Developments of In-Situ SEOP Polarized $^3$He Neutron Spin Filter in Japan

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Abstract. We launched the polarized $^3$He neutron spin filters (NSF) project in order to provide neutron polarization for the pulsed neutron beams in Japan. We adopted the in-situ spin exchange optical pumping (SEOP) technique to polarize the nuclear spin of $^3$He atoms because it has some advantages for our applications. The overall system size is compact and it avoids the problem of the time decay of nuclear spin of $^3$He thus suppressing the costs of maintenance and providing other advantages [1, 2] with respect to data analysis and quality. In this paper, we performed pulsed neutron beam tests of our compact in-situ SEOP NSF system at the BL10 beamline in the Materials and Life Science Experimental Facility of the Japan Proton Accelerator Research Complex (J-PARC). The polarization of the $^3$He gas reached was 73 % and a pump-up time constant of 9.5 h was observed. This paper is a status report about the development of in-situ SEOP NSF system for the pulsed beam at J-PARC.

1. Introduction
Polarized neutron scattering techniques are very important and powerful tools to study the structures of magnetic materials, soft matters and so on [3, 4, 5]. Because user operation of J-PARC started in December of 2008 it is urgently necessary for us to develop neutron spin filters for our pulsed neutron scattering experiments. To polarize the neutron beam, Heusler alloy crystals [6] and magnetic supermirror devices [7] have been used widely for several tens of years. But the Heusler alloy crystals only provide monochrome polarized neutron beams and the supermirror devices can not deal well with thermal (i.e. 1.8 Å mean wavelength) neutron beams. In the last several years, another method, polarized $^3$He neutron spin filters (NSF), have been extensively developed and become popular [8]. NSF s work because $^3$He has a very large absorption cross section for neutrons in the opposite spin state to that of the $^3$He nucleus and largely transmit the spin-parallel state for reasonable $^3$He polarizations while the neutron scattering cross section of $^3$He is small. Compared with other spin filters such as

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Heusler crystals and magnetic supermirrors, the $^3$He gas NSF have the following advantages: it can polarize various energy of neutrons such as cold, thermal and epithermal neutrons and it can be used for wide area and large divergence neutron beams. These characteristics of polarized $^3$He are convenient for use at J-PARC as a NSF. So we launched the project team aiming to provide polarized $^3$He NSFs for the pulsed neutron beams in Japan at J-PARC.

There are two major techniques to polarize the $^3$He nuclear spins, one is the spin exchange optical pumping (SEOP) technique [9] and the other is the metastability exchange optical pumping (MEOP) technique [10]. Comparing with these two techniques, the SEOP technique has some advantages as described below. The overall size of a SEOP system is small enough to install into the instruments and the initial investment cost is almost one tenth of that of a MEOP system. Further the system configuration and use is simple because it can polarize the NSF cell directly and thus does not need daily maintenance. Whereas if we where to prepare the NSF by using a MEOP system, we would need to compress and transfer the polarized $^3$He gas into the NSF cells using a large system and then transfer the NSF to the neutron beam. In addition to these advantages, in-situ SEOP NSF system can avoid the time decay of the $^3$He nuclear spin experienced when off line polarized gas is used. On the other hand, the present SEOP NSF system has some disadvantages. The productive capacity of the SEOP system is quite small and the SEOP system cannot polarize a complicated NSF cell such as a fan shape cell or cell with Si crystal windows, etc. whereas the MEOP based system is suitable for such cells, and can have a higher capacity per system. Despite these drawbacks, considering the advantages we adopted the in-situ SEOP technique to polarize the NSF cells.

2. Design of the in-situ SEOP system

The $^3$He NSF will work as a neutron polarizer or a neutron spin analyzer. Most of the instruments in the J-PARC MLF typically have an incident neutron beam size of less than (40 x 40) mm$^2$. So in case of using the NSF as a polarizer for the injected beam, a cylindrical cell with a diameter of 50 mm is sufficient. In the case of polarisation analysis, because most of the instruments in the J-PARC MLF have large solid angle detector banks, the NSF cells are required to cover them. The shape of the NSF cells should become more complex such as a cylindrical cell with a large diameter, a fan shape cell, etc. It is thought that the development of the system that uses a small NSF cell is easier. So we decided to develop the in-situ SEOP NSF system for incident beam polarizer first.

![Figure 1](image)

**Figure 1.** (a) Picture of the improved in-situ SEOP NSF system. (b) Wavelength and bandwidth of the laser was tuned by external cavity. (c) Picture of the laser spot at cell position.
Fig. 1(a) shows the picture of the inside of the in-situ SEOP NSF system. The optics is put in the laser shield box made of black anodized aluminium board for laser safety. The laser shield box has a dimension of \((60 \times 60 \times 30)\) cm\(^3\). In this system we used a nLight VSA-100-796 diode laser (DL) with varied output power (up to 100 W at 120A) and a Newport laser driver model 5600 (up to 65 A). Because of the current limitation, the laser diode was driven at 47 W. The linear polarized laser beam emitted from the laser diode passes through a half-wave \((\lambda/2)\) plate to rotate the direction of polarization and to change the ratio of p-wave to s-wave. Here we control the laser power of the p-wave component to 14 W. A polarizing beam splitter (PBS) separates the laser beam into the p-wave and the s-wave components [11]. Then the p-wave and s-wave components are sent to an external cavity and beam transform optics, respectively. The external cavity controls the wavelength and narrows the bandwidth of the laser. Fig. 1(b) shows the spectra of the emitted laser narrowed by the external cavity. The FWHM of the emitted laser was reduced to 0.17 nm. The beam-transform optics enlarge the laser beam spot size enough to illuminate the entire cell and converts the linearly polarized laser into circularly polarized laser light. Fig. 1(c) shows the laser beam spot at the cell position. We optimized the configuration of the optics for an NSF cell with a 34 mm diameter, which was used for the on-beam test. Details of the NSF cell are described next section. The beam spot size was sufficiently enlarged and the laser power density was more than 1 W/cm\(^2\) over the entire cell. The cell is put into the oven in the solenoid coil, which can provide a magnetic environment with a transverse magnetic field gradient of less than 0.0005 cm\(^{-1}\) within a cylindrical space with a diameter of 50 mm and length of 100 mm for the \(^3\)He gas NSF cell [2].

3. Polarization tests
We performed tests with a pulsed neutron beam on the NOBORU beamline at J-PARC MLF. Fig. 2 shows the schematic drawing and a picture of the experimental setup. In this test, we used a cylindrical NSF cell with a total \(^3\)He gas quantity of 16.9 atm-cm. The dimensions of the NSF cell were 34 mm in diameter and 53 mm in length. The neutron beam monitor, NSF cell and resister divide photomultiplier tube (RPMT) 2-dimensional position sensitive detector (2D PSD) [12] were located 12.6 m, 13.0 m and 14 m far from the moderator, respectively. The beam size was set to \((20 \times 20)\) mm\(^2\). The NSF cell was heated to 180 °C during the experiment.

![Figure 2](image_url)

**Figure 2.** (a) Picture of the NSF cell with a diameter of 34 mm, length of 53 mm and total \(^3\)He gas quantity of 16.9 atm-cm. (b) Schematic drawing of the experimental set up at BL10 beamline in J-PARC. (c) Picture of the in-situ SEOP system installed into BL10.

We performed optical pumping for 60 hours and then measured the wavelength dependence of the neutron beam transmission intensity through the NSF cell filled with polarized \(^3\)He gas. After that we stopped the optical pumping, depolarized the \(^3\)He gas in the NSF cell by using a permanent magnet and measured the neutron beam transmission intensity of the depolarized NSF cell. Results are shown in figure 3(a), the obtained data were normalized by
the neutron beam monitor counts. The polarization of \(^3\)He gas in the NSF cell is calculated from the neutron beam transmission intensity of the NSF cell filled with unpolarized \(^3\)He gas \(T_0\) and polarized \(^3\)He gas \(T\) by following equations:

\[
T_0 = e^{-\sigma \rho t},
\]

\[
\frac{T}{T_0} = \cosh \left( P_{\text{He}} \sigma \rho t \right),
\]

where \(T_0 = e^{-\sigma \rho t}, P_{\text{He}}\) is the \(^3\)He polarization, \(\sigma\) is the neutron absorption cross section for unpolarized \(^3\)He, \(\rho\) is the number density of \(^3\)He and \(t\) is the length of the \(^3\)He gas \[2\]. The analyzed neutron beam polarization vs. neutron wavelength is shown in figure 3(b). The \(^3\)He gas polarization was 73 % and independent of the wavelength, thus confirming the accuracy of the neutron calibrations. After adjusting the optics, we measured the pumping time dependence of the \(^3\)He gas polarization for 50 hours. The result is shown in figure 3(c). The \(^3\)He gas polarization finally reached to 70 % and a pump-up time constant of 9.5 h was observed. We performed a neutron beam test at the NOP beamline of the Japan Research Reactor-3 (JRR-3) research reactor in JAEA before. The NOP beamline can provide a highly polarized neutron beam (P>99 %) with a wavelength of 8.4 angstrom. We studied the dependence of \(^3\)He polarization on temperature. Results of this study show that \(^3\)He polarization was finally saturated at 73 % at an optimum temperature of 180 degree and the observed \(T_{\text{UP}}\) was 9.5 h. Those results are almost consistent with our previous experiments performed using a continuous neutron beam on the NOP port in the JRR-3 guide hall. The cause of the suppressed maximum polarization from 73 % to 70 % is considered to be due to improper adjustment of the optics.

\[\text{Figure 3. (a) Wavelength dependence of the transmitted neutron beam intensity for the NSF with polarized and depolarised } ^3\text{He gas. (b) Calculated neutron polarization. (c) Pumping time dependence of the } ^3\text{He gas polarization measured during in-situ SEOP.} \]
4. Summary
We designed the compact in-situ SEOP NSF system aiming to use it as a polarizer for incident beams at J-PARC and performed a pulsed neutron beam tests of it at the J-PARC BL10 beamline. A $^3$He gas polarization of 73 % and a pump-up time constant of 9.5 h was observed. These results were consistent with our previous tests performed at JRR-3 while using the continuous neutron beam there. In summary we succeeded to polarize the pulsed neutron beam at J-PARC by using the compact in-situ SEOP NSF system.

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