PHYSICAL REVIEW A **81**, 033422 (2010)

Enhanced polarization and mechanisms in optically pumped hyperpolarized ^{3}He in the presence of ^{4}He

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(Received 4 July 2009; revised manuscript received 9 December 2009; published 26 March 2010)

This work reports an enhanced polarization and mechanisms in optically pumped (OP) hyperpolarized ^{3}He in the presence of ^{4}He. The cells contain Rb metal, 60-torr N_2, and different pressures of ^{3}He and ^{4}He. In the absence of ^{4}He, the polarization of ^{3}He increases monotonically from 4.5% to 8% when the pressure of ^{3}He is increased from 300 to 1500 torr. In the presence of 1850-torr ^{4}He gas, the polarization of ^{3}He is enhanced from 7% to 30% for a cell containing 600-torr ^{3}He and 60-torr N_2. The wall relaxation factors X for OP cells with and without buffering ^{4}He gas were derived. It was found that the ^{4}He gas confines the ^{3}He atoms to a diffusion-limited region which effectively reduces the wall relaxation factor X. Mechanisms contributed to relaxation are addressed and discussed.

DOI: 10.1103/PhysRevA.81.033422 PACS number(s): 33.25.+k

I. INTRODUCTION

Spin-exchange optical pumping (SEOP) [1–5] is widely used to produce hyperpolarized ^{3}He for a wide variety of scientific and medical applications. The applications include neutron spin filters [6], quantum computation [7], surface nuclear magnetic resonance (NMR) [8], and magnetic resonance imaging (MRI) [9–11]. In all these experiments, to obtain a high polarization and maintain a long relaxation time for hyperpolarized noble gas are both essential issues. Fabrication of different kinds of cells [12,13] or cells with surface coatings [14] has been attempted to achieve these goals. High polarization of P_{Rb} can be reached if the cells are constructed from GE 180 glass (GE Lighting Component Sales, Cleveland, OH 44117) [14]. However, these cells are difficult to fabricate. Coatings can effectively reduce the wall relaxation and increase the longitudinal relaxation time T_1 [15]. However, the coating procedures can be tedious or time consuming. This study reports an alternative method for enhancing polarization by buffering refillable cells with ^{4}He gas. The cells originally filled with Rb, ~60-torr N_2 and ^{3}He, are then buffered with different pressures of ^{4}He. Enhancement of polarization in optically pumped (OP) hyperpolarized ^{3}He were observed in the presence of ^{4}He. In the absence of ^{4}He, the polarization of ^{3}He is enhanced from 4.5% to 8% when the pressure of ^{3}He is increased from 300 to 1500 torr at 200°C. In the presence of 1850-torr ^{4}He, the polarization of ^{3}He is enhanced from 7% to 30% for a cell filled with 600-torr ^{3}He. Hyperpolarized ^{3}He with longitudinal relaxation time T_1 is longer than 6 h and can be routinely produced after 4 h of optical pumping. The polarization as a function of time at various temperatures during optical pumping and relaxation, respectively, was used to derive the wall relaxation factors X for OP cells with buffering ^{4}He gas. The results were compared with that of an OP cell without buffering ^{4}He. It was found that the ^{4}He gas confines the ^{3}He atoms to a diffusion-limited region which effectively reduces the value of X. We demonstrate that the gradient field causes a diffusive motion of ^{3}He and enhances the relaxation. It is highly recommended to produce hyperpolarized noble ^{3}He in high homogenous magnetic fields. Hyperpolarized ^{3}He with 30% polarization can be routinely produced and a longitudinal relaxation time T_1 of 6 h after 4 h of optical pumping can be obtained. Mechanisms of relaxation in OP ^{3}He will be addressed and the results will be discussed.

II. EXPERIMENT

Figure 1 shows a schematic of a system with optical pumping and NMR detection used for characterizing hyperpolarized ^{3}He with and without the presence of ^{4}He gas. A Helmholtz coil generated a magnetic field of 1.5 mT in optical pumping with field homogeneity of ~ 1 part per 1×10^3. A refillable Pyrex glass cell containing ^{4}He, N_2, ^{3}He, and a few mg of Rb was heated up with hot air. The cell was situated in a magnetic field B_0 which dictates the orientation for polarizing the spins of atoms. A right-hand circularly polarized (σ^+) laser light at 794.7 nm was used to pump the cells. The ^{3}He NMR signals were measured with a pulse NMR spectrometer. A radio-frequency (rf) coil placed around the cell inside the oven was used to tilt the magnetization. The sequences used to investigate the free induction decay NMR signal are shown in Fig. 1(c). In order to remove impurities and moisture absorbed in the inner-wall surface of the glass, the cells were baked at 200°C and pumped with a high-vacuum pumping station for 2–3 days. A high-vacuum pumping system evacuated the cell to a base pressure of 10^{-6} torr. After the cell had been evacuated, the cell was filled with Rb metal. The cell was then connected to the gas filling system to fill or refill cells with ^{3}He (99.5% pure), ^{4}He (99.9995% pure), and N_2 (99.9995% pure) gases. The surplus oxygen and moisture were collected via a moisture and oxygen trap (OT3 trap, Agilent Technologies, Santa Clara, CA). Homemade refillable cells with glass valves allowed one to repeatedly refill gases. The cell body was in a

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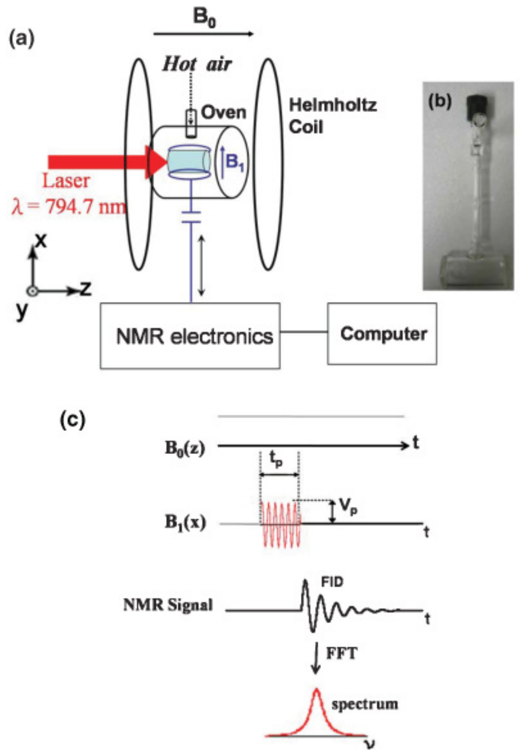

FIG. 1. (Color online) (a) Schematic of a system with optical pumping and NMR detection used for characterizing hyperpolarized ^{3}He with and without the presence of ^{4}He gas. (b) Refillable cell. (c) Sequences used to detect NMR signals.

cylindrical shape (3 cm inner diameter and 6 cm long), rounded at both ends, with a volume of 42 cm^3. The valve was right angle, all glass [16], and connected to the cell via a glass tube which was 11 cm in length and 5 mm in inner diameter. The cells were heated from 150°C to 200°C while a constant field of 1.5 mT was applied during the NMR experiments. An appropriate B_1 pulse level and time duration generated a 15° low flip angle of polarization and the free induction decay NMR signals were measured.

To characterize the ^{3}He polarization $P_{^3\mathrm{He}}$, the measured NMR signal $S_{^3\mathrm{He}}$ was compared with that of tap water $S_{^1\mathrm{H}}$. The geometry of tap water was the same as that of the ^{3}He cell. Measurements of polarization were done at the same NMR frequency and rf pulse amplitude. The polarization ratio $P_{^3\mathrm{He}}/P_{^1\mathrm{H}}$ is obtained from the relation [17]

$$\frac{P_{^3\mathrm{He}}}{P_{^1\mathrm{H}}} = \frac{S_{^3\mathrm{He}}}{S_{^1\mathrm{H}}} \frac{\gamma_{^1\mathrm{H}}^2}{\gamma_{^3\mathrm{He}}^2} \frac{n_{^1\mathrm{H}}}{n_{^3\mathrm{He}}}, \tag{1}$$

where P is the polarization, S is the signal amplitude, γ is the gyromagnetic ratio, and n is the spin density. The spin density for the ^{3}He cell was calculated from the measured pressure.

III. RESULTS AND DISCUSSION

Figure 2 shows the polarization as a function of time during optical pumping and relaxation without buffering ^{4}He at different temperatures in magnetic field of 1.5 mT. The pressure of ^{3}He is 500 torr while that of N_2 is 70 torr. The polarization increases as the temperature of the OP cell is increased. To avoid damaging the insulation of the receiving coils, the experiments were performed only up to 200°C.

Figure 3 shows the polarization of ^{3}He as a function of time for a cell buffered with different pressures of ^{4}He at 200°C during optical pumping and relaxation. The cell was filled with 600-torr ^{3}He and 60-torr N_2, whereas the pressure of buffered ^{4}He varied from zero to 1850 torr. The maximum polarization of ^{3}He at 4 h of optical pumping increases linearly from 7% to 30% when the pressure of ^{4}He is increased from 0 to 1850 torr. The polarization during optical pumping can be described by the following equation [18]:

$$P_{^3\mathrm{He}} = P_{\mathrm{Rb}} \frac{\gamma_{\mathrm{se}}}{\gamma_{\mathrm{se}} + \Gamma_1} [1 - e^{-(\gamma_{\mathrm{se}} + \Gamma_1)t}], \tag{2}$$

where $P_{^3\mathrm{He}}$ is the polarization of ^{3}He, P_{Rb} is the polarization of Rb, γ_{se} is the spin-exchange rate, and Γ_1 is the longitudinal relaxation rate of ^{3}He that relates to T_1 by the equation $T_1 = 1/\Gamma_1$. During the relaxation period, polarization P_{off} can be described by the formula

$$P_{\mathrm{off}} = P_0 e^{-\Gamma_1 t}, \tag{3}$$

in which P_0 is the polarization at the instant that the optical pump was turned off. γ_{se} and the longitudinal relaxation time T_1 were derived by fitting the experimental data into Eqs. (2) and (3). In the fitting, the ideal gas law $n_{\mathrm{Rb}} = RT/p$ was used to calculate the rubidium density n_{Rb}, where R is Avogadro's constant, T is the temperature, and p is the pressure. The

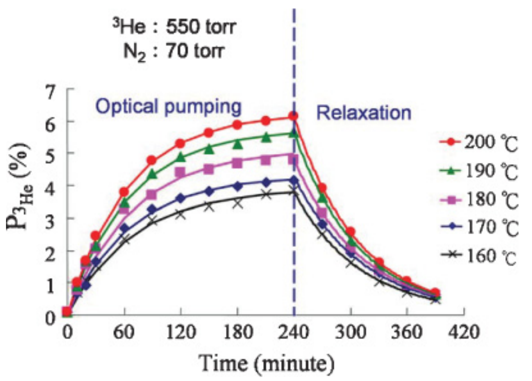

FIG. 2. (Color online) Polarization of ^{3}He as a function of time during optical pumping and relaxation at different temperatures.

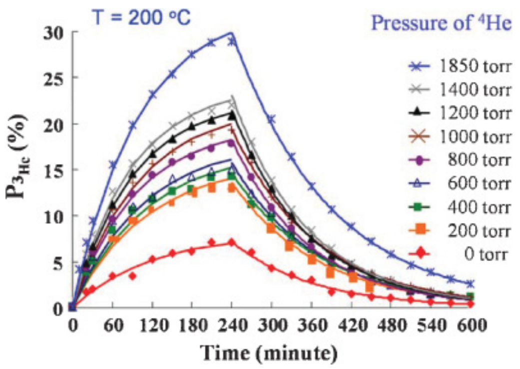

FIG. 3. (Color online) Polarization of ^{3}He as a function of time during optical pumping and relaxation for cells filled with different pressures of ^{4}He at 200°C.

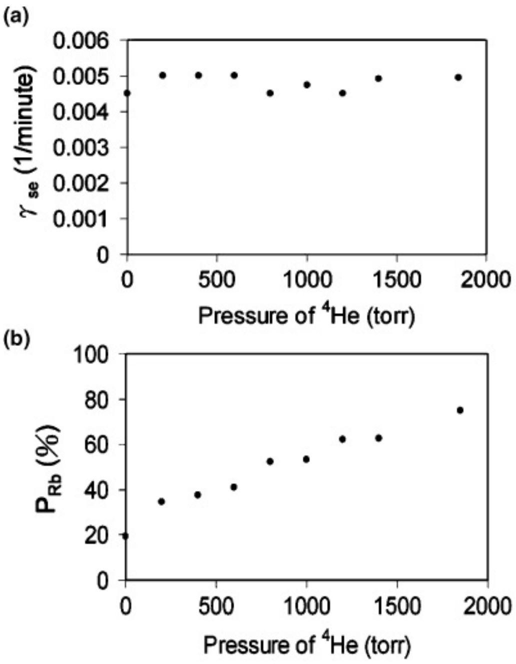

FIG. 4. (a) Spin-exchange rate γ_{se} and (b) P_{Rb} as a function of the pressure of ^{4}He at 200°C.

pressure $p(T)$ of Rb vapor was estimated from the relation [19,20] $\mathrm{Log}_{10}\ p(T) = 9.318–4040/T$, where p is in Newtons/m^2 and T is in Kelvin.

Figure 4 shows γ_{se} and P_{Rb} as functions of the pressure of ^{4}He at 200. During optical pumping γ_{se} is found to be $\sim$0.005 1/min and is independent of the pressure of ^{4}He. The P_{Rb} is 20% when ^{4}He is absent. The P_{Rb} is enhanced linearly from 20% to 80% when the pressure of ^{4}He is increased from zero to 1850 torr. The ^{4}He gas broadens the absorption linewidth of Rb atoms [21,22], which enhances the absorption of laser light. Therefore, there is an enhancement of ^{3}He polarization when the pressure of ^{4}He is increased. During the relaxation, the polarization P_{off} can be described by the relation: $P_{off} = P_0 e^{-\Gamma_1 t}$. The relaxation time $T_1 = 1/\Gamma_1$ of ^{3}He, measured in a field homogeneity of 1 part per 10^3, is improved from 2.05 to 2.46 h when the pressure of ^{4}He is increased from zero to 1850 torr. In addition to enhancing the polarization of ^{3}He and the buffering, ^{4}He can reduce the wall relaxation rate.

Figure 5 shows the polarization of ^{3}He as a function of time at 200°C in different field homogeneities. The cell used for pumping contains 70-torr N_2, 1200-torr ^{3}He, and 600-torr ^{4}He and Rb metal. The $\Delta f/f = 0.00102$ corresponds to a field homogeneity of 1.02 parts in 10^3 in the sample region while the $\Delta f/f = 0.000933$ corresponds to a field homogeneity 0.933 parts in 10^3, where Δf is the spectral linewidth and f is the resonance frequency. When the field homogeneity in the sample space is improved from 1.02 parts per 10^3 to 0.933 per 10^3 (8.529% improvement), the polarization of ^{3}He is increased from 10.06% to 19.3% (82.1% improvement) and the relaxation time T_1 from 1.82 to 5.75 h (216% improvement). However, the change in the γ_{se} is not changed much. The results suggest that the field gradient affects the polarization of both Rb and ^{3}He significantly, but not γ_{se}. The effective relaxation rate T_1^{-1} is affected by the ^{3}He interacted with the wall [23], gradient field, dipole-dipole interaction [24], etc. The T_1^{-1} can be decomposed mainly into following components:

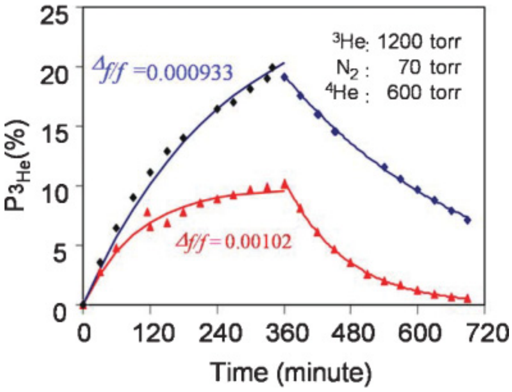

FIG. 5. (Color online) Polarization of ^{3}He as a function of time when $\Delta f/f = 0.00102$ and $\Delta f/f = 0.000933$ at 200°C.

$$1/T_1 = 1/T_{1,\mathrm{wall}} + 1/T_{1,\mathrm{field\ gradient}} + 1/T_{1,\mathrm{dipole-dipole}} + 1/T_{1,\mathrm{others}}, \qquad (4)$$

where $1/T_1 = 1/T_{1,\mathrm{wall}} + 1/T_{1,\mathrm{field\ gradient}} + 1/T_{1,\mathrm{dipole-dipole}}$, and $1/T_{1,\mathrm{others}}$ are the relaxation rate due to the wall, field gradient, dipole-dipole interaction, and other interactions, respectively. “Other interactions” refers to factors not considered, for instance, the interaction of atoms in the dark region, etc. The basic mechanism of wall relaxation is the result of the interaction between ^{3}He and paramagnetic electrons in the wall. If the magnetic impurities present in the wall can be removed, then the relaxation time can be improved significantly. The gradient field causes a diffusive motion of atoms that deteriorates the polarization. The field gradient plays an essential role in enhancing the polarization of ^{3}He. The polarization is significantly enhanced by reducing the field gradient and its improvement is demonstrated in this work. The intrinsic dipole-dipole interaction is important at high pressures of several atmospheres and negligible at low pressures of several torr in the cells. In the present study, the dipole-dipole interaction is not significant. In addition to wall relaxation, dipole-dipole, and field gradient interactions, other interactions, such as anisotropic dipole interaction, can become significant at a high pressure of ^{3}He.

Efforts were put into improving the polarization of hyperpolarized ^{3}He. Coatings can effectively reduce the wall relaxation [15]. Jacob *et al.* [25] developed a protocol for the consistent fabrication of glass cells. In general, a typical pumping time ranging from 12 to 20 h is required to reach a polarization of 40%, and 20% polarization of ^{3}He is reached in 3–5 h. Instead, the OP ^{3}He in the presence of ^{4}He demonstrated in this study shows a significant enhancement in polarization. The polarization of ^{3}He is enhanced to 30% by buffering ^{4}He to a pressure of 1850 torr. The polarization of Rb is enhanced by a factor of 4 after 4 hours of optical pumping. The present method of enhancing polarization of ^{3}He by buffering ^{4}He is simple, easy to handle, and can be of great interest for lung imaging in small animals.

In a study of the limits of polarization for SEOP of ^{3}He, Babcock *et al.* [26,27] measured the temperature dependence of ^{3}He relaxation in a wide temperature range. An excess

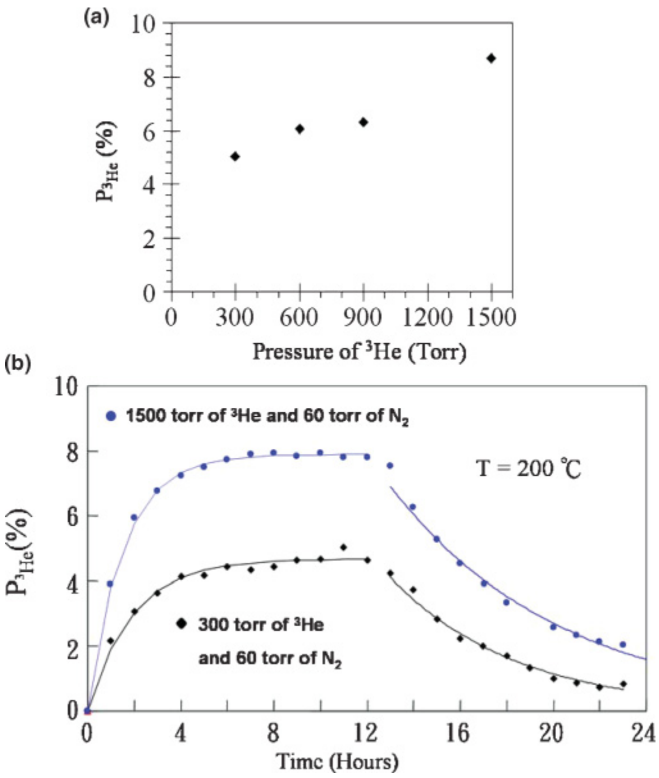

FIG. 6. (Color online) (a) Polarization of ^{3}He as a function of the pressure of ^{3}He. (b) Polarization of ^{3}He as a function of pumping time.

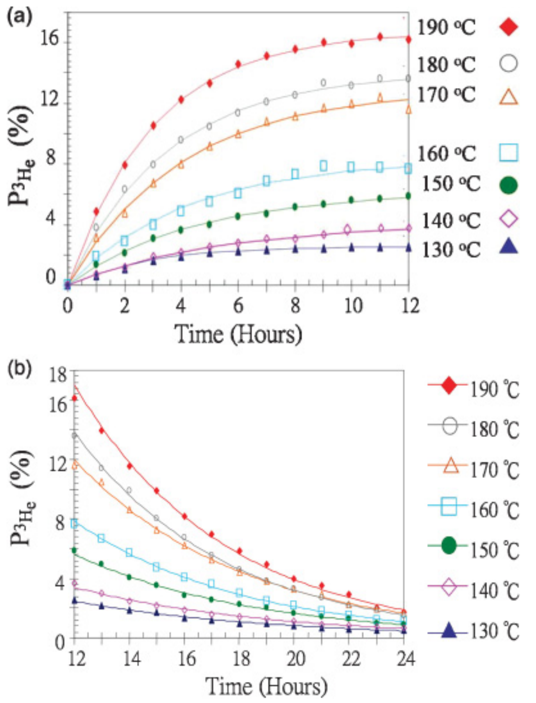

FIG. 7. (Color online) Polarization of ^{3}He as a function of time for an OP cell at various temperatures during (a) optical pumping and (b) relaxation.

relaxation that scales with the alkaline metal density was discovered. Also, the surface relaxation and anisotropic spin-exchange contributions to the relaxation were reported. In the present study of polarization of Rb and ^{3}He gas in the presence of ^{4}He, it was found that P_{Rb} and $P_{^3He}$ are enhanced significantly. The enhancement of $P_{^3He}$ is dominated by exchanging P_{Rb} to $P_{^3He}$ via collision. Furthermore, the field gradient affects the polarization of Rb and hence relaxation time of ^{3}He, but the changes to γ_{se} are minimal. The present observed unchanged γ_{se} is consistent with the reported data [28], which shows that the γ_{se} is expected to be constant for OP cells pumped at fixed temperatures.

Figure 6(a) shows the polarization of ^{3}He as a function of pressure in the absence of ^{4}He. The polarization of ^{3}He increases from 4.5% to ~8% when the pressure is increased from 300 to 1500 torr. Figure 6(b) shows the polarization of ^{3}He as a function of time for OP cells filled with 300- and 1500-torr ^{3}He, respectively, with the pressure of N_2 at 60 torr. Each cell was pumped at 200 °C. After optical pumping of 6 h, the polarization of ^{3}He was 4.5% for the cell containing 300 torr of ^{3}He and the polarization enhanced to 8% when the pressure of ^{3}He increased to 1500 torr. There is an enhanced polarization due to the increased γ_{se} when the pressure of ^{3}He is increased. The relaxation rate Γ_1 is estimated to be 5×10^{-5} 1/s ($T_1 = 1/\Gamma_1 = 5.55$ h) when the pressure of ^{3}He is 300 torr and reduces to 3.75×10^{-5} 1/s ($T_1 = 7.4$ h) when the pressure of ^{3}He increases to 1500 torr.

Figures 7(a) and 7(b) show the polarization as a function of time for an OP cell filled with 1200-torr ^{3}He, 1200-torr ^{4}He, and 60-torr N_2 at various temperatures during optical pumping and relaxation, respectively. The polarization of ^{3}He increases as the temperature of the OP cell increases. The increased polarization is attributed to the increased concentration of Rb. Therefore, more Rb atoms are contributed to the enhanced polarization during the optical pumping.

The relaxation rate, Γ_1, at the higher temperature can be written as $\Gamma_1 = \Gamma_r + k_{se}$ [Rb] $= \Gamma_r + \gamma_{se}$, where Γ_r is the relaxation rate at 300 K and $\gamma_{se} = k_{se}$ [Rb]. Therefore, the polarization $P_{^3He}$ (T) of ^{3}He at a fixed temperature T can be expressed as [28]

$$P_{^3He}(T) = \{P_{Rb}\gamma_{se}/[\gamma_{se}(1+X)+\Gamma_r]\}\{1 - e^{-[\gamma_{se}(1+X)+\Gamma r]t}\}, \tag{5}$$

where X is the wall relaxation factor. The temperature-dependent parameters T_1 and Γ_{He} were obtained by fitting the data acquired during relaxation into Eq. (5) at various temperatures. The results are shown in Table I, where

TABLE I. The longitudinal relaxation time $T_1 = 1/\Gamma_1$ and the relaxation rate Γ_{He} of hyperpolarized ^{3}He at various temperatures. Also shown is the concentration of Rb given by [29]: $[Rb] = 10^{(9.55-4132/T)}/(1.38 \times 10^{-17})T$ in units of cm^{-3}, in which T is the temperature and is in units of Kelvin.

Temperature (K)	T_1 (h)	Γ_{He} (1/s)	[Rb](cm^{-3})
190	5.37	5.68×10^{-5}	6.65×10^{14}
180	5.39	4.20×10^{-5}	4.32×10^{14}
170	5.95	2.83×10^{-5}	2.75×10^{14}
160	6.07	1.99×10^{-5}	1.71×10^{14}
150	6.50	1.26×10^{-5}	1.04×10^{14}
140	7.09	6.39×10^{-6}	6.20×10^{13}
130	7.28	3.76×10^{-6}	3.59×10^{13}

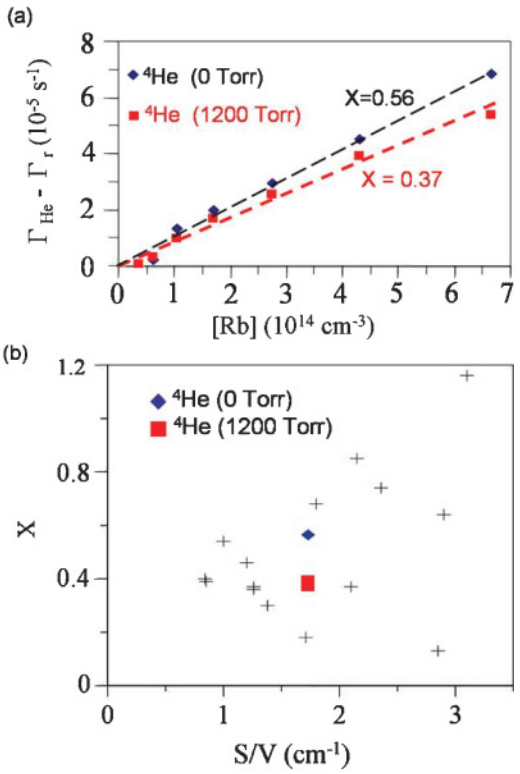

FIG. 8. (Color online) (a) $(\Gamma_{\mathrm{He}} - \Gamma_{\mathrm{r}})$ as a function of the concentration of rubidium [Rb], where $\Gamma_{\mathrm{He}} = k_{\mathrm{se}}[\mathrm{Rb}](1 + X) + \Gamma_{\mathrm{r}}$ is the total relaxation rate. (b) The X for a cell buffering with 1200-torr ^{4}He is marked with red squares, while the X for cells without buffering ^{4}He is marked with blue diamonds. Also shown are the parameters (+'s) from Ref. [28].

$\Gamma_{\mathrm{He}} = k_{\mathrm{se}}$ [Rb] $(1 + X) + \Gamma_{\mathrm{r}}$. It was found that T_1 is 7.28 h when $T = 130\,^\circ\mathrm{C}$ and T_1 reduces to 5.37 h when the temperature is increased to $T = 200\,^\circ\mathrm{C}$. The value of Γ_{He} is 3.76×10^{-6} (1/s) at $T = 130\,^\circ\mathrm{C}$ and it increases linearly to 5.68×10^{-5} (1/s) when $T = 200\,^\circ\mathrm{C}$. Both $1/T_1$ and Γ_{He} increase linearly as the temperature increases. This fact is attributed to the increasing wall relaxation.

Figure 8(a) shows $(\Gamma_{\mathrm{He}} - \Gamma_{\mathrm{r}})$ as a function of the concentration of rubidium [Rb], where $\Gamma_{\mathrm{He}} = k_{\mathrm{se}}$ [Rb] $(1 + X) + \Gamma_{\mathrm{r}}$ is the total relaxation rate for cells A and B. Cell A was filled with 1200-torr ^{3}He, 1200-torr ^{4}He, and 60-torr N_2. Cell B was filled with 1200 torr of ^{3}He and 60 torr of N_2. It is found that $(\Gamma_{\mathrm{He}} - \Gamma_{\mathrm{r}})$ increases linearly when the concentration [Rb] of Rb is increased for both cells. From the curve of $(\Gamma_{\mathrm{He}} - \Gamma_{\mathrm{r}})$ vs [Rb], the wall relaxation factor can be derived and is $X = 0.37$ for cell A, shown as red squares in Fig. 8(a). The wall relaxation factor is $X = 0.56$ for cell B, shown in Fig. 8(a) as blue diamonds. The wall relaxation factor for cell A is smaller compared with that of cell B. Figure 8(b) shows the wall relaxation factor X's reported by Babcock *et al.* [28] as +'s, showing the X's as a function of S/V for cells without buffering ^{4}He, where S is the surface area and V is the volume. In this figure, the results from our study are also included for the comparison purpose. In addition, to enhance the polarization of P_{Rb} and γ_{se} of ^{3}He effectively, the buffering ^{4}He can reduce the wall relaxation factor of OP cells. The present results suggest that the ^{4}He gas confines the ^{3}He atoms to a diffusion-limited region which effectively reduces the wall relaxation factor X.

IV. CONCLUSION

In summary, an enhancement of polarization in OP ^{3}He in the presence of ^{4}He is demonstrated. In the absence of ^{4}He, the polarization of ^{3}He is 4.5% for a cell containing 300-torr ^{3}He and enhanced to 8% when the pressure is increased to 1500 torr. In the presence of 1850-torr ^{4}He gas, the polarization of ^{3}He is enhanced from 7% to 30% for a cell containing 600-torr ^{3}He and 60-torr N_2. ^{3}He with 30% polarization and T_1 longer than 6 h can be routinely produced after 4 h of optical pumping. The buffering ^{4}He gas can significantly enhance the polarization of ^{3}He and reduce the wall relaxation factor X. Enhancing the polarization of hyperpolarized ^{3}He in the presence of ^{4}He can be promising in lung imaging [30].

ACKNOWLEDGMENTS

This work is supported by Grant No. 98-2112-M-002-010.

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[1] M. A. Bouchiat, T. R. Carver, and C. M. Varnum, Phys. Rev. Lett. **5**, 373 (1960).
[2] T. G. Walker and W. Happer, Rev. Mod. Phys. **69**, 629 (1997).
[3] W. Happer, Rev. Mod. Phys. **44**, 169 (1972).
[4] R. L. Gamblin and T. R. Carver, Phys. Rev. **138**, A946 (1965).
[5] X. Zeng, E. Miron, W. A. van Wijngaarden, D. Schreiber, and W. Happer, Phys. Lett. A **96**, 191 (1983).
[6] D. R. Rich, T. R. Gentile, T. B. Smith, and A. K. Thomson, and G. L. Jones, Appl. Phys. Lett. **80**, 2210 (2002).
[7] T. Rõõm, S. Appelt, R. Seydoux, E. L. Hahn, and A. Pines, Phys. Rev. B **55**, 11604 (1997).
[8] M. S. Albert, D. G. Cates, B. Driebuys, W. Happer, B. Saam, C. S. Springer, and A. Wishnia, Nature (London) **370**, 199 (1994).
[9] C. H. Tseng, G. P. Wong, V. R. Pomeroy, R. W. Mair, D. P. Hinton, D. Hoffmann, R. E. Stoner, F. W. Hersman, D. G. Cory, and R. L. Walsworth, Phys. Rev. Lett. **81**, 3785 (1998).
[10] S.-H. Liao, H.-C. Yang, H.-E. Horng, S. Y. Yang, M. J. Chen, and C.-H. Yang, J. Appl. Phys. **104**, 063918 (2008).
[11] B. Chann, E. Babcock, L. W. Anderson, T. G. Walker, W. C. Chen, T. B. Smith, A. K. Thomson, and T. B. Gentile, J. Appl. Phys. **94**, 6908 (2003).
[12] R. E. Jacob, J. Teter, and B. Saam, W. C. Chen, and T. R. Gentile, Phys. Rev. A **69**, 021401(R) (2004).
[13] W. Heil, H. Humblot, E. Otten, M. Schafer, R. Sarkau, and M. Leduc, Phys. Lett. A **201**, 337 (1995).
[14] G. L. Jones, T. R. Gentile, A. K. Thompson, Z. Chowdhuri, M. S. Dewey, W. M. Snow, and F. E. Wietfeldt, Nucl. Instrum. Methods Phys. Res. A **440**, 772 (2000).

[15] S. R. Breeze, S. Lang, I. M. Moudrakoviki, C. I. Rotchiffe, J. A. Ripmeester, and B. Simard, J. Appl. Phys. **86**, 4040 (1999).

[16] Part No. 826460–004, Kimble/Kontes, Vineland, NJ.

[17] B. Saam and M. S. Conradi, J. Magn. Reson. **134**, 67 (1998).

[18] R. E. Jacob, S. W. Morgan, B. Saam, and J. C. Leawoods, Phys. Rev. Lett. **87**, 143004 (2001).

[19] C. B. Alcock, V. P. Itkin, and M. K. Horrigan, Can. Metall. Q. **23**, 309 (1984).

[20] in *CRC Handbook of Chemistry and Physics*, edited by David R. Lide (CRC Press, Boca Raton, FL, 1994), 75th ed.

[21] D. Aumiler, T. Ban, and G. Pichler, Phys. Rev. A **70**, 032723 (2004)

[22] A. Andalkar and R. B. Warrington, Phys. Rev. A **65**, 032708 (2002)

[23] F. D. Colegrove, L. D. Schearer, and G. K. Waltes, Phys. Rev. **132**, 2561 (1963).

[24] R. Barbé, M. Leduc, and F. Laloë, J. Phys. **35**, 699 (1974).

[25] R. E. Jacob, S. W. Morgan, and B. Saam, J. Appl. Phys. **92**, 1588 (2002).

[26] B. Chann, E. Babcock, L. W. Anderson, and T. G. Walker, Phys. Rev. A **66**, 032703 (2002).

[27] E. Babcock, B. Chann, T. G. Walker, W. C. Chen, and T. R. Gentile, Phys. Rev. Lett. **96**, 083003 (2006).

[28] E. Babcock, B. Chann, T. G. Walker, W. C. Chen, and T. R. Gentile, Phys. Rev. Lett. **96**, 083003 (2006).

[29] T. J. Killian, Phys. Rev. **27**, 578 (1926).

[30] H. E. Möller, X. J. Chen, B. Saam, K. D. Hagspiel, G. A. Johnson, T. A. Altes, E. E. de Lange, and H.-U. Kauczor, Magn. Reson. Med. **47**, 1029 (2002).