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In-situ Polarized ^{3}He-Based Neutron Polarization Analyzer for SNS Magnetism Reflectometer

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Abstract. We report here the construction and neutron transmission test results of an *in-situ* polarized ^{3}He-based neutron polarization analyzer system for the Magnetism Reflectometer at the Spallation Neutron Source, Oak Ridge National Laboratory. The analyzer uses the Spin-Exchange Optical Pumping method to polarize the ^{3}He nuclei of a cell of ^{3}He gas. Polarized neutrons scattered from the sample are intercepted by the polarized ^{3}He gas which strongly absorbs neutrons in one spin-state while allowing most neutrons in the other spin-state to pass through. To maintain a stable analyzing efficiency during an experiment, the ^{3}He gas is continuously polarized *in-situ* on the instrument. Neutron transmission measurements showed that 73% ^{3}He polarization was reached in this setup.

1. Introduction

Polarized ^{3}He neutron spin filters are based on the spin-dependence absorption of the neutrons by ^{3}He. If the ^{3}He nuclear spin and the neutron spin are anti-parallel, the absorption is very strong. If the spins are parallel, there is considerably less absorption. The transmission of spin+ (spin-parallel) neutrons and spin- (spin-anti-parallel) neutron beam through a cylindrical cell of polarized ^{3}He gas are

$$T_{\pm} = T_e \exp\left(-n\sigma_0 l\lambda \pm n\sigma_0 l\lambda P_{He})\right), \tag{1}$$

where T_e is the transmission of the empty cell, n is the number density of the ^{3}He gas, the absorption cross-section σ_0 = 2966 x 10^{-24} cm^2 for λ = 1 Å [1], l is the path length through the gas, and P_{He} is the

^{3}He polarization. The empty cell transmission is weakly dependent on the neutron wavelength and is taken to be a constant in thermal and cold neutron scattering applications. With an incident polarized neutron beam, placing the polarized ^{3}He after a sample analyzes the polarization of the scattered neutrons. The neutron polarization analyzing efficiency P of a cell of polarized ^{3}He gas is

$$P = \frac{T_+ - T_-}{T_+ + T_-} = \tanh\left(n\sigma_0 l\lambda P_{He}\right). \tag{2}$$

The wavelength dependence of the ^{3}He neutron spin filter analyzing efficiency is gradual. It can be used as a broadband neutron spin-filter. In addition, the spin filter can accommodate a large beam cross-section. For typical beam divergence used in neutron scattering, its analyzing efficiency is virtually independent of the angular divergence of the neutron beam. Because of these characteristics, polarized ^{3}He has increasingly been used in neutron scattering works.

2. *In-situ* analyzer

We have been working with the polarized ^{3}He research community to develop the use of polarized ^{3}He based neutron spin filters [2-4]. Drawing on the experiences of the previous development, we have developed an *in-situ* polarization analyzer for the SNS Magnetism Reflectometer [5].

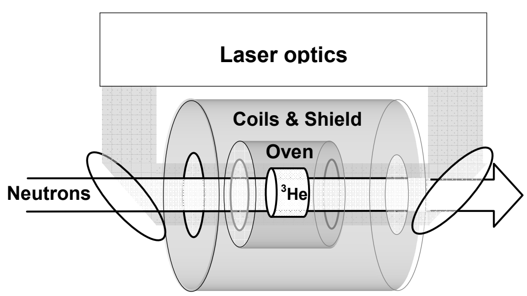

Figure 1. Schematic diagram of the analyzer. The details are explained in the text.

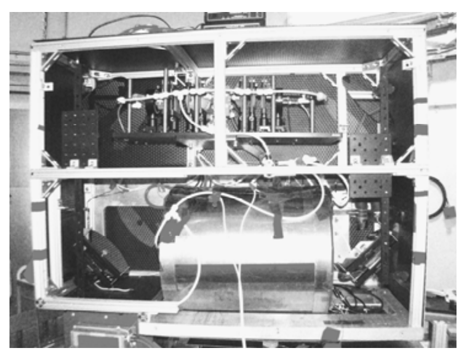

Figure 2. Analyzer setup at the reflectometer. Upper: Laser optics. Lower: Analyzer.

Figure 1 illustrates the setup of the analyzer system. The key component is a cell of polarized ^{3}He gas in the neutron flight path. The cell, called "Barbera", was made by the National Institute of Standards and Technology team [6]. It is made of aluminosilicate glass and is 11.8 cm in inner diameter and 7.5 cm in length. The ^{3}He gas pressure in the cell is 1.52 bar. As we used the Spin-Exchange Optical Pumping (SEOP) method to polarize the ^{3}He gas [7], the working substances included alkali metals and 120 mbar of nitrogen gas. Barbera was a "hybrid cell" which used both rubidium and potassium [8]. Figure 2 shows a picture of the setup.

The cell was placed in an oven that heats it to 200ºC. In a departure from the convention, non-inductive electric heater pads driven by direct current instead of hot air were used [9]. The cylindrical shape oven was made of Teflon. Double c-axis sapphire windows on both ends of the oven allowed passages of neutrons and light. The temperature controlled the vapor pressure of the alkali, which determined the polarizing speed of the ^{3}He. Additional thermal insulation was used outside the oven. A compensated solenoid provided the uniform magnetic field to maintain the ^{3}He polarization. The solenoid was enveloped by a cylindrical μ-metal enclosure with openings for passages of neutrons and light. The enclosure improved the field uniformity at the cell and shielded the ^{3}He from external magnetic interference. Compressed air flow kept the enclosure at near room temperature.

In the SEOP method for polarizing ^{3}He, circularly polarized light tuned to the $5s_{1/2} - 5p_{1/2}$ D1 transition of the rubidium at 794.7 nm is shined on the cell along the field direction. The light optically pumps the rubidium atoms from one magnetic sublevel of the $5s_{1/2}$ ground state to the $5P_{1/2}$ state. The excited rubidium atoms return to either sublevel with equal probability through a collisional de-excitation from the nitrogen gas molecules. Optically pumping on one of the sublevels depletes its population and polarizes the rubidium vapor in milliseconds. The use of a hybrid cell reduced the demand of light power to compensate the loss of rubidium polarization. In our setup, we used a 150 W 3-bar stack solid state laser. A Volume Bragg Grating in front of each bar centered the emissions at 794.7 nm and narrowed the bandwidth to 0.6 nm full-width-at-half-maximum. An electronically controlled liquid crystal retarder was used to control the chirality of the light. We used two similar laser optics setups to shine light with opposite chirality from both sides of the ^{3}He cell. The laser optics was placed above the μ-metal enclosure. 350 μm-thick (002) oriented silicon wafers with polarization-preserving dielectric coating reflected the light towards the ^{3}He cell while allowing neutron passage with little attenuation.

When a polarized rubidium or potassium atom collides with a ^{3}He atom, there is a finite probability that the ^{3}He nuclei and the alkali atomic electron undergo spin-exchange hyperfine interaction. The result is polarized ^{3}He nuclei. It takes tens of hours for the ^{3}He gas to reach its equilibrium polarization, typically in the range of 70-80%.

A sine-coil was placed in the space between the oven and the solenoid to provide a transverse radio-frequency field for a nuclear magnetic resonance (NMR) method called “adiabatic fast passage” (AFP). By sweeping the r.f. frequency through the ^{3}He Larmor frequency at a selected sweep rate, the ^{3}He polarization was flipped between parallel and anti-parallel to the solenoid field. This enables the measurement of spin+ and spin- neutron intensities. We tested one flip every 2 minutes.

The analyzer system was covered with laser shielding panels and mounted on an elevator at the detector table of the reflectometer. It was lowered into the neutron flight path when used. The ^{3}He was continuously polarized during an experiment to maintain a stable analyzing efficiency. Free Induction Decay (FID) of the ^{3}He NMR signal was used to monitor the ^{3}He polarization.

3. Neutron Transmission Measurement

Neutron transmission through the analyzer was determined by measuring the transmitted intensities with the analyzer in the neutron beam and with the analyzer removed. To avoid the uncertainty due to the efficiency of neutron spin-transport, we used iron plates to depolarize the incident neutrons. Each transmission was measured using spin+ and spin- incident neutron beam. The results with either spin state of the incident beam were virtually identical. This confirmed that the neutron beam was depolarized. The transmission of unpolarized neutrons through the analyzer system is

$$T_N = \left(T_+ + T_-\right)/2 = T_e \exp\left(-n\sigma_0 l\lambda\right)\cosh\left(n\sigma_0 l\lambda P_{He}\right), \tag{3}$$

where T_e includes the transmission through the cell walls, the silicon mirrors, and the sapphire windows. To separately determine the “cell thickness” $n\sigma_a l$, we also depolarized the cell and measured the unpolarized neutron transmission:

$$T_0 = T_N\left(P_{He} = 0\right) = T_e \exp\left(-n\sigma_0 l\lambda\right). \tag{4}$$

Measuring the intensities of cell-polarized and cell-unpolarized also allow a cross-check that is independent of T_e. The analyzing efficiency is related to the two transmissions by

$$P = \left(1 - \frac{T_0^2}{T_N^2}\right)^{1/2}. \tag{5}$$

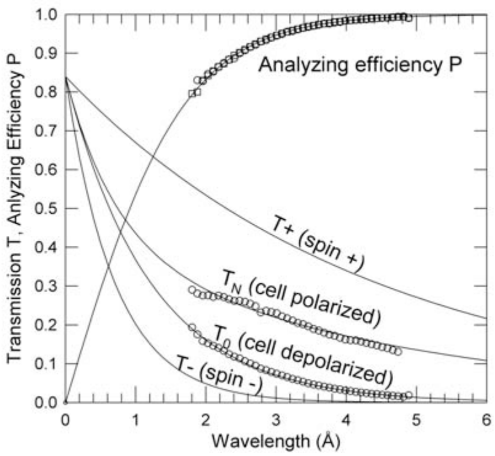

Figure 3. Measurements of unpolarized neutron transmission through the ^{3}He cell.

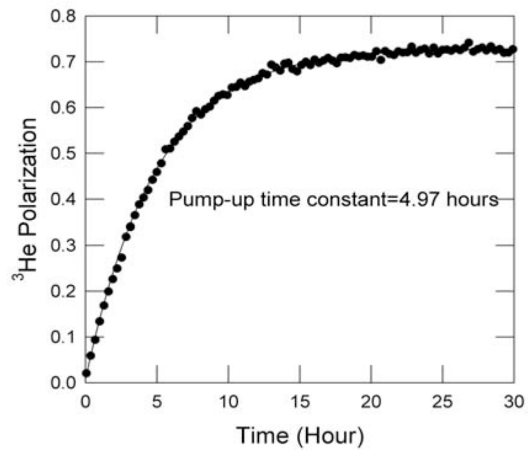

Figure 4. ^{3}He polarization as a function of time during the polarizing process.

Figure 3 shows the measured T_N and T_0 after the ^{3}He polarization reached equilibrium. Each dataset was measured for 1 hour counting time. The 1 hour counting time was chosen to reduce the amount of data during more than 2 days of continuous measurements. The data was normalized to the proton count of the accelerator to account for accelerator fluctuations. The analyzing efficiency was obtained by processing the data using equation (5). The data were fitted to equation (3) and (4) from which we determined the ^{3}He polarization to be 73%. Given the high accumulated neutron counts, the statistical error was 0.1%. We believe systematic uncertainties were the primary source of uncertainties in these measurements. Given the limited time available, however, we were not able to carry out addition measurements for determining the uncertainties. The cell thickness $n\sigma_a l$ = 0.825 at λ = 1 Å agreed with a previous NIST result ($n\sigma l$ = 4.14 at λ = 4.96 Å) and we obtained T_e = 0.84. The curve-fitting to the analyzing efficiency confirmed the parameters. We include also the expected T_+ and T_- for this system in the figure. The ^{3}He polarizing process was monitored by FID measurement. The data was scaled to the ^{3}He polarization determined from the neutron measurements. Fitting the data to a saturating exponential curve gives a pump-up time-constant of 4.97 hours. This is considerably shorter than the 10-15 hour time-constant we expected at 200ºC. We believe laser heating of the cell as a result of the SEOP process resulted in the cell temperature higher than temperature measured by a resistance temperature detector the oven.

In conclusion, we have constructed a polarized ^{3}He based neutron polarization analyzer for the SNS Magnetism Reflectometer. Neutron transmission measurement showed a saturation ^{3}He polarization of 73%. The polarizing process in this setup had a pump-up time-constant of 4.97 hours.

4. References

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