Enhancement of SQUID-Detected NMR Signals with Hyperpolarized Liquid ^{129}Xe in a 1 μT Magnetic Field

J. J. Heckman, M. P. Ledbetter, and M.V. Romalis

Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

(Received 18 April 2003; published 5 August 2003)

We report an enhancement of proton NMR signals by a factor of 10^6 by cross polarization with hyperpolarized liquid ^{129}Xe in an ultralow magnetic field of 1 μT. The NMR signals from cyclopentane, acetone, and methanol are detected using a commercial high-T_c SQUID magnetometer with a signal-to-noise ratio of up to 1000 from a single 90° tipping pulse. This technique allows a wide range of low-field NMR measurements and is promising for the detection of intermolecular scalar spin-spin couplings. Scalar intermolecular couplings can produce a shift of the average NMR frequency in a hyperpolarized sample even in the presence of rapid chemical exchange.

DOI: 10.1103/PhysRevLett.91.067601 PACS numbers: 76.60.–k, 85.25.Dq, 82.56.Hg, 82.56.Na

Enhancement of NMR signals with laser-polarized ^{129}Xe using the spin polarization induced nuclear Overhauser effect (SPINOE) [1] has been studied in a number of systems [2–5] and was recently reviewed in [6]. While in a typical NMR field of 10 T the enhancement over the thermal spin polarization $P_{\text{th}} = \mu B/kT$ is not very large, the enhanced spin polarization is proportional to the nonthermal polarization of ^{129}Xe and is independent of the magnetic field. Thus, this technique can be used in lower magnetic fields with lower magnet costs and smaller field inhomogeneities without a loss in nuclear spin polarization. However, for conventional NMR detection using an rf induction coil the signal is proportional to the NMR frequency and the signal-to-noise ratio (SNR) still decreases linearly with the magnetic field.

Here we report on the first use of SQUIDs for the detection of SPINOE-enhanced NMR signals. SQUID magnetometers are directly sensitive to the magnetic field flux generated by the polarized spins rather than the rate of change of the magnetic flux, and their signal is independent of the NMR frequency. SQUIDs have been previously used for the detection of NMR signals [7], including recent work with ^{129}Xe [8,9] and organic liquids [10]. NMR chemical shifts have also been observed in a low magnetic field using SQUIDs [9]. These measurements either relied on thermal nuclear spin polarization or detected NMR signals from laser-polarized ^{3}He or ^{129}Xe. Here we use a commercial high-T_c SQUID magnetometer to obtain very strong NMR signals from SPINOE-enhanced protons in mixtures of hyperpolarized liquid ^{129}Xe with cyclopentane, acetone, and methanol. In an ultralow magnetic field of 1 μT we obtain proton NMR signals from a cyclopentane-Xe mixture with an SNR of about 1000 for a single 90° pulse with an initial ^{129}Xe polarization of 2%. This SNR is much higher than that obtained in recent experiments with SPINOE-enhanced proton signals using traditional rf coils in a field of 1 mT [5] or thermally polarized protons detected using a low-T_c SQUID magnetometer [10]. Even higher SNRs should be possible since our high-T_c SQUID magnetometers had a noise level of 100 fT/Hz$^{1/2}$, while low-T_c SQUIDs or noncryogenic atomic magnetometers [11] with a noise level of about 1 fT/Hz$^{1/2}$ are available. ^{129}Xe spin polarizations as high as 65% have also been obtained [12], and in combination with more efficient methods for accumulating large quantities of polarized ^{129}Xe [13], can lead to further increase in signal strength. Thus, the detection of NMR signals enhanced with hyperpolarized ^{129}Xe using SQUID or atomic magnetometers is a promising technique for NMR spectroscopy of a wide range of substances and surfaces [14] in low magnetic fields.

Operating in very low magnetic fields offers a number of advantages. We obtain proton NMR linewidths as narrow as 0.04 Hz without using shimming coils. The largest source of magnetic field inhomogeneities is the long-range dipolar field produced by the ^{129}Xe magnetization. Effects of dipolar fields on NMR dynamics have been recently studied in water [15], ^{3}He [16], and ^{129}Xe [8]. We believe this is the first study of heteronuclear long-range dipolar effects. We observe large changes in the proton transverse spin relaxation time T_2^* and the Larmor precession frequency associated with the decay of ^{129}Xe spin polarization.

We also consider the possibility of measuring a scalar nuclear spin-spin coupling by detecting a shift of the average NMR frequency in a hyperpolarized sample. A scalar J coupling of the form $\mathcal{H}/h = J\mathbf{I}_1 \cdot \mathbf{I}_2$ is caused by a second-order electron-nucleus Fermi-contact interaction and is commonly measured by looking at the splitting between several lines that appear in the NMR spectrum of I_1 spins due to different values of $(\mathbf{I}_2)_z$ in different molecules. However, this technique becomes ineffective when J is smaller than the rate of chemical exchange between molecules. It makes it particularly difficult to measure J couplings in van der Waals and other weakly bound molecules, which have recently attracted theoretical attention [17–20]. With sufficiently high polarization one can measure the shift of the NMR frequency of spins I_1 due to the average polarization of spins I_2, $\Delta\nu_1 = \langle J\rangle\langle I_{2z}\rangle$. Here $\langle J\rangle$ denotes a thermodynamic average of the spin-spin coupling, which, neglecting high density correlations, is given by $\langle J\rangle = n_2 \int J(r)\exp[-V(r)/kT]d^3r$, where $V(r)$ is the interatomic potential and n_2 is the I_2 spin density.

Averaged scalar shifts due to electron-nuclear interactions are usually parametrized by [21]

$$\Delta\nu_1 = \frac{\gamma_1}{2\pi}\kappa\frac{8\pi}{3}\mathbf{M}_{2z}, \qquad (1)$$

where $\mathbf{M}_2$ is the magnetization of spins I_2. Here $\kappa = 1$ corresponds to a frequency shift in a spherical cell for classical noninteracting spins that are as likely to be on top of each other as at any other separation. For electron-nuclear interactions $\kappa > 1$ because of mutual attraction, while for an effective nuclear-nuclear interaction we expect $\kappa \ll 1$. Recent calculations for ^{129}Xe-CH$_4$ and ^{129}Xe-benzene van der Waals complexes [20] indicate that $J_{\text{Xe-H}}$ and $J_{\text{Xe-C}}$ are on the order of 0.3 Hz. Assuming the same size J coupling for mixtures of liquid ^{129}Xe with cyclopentane or methanol, this corresponds to $\kappa \simeq 6 \times 10^{-4}$. Here we set a limit on the proton frequency shift of less than 0.03 Hz due to $J_{\text{Xe-H}}$ in cyclopentane, corresponding to $\kappa < 0.01$ for ^{129}Xe in natural abundance with 2% spin polarization. It should be possible to detect van der Waals J couplings in this system using enriched ^{129}Xe and higher spin polarizations.

Our measurements are performed in a 1.2 cm diameter spherical cell and the NMR signals are detected by two high-T_c magnetometers [22] submerged in LN$_2$ and located 1.6 cm away from the center of the cell, as shown in Fig. 1. The SQUIDs are oriented at 45° to the magnetic field and are sensitive to both the dc magnetic field created by M_z and ac fields created by precessing transverse magnetization. Initially the cell is half filled with one of the organic liquids through a thin Teflon tube inserted into the cell through the access port. The liquid is degassed *in situ* by freeze-thaw cycles under vacuum. After several cycles the liquid stops bubbling during thawing and several more cycles are performed to ensure sufficient removal of oxygen. The measurements are performed at about 170 K, above the freezing point of mixtures of xenon with cyclopentane, acetone, and methanol. We use a common spin-exchange technique [23] to produce hyperpolarized liquid ^{129}Xe. It is first accumulated in ice form outside of the shields and then distilled into the sample cell where it condenses as a liquid and mixes with the organic sample. In some runs we inserted a thin copper wire into the cell through the access port to stir the liquids in the cell.

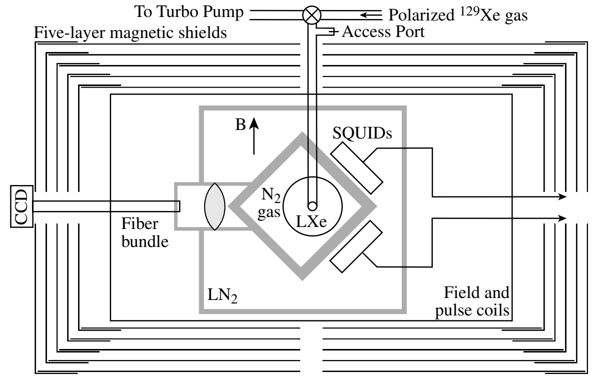

FIG. 1. Experimental setup of the sample cell and SQUID detectors. The cell is monitored using a CCD camera and its temperature is controlled by flowing cold N$_2$ gas. The access port is used to insert a thin Teflon tube through which organic liquids are injected into the cell.

The NMR signals are detected in a field of 0.95 μT corresponding to a ^{129}Xe frequency of 11.2 Hz and proton frequency of 40.4 Hz. The spins are tipped using true corotating field pulses generated by two frequency synthesizers driving orthogonal rf coils with a 90° phase difference. A typical duration for a 90° proton rf pulse is 0.2 s. The same pulse tips ^{129}Xe spins by about 0.7°, as determined by the numerical solution of the Bloch equations. We determine spin polarization of the protons from the size of the ac SQUID signal. The ^{129}Xe polarization is easier to determine from the dc shift of the SQUID signal due to changes in M_z because ^{129}Xe ac signals do not

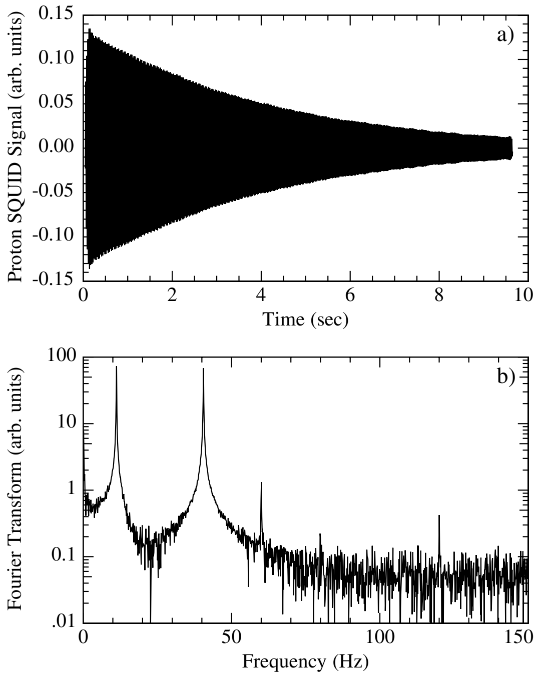

FIG. 2. (a) A proton NMR signal from cyclopentane following a single 90° pulse enhanced by SPINOE with hyperpolarized ^{129}Xe ($P_{\text{Xe}} = 2\%$). The proton signal is separated from the ^{129}Xe signal using a Fourier filter with a pass band from 35 to 45 Hz. (b) Fourier transform of the SQUID signal showing H and ^{129}Xe NMR peaks. The signal-to-noise ratio for protons is about 1000.

decay fully between pulses. The absolute magnetic field sensitivity of the SQUIDs is calibrated using external field coils. The position of the SQUIDs relative to the Xe cell is determined using a calibration loop attached to the cell by measuring the SQUID signal induced by a small current flowing through the loop. The ac signals are fit to a decaying exponential to obtain values for T_2^* of each spin species. Several runs with cyclopentane, acetone, and methanol gave consistent results.

A proton NMR signal from cyclopentane following a single 90° pulse is shown in Fig. 2. The time evolution of the ^{129}Xe and H magnetizations after mixing is shown in Fig. 3. For the ^{129}Xe-cyclopentane mixture H and ^{129}Xe signals closely track each other and decay exponentially with similar time constants. Xe dissolves well in cyclopentane since it is a nonpolar liquid and we expect that the two liquids are well mixed. In the ^{129}Xe-acetone mixture the NMR signals do not track each other. We believe that this behavior is due to complicated mixing dynamics of ^{129}Xe with acetone, which is a polar liquid. At first, rapid condensation of ^{129}Xe liquid on top of the acetone leads to their mixing in the interfacial layer, which causes the initial rapid increase of the acetone H signal. After an initial rise the acetone signal decays with a time constant of about 80 s to about 1/3 of its initial value due to rapid decay of the ^{129}Xe polarization in the mixed region. At later times the proton signal is maintained by diffusion of ^{129}Xe from the unmixed regions and the proton signal decays with a time constant of about 300 s. Similarly, the total ^{129}Xe signal shows a faster decay immediately after reaching the maximum but at later times decays with a time constant of about 350 s. Similar behavior is observed with methanol.

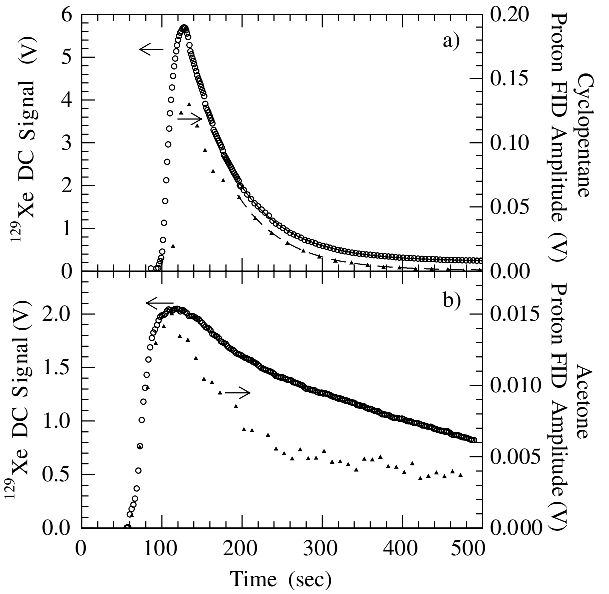

FIG. 3. Time evolution of ^{129}Xe (open circles plotted against the left axis) and H (filled triangles plotted against the right axis) magnetization for (a) cyclopentane and (b) acetone. For cyclopentane both ^{129}Xe and H signals decay exponentially, as shown with solid and dashed lines, respectively, with the same time constant of 62 s.

We operate in the regime of very low magnetic field gradients and high magnetization, where the transverse spin relaxation time is significantly affected by the gradients of the magnetization. The sample is contained in a spherical cell, for which a uniform magnetization distribution does not create any internal magnetic field. However, nonuniformity of the magnetization profile or deviations of the cell from a spherical shape can cause magnetic field gradients proportional to the ^{129}Xe magnetization. Figure 4(a) shows changes in the transverse spin relaxation T_2^* of cyclopentane and of ^{129}Xe in the mixture as a function of time. The relaxation time of ^{129}Xe at first decreases as the cell is being filled and then increases by a large factor as the ^{129}Xe magnetization becomes more uniform and then decays. In cyclopentane T_2^* increases at first but then saturates at a value of about 8 s, while the ratio of $T_2^*(^{129}\mathrm{Xe})/T_2^*(\mathrm{H})$ becomes substantially larger than $\mu_{\mathrm{H}}/\mu_{\mathrm{Xe}} = 3.6$, indicating that the magnetic field gradients are no longer limiting $T_2^*(\mathrm{H})$. From several such runs we find that the intrinsic value of T_2 in cyclopentane under these conditions is 8 ± 2 s. We determine the value of T_1 in cyclopentane using a saturation-recovery measurement by analyzing the ratio of the proton and ^{129}Xe signals as a function of separation between proton 90° pulses and find $T_1 = 9 \pm 2$ s. The two relaxation times are the same within errors, as would be

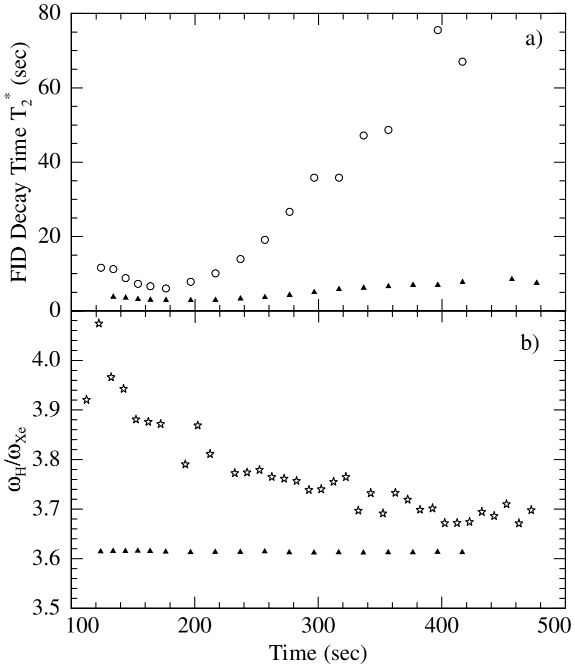

FIG. 4. (a) Transverse relaxation time T_2^* for ^{129}Xe (circles) and protons in cyclopentane (triangles) as a function of time. The evolution of the ^{129}Xe magnetization for the same run is shown in Fig. 3. (b) Changes in the ratio of H to ^{129}Xe NMR frequencies as a function of time for cyclopentane (triangles) and acetone (stars).

TABLE I. Summary of polarization enhancement data with ^{129}Xe. For ^{129}Xe T_1 measurements in acetone and methanol the first number refers to the initial decay constant of the Xe-enhanced H signal while the second number refers to the decay at later times.

Chemical	P_{Xe} (%)	SNR	^{129}Xe T_1 (s)	Proton T_2 (s)	P_H measured ($\times 10^{-6}$)	P_H predicted ($\times 10^{-6}$)
Cyclopentane	1.9	1000	62	8 ± 2	8.5	6.7
Acetone	0.7	25	90;350	2 ± 0.5	0.53	0.62
Methanol	0.6	6	50;200	1 ± 0.2	0.19	0.26

expected in the regime of extreme motional narrowing, and are in agreement with a measurement of T_1 in [2].

All our measurements with cyclopentane, acetone, and methanol are summarized in Table I. We find that T_1 for ^{129}Xe mixed with organic compounds at 1 μT is significantly shorter than 1000 s obtained at 1.4 T in [2]. The equilibrium value of enhanced proton polarization is given by the Solomon equations [1]. In the limit $T_1(\mathrm{H}) \ll T_1(^{129}\mathrm{Xe})$ and for both P_H and P_{Xe} much larger than the thermal polarization, the equilibrium H polarization is given by $P_H = P_{Xe}[^{129}\mathrm{Xe}]r_{XeH}T_1(\mathrm{H})/2$, where r_{XeH} is the cross-relaxation rate of ^{129}Xe atoms by protons per unit proton density. For cyclopentane it was measured in [2] at 200 K, $r_{XeH} = 5 \times 10^{-26}$ cm^3 s^{-1}. Using this value of r_{XeH} for all three chemicals and assuming that $T_1 = T_2$ we find good agreement with the measured values of H polarization. For acetone and methanol the agreement is somewhat fortuitous, since r_{XeH} has not been measured and the liquids do not fully mix. Compared with the thermal proton polarization in a field of 0.95 μT, our H polarization in cyclopentane has an enhancement factor of 1.5×10^6.

We can also observe large shifts of the ^{129}Xe and ^{1}H NMR frequencies due to the magnetic fields produced by hyperpolarized ^{129}Xe. For a uniformly magnetized spherical sample the frequency shift is given by Eq. (1). However magnetic field gradients due to poor mixing of ^{129}Xe or deviations of the cell from spherical geometry can lead to larger magnetic fields that are proportional to the ^{129}Xe magnetization. Figure 4(b) shows the ratio of H NMR frequency to ^{129}Xe frequency as a function of time for runs with cyclopentane and acetone. In acetone the large shift is due to a highly nonuniform distribution of ^{129}Xe in the cell due to poor solubility of acetone in Xe. In contrast, for the Xe-cyclopentane solution the ratio of the frequencies is quite constant. We find that in all cyclopentane runs the frequency ratio changes by less than 0.0035, corresponding to $\kappa < 0.01$ for H-^{129}Xe spin-spin coupling.

In conclusion, we obtained strong proton NMR signals from several common organic liquids in an ultralow magnetic field of 1 μT using SQUID magnetometers and hyperpolarized ^{129}Xe. This technique enables a wide variety of low-field NMR measurements. In addition, we studied unique aspects of the dynamics of proton signals in the presence of large ^{129}Xe magnetization.

This research was supported by the NSF, the DOE, the Packard Foundation, and Princeton University.

---

[1] G. Navon, Y.-Q. Song, T. Room, S. Appelt, R. E. Taylor, and A. Pines, Science **271**, 1848 (1996).

[2] R. J. Fitzgerald, K. L. Sauer, and W. Happer, Chem. Phys. Lett. **284**, 87 (1997).

[3] T. Room, S. Appelt, R. Seydoux, E. L. Hahn, and A. Pines, Phys. Rev. B **55**, 11 604 (1997).

[4] J. C. Leawoods, B. T. Saam, and M. S. Conradi, Chem. Phys. Lett. **327**, 359 (2000).

[5] S. Appelt, F. W. Haesing, S. Baer-Lang, N. J. Shah, and B. Blumich, Chem. Phys. Lett. **348**, 263 (2001).

[6] B. Goodson, J. Magn. Reson. **155**, 157 (2002).

[7] Y. S. Greenberg, Rev. Mod. Phys. **70**, 175 (1998).

[8] M. P. Ledbetter and M. V. Romalis, Phys. Rev. Lett. **89**, 287601 (2002).

[9] A. Wong-Foy, S. Saxena, A. J. Moule, H. M. L. Bitter, J. A. Seeley, R. McDermott, J. Clarke, and A. Pines, J. Magn. Reson. **157**, 235 (2002).

[10] R. McDermott, A. H. Trabesinger, M. Mück, E. L. Hahn, A. Pines, and J. Clarke, Science **295**, 2247 (2002).

[11] I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis, Nature (London) **422**, 596 (2003).

[12] A. L. Zook, B. B. Adhyaru, and C. R. Bowers, J. Magn. Reson. **159**, 175 (2002).

[13] N. N. Kuzma, B. Patton, K. Raman, and W. Happer, Phys. Rev. Lett. **88**, 147602 (2002).

[14] J. Smith, K. Knagge, L. J. Smith, E. MacNamara, and D. Raftery, J. Magn. Reson. **159**, 111 (2002).

[15] Y.-Y. Lin, N. Lisitza, S. Ahn, and W. S. Warren, Science **290**, 118 (2000).

[16] P. J. Nacher, N. Piegay, F. Marion, and G. Tastevin, J. Low Temp. Phys. **126**, 145 (2002).

[17] F. R. Salsbury and R. A. Harris, Mol. Phys. **94**, 307 (1998).

[18] A. Bagno, G. Saielli, and G. Scorrano, Chem. Eur. J. **8**, 2047 (2002).

[19] J. Vaara, J. Jokisaari, R. E. Wasylishen, and D. Bryce, Prog. Nucl. Magn. Reson. Spectrosc. **41**, 233 (2002).

[20] A. Bagno and G. Saielli, Chem. Eur. J. **9**, 1486 (2003).

[21] S. R. Schaefer, G. D. Cates, T. R. Chien, D. Gonatas, W. Happer, and T. G. Walker, Phys. Rev. A **39**, 5613 (1989).

[22] Tristan Technologies, Inc., 6185 Cornerstone Court East, Suite 106, San Diego, CA 92121, USA.

[23] B. Driehuys *et al.*, Appl. Phys. Lett. **69**, 1668 (1996).