Development of a polarized $^3$He neutron spin filter for POLANO at J-PARC

T Ino$^{1,2,3}$, M Ohkawara$^4$, K Ohoyama$^5$, T Yokoo$^{1,2,3}$, S Itoh$^{1,2,3}$, Y Nambu$^4$, M Fujita$^4$, H Kira$^6$, H Hayashida$^6$, K Hiroi$^{7,2}$, K Sakai$^{7,2}$, T Oku$^{7,2}$, and K Kakurai$^6$

$^1$ Institute of Materials Structure Science, KEK, Tsukuba, Ibaraki 305-0801, Japan
$^2$ J-PARC Center, Tokai, Ibaraki 319-1195, Japan
$^3$ SOKENDAI - The Graduate University for Advanced Studies, Tsukuba, Ibaraki 305-0801, Japan
$^4$ Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
$^5$ Graduate School of Science and Engineering, Ibaraki University, Hitachi, Ibaraki 316-8511, Japan
$^6$ Comprehensive Research Organization for Science and Society, Tokai, Ibaraki 319-1106, Japan
$^7$ Japan Atomic Energy Agency, Tokai, Ibaraki 319-1184, Japan

takashi.ino@kek.jp

Abstract. We have developed a polarized $^3$He neutron spin filter (NSF) for a new polarized neutron spectrometer, POLANO, at the Japan Proton Accelerator Research Complex (J-PARC). POLANO aims to utilize high energy neutrons polarized by a $^3$He NSF and spin analyzed by an array of magnetic supermirrors for inelastic neutron scattering. The $^3$He gas is continuously polarized in-situ by spin-exchange optical pumping to provide a highly and stably polarized neutron beam. The POLANO $^3$He NSF is designed to polarize neutrons with energies as high as 200 meV and fit in a restricted space. It is equipped with adiabatic fast passage NMR that enables one to flip the $^3$He spins, and consequently, the neutron spins.

1. Introduction

POLANO is a polarization analysis inelastic neutron spectrometer that has been newly constructed at the Materials and Life Science Experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC) for the investigation of the spin dynamics of materials [1]. POLANO is the first spectrometer dedicated to polarized neutron experiments at MLF with wide momentum-energy coverage for the investigation of dynamical properties of materials. It employs a $^3$He neutron spin filter (NSF) for the initial beam polarization with incident neutron energies as high as 200 meV and an array of magnetic supermirrors for the spin analysis of the scattered neutrons. A converging neutron beam is focused at the sample position with a beam size of 20 mm by 20 mm, which is 50 mm by 50 mm at the $^3$He NSF position. The basic instrumental parameters are summarized in Table 1.

The $^3$He NSF of POLANO has to satisfy certain criteria that include a specific range of neutron energies, continuous operation for weeks, ability to fit in a restricted space, spin flipping, and the J-PARC safety standards. Such a $^3$He NSF had been designed as described in a previous paper [2], and we have realized one that will be installed in the spectrometer. The $^3$He NSF can fit in the restricted
space available, i.e. 60 cm along the beamline and 60 cm wide, between the Fermi chopper and sample vacuum chamber as illustrated in figure 1. The $^3$He gas is polarized in-situ by spin-exchange optical pumping (SEOP) to maintain a stable $^3$He polarization for weeks. It is equipped with an adiabatic fast passage (AFP) NMR that is capable of flipping the $^3$He spins instantaneously [3]. Each component of the POLANO $^3$He NSF is described in the next section.

Table 1 Basic instrumental parameters of POLANO.

| Parameter                              | Value                          |
|----------------------------------------|--------------------------------|
| $L_1$ (moderator-sample distance)      | 17.5 m                         |
| $L_2$ (sample-detector distance)       | 2.5 m                          |
| $L_3$ (Fermi chopper-sample distance)  | 1.85 m                         |
| Energy resolution                      | $\Delta E/E_i \sim 5\%$ at elastic position |
| Momentum resolution                    | $\Delta Q/k_i \sim 2\%$        |
| Sample size                            | 20 mm $\times$ 20 mm           |
| Detector coverage                      | -30° to 130° (horizontal)      |
|                                        | -10° to 10° (vertical)         |

Figure 1 Schematic view of the POLANO spectrometer around the sample position (neutron beam propagation from left to right). The $^3$He NSF is situated in the space shown by a dashed square between the Fermi chopper and vacuum chamber.

2. $^3$He NSF of POLANO
In POLANO, the neutron beam profile at the position of the $^3$He NSF is a square with a side length of ~5 cm, and neutrons with energies up to 200 meV need to be polarized. However, at the first stage of the POLANO project, the aim was to concentrate primarily on a safe and stable operation of the $^3$He NSF. Hence, we restricted the coverages of the beam profile and neutron energies to a diameter of ~5 cm, collimated by sintered B$_4$C at the entrance of the $^3$He NSF, and 100 meV, respectively.
Figure 2 illustrates a schematic view of the $^3$He NSF of POLANO. A $^3$He cell is situated inside an oven at the center of a magnetically shielded solenoid. A laser with a wavelength of the Rb D$_1$ resonance is guided to the $^3$He cell using mirrors for the optical pumping of Rb. These components are described in the following subsections.

![Figure 2 Schematic view of the $^3$He NSF of POLANO (for details, see text).](image)

2.1. $^3$He cells
The neutron polarization $P_n$ and transmission $T_n$ for an unpolarized neutron beam passing through polarized $^3$He gas are given by

$$P_n = \tanh(P_{He} \sigma \rho d),$$

$$T_n = e^{-\sigma \rho d} \cosh(P_{He} \sigma \rho d),$$

where $P_{He}$ is the $^3$He polarization, $\sigma$ is the spin-averaged neutron absorption cross section that depends on the neutron energy, $\rho$ is the number density of $^3$He atoms, and $d$ is the thickness of the $^3$He gas. In polarized inelastic neutron scattering measurements, a high polarization such as $P_n \geq 0.90$ or 0.95 is often desired. Figure 3 shows the variation of the effective $^3$He gas thickness $\rho d$ as a function of the neutron energy necessary to achieve a high polarization of between $P_n = 0.90$ and 0.95 for a
given value of $P_{He} = 0.75$. For the time being, POLANO utilizes polarized neutrons with energies ranging from 10 to 100 meV that can be realized using polarized $^{3}$He gas with effective $^{3}$He thicknesses ranging from 10 to 35 atm·cm as seen in figure 3. We are preparing suitable $^{3}$He cells for these neutron energies.

![Figure 3 Variation of the effective $^{3}$He gas thickness $\rho d$ as a function of the neutron energy in order to achieve a high polarization of $P_n = 0.90$ or 0.95.](image)

Alkali metal hybrid SEOP [4] that uses a cell containing pressurized $^{3}$He gas, ~0.1 atm of N$_2$ gas, and small quantities of Rb and K, is widely used to enhance the optical pumping efficiency. During the optical pumping of Rb in hybrid SEOP, a $^{3}$He cell is heated to 200–250 °C, thereby increasing the gas pressure inside the cell from 3 atm at ambient temperature to approximately 5 atm at the elevated temperature. Finite element method calculations and pressure tests of glass cells are being performed to develop pressure safe $^{3}$He cells. Two of our $^{3}$He cells are presented in Fig. 4.
Figure 4: Typical $^3$He cells. Outer diameters of both cells are 60 mm. Outer lengths are 60 mm (left) and 100 mm (right). Wall thicknesses are approximately 2 mm and $^3$He gas pressures are ~2.5 atm at ambient temperature for both cells.

### 2.2. Static magnetic field

Magnetic field homogeneity is one of the important requirements for $^3$He NSF. $^3$He spin relaxation caused by a magnetic field gradient follows the equation

$$\Gamma_{mug} = \frac{D \left( \nabla B_x + \nabla B_y \right)^2}{B_0^2}$$

where $D$ is the diffusion constant of $^3$He atoms, and $B_0$ is the strength of the primary magnetic field. $B_x$ and $B_y$ denote transverse magnetic fields [5]. A magnetically shielded solenoid with compensation coils was designed including neutron guide coils that fit in the available space. There are two requirements that the magnetic field needs to satisfy: (1) the field gradient $\sqrt{\nabla B_x^2 + \nabla B_y^2} / B_0 < 1 \times 10^{-3}$ cm$^{-1}$ at the $^3$He cell position so as to reduce the $^3$He spin relaxation to an acceptable level, and (2) the neutron guide field strength $> \sim 2$ mT for $|Z|<350$ mm from the solenoid center in order to suppress the depolarization of the neutron spins where the magnetic field direction changes by 90 degrees along a neutron path of 20 cm after the guide coil [6]. The magnetic coils are schematically shown in figure 5. Calculation results of the field gradient around the $^3$He cell position and the guide field strength are shown in figure 6.
Figure 5 Cross-sectional view of the magnetically shielded solenoid with compensation coils and neutron guide coils. The $^3$He cell shown is cylindrical with a diameter and length of 60 mm and 100 mm, respectively. The coil currents are 559 A-turn, 41 A-turn, and 462 A-turn for the solenoid, each compensation coil, and each guide coil, respectively. The permalloy shield is 0.6 mm thick. The left guide coil ensures the symmetry of the magnetic system.

Figure 6 Magnetic field gradient (top) and field strength (bottom) of the POLANO $^3$He NSF coils as illustrated in figure 5. The Z axis is along the neutron beamline and the center of the $^3$He cell is at (R,Z) = (0,0).
2.3. Oven, heater, and AFP

In the POLANO $^3$He NSF, a $^3$He cell is heated to 200–250 °C in an oven made of aluminum that is wrapped with a flexible polyimide heater. The polyimide heater is specially designed to minimize magnetic field production due to the heater current. It consists of two layers of nickel-chromium foil that have identical strip patterns, separated by a polyimide film. The heater currents passing through the strips of the two layers are opposite in direction to each other so that the magnetic fields produced by the heater currents are canceled. Additional polyimide films are attached to both surfaces of the heating element for electrical insulation [7]. Figure 7 shows a photograph of a cylindrical aluminum oven wrapped with polyimide heater.

![Cylindrical aluminum oven wrapped with polyimide heater](image)

Figure 7 Cylindrical aluminum oven wrapped with polyimide heater. The oven is 120 mm in diameter and 160 mm long. The polyimide heater is secured using nonmagnetic brass or titanium wires. During operation, polyimide foam is attached to the polyimide heater for thermal insulation (the foam has been removed before taking the photograph).

Inside the oven, a cosine-theta coil is arranged to produce a uniform alternating magnetic field for AFP NMR [8]. The frequency of the coil current is swept and the $^3$He spins are adiabatically flipped in a static magnetic field when the frequency crosses the Larmor resonance value. The sweeping speed used in the POLANO $^3$He NSF is 100 kHz/s. The depolarization of the $^3$He spin by one AFP spin flip was measured to be 0.0005, which, though not negligible, is acceptably small for practical use. Figure 8 shows the cosine-theta coil inside the cylindrical aluminum oven.
2.4. Laser and optical system

A high power laser diode array (LDA) with a chirped volume Bragg grating (VBG) in the POLANO $^3$He NSF emits a laser light with a power of ~70 W and a wavelength width < 0.2 nm (full width at half maximum) at the Rb D$_1$ frequency [9]. The center wavelength can be tuned remotely by moving the translation position of the chirped VBG. A quarter wave plate that converts linear polarization into circular polarization is placed after the chirped VBG. Its rotational position is also remotely controlled in order to reverse the polarity of the laser (right or left-handed) according to the spin state of $^3$He. Next, the laser profile is reshaped using lenses to match that of the $^3$He cell. The laser is reflected using two mirrors to illuminate the $^3$He cell parallel to the neutron beam. The transmission spectrum of the $^3$He cell is measured by an optical spectrum analyzer (OSA) using a partial reflection mirror and an optical fiber. A schematic of the laser optical system is shown in figure 2. Si wafers are used as substrates in the full and partial reflection mirrors in the neutron beamline in order to minimize unwanted neutron scattering.

The POLANO $^3$He NSF including the optical and magnetic systems is shown in figure 9. All the optical components as well as the coils, oven, and $^3$He cell are enclosed in a laser shield box for safety.
2.5. Safety measures

The POLANO $^3$He NSF system is equipped with interlocks for safety. The interlock system monitors the temperatures of the LDA, $^3$He cell, polyimide heater, and solenoid as well as the flow rate and hydraulic pressure of the coolant water for the LDA. The heater voltage and current are continuously monitored to detect heater burnout. The interlock system automatically shuts down the laser and heater current when the parameters exceed acceptable levels. Physical guards and interlock switches are also included in the system to prevent injuries due to the laser and high operating temperatures.

3. Optical pumping test

An optical pumping test was performed for the POLANO $^3$He NSF in an off-site laboratory. A $^3$He cell inside the oven was kept at 240 °C for continuous optical pumping. The polarity of the laser was reversed every 15 minutes along with the $^3$He spins using AFP NMR. Figure 10 shows the variation of the peak height of the measured AFP NMR signals that are proportional to the $^3$He polarization over four days. Positive and negative signals were alternately observed corresponding to the change of the spin states from down to up and vice versa. The $^3$He polarization increased for approximately 30 hours from the start of the optical pumping, after which it reached a maximum. The time constant of the polarization build-up was 5.5 hours. The optical pumping was continued for an additional 60 hours, during which the $^3$He polarization stayed at a constant value until the end of the experiment.

Figure 9 POLANO $^3$He NSF viewed from the top. All components are fixed on a 60 cm × 60 cm optical table and enclosed in a laser shield box for safety.
Figure 10 AFP NMR signals measured every 15 minutes during an optical pumping test of the POLANO $^3$He NSF. Positive and negative signals correspond to the changes of the $^3$He spin states from down to up and vice versa. A $^3$He cell with a diameter of 60 mm and a length of 60 mm filled with $^3$He at 2.3 atm was used.

4. Summary and plans for future upgrade
We have developed an in-situ polarized $^3$He NSF that will be installed in POLANO for incident neutron beam polarization. Polarized neutron beams with diameters of 50 mm and energies up to 100 meV will be provided by this $^3$He NSF at the first stage of the POLANO operation. A continuous optical pumping test performed off-site demonstrated a successful operation of the POLANO $^3$He NSF. We have performed similar tests with different $^3$He cells and have not encountered any problems so far. The $^3$He polarizations measured using Rb electron paramagnetic resonance shifts for several $^3$He cells were found to be 70–75 % [10]. We will perform further optical pumping tests for longer periods to investigate the durability of the $^3$He NSF before final installation in POLANO.

The usable neutron beam energy and diameter will be increased with larger $^3$He cells in the near future. According to figure 3, an effective $^3$He thickness of approximately 50 atm·cm is required to polarize neutrons with an energy of 200 meV. Taking into consideration the safety issues pertaining to the use of the $^3$He cells at high pressure and large cell volumes, the $^3$He gas pressure at room temperature and thicknesses should lie between 2.5–5 atm and 10–20 cm, respectively. The cell diameter will also have to be increased to 80 mm in order to accommodate the complete neutron beam profile. Further studies are necessary to fabricate such large cells that can withstand higher gas pressures. In the current design, only one end of the $^3$He cell is illuminated by the laser. The $^3$He polarization can be increased by illuminating both ends of the $^3$He cell. Increasing the laser power will also be beneficial for $^3$He cells with larger volumes. Designing of the double laser system is currently under progress and will constitute the next upgrade of the POLANO $^3$He NSF.

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