CHEMISTRY
A European Journal

Supporting Information

Long-Lived Spin States for Low-field Hyperpolarized Gas MRI

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1. Materials and Methods

Ultra-high (>99.999%) purity H_2 gas was used to produce H_2 enriched to >90% with parahydrogen using parahydrogen generator described earlier [24]. Propene (Sigma-Aldrich, p/n 295663) was used as is. Rh on TiO_2 catalyst (~ 50 mg load) was used with an average Rh particle size of ~ 1.6 nm [13].

High-field NMR spectroscopy study shown in Figure 1B was performed at 9.4 T using Bruker high-resolution NMR spectrometer.

Varian 4.7 T preclinical MRI scanner was used for high-field MRI studies shown in Figures 1D and 1E. The experiments were conducted with a custom-built 38 mm ID dual-channel radio frequency (rf) coil, with the proton channel tuned to 200.25 MHz. All the experiments used the static magnetic field B_0 shim values obtained on a 10 mL sample of deionized water with half-height line width of ~3 Hz.

Both 4.7 T MRI (Figures 1D and 1E) imaging experiments used Varian's version of a 3D gradient echo (GRE) sequence called ge3D with a total acquisition time (AQ) of 21.4 s and spectral width (SW) of 40 kHz. GRE excitation rf pulse had a Gaussian shape with a pulse width of 500 μs for propane (15° at 76 mW) and water (2° at 1.3 mW) acquisitions. The repetition time (TR) for MRI experiments was 3.48 ms, while the echo time (TE) was 1.76 ms respectively. Isotropic imaging spatial resolution (voxel size) was $0.5\times0.5\times0.5$ mm^3 (125 nL) with $48\times48\times32$ mm^3 field of view (FOV) and $96\times96\times64$ imaging matrix. No compressed sensing or image acceleration was employed. 4.7 T MRI experiments were conducted using a spiral phantom constructed of Tygon^{TM} (3/32 in. ID × 3/16 in. OD, McMaster Carr, #5552K22) tubing wrapped around plastic syringe to provide the 3D structure for imaging studies. The phantom was longer than the imaging field of view (FOV) and was placed in the center of the rf coil. For each hyperpolarized imaging experiment, propene (PHIP precursor) was mixed with parahydrogen in 1:2 molar ratio (40 psi propene and 80 psi parahydrogen) to yield a mixture of hyperpolarized propane and residual unreacted parahydrogen (~1:1 ratio) after passing it over a solid Rh/TiO_2 hydrogenation catalyst placed inside 1/8 in. copper tubing heated to ~100 °C. Approximately 50 mg of the Rh/TiO_2 catalyst was packed in the copper tubing using glass wool to prevent catalyst loss. The propane was delivered into the spiral phantom (via 1/8 in. OD PTFE tubing with 1/16 in. ID) and released via the outlet (placed after the phantom) without any backpressure or additional flow restriction. Continuous flow rate (15 mL/min) of hyperpolarized propane/residual parahydrogen mix was maintained until the imaging acquisition was completed. The concentration of resulting propane gas was estimated to be ~20 mM based on the 1:1 ratio of residual parahydrogen and HP propane gas, room temperature of gas (~300 K) and 1 atm of total pressure. The phantom for water imaging was prepared differently, with deionized water completely filling the spiral phantoms and the inlet and outlet plugged. Polarization enhancement of HP propane at 4.7 T was calculated by performing a single scan NMR spectroscopy of flowing HP gas and water in the same phantom using the previously described method [25]. Calculated in this fashion $\%P_H$ was ~1% per one methylene and one methyl protons H_a and H_b (see Figure 1A).

For low-field MRI experiments at 0.0475 T, the flow was stopped after ~1 s of initial gas flow, and the gas was allowed to compress resulting in the final estimated total pressure of ~9.5 bar and the estimated gas phase temperature of 373 K. Note that the gas was not cooled by a very short delivery path using the same tubing as in high-field 4.7 T studies described in the above paragraph. The reaction yield was estimated to be ~100% for calculation of $\%P_H$ detected in the 0.0475 T inside the approximately cylindrical 2 mL phantom. Note that the phantom contains a significantly wider cylindrical section seen in Figure 3E as a disc around the main phantom section. All 0.0475 T experiments were conducted with Magritek (Wellington, New Zealand) instrumentation with on-site assembly [19,25]. Custom 38 mm ID rf coil was used [19]. The spectrum of HP propane was referenced to a spectrum of thermally polarized water using the same spectroscopic parameters and 45° rf excitation pulse. The polarization enhancement factor for propane was calculated as follows: $\varepsilon = (S_{HP}\times\chi_{H2O})/(S_{H2O}\times\chi_{HP}) \sim 5\,100$, where S_{HP} and S_{H2O} are the integrals of the NMR signals of HP propane and thermally polarized water, respectively, and χ_{H2O} and χ_{HP} are molar quantities of water and produced HP propane (calculated as estimated gas phase concentration of ~150 mM at 4.7 bar partial pressure and 373 K temperature and multiplied by the phantom volume of ~ 2 mL). The resulting $\%P_H$ of 0.08% of HP propane was calculated as follows: $\%P_{HP} = \varepsilon\times\%P_{THERMAL}$, where $\%P_{THERMAL} = 1.6\times10^{-7}$ or $1.6\times10^{-5}\%$ at 0.0475 T [25].

All imaging parameters for 0.0475 T images shown in Figure 3 are provided in the corresponding figure caption.

Signal-to-noise ratio (SNR) for all images is reported as the intensity of the voxel with the maximum signal divided by the RMS noise. RMS noise was calculated by measuring peak-to-peak noise in images, and dividing the peak-to-peak noise value by $2\times\sqrt{2}$.

2. Low-field NMR spectra simulations

^{1}H NMR spectra for propane and ^{13}C-labeled propanes were calculated based on the conventional spin-density matrix formalism. For propane, the following parameters were used: δ=0.899 ppm (methyl, 6H), δ=1.336 ppm (methylene, 2H), J_{HH}=7.4 Hz. For ^{13}C-labeled propane, $^1J_{CH}$=125 Hz was used.

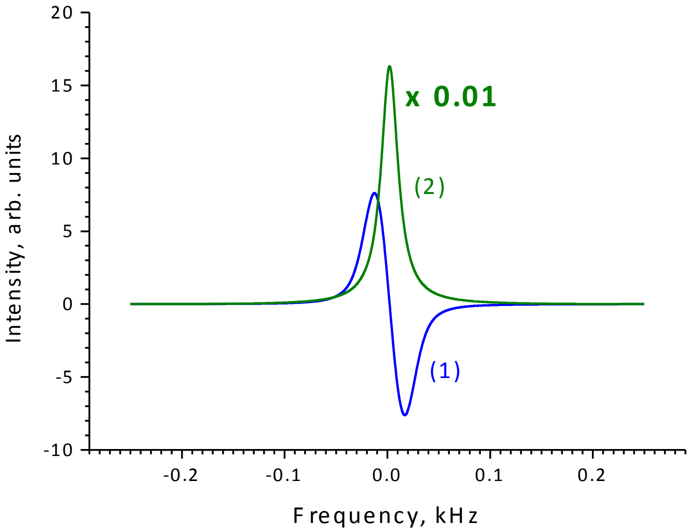

Figure S1. Calculated ^{1}H NMR spectra of HP propane at 47.5 mT. Blue (1): the spectrum after a single 45º-pulse: green (2) - the spectrum for the same molecule after application of the SLIC pulse sequence (B_1=14.8 Hz applied for 2 s at zero offset) followed by a 45º-degree pulse phase-shifted by 90 degrees relative to the cw rf. Note that the green trace is scaled down (1/100) for a better presentation.

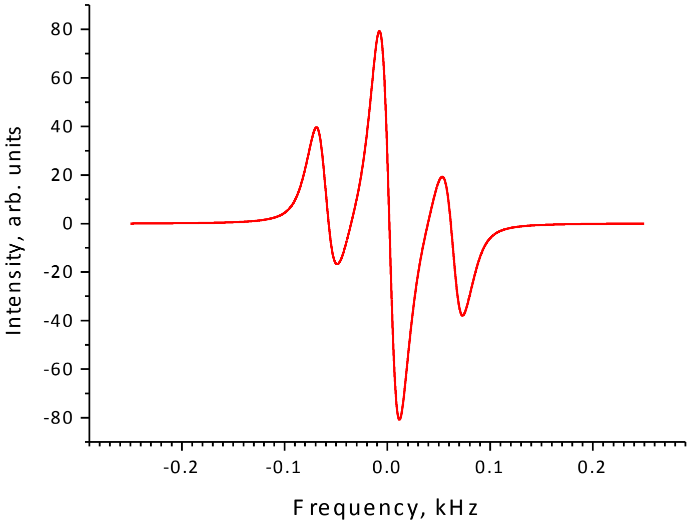

Figure S2. The ^{1}H NMR spectrum calculated as a weighted sum of the spectra of HP propane isotopomers at 47.5 mT. The spectra of the three ^{13}C-labeled propane molecules, corresponding to the ^{13}C label in three different positions with respect to the nascent protons of parahydrogen in propane, were summed, multiplied by 0.0101 to take into account ^{13}C natural abundance, and added to the spectrum of ^{13}C-free propane molecule (the one shown in blue in Figure S1).

3. Movies Captions:

Movie S1. 3D rendering of MRI image shown in Figure 1D.

Movie S2. 3D rendering of MRI image shown in Figure 1E.