High rate production of polarized $^3$He with meta-stability exchange method

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Recent progress in the development of high intensity infrared fiber lasers enables us to produce highly polarized $^3$He nuclei by the meta-stability exchange method.$^1$ Polarization with $P \gtrsim 0.8$ has been realized,$^2$–$^4$ and the polarized $^3$He gas has been used as polarized $^3$He targets for nuclear physics experiments as well as signal source for lung magnetic resonance imaging (MRI). The meta-stability exchange method produces polarized $^3$He nuclei much faster than the spin-exchange method because the pumping rate, i.e., the rate at which $^3$He nuclei can be polarized, is much higher. This advantage is suitable for applications such as on-demand production for lung MRI. Another important feature of the meta-stability exchange method is simultaneous production of polarized $^3$He$^+$ ions. The electrons of $^3$He$^+$ ions are also polarized, and thus they can be applied for investigation of material surfaces.$^5$ For polarized $^3$He targets, higher nuclear polarization has been required for experiments, and higher polarization can be achieved with slower relaxation rate resulting in slower pumping rate. For the above-mentioned applications, on the contrary, faster pumping rate with reasonable nuclear polarization is suitable. Therefore, we have investigated the relation between the pumping rate and the nuclear polarization in high pumping rate region.

The meta-stability exchange method is an extension of ordinary optical pumping method.$^6$ Figure 1 shows a schematic of our PLUM system (PLUM stands for Polarizer with Laser Using Meta-stability exchange). A $^3$He gas with a pressure of 0.3 Torr is sealed in a Pyrex glass cell with a size of $3\,\text{cm}^3 \times 5\,\text{cm}^2$. This $^3$He cell is set in a uniform magnetic field of 13 G generated by a Helmholtz coil in order to keep the polarization. In the meta-stability exchange method, first $^3$He atoms are excited to the meta-stable $2^3S_1$ state by applying an RF field with a frequency of $f=1$–$10$ MHz. Secondly, $^3$He atoms in $2^3S_1$ are optically pumped to the $2^3P$ state with $\sim 1083$ nm infrared light produced by a Keopsys fiber laser module.$^7$ We use a linearly polarizing beam-splitter cube followed by a quarter-wave plate to circularly polarize the laser light. For the cell with 3 cm diameter, we expand the beam with a Galilean type beam expander. By using left-handed circularly polarized light, only two sublevels of $M_F = -3/2$ and $-1/2$ out of four sublevels of $M_F = \pm 3/2$ and $\pm 1/2$ in $2^3S_1$ are concerned with
the optical pumping, which results in atomic (= total spin $F$) polarization for $^3\text{He}$ atoms in the meta-stable $2^3\text{S}_1$ state. There are nine transitions $C_1$–$C_9$ between $2^3\text{S}_1$ and $2^3\text{P}$, and $C_8$ and $C_9$ transitions are known to be efficient for production of highly polarized $^3\text{He}$. The $C_8$ and $C_9$ transitions correspond to $(2^3\text{S}_1,F = 1/2) \rightarrow (2^3\text{P}_0,F = 1/2)$ and $(2^3\text{S}_1,F = 3/2) \rightarrow (2^3\text{P}_0,F = 1/2)$, respectively. Finally, the atomic polarization is transferred to the nuclear polarization of the ground state by meta-stability exchange collisions.

Figure 2 shows the measured transmission of infrared light as a function of wave length with an RF discharge frequency of $f = 6.5 \text{ MHz}$. Resonance absorptions for $C_1$–$C_9$ transitions are clearly observed in the spectrum. The observed width of $\sim 2 \text{ GHz}$ corresponds to the intrinsic linewidth of the fiber laser, which is suitable for efficient optical pumping because the linewidth well matches to the $\sim 2 \text{ GHz}$ Doppler bandwidth of the $^3\text{He}$ gas. This narrow linewidth is sufficient to resolve the 6.7 GHz hyperfine splitting in the $2^3\text{S}_1$ state, which enables us to use the $C_8$ and $C_9$ transitions separately.

The nuclear polarization of $^3\text{He}$ can be obtained by measuring the circular polarization of an optical line at 668 nm $(3^1\text{D}_2 \rightarrow 2^1\text{P}_1)$. An isolation of 668 nm light is performed using a Thorlabs laserline filter FL670. The circular polarization of the isolated light is measured using a Thorlabs polarization analyzing system PAX5710VIS. Figure 3 shows the typical $^3\text{He}$ nuclear polarization deduced from the circular polarization of 668 nm light as a function of time. The laser was tuned for the $C_8$ transition, and was irradiated from $t = 30$ to 130 s with an RF discharge frequency of $f = 8.3 \text{ MHz}$. The measurements were performed for several RF discharge intensities which resulted in 668 nm light powers of $-54 \sim -48 \text{ dBm}$ on the system. The nuclear polarization $P$ reaches its saturation value with an effective laser power of $\sim 400 \text{ mW}$ on the cell, and it is insensitive to the applied RF frequencies. The time dependence of $P$ is expressed as $P_0[1 - \exp(-t/\tau_p)]$ where $P_0$ is the final polarization for $t \rightarrow \infty$ and $\tau_p$ is the pumping time, and the solid curves in Fig. 3 are the results of fitting. The pumping time $\tau_p$ was short as 1–6 s, which is an unique feature of the meta-stability exchange method. The maximum nuclear polarization of $P_0 = 72\%$ was obtained in $-54 \text{ dBm}$ case. The relaxation of $P$ after stopping the laser irradiation is expressed as $P_0[\exp(-t/\tau_r)]$ where $\tau_r$ is the relaxation time, and the dashed curves in Fig. 3 are the results of fitting. The relaxation time $\tau_r$ was long as 3–19 s compared with the pumping time $\tau_p$.

The relation between $\tau_r$ and $P_0$ is shown in Fig. 4(a). The Caltech data$^4$ for a 0.3 Torr cell with $f = 10 \text{ MHz}$ are also represented in the large $\tau_r$ region. It is found that in the whole $\tau_r$ region, the $C_8$ transition is the better choice to obtain higher polarization $P_0$ at fixed $\tau_p$. The nuclear polarization $P_0$ can be expressed using $\tau_p$ and $\tau_r$ as

$$P_0 = P_\infty \frac{1}{1 + \tau_p/\tau_r},$$

where $P_\infty$ is the maximum polarization for $\tau_r \rightarrow \infty$. The solid curves in Fig. 4 are the results
of fitting with Eq. (1) with constant $\tau_p$, which reproduce the measured data reasonably well.

The pumping rate $R$ can be defined as $R = N P_0 / \tau_p$ where $N$ is the number of $^3$He atoms in the cell. The relations between $R$ and $P_0$ are displayed in Fig. 4(b) for the measurements with $f = 9.6$ MHz. The nuclear polarization $P_0$ decreases almost linearly as the pumping rate $R$ increases. The solid curves are reproduction of the data with linear functions, which reproduce the data very well. In the low $R$ region of $R \lesssim 4 \times 10^{18}$ atoms/s, the $C_8$ transition is the better choice to obtain higher polarization $P_0$, and this transition has been generally used to prepare polarized $^3$He targets. In the present high $R$ region, on the contrary, the $C_9$ transition is the better choice because the nuclear polarization less depends on the pumping rate and thus it takes a higher value in this region. This is mainly due to a smaller $\tau_p$ value for $C_9$ compared with the corresponding $\tau_p$ for $C_8$, and thus the pumping rate $R$ for $C_9$ becomes higher. It is found that high rate production of $R \simeq 2 \times 10^{19}$ is possible with keeping the polarization $P_0 \simeq 50\%$ by using the $C_9$ transition. This high rate is useful for applications which require on-demand production such as lung MRI.

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Fig. 1. Schematic view of the PLUM system.

Fig. 2. Transmission of infrared light in $^3$He gas as a function of wave length. The $C_1$–$C_9$ peaks correspond to the resonance absorptions from $2^3S_1$ to $2^3P$. 
Fig. 3. Build-up and relaxation of nuclear polarization $P$ as a function of time. See text for details.

Fig. 4. (a) Nuclear polarization $P_0$ as a function of relaxation time $\tau_r$ for $C_8$ and $C_9$ transitions. The data in large $\tau_r$ region are the Caltech data. The solid curves are the results of fitting with Eq. (1). (b) Nuclear polarization $P_0$ as a function of pumping rate $R$ for $C_8$ and $C_9$ transitions. The solid lines are the results of fitting with linear functions.
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