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^{3}He spin filters for a thermal neutron triple axis spectrometer

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Abstract

We have tested two ^{3}He neutron spin filters (NSF), one for the polarizer and one for the analyzer, in conjunction with a doubly focusing pyrolytic graphite (PG) monochromator on the state-of-the-art BT-7 thermal triple axis spectrometer (TAS) at the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR). This system will provide significantly better neutronic performance for polarization analysis over a conventional TAS with Heusler crystals. We discuss the scheme for employing NSFs on the TAS instrument, including the ^{3}He cell design, spin-exchange optical pumping (SEOP) of these large ^{3}He cells, and the holding fields on the spectrometer. Using Rb/K hybrid SEOP, we have produced 75% ^{3}He polarization for the 11 cm diameter cells for TAS in less than two days.

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1. Introduction

Polarized neutron scattering (PNS) is a powerful tool that probes magnetic structures and spin dynamics in a wide variety of magnetic materials [1]. It has been successful for many applications with polarizers such as supermirrors and Heusler crystals. However, the severe intensity loss or the inability to cover divergent beams with these polarizers precludes many PNS experiments. Polarized ^{3}He gas, produced by optical pumping, can be used to polarize or analyze neutron beams because of the strong spin dependence of the neutron absorption cross section for ^{3}He gas. Polarized ^{3}He neutron spin fitters (NSF) are of growing interest in the PNS community due to recent significant improvements in their performance [2–4]. Compared to supermirrors and Heusler crystals, ^{3}He NSFs have two main advantages: (1) they are broadband and can polarize thermal or hot neutrons effectively and (2) they can polarize both large area and large divergence neutron beams.

Heusler crystals used in today's neutron spectrometers typically have thermal neutron reflectivity of 25–30% for the reflected spin state and routinely provide a neutron polarization of 95% [5]. Modernizing thermal triple axis spectrometers (TASs) require higher flux at the sample, higher useful detected count rates, lower background, and faster data acquisition. A large double-focusing pyrolytic graphite (PG) monochromator can provide a dramatic increase in flux at the sample compared to a traditional thermal TAS [6]. Heusler crystals are difficult to assemble and magnetize in the large focusing arrays required for these new methods. Additionally, ^{3}He spin filters have greater versatility in the selection of energy and polarization. In order to utilize these instrumental advances for polarized thermal neutron beams, it is advantageous to use ^{3}He polarizers instead of Heusler crystals.

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On the ILL IN20 thermal TAS, a PG monochromator in conjunction with a ^{3}He polarizer outperformed a Heusler crystal monochromator for wavelengths below 0.18 nm, despite a relatively low ^{3}He polarization of 48% [7]. During the last several years, the achievable ^{3}He polarization has been significantly improved for both the spin-exchange optical pumping (SEOP) and metastability-exchange optical pumping (MEOP) methods. For SEOP, using 52 W of spectrally narrowed 795 nm diode laser light, we now routinely polarize 1 l, long relaxation time cells to 75% ^{3}He polarization with a polarizing rate up to 2.4 bar-L/day [8]. Recently, we obtained a ^{3}He polarization of 76% on the Center for Neutron Research NG-1 polarized neutron reflectometer. For the MEOP method, ^{3}He polarization up to 72% in the storage NSF cell has been achieved with typical relaxation times of 150 h [9].

In this paper, we discuss applications of ^{3}He NSFs in conjunction with a doubly focusing PG monochromator for the BT-7 thermal TAS at the NCNR. Using a doubly focusing PG monochromator has allowed us to reach a neutron flux at the sample on BT-7 of $1.8 \times 10^8\,\mathrm{cm^{-2}\,s^{-1}}$ at 40 meV (0.143 nm) [10]. At a ^{3}He polarization of 75%, the total neutron transmission through a ^{3}He polarizer with a polarizing efficiency of 95% is about 0.23. Hence the polarized neutron flux at the sample will be $4.1 \times 10^7\,\mathrm{cm^{-2}\,s^{-1}}$, which is about a factor of 18 higher than the decommissioned BT-2 thermal TAS at the NCNR. Combined with another factor of 1.8 gained from a ^{3}He analyzer over a Heusler crystal, the intensity gain in the detector will be a factor of 35.

2. BT-7 TAS beam geometry

The BT-7 thermal TAS at the NCNR [10] features the choice of either a Cu(220) or PG(002) doubly focusing monochromator, providing a useful continuous incident neutron energy range from 5 to 200 meV. Each doubly focusing monochromator has an active area 20 cm high and 20 cm wide. The distances from the monochromator to the exit of its drum and to the sample are 117 and 208 cm, respectively. Due to the doubly focusing geometry, it would be ideal to locate the ^{3}He NSF close to the sample in order to reduce the ^{3}He cell diameter and hence the volume of the ^{3}He cell. Due to space constraints we located the cell 80 cm away from the sample. The resulting space available for the ^{3}He NSF is only 27 cm. The beam height at the ^{3}He polarizer cell is expected to be 10 cm.

At the downstream side of the sample, the space available for the ^{3}He analyzer between the detector enclosure and the sample enclosure is 58 cm, including a magnetically shielded solenoid (MSS), a possible spin flipper, and a guide field. The distance between the sample and the 7.6 cm tall PG analyzer is 142 cm. The beam height at the ^{3}He analyzer cell was about 6.5 cm.

3. ^{3}He neutron spin filter design

Employing ^{3}He NSFs requires suitable design of the ^{3}He cells, optical pumping, and holding field. Due to the large size of these cells, we employed mixtures of potassium and rubidium to increase the spin-exchange optical pumping efficiency [8,11].

3.1. ^{3}He cells

The goal for the ^{3}He cell design is to make ^{3}He cells with long lifetimes (>200 h) and appropriate potassium-to-rubidium vapor density ratio, D. Thermal neutron instruments such as the BT-7 thermal TAS require a higher ^{3}He gas thickness (product of the ^{3}He pressure and the cell length) as compared to cold neutron instruments. Increasing the ^{3}He pressure reduces the maximum ^{3}He polarization relaxation time which is set by ^{3}He dipole–dipole relaxation [12], and increases the risk of cell explosion. Increasing the cell length increases the required laser power.

The cylindrical ^{3}He cells are blown from GE180 [13] glass. For the BT-7 TAS, the cells must be about 11 cm in diameter to cover the entire neutron beam. It is difficult to make such large, reblown, GE180 cells which will also hold high gas pressures. For SEOP the gas pressure is increased over its room temperature value at the typical temperature of 483 K. When blowing the cells, one must strike a balance between uniform path length and sufficient rounding of the corners so as to maintain structural integrity. When filling the cells, practice and care are required to obtain appropriate values of D. For $D>10$, the maximum ^{3}He polarization is reduced, whereas for $D<1.5$ the utility of hybrid SEOP is reduced. We have successfully made four cells with D between 2 and 6, for which information is listed in Table 1. The ^{3}He polarization relaxation times are between 300 and 450 h, and we have obtained ^{3}He polarization between 75% and 78% with pump-up time constants of 8–12 h.

3.2. Hybrid SEOP for large ^{3}He cells

For the SEOP method, the laser power needed is roughly proportional to the cell volume. Large cells such as those used on BT-7 require substantial laser power to maintain fully polarized alkali electrons (to maximize the ^{3}He

Table 1
Hybrid ^{3}He cells, with the potassium–rubidium vapor density ratio, D, at 483 K and the maximum values of the ^{3}He polarization, P_{He}, obtained in each cell

Cell name	D	d	l	V	p	T_1 (h)	P_{He}
Zinfandel	2.5	11.6	8.9	940	1.86	330	0.78
Chianti	2.0	11.8	8.1	875	1.82	290	0.75
Barbera	4.4	11.8	7.5	820	1.52	310	0.76
Syrah	6.2	10.2	9.7	790	1.43	450	0.76

The relative standard uncertainty in measurements of the ^{3}He polarization is 5%. All cells are cylindrical, with diameter d and length l in cm, volume V in cm^3, and ^{3}He partial pressure p in bar. All cells were spin-exchange optically pumped using 52 W of spectrally narrowed 795 nm laser light from two 50 W diode bars.

polarization). We employed two spectrally narrowed 795 nm diode lasers, each based on a 50 W diode bar to illuminate the cell from both sides. A total of 52 W of laser light was incident on the SEOP cell. With this setup, we have recently studied the SEOP efficiency of ^{3}He gas using pure Rb and mixtures of Rb and K [8]. For the cells listed in Table 1, the improvement in spin-exchange efficiency is typically a factor of two, which allows such cells to be polarized at the same rate as a pure rubidium cell with half the laser power.

3.3. Holding field design

We have constructed a small MSS for the BT-7 polarizer given the restricted space available. The solenoid has an outer diameter of 20 cm and an outer length of 25 cm, which can just fit into the incident beam path. The hole in each end cap is 11.2 cm to pass neutrons. Calculations revealed that the best radial location for end compensation is near the holes. We experimentally optimized the number of compensation turns to be 9 by measuring the field gradient and by measuring the relaxation time of a low-pressure ^{3}He cell polarized by the MEOP method [2]. We have measured the relaxation time of the cell *Barbera* (see Table 1) in the polarizer solenoid to be 140 h, which implies an average fractional field gradient of $6 \times 10^{-4}\,\mathrm{cm}^{-1}$. This value was obtained both on and off the beam line, which indicates that the 10 G guide field did not cause depolarization.

For the analyzer, we employed a 30 cm diameter, 46 cm long MSS with a 8.9 cm diameter hole in each end cap. In this MSS, the field gradient has been measured to be $2 \times 10^{-4}\,\mathrm{cm}^{-1}$ [3], which decreased the relaxation time of the cell *Syrah* from 450 to 350 h. The field gradient for the polarizer solenoid is much worse than the analyzer solenoid simply because less space is available along the neutron beam path and the holes in the end caps are larger for the polarizer.

4. ^{3}He NSF test on the BT-7 triple axis spectrometer

We performed a test on the BT-7 thermal TAS at a wavelength of 0.236 nm using a ^{3}He polarizer and a ^{3}He analyzer. Besides standard TAS elements [10], there was a ^{3}He polarizer immediately outside the monochromator drum, a ^{3}He analyzer between the sample enclosure and the detector enclosure, a PG filter, and a spin flipper between the sample and the ^{3}He polarizer. A longitudinal guide field (10–15 G) was used to adiabatically rotate the neutron spin from the longitudinal direction to the vertical direction for the polarizer and from the vertical direction to the longitudinal direction for the analyzer.

We employed the cell *Zinfandel* as polarizer and *Syrah* as analyzer. Since we only had one SEOP apparatus for optical pumping, we terminated the optical pumping of the analyzer cell *Syrah* two days before the run and optically pumped the polarizer cell *Zinfandel* in the last two days. Choosing this order allowed us to obtain roughly equal time-averaged polarization on the beam line, and a demonstration of close to the maximum initial polarization for the polarizer. Despite the two-day relaxation of the analyzer cell *Syrah* and the limited time to optically pump the polarizer cell *Zinfandel*, we obtained initial values of ^{3}He polarization on the BT-7 instrument of 71% and 73% in the polarizer cell and analyzer cell, respectively. We are constructing two new SEOP stations to provide for polarized beam operation on BT-7. With these two SEOP stations, we will be able to deliver typical initial polarization values of 75% in both cells on the beam line.

The polarizer had an initial polarizing efficiency (flipping ratio) of 0.97 (66) and an initial absolute transmission of 0.19. The analyzer had an initial analyzing efficiency (flipping ratio) of 0.94 (32) and an initial transmission for the desired spin state of 0.45. Hence the initial overall flipping ratio would have been 22 if the spin transport and the spin flipper had been perfect. However, we only reached an initial overall flipping ratio of 7. Therefore, we encountered some neutron depolarization from either the spin transport or the flipper or both, which is determined to be about 0.83. We are investigating this depolarization issue. We determined the relaxation time of ^{3}He polarization for both polarizer and analyzer using the initial and final ^{3}He polarization in a 64 h test run. We determined relaxation times of 130 and 350 h in the polarizer and analyzer solenoid, respectively. This was consistent with offline field gradient measurements and ^{3}He polarization relaxation measurements.

5. Conclusions

We have employed a polarized ^{3}He spin filter to polarize a 10 cm tall thermal neutron beam at 14.7 meV (0.236 nm) and a second polarized ^{3}He spin filter to spin-analyze the scattered beam on the BT-7 thermal TAS at the NCNR. We have constructed a MSS 20 cm in diameter and 25 cm long to fit into available space on the instrument. The solenoid has a reasonably uniform field despite the limited space, yielding a ^{3}He polarization relaxation time of 130 h for the large BT-7 cells. Both ^{3}He polarizer and analyzer performed well. We obtained initial ^{3}He polarization of 71% and 73% for the polarizer and the analyzer, respectively, using a single SEOP system. The use of a large area (20 cm high and 20 cm wide) doubly focusing PG monochromator and a polarized ^{3}He neutron spin filter has allowed a substantial improvement of the polarized neutron beam intensity at the sample on BT-7. Polarized ^{3}He NSFs will be routinely used as polarizing elements at the BT-7 TAS at the NCNR.

Using hybrid SEOP with 52 W of spectrally narrowed laser light, we have optically pumped ^{3}He cells up to 1 L in volume to 75% polarization. As far as we know, it is the first time such high polarization has been reached for such large cells using the SEOP method.

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