produce a field at 15 Gauss.

Figure 3. (a) The cell in the oven with heating pads in place; (b) the oven in the solenoid.

The system’s base has a cut to fit optical breadboard that has ¼”-20 tapped holes in a 1” spacing pattern across its surface. This layout, as well as the use of a 200W fiber-coupled laser (0.35nm spectral linewidth), results in more simplified optics which simplifies the laser alignment (Figure 4a). After assembly, the dimension of the system is measured to be 61 cm in length along the axis of the
neutron beam, 58 cm in width and 46 cm in height. The 80/20® outer frame used has enough space to house all of the optics and the solenoid, while still being compact enough to fit safely on the beamline table. The system was enclosed by laser safety panels with interlock switches on every side of the cube shape (Figure 4b). The interlock switches are set to shut down the laser system if any of the panels are removed.

3. Tests and Results
The double cell was prepared and filled using the lab-based filling station [11] at the Oak Ridge National Laboratory. The cell was filled with 653 torr of $^3$He and 47 torr of N$_2$. Rubidium was driven into the bottom cell only. The heating pads, optics, and laser were all tested in the lab before transferred to the polarized neutron development beamline HB-2D at High Flux Isotope Reactor (HFIR). At the beamline the system was mounted onto a hydraulic height-adjustable optical table so that transmission measurements could be performed for both the top and the bottom cell. This setup at the beamline is shown in Figure 5.

![Figure 4. (a) Optical layout of the double cell system; (b) the enclosed system.](image)

![Figure 5. The system setup at beamline HB-2D at HFIR. The system was sitting on an optical table. One side panel was removed for illustration purpose.](image)
In order to determine the temperature of the bottom cell, several neutron transmission measurements were performed: direct beam transmission without the cell, transmission with the cell at room temperature, transmission with the heating pads on and the laser off and transmission with both the heating pads and the laser on. These measurements were repeated for both the top and bottom cell.

The direct beam transmission was used to get a baseline reading. The neutron transmissions with the cell at room temperature were used to determine the inner length (IL) of the cell. The neutron transmission with the heating pads on and the laser off was used to determine if the calculated temperature and the measured temperature were in good agreement with each other. In this setting, the difference between the bottom cell wall temperature and the temperature inside the bottom cell should be negligible. Once it was determined that the calculated and measured temperatures agreed, neutron transmission measurements with the laser on full power were done to determine the temperature of the bottom cell. All of these measurements were performed when the temperatures in both the top and the bottom cell have stabilized.

Table 1 shows a summary of the test results.

|                  | Top Cell trans. | Bottom Cell trans. | IL Top Cell (cm) | IL Bottom Cell (cm) | T Top Cell (°C) | T Bottom Cell Wall (°C) | T Glass Stem (°C) | T Bottom Cell Calculated (°C) |
|------------------|-----------------|--------------------|------------------|---------------------|-----------------|------------------------|--------------------|-------------------------------|
| Room Temperature | 0.307           | 0.121              | 3.9              | 7.3                 | 23.6            | 23.3                   | 26.0               | 26.0                          |
| Heater on Laser off | 0.250          | 0.130              | 3.9              | 7.3                 | 31.5            | 109                    | 102.5              | 105                          |
| Heater/Laser on   | 0.184           | 0.219              | 3.9              | 7.3                 | 34.8            | 245.3                  | 178                | 380                          |

With the laser off, in which the spin-exchange process doesn’t take place, the temperature read by the thermal couple on the bottom-cell wall should be close to the temperature of the gas temperature inside the cell. From table 1, the calculated and measured temperature in the bottom cell indeed showed good agreement which showed the validity of applying the ideal gas law to 3He. In addition, as expected, the oven temperature taken by the temperature reading on the glass stem was also close to the measured and calculated bottom-cell temperature. With the laser on at full power, spin-exchange process took place and the quenching gas N2 would heat up the internal gas substantially. The measurements revealed that the bottom cell temperature was elevated by about 135 °C compare to the bottom cell wall temperature, and by almost 200 °C compare to the oven temperature. The temperature change in the top cell was small compared to the change in the bottom cell.

4. Conclusion
We successfully demonstrated a direct 3He temperature measurement using neutron transmission. A 135-200 °C temperature increase has been observed in our measurements. This confirms that the temperature inside the cell is higher than the oven temperature due to reemission heating from the quenching gas. To our knowledge, this is the first time that this temperature difference has been experimentally confirmed. How such an increase of temperature would affect spin-destruction and spin-relaxation of polarized 3He is still unknown and requires further investigation. Since our purpose was only to observe the heating phenomenon, the 3He was not highly polarized. Further experiments will be carried out for more precision measurements, including the polarized 3He temperature.
measurement and the $^3$He lifetime measurement at high temperatures. We hope such an effort will help solve the mystery of the “X-factor” [12].

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