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Development of ^{3}He polarized neutron spin filters at KEK

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Abstract

Development of neutron spin filters based on polarized gaseous ^{3}He is underway at KEK. Spin-exchange optical pumping is employed to polarized ^{3}He nuclei. Quartz glass cells and sapphire cells are studied as ^{3}He containers. Spin relaxation times of more than 200 h have been observed for quartz glass cells with ^{3}He pressures of 3 atm. Using a pulsed neutron beam, polarizations of ^{3}He were measured for a quartz glass cell and a sapphire cell with ^{3}He pressures of 3 atm to be $54\pm2\%$ and $63\pm1\%$, respectively.

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1. ^{3}He neutron spin filter

Polarized gaseous ^{3}He can be used as a broadband neutron spin filter from cold to epi-thermal energy regions. In addition to the broadband nature, the ^{3}He spin filter has lower background compared to the magnetic mirror polarizer or the proton polarizer since no gamma rays are produced in the ^{3}He-neutron reaction. Recent advance in solid-state laser technology allows one to polarize a large volume of ^{3}He gas, and thus a large area or a large solid angle can be covered with polarized ^{3}He gas as a neutron spin analyzer as well as a neutron polarizer.

We employ spin-exchange optical pumping (SEOP) to polarize ^{3}He nuclei [1]. Nuclear polarization of ^{3}He is achieved in spin exchange between ^{3}He nuclei and rubidium atoms through a hyperfine interaction. Rubidium electrons are polarized by the optical pumping through the D1

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transition with circularly polarized light of 795 nm. In SEOP, the polarization build-up of ^{3}He is dominated by the spin-exchange rate and the spin-relaxation rate of ^{3}He as expressed in

$$P_{\mathrm{He}} = \frac{\gamma_{\mathrm{se}}}{\gamma_{\mathrm{se}} + \Gamma_{\mathrm{R}}} P_{\mathrm{Rb}}(1 - \mathrm{e}^{-(\gamma_{\mathrm{se}}+\Gamma_{\mathrm{R}})t}), \quad (1)$$

where P_{Rb} is the rubidium polarization; t is time; γ_{se} and Γ_{R} are the spin-exchange rate and the spin-relaxation rate, respectively. The spin-exchange rate γ_{se} is typically from $1/(5\,\mathrm{h})$ to $1/(20\,\mathrm{h})$ depending on cell temperature. The rubidium polarization P_{Rb} depends on the polarization of the incident laser, laser power, and rubidium number density. To achieve a high rubidium polarization is relatively easy for small cells with high-power diode lasers. For $t \to \infty$, the maximum ^{3}He polarization becomes

$$P_{\mathrm{He}} = \frac{\gamma_{\mathrm{se}}}{\gamma_{\mathrm{se}} + \Gamma_{\mathrm{R}}} P_{\mathrm{Rb}}. \quad (2)$$

To achieve a large ^{3}He polarization, Γ_{R} must be much smaller than γ_{se}. Compared with a spin-exchange rate of $1/(5\,\mathrm{h})$ to $1/(20\,\mathrm{h})$, a spin relaxation time T_1 ($= 1/\Gamma_{\mathrm{R}}$) of 100 h or longer is preferred. In addition, with a very long relaxation time, it may no longer be necessary to polarized ^{3}He at a spectrometer (in situ) for many neutron scattering experiments. One can optically pump a ^{3}He cell anywhere and then transport it to a neutron spectrometer for use [2]. In the case of this use, no laser, optics, or heating system is necessary at a spectrometer, and the ^{3}He spin filter can be much simplified.

The spin relaxation rate Γ_{R} is usually dominated by the wall interaction in which ^{3}He polarization is lost in collisions with iron contained in cell walls. The adsorption energy or the helium permeability of wall materials is also related with the wall relaxation. Timsit and Daniels suggest that the wall relaxation depends on a combination of iron content and helium permeability [3]. Other significant contributions are the ^{3}He–^{3}He magnetic dipolar spin relaxation [4], magnetic inhomogeneity [5], and gaseous impurities. The ^{3}He–^{3}He dipolar interaction is a physical process that limits the spin relaxation time independent of the quality of cells. At room temperature, the dipolar relaxation rate is

$$\tau = \frac{744}{[^3\mathrm{He}]}\ \mathrm{h}, \quad (3)$$

where $[^3\mathrm{He}]$ is the ^{3}He density in amagats. (An amagat is a unit of density corresponding to 1 atm at 0 °C.)

The neutron polarization with respect to the ^{3}He polarization is given by

$$P_{\mathrm{n}} = \tanh(P_{\mathrm{He}}\sigma\rho l), \quad (4)$$

where P_{He}, σ, ρ, l are the ^{3}He polarization, the absorption cross-section for unpolarized neutrons, the ^{3}He number density, and the ^{3}He thickness, respectively. The hyperbolic-tangent function gives rise to a higher neutron polarization than that of ^{3}He at the cost of neutron intensity by using a thicker cell [6]. The neutron transmission is given by

$$T_{\mathrm{n}} = \mathrm{e}^{-\sigma\rho l}\cosh(P_{\mathrm{He}}\sigma\rho l). \quad (5)$$

Both neutron polarization and transmission depend on neutron energy, where the absorption cross-section σ is inversely proportional to neutron velocity. One can optimize a useful energy range by adjusting the density (the pressure) and the thickness of ^{3}He. Fig. 1 shows calculations of the neutron polarization and the transmission for ^{3}He of $\rho l = 15\,\mathrm{atm}\cdot\mathrm{cm}$, which is optimized for thermal neutrons. One can notice that $\rho l = 15\,\mathrm{atm}\cdot\mathrm{cm}$ is thick enough to obtain very high neutron polarizations (>99%) in cold energy regions, which may be useful for some precise measurements. Eqs. (4) and (5) are characterized by $\sigma\rho l$, and thus the energy dependences of P_{n} and T_{n} do not change with ρl—the functions of P_{n} and T_{n} only shift along the energy axis in accordance with ρl in logarithmic scale plots.

The neutron polarization and the transmission are also calculated in accordance with the ^{3}He spin relaxation (Fig. 2). In the calculations, the initial ^{3}He polarization is 80%, and the spin relaxation time is 200 h. The neutron polarization changes slowly with time while the transmission drops rather faster at the optimized energy. Rich et al. have observed very long relaxation times (as long as 840 h) for low pressure (~1 atm) cells [7]. With such a cell, one can virtually obtain a stable