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Improvements and Polarization Tests of ^{3}He Neutron Spin Filter Based on Spin Exchange Optical Pumping in Japan

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ABSTRACT

We began the development of the on beam spin exchange optical pumping system aiming to use it s a neutron spin filter for incident beam polarisation and polarisation analysis. In our previous spin exchange optical pumping system, an external cavity for narrowing the bandwidth of the laser and beam transform optics for enlarge the laser beam spot size were connected in series. We installed a prism beam splitter into the system to separate these two parts. In the improved system, adjustment of the optics was simplified, the bandwidth of the laser was improved and homogeneous laser power density over the entire cell was obtained.

1. Introduction

Polarized neutron scattering techniques are very important and powerful tools to study the structures of magnetic materials and soft matters. In addition to the research reactor of JRR-3 under operation, the pulsed neutron source of J-PARC began operation in 2008 in Japan. It is urgently necessary for us to develop the neutron spin filters (NSF) for polarized neutron scattering experiments. ^{3}He has a very large absorption cross section for only neutrons in opposite spin state to that of the ^{3}He nucleus. The scattering cross section of ^{3}He is small. These two features allow nuclear spin polarized ^{3}He gas to work as a NSF. Compared with other spin filters such as Heusler crystal and magnetic supermirrors, the ^{3}He gas NSF have following advantages [1]: it can polarize various energy of neutrons such as cold, thermal and hot neutrons, it can work for broadband neutrons and it can be used for wide area and large divergence neutron beams. These characteristics of polarized ^{3}He are convenient in use at J-PARC as NSF. Therefore we started the polarized ^{3}He gas spin filter project in Japan.

There are two techniques to polarize the ^{3}He nuclear spins, spin exchange optical pumping (SEOP) method [2] and metastability exchange optical pumping (MEOP) method [3]. The pressure of ^{3}He gas in the optical pumping cell of the SEOP system is typically 1~3 bar, and the cell of the length several centimeters can be used as NSFs. In the MEOP method, the optical pumping is done at pressures of 1 mbar and the polarized ^{3}He gas is preserved in a container after compressing. Because the SEOP technique does not require the sophisticated compressor system used in the MEOP system, the size of the SEOP system is relatively compact. The SEOP system can be built into the beamline and can polarize the ^{3}He in-situ. We began the development of the on beam SEOP system aiming to use it as a NSF for incident beam polarisation and polarisation analysis.

2. The SEOP system

2.1. SEOP process

A schematic diagram of the SEOP process is shown in Fig. 1. The ^{3}He gas of 1 ~ 3 bar, nitrogen gas of about 0.1 bar and droplets of Rb are enclosed in the optical pumping cell. The cell is heated up to 160 degree to vaporize the Rb. A uniform magnetic field of ~20 G is applied around the cell in order to preserve the polarization. In the SEOP method, polarization of the ^{3}He gas is achieved in two steps. In the first step, the valence electron of the vaporized Rb atoms are polarized by circularly-polarized laser light. The laser light of 794.8 nm in wavelength excites the principal electric dipole transition of the valence electron from the $m_s=\pm 1/2$ to the $m_j=\mp 1/2$ state. We used sigma plus circularly-polarized laser, which only can excites atoms in the m_s=-1/2 state under angular momentum conservation and then decays to $m_s=\pm 1/2$ states. Atoms that decay to the m_s=+1/2 state remain in that state, but atoms that decay to the m_s=-1/2 state excited by laser and then the polarization of the electronic spin of the Rb is polarized. The nitrogen in the cell suppresses emission of photons, which depolarize other atoms. In the second step, the spin exchange in binary collisions occurs due to the hyperfine interaction of the Rb electron with the nuclear spin of ^{3}He. Because the probability of such collisions is very low, it takes long time to polarize the ^{3}He. The steady state of ^{3}He polarization is given by [4]

$$P_{He} = P_{Rb} \frac{\kappa_{SE}[Rb]}{\kappa_{SE}[Rb](1+X)+\Gamma}, \qquad (1)$$

where P_{He} and P_{Rb} are the polarizations of the ^{3}He and Rb, respectively, $[Rb]$ is the density of the Rb vapor, Γ is the relaxation ratio of ^{3}He polarization and X is an additional relaxation ratio of ^{3}He polarization.

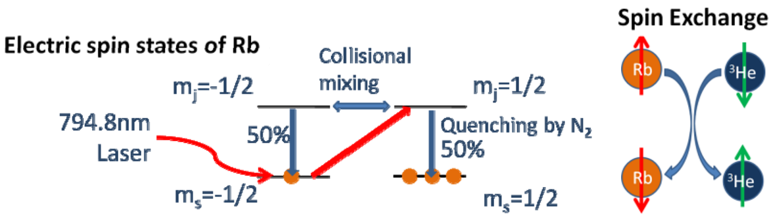

Fig.1 A schematic diagram of the SEOP process.
In the SEOP method, electronic spin polarization of Rb atoms are produced by optical pumping first, and then the polarization is transferred to the ^{3}He nuclei by the hyperfine interaction during collisions.

2.2. Design of the SEOP system

Figure 2 shows a schematic drawing of the on beam SEOP NSF system [5]. The optics is put in the laser shield box made of the black anodized aluminum board for laser safety. The laser shield box has a dimension of 60 x 60 x 30 cm. The NSF system consists of three parts with different functions. The external cavity controls the wavelength and narrows the bandwidth of the laser. The beam-transform optics, which is put on the downstream of the external cavity, enlarges the laser beam spot size enough to illuminate the entire cell and converts the linearly polarized laser into circularly polarized laser light. In the downstream, there is a coil with a built-in oven with quarts windows. The optical pumping cell is put in the oven and heated up to 160 degrees. An external magnetic field of several ten gauss is applied to the cell.

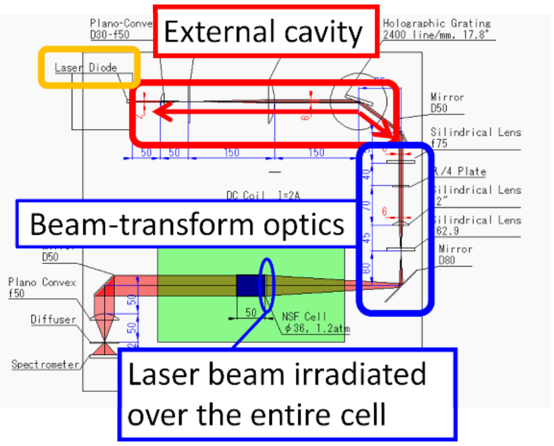

Fig.2 A schematic drawing of the on beam SEOP NSF system.

3. Improvement of the optics

3.1. Confirmation of the SEOP system

First, we checked the conditions of the laser at cell position. In previous test performed by Ino *et al* [5], the ^{3}He polarization reached 50% and not saturated yet. Figure 3 (a) shows the spectrum of the emitted laser at cell position (without cell). The D_2 line of the Rb was observed at 794.7 nm. The full width of half maximum (FWHM) of the obtained wavelength distribution pattern was 0.31 nm. It was confirmed that the external cavity worked, but not sufficiently narrowed the bandwidth. Figure 3 (b) shows the laser beam spot at cell position. Though the diameter of the cell was 3 cm, the laser beam spot size was 2×2.5 cm^2. Strong inhomogeneous beam power distribution was also observed. It was considered that the laser power density is insufficient for homogeneous optical saturation of the resonance transition over the entire cell. During the experiment, the gratings angle on the external cavity need to be changed several times to optimize the wavelength of the laser. In this SEOP system, when the angle of the grating in the external cavity was changed to adjust wavelength, it we confirmed that the shape and power density distribution of the laser spot changed. The series connection of the external cavity and the beam-transform optics also cause problem.

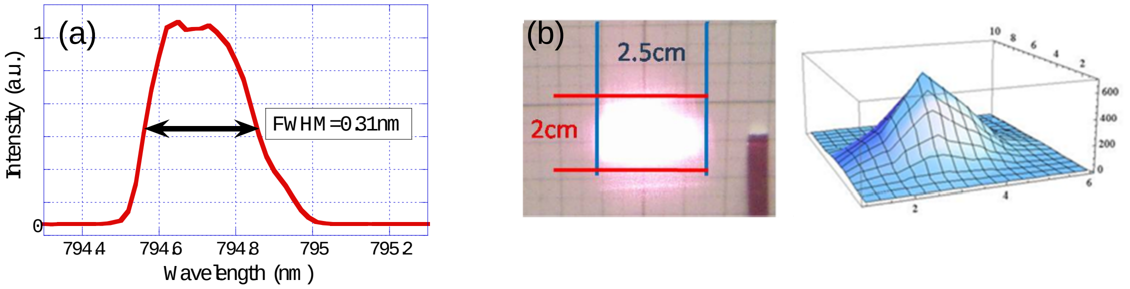

Fig.3 (a) spectrum of the emitted laser at cell position.
(b) observed laser beam spot at cell position.

3.2. Improved optics and laser settings

The SEOP system using a prism beam splitter (PBS) was reported by S. Boag *et al*. [6]. So we introduced the PBS after the half lambda plate to separate the external cavity and the beam-transform optics first. The picture of the improved system is shown in Fig. 4. The beam spot at the cell position will be no longer influenced by the adjustment of the grating. Figure 5(a) shows the spectra of the emitted laser of improved system. The FWHM of the emitted laser was reduced to 0.17 nm. The improved optics is 1.6 times as efficient as the previous one. Next, we installed and optimized the beam-transform optics. Figure 5(b) shows the laser beam spot and power density map at cell position. It was confirmed that the sufficient laser power density is obtained over the entire cell. The beam spot size was 1.4 times enlarged.

Neutron beam test with this improved on beam SEOP system is planned in near feature.

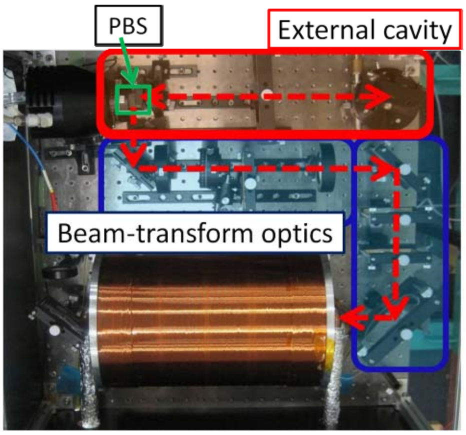

Fig.4 picture of the improved on beam SEOP system with the PBS.

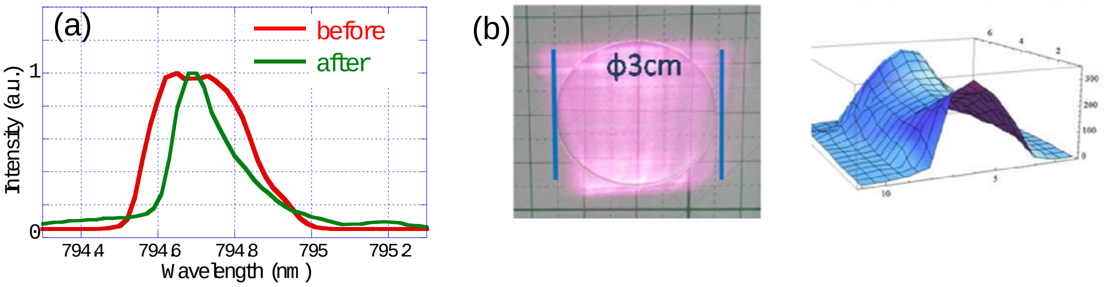

Fig.5 (a) spectrum of the emitted laser of before and after improving system.
(b) observed laser beam spot at cell position.

4. Summary

In our preliminary neutron beam test, the obtained polarization of the ^{3}He gas was only 10%. We investigated the cause of that result and found following problems: an external cavity to yield narrow-bandwidth emission from a high-power laser-diode array did not work well, the laser power distributed inhomogeneously at the ^{3}He cell position. To solve these problems, we improved our SEOP system by installing the PBS, optimizing the beam-transform optics.

5. References

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