Multidimensional Mapping of Spin-Exchange Optical Pumping in Clinical-Scale Batch-Mode $^{129}$Xe Hyperpolarizers

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Supporting Information

ABSTRACT: We present a systematic, multiparameter study of Rb/$^{129}$Xe spin-exchange optical pumping (SEOP) in the regimes of high xenon pressure and photon flux using a 3D-printed, clinical-scale stopped-flow hyperpolarizer. In situ NMR detection was used to study the dynamics of $^{129}$Xe polarization as a function of SEOP-cell operating temperature, photon flux, and xenon partial pressure to maximize $^{129}$Xe polarization ($P_{Xe}$). $P_{Xe}$ values of 95 ± 9%, 73 ± 4%, 60 ± 2%, 41 ± 1%, and 31 ± 1% at 275, 515, 1000, 1500, and 2000 Torr Xe partial pressure were achieved. These $P_{Xe}$ polarization values were separately validated by ejecting the hyperpolarized $^{129}$Xe gas and performing low-field MRI at 47.5 mT. It is shown that $P_{Xe}$ in this high-pressure regime can be increased beyond already record levels with higher photon flux and better SEOP thermal management, as well as optimization of the polarization dynamics, pointing the way to further improvements in hyperpolarized $^{129}$Xe production efficiency.

INTRODUCTION

The nuclear spins of xenon and other noble gases can be hyperpolarized (HP) to order unity by the process of spin-exchange optical pumping (SEOP). In this two-step process, the electron spins of an alkali metal vapor such as rubidium are first polarized by the absorption of angular momentum from rubidium and performing low-field MRI at 47.5 mT. It is shown that $P_{Xe}$ in this high-pressure regime can be increased beyond already record levels with higher photon flux and better SEOP thermal management, as well as optimization of the polarization dynamics, pointing the way to further improvements in hyperpolarized $^{129}$Xe production efficiency.

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increased alkali metal spin-destruction rates from non-spin-conserving collisions with Xe. But fundamentally laser photons are the source of $^{129}$Xe hyperpolarization; thus, the decreasing cost of laser diodes narrowly tuned to the alkali metal rubidium D$_1$ wavelength (794.8 nm) has made economically feasible the higher photon fluxes required to improve $M_{Xe}$ when Xe partial pressures are high.

In the present work, a 200 W laser diode array (LDA) was used in a 3D-printed automated $^{129}$Xe polarizer to study SEOP dynamics as a function of xenon density, laser power, and SEOP-cell temperature. More specifically, the SEOP polarization conditions at several partial pressures of natural abundance Xe (26.44% $^{129}$Xe isotope enrichment) were studied: (i) 275 Torr Xe and 1725 Torr N$_2$, (ii) 515 Torr Xe and 1485 Torr N$_2$, (iii) 1000 Torr Xe and 1000 Torr N$_2$, (iv) 1500 Torr Xe and 500 Torr N$_2$, and (v) 2000 Torr Xe and 200 Torr N$_2$, where the gases were loaded with an accuracy of ±25 Torr. The reader is also directed to Supporting Information for detailed descriptions of the experimental setup, which represents the second-generation device of our HXTC consortium (Figure 1). For each SEOP cell loading, data were obtained for a range of incident laser power levels (approximately 100, 125, 140, or 170 W) and variable SEOP-cell surface temperatures ranging from 42 to 92 °C. For each condition, measurement of $^{129}$Xe polarization dynamics allowed the rate constant for $P_{Xe}$ accumulation ($\gamma_{SEOP}$) and the maximum attainable steady-state $P_{Xe}$ value [$P_{Xe}(t \to \infty)$ or $^{129}$Xe $P_{max}$] to be determined from exponential fits. The temperature of the SEOP cell was monitored by a thermistor mounted directly to its surface; temperature control allows the Rb concentration in the gas phase to be varied.

### METHODS

**Spin-Exchange Optical Pumping (SEOP) Polarizer.** The SEOP 3D-printed portable polarizer (Figure 1) consists of a 200 W frequency narrowed volume holographic grating (VHG) laser diode array (LDA), a custom 3D-printed thermostatically cooled (TEC) optical pumping (OP) oven, a 0.5 L SEOP cell, an electromagnet providing 47 kHz $^{129}$Xe and $^1$H Larmor frequencies, in situ NMR polarimetry endowed by a Magritek Kea2 system, and a Magritek 88 mm bore magnet for ex situ MRI (Magritek, Wellington, New Zealand). The components of the polarizer have been discussed in detail previously and thus are only discussed briefly here.

**In Situ Low-Field NMR and IR Spectroscopy.** In situ NMR polarimetry for these experiments was performed via single-shot $^{129}$Xe NMR at 47 kHz (Figure 2a) calibrated against $^1$H NMR at the same frequency from a sample of thermally polarized water doped with 10 mM CuSO$_4$ inside a 0.5 L SEOP-cell phantom (200 000 scans, Figure 2b). The polarizer allows the Rb electron spin polarization, $P_{Rb}$, to be estimated by comparing the integrated intensities of transmitted laser spectra measured with and without the applied magnetic field (e.g., Figure 2c). For each set of conditions, $P_{Xe}$ was sampled every 5–20 min throughout SEOP; the process is repeated by either destroying the $^{129}$Xe polarization with a series of “crusher” pulses or allowing it to decay with the laser off. The time-course examples in Figure 2d,e show the excellent reproducibility of $P_{Xe}$, $P_{Rb}$, and $\gamma_{SEOP}$ in these experiments (and those values were not sensitive to the application of the rf pulses). Once steady-state $^{129}$Xe polarization was achieved, growth curves can be extracted (e.g., Figure 2f) and fit to an exponential: $P_{Xe}(t) = P_{max}[1 - \exp(-\gamma_{SEOP}t)]$. In the absence of SEOP, in-cell room-temperature (rt) measurement of the spin–lattice relaxation time constant ($T_1$) can be obtained after steady-state $P_{Xe}$ has been achieved by quickly bringing the cell to room temperature to minimize the Rb gas-phase concentration, turning off the laser, and performing in situ NMR polarimetry while the polarization decays; for example, the data in Figure 2g were fit to an exponential decay curve: $P_{Xe}(t) = P_{Xe}(0) \exp[-r/T_{x}t]$, where $r_{Xe} = 1/T_{1}$. is the $^{129}$Xe spin-destruction-rate, here exhibiting an ultralong in-cell $^{129}$Xe $T_1$ of 150.5 ± 2.5 min (or 2.5 h). Particularly when optimizing SEOP under the regimes of high [Xe] and laser power, it is also important to be observant for the onset of positive feedback effects that give rise to dramatic increases in [Rb] and laser absorption over time (and ultimately poorer $P_{Xe}$). Examples showing the manifestation of such “Rb-runaway” effects are provided in Figure 2h, which shows behavior where relatively small increases in cell surface temperature result not only in reduced peak $P_{Xe}$ but also in reduced $P_{Xe}$ over time. Such effects are discussed in greater detail in Results and Discussion.

**Ex Situ Low-Field NMR Spectroscopy and MRI Imaging.** Ex situ $P_{Xe}$ at 47.5 mT was calculated by comparing the $^1$H NMR signal with the $^{13}$C signal at 508 kHz $^{13}$C Larmor frequency from a reference sample of thermally polarized sodium 1-13C-acetate dissolved in D$_2$O (Figure 4a). The $^{129}$Xe $T_1$ relaxation time inside the polypropylene phantom sphere was ~9.2 min (Figure 4c), which is sufficient for short-term storage of HP $^{129}$Xe. Moreover, this $^{129}$Xe $T_1$ value was used in parallel experiments to precisely calibrate the rf excitation pulse for the 47.5 mT rf probe shown in Figure 5f; the image signal decay is due to both $T_1$ decay and excitation rf pulses. A y-slice...
projection of fast gradient echo (GRE) imaging with millimeter-scale spatial resolution without slice selection shows the excellent 129Xe signal intensity (Figure 5a). All 20 images (Figure 5b–c, selected images shown) were acquired identically with TE = 4.0 ms, TR = 80 ms (limited by the spectrometer electronics response time), 50% k-space sampling, 64 × 64 imaging matrix with 72 × 72 mm² field of view (FOV), and a spectral width of 20 kHz. Given the relatively long T₁ in the phantom (Figure 4c), the decay of the hyperpolarized signal was primarily due to rf-pulse-induced polarization loss in Figure 5f. The calibrated rf pulse width for the HP 129Xe was used for calculation of %Pₓ (Figure 5b, e). %Pₓ, %Pₓ, and %Pₓ are displayed in Figure 3: Figure 3a provides example plots of %Pₓ and %Pₓ as functions of non-equilibrium Rb runaway in a 1500 Torr Xe SEOP cell using only 100 W laser power: a normal build-up curve at 72 °C (black squares), a mildly distorted build-up curve at 82 °C (red circles), and a significantly distorted build-up curve at 92 °C (orange triangles). All spectra were recorded with a surface coil using small radiofrequency (rf) excitation pulses with little to no measurable effect on 129Xe magnetization. Except for the fitting curves in (f) and (g), connecting lines are meant only to guide the eye.

### RESULTS AND DISCUSSION

The dependence of 129Xe polarization and its dynamics as functions of temperature, photon flux, and xenon partial pressure was systematically studied under stopped-flow operation in the regimes of high xenon density and photon flux. Results for five Xe:N₂ SEOP-cell compositions at four different LDA incident powers (approximately 100, 125, 140, and 170 W) with SEOP-cell surface temperatures ranging from 42 to 92 °C are displayed in Figure 3: Figure 3a provides example plots of %Pₓ and %Pₓ as functions of non-equilibrium Rb runaway in a 1500 Torr Xe SEOP cell using only 100 W laser power: a normal build-up curve at 72 °C (black squares), a mildly distorted build-up curve at 82 °C (red circles), and a significantly distorted build-up curve at 92 °C (orange triangles). All spectra were recorded with a surface coil using small radiofrequency (rf) excitation pulses with little to no measurable effect on 129Xe magnetization. Except for the fitting curves in (f) and (g), connecting lines are meant only to guide the eye.

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**Figure 2.** (a) Example of an in situ low-field 129Xe NMR spectrum from a SEOP-cell during SEOP (single scan, B₀ = 4.00 mT). (b) Corresponding 1H NMR spectrum from a thermally polarized water reference sample using 200 000 scans, B₀ = 1.10 mT. (c) Examples of field-cycled near-IR spectra of laser light transmitted through the SEOP-cell used to estimate Pₓ: room temperature before SEOP (dark gray), during SEOP with B₀ electromagnetic on (blue), and during SEOP with B₀ electromagnetic turned off (red). (d, e) Examples of data sets for studying time-resolved SEOP build-up and decay kinetics using a cell containing 1000 Torr (each) of Xe and N₂ gas (143 W laser power, 65 °C). (d) Plot showing reproducibility of Pₓ accumulation following the application of >500 rf “crusher” pulses that nearly zero-out the 129Xe polarization (time periods marked by vertical green bars); Pₓ (red circles) was sampled via field-cycled near-IR spectroscopy (c) before and after application of the crusher pulses. (e) Similar to (d), with 129Xe NMR signals acquired with different interpulse durations and with polarization decay observed after turning the laser off (times demarked with vertical arrows); here 129Xe decay was observed with the SEOP cell temperature maintained at 65 °C. Pulse delay (PD) refers to timing between NMR acquisitions during build-up. (f) Exponential buildup of 129Xe polarization during the SEOP process for a cell filled with 2000 Torr of Xe and 200 Torr of N₂. (g) T₁ decay of HP 129Xe at r.t. obtained with the laser turned off. (h) Time-course examples showing the temperature-dependent effects of nonequilibrium Rb runaway in a 1500 Torr Xe SEOP cell using only 100 W laser power: a normal build-up curve at 72 °C (black squares), a mildly distorted build-up curve at 82 °C (red circles), and a significantly distorted build-up curve at 92 °C (orange triangles). All spectra were recorded with a surface coil using small radiofrequency (rf) excitation pulses with little to no measurable effect on 129Xe magnetization. Except for the fitting curves in (f) and (g), connecting lines are meant only to guide the eye.

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reflects the spin-exchange rate, since generally \( k_{\text{SE[Rb]}} > \Gamma_{\text{Xe}} \) or \( k_{\text{SE[Rb]}} \gg \Gamma_{\text{Xe}} \) under our conditions. (At the highest temperatures studied, \( k_{\text{SE[Rb]}} \gg \Gamma_{\text{Xe}} \) at the lowest temperatures \( k_{\text{SE[Rb]}} \) can approach or become less than \( \Gamma_{\text{Xe}} \), and \( \Gamma_{\text{Xe}} \) is expected to have a more mild dependence on surface temperature that trends in the opposite direction.)

However, \( P_{\text{max}} \) exhibits significantly different behavior, for example, peaking at \( \sim 72 \, ^\circ\text{C} \) for the data in Figure 3a. \( P_{\text{max}} \) is given by

\[
P_{\text{max}} = \frac{k_{\text{SE[Rb]}}}{k_{\text{SE[Rb]}} + \Gamma_{\text{Xe}}} \langle P_{\text{Rb}} \rangle
\]

where \( \langle P_{\text{Rb}} \rangle \) is the spatial average of the local Rb electron spin polarization, \( P_{\text{Rb}}(r) \), which itself is determined by

\[
P_{\text{Rb}}(r) = \frac{\gamma_{\text{OP}}(r)}{\gamma_{\text{OP}}(r) + \Gamma_{\text{Rb}}} \langle P_{\text{Rb}} \rangle
\]

where \( \gamma_{\text{OP}}(r) \) is the local Rb optical pumping rate (the integrated product of the laser flux at position \( r \) and the Rb absorption cross section) and \( \Gamma_{\text{Rb}} \) is the Rb electronic spin destruction rate (which is essentially proportional to \( \langle \text{Xe} \rangle \) under our conditions). Intuitively from eq 2, \( ^{129}\text{Xe} \). \( P_{\text{max}} \) \( \rightarrow \) \( \langle P_{\text{Rb}} \rangle \) when \( k_{\text{SE[Rb]}} \gg \Gamma_{\text{Xe}} \) which occurs at higher temperatures. However, having higher Rb densities generally translates into greater optical density, which in turn gives rise to reduced transmittance of the laser light and hence poorer illumination throughout the cell, lower \( \gamma_{\text{OP}} \), and ultimately reduced \( P_{\text{Rb}} \), thereby decreasing \( P_{\text{max}} \). Thus, \( P_{\text{max}} \) initially grows with increasing temperature as more Rb is vaporized (e.g., Figure 3a), but once \( \langle \text{Rb} \rangle \) becomes too high, overall \( P_{\text{max}} \) decreases in accordance with eq 3, resulting in lower \( ^{129}\text{Xe} \) \% \( P_{\text{max}} \) at some of the highest temperatures studied.

The highest \% \( P_{\text{max}} \) values in the contour plots of Figure 3c–l were always achieved at the maximum LDA power of 170 W. However, as the Xe density increased, the optimal temperature decreased from 92 to 62 \(^\circ\text{C} \), in qualitative agreement with our previous results obtained at a much smaller scale. This inverse relationship between Xe density and optimal cell surface temperature, an effect amplified by the use of frequency-narrowed lasers, may be explained in part by the fact that as \( \langle \text{Xe} \rangle \) rises, Xe-induced Rb spin-destruction becomes increasingly dominant; thus, lowering the cell temperature helps maintain a sufficient "photon-to-Rb" ratio to ensure high global \% \( P_{\text{max}} \) (provided that the cell \( ^{129}\text{Xe} \), \( T_{1} \) is sufficiently long). The effect may also be exacerbated by greater in-cell temperature gradients caused by (i) greater absorption of laser energy and (ii) the several-fold lower thermal conductivity of Xe compared to that of \( \text{N}_{2} \). Indeed, the effects of differential heating are also manifested in the \( \gamma_{\text{SEOP}} \) maps: \( \gamma_{\text{SEOP}} \) (and hence \( \gamma_{\text{SE}} \)) is not a constant of exterior cell temperature but shows some variation. For example, the value at 100 W, 82 \(^\circ\text{C} \) for the 2000 Torr Xe gas composition is nearly twice that for the 275 Torr Xe gas composition; overall, apparent \( \gamma_{\text{SEOP}} \) values tend to increase with increasing laser power and \( \langle \text{Xe} \rangle \), consistent with higher-than-expected Rb vapor densities (and higher internal temperatures) under these conditions.
For Five Gas Mixtures

\[ \gamma \]

results in decreasing \([R_b]\), thereby increasing if the increased heat load could be mitigated, greater LDA does not have as pronounced a manifestation in the transmitted regimes generally fails to regain e

“hysteretic, as simple temperature reduction to normal operating exterior cell surface temperatures. The behavior is also “self-reinforcing pattern. The e

from the gas into the inner surface of the cell (and Rb pools) in the cell and hence more laser absorption and heat dissipation which may be followed by deteriorating severity: In full Rb runaway, one sees a dramatic decrease in the vapor phase over a short time;9,21 the increasing \([R_b]\) pre-runaway takes place when undissipated heat from laser absorption or cell heating rapidly compounds the amount of “runaway

which may be followed by deteriorating


does not have as pronounced a manifestation in the transmitted laser’s near-IR spectroscopy but is readily observed during measurements of the kinetics of \(P_{xe}\) build-up. Examples of “Rb pre-runaway” can be seen in Figure 2h (orange trace), where \(P_{xe}\) grows, passes the maximum, and then dips. The effect is less pronounced in Figure 2b (red trace) and nonobservable in Figure 2h (black trace). While true “Rb runaway” causes % \(P_{xe}\) to irreversibly deteriorate and requires a restart of the SEOP procedure from initial conditions to lower [Rb], “Rb pre-runaway” is not hysteretic and can be more easily controlled by reducing the cell temperature. However, it results in lower polarization (Figure 2h). In any case, these deleterious effects are more problematic for higher Xe densities because of the greater Rb spin-destruction rates (and hence greater light absorption from more poorly polarized Rb, as well as any possible contributions from reduced thermal conductivity).

Table 1 summarizes the maximum achieved \(^{129}\text{Xe}\) polarization (% \(P_{max}\)) for every Xe:N2 mix studied. The results show not only the trend of decreased % \(P_{max}\) with increasing Xe in-cell pressure but also a corresponding decrease in \(\gamma_{SEOP}\) measured at these optimal conditions, a finding that predominantly reflects the lower concentration of Rb vapor that must be attained to achieve maximal \(^{129}\text{Xe}\) polarization at higher Xe densities. Nevertheless, the optimization process allows the total magnetization \((M_{xe})\) to continue to grow despite the decrease in % \(P_{max}\) as the \(^{129}\text{Xe}\) density increases faster than % \(P_{max}\) decreases. While the \(^{129}\text{Xe}\) polarization values (and amounts) are significantly higher here than those in ref 21, the improvement in \(M_{xe}\) from 1000 to 2000 Torr of Xe is

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
\text{Xe/N}_2 \text{ partial pressure (Torr)} & \text{C}_{129\text{Xe}} \text{(mM)} & \% P_{xe}(max) (\%) & \% P_{xe}(max,app) (\%) & M_{xe}(max) (\text{mM}) & \text{production cycle time (min)} & \text{apparent production rate (L/h)} \\
\hline
275/1725 & 3.9 & 95 \pm 9 & 13 \pm 1 & 3.7 \pm 0.3 & 51 & 0.94 \\
515/1485 & 7.4 & 73 \pm 4 & 19 \pm 1 & 5.4 \pm 0.3 & 53 & 0.91 \\
1000/1000 & 14.3 & 60 \pm 2 & 30 \pm 1 & 8.5 \pm 0.3 & 98 & 0.49 \\
1500/500 & 21.4 & 41 \pm 1 & 31 \pm 1 & 8.8 \pm 0.2 & 84 & 0.57 \\
2000/200 & 28.6 & 31 \pm 1 & 28 \pm 1 & 9.0 \pm 0.2 & 98 & 0.49 \\
\hline
\end{array}
\]

\[ \text{(and amounts) are signi}\]
more marginal. Higher laser power may provide further improvements in % $P_{\text{max}}$ (and $M'_{\text{Xe}}$) at high [Xe] by allowing operation with higher Rb densities and hence higher $\gamma_{\text{SEOP}}$ rates. Other useful metrics describing the overall hyperpolarizer performance summarized in Table 1 include the apparent % $P_{\text{Xe}}(\text{max})$ due to Xe dilution by N$_2$ gas (% $P_{\text{Xe}}(\text{max,app})$), production cycle time, and apparent production rate of hyperpolarized gas (L/h). % $P_{\text{Xe}}(\text{max,app})$ is a useful metric$^{23}$ because it takes into account HP Xe dilution by N$_2$ gas, which has not been eliminated because the HP Xe cryocollection step was obviated. Production cycle time corresponds to the time necessary to complete the production of $\sim$0.8 L of HP Xe/N$_2$ gas composition and return the hyperpolarizer (i.e., gas reloading, etc.) to the same step in the operational cycle. Computed in this fashion production cycle time was used for estimating the apparent production rate of the hyperpolarizer in liters of hyperpolarized Xe/N$_2$ mixture per hour. The production rate in L/h is truly the characteristic of continuous-flow hyperpolarizers, and the apparent production rate values computed in Table 1 should be used with care for direct comparison with continuous-flow hyperpolarizers, because the batch-mode method used here produces a single batch per each production cycle, and there is no produced HP $^{129}$Xe until the cycle is finished.

To validate the in situ NMR results, the polarized contents of the SEOP-cell filled with 1000 Torr of Xe and 1000 Torr of N$_2$ was transferred into an evacuated ($<10^{-3}$ Torr) 0.05 L hollow polypropylene sphere located in a rf probe of a 47.5 mT imaging system$^{45,59,60}$ (see Supporting Information for details). In-cell $P_{\text{Xe}}$ was measured in situ as 54 ± 5% before the transfer, and a $P_{\text{Xe}}$ value of 51 ± 2% was detected in the 47.5 mT preclinical MRI scanner (558.6 kHz $^{129}$Xe Larmor frequency), corresponding to polarization enhancement $\epsilon > 11 000 000$ after the gas transfer (Figure 4b). The HP $^{129}$Xe transfer from the polarizer was performed without a cryocollection process.$^{24,25,30}$ Figure 5 also demonstrates the feasibility of millimeter-scale MRI of hyperpolarized $^{129}$Xe at very low magnetic fields using frequency optimized rf coils.$^{54}$

■ CONCLUSIONS

Simultaneous optimization of various SEOP conditions (Xe density, cell surface temperature, and photon flux) combined with previously reported SEOP hardware improvements$^{24,29,30}$ yielded greatly improved % $P_{\text{Xe}}$. Indeed, very high values of % $P_{\text{Xe}}$ and $M'_{\text{Xe}}$ were demonstrated here for dense (up to 2000 Torr of Xe in 2200 Torr total) Xe gas mixtures, in part enabled by optimized laser illumination throughout the cell, ultralong in-cell $^{129}$Xe relaxation times, and efficient thermal management that also allows for diligent avoidance of “Rb runaway” regimes. The SEOP condition maps provide guidance for the production of highly polarized $^{129}$Xe gas at different xenon densities for a wide variety of applications ranging from materials science to biomedical imaging. Furthermore, our results indicate that the $P_{\text{Xe}}$ values at higher Xe densities are still laser-power-limited. Thus, while the benefit in total Xe magnetization was less substantial at the highest Xe densities studied, the advantage will likely be improved when more powerful LDA instrumentation is available provided that the greater thermal loads can be mitigated. Finally, the highly reproducible maps of $\gamma_{\text{SEOP}}$ build-up rates, combined with automated fine control of cell conditions and real-time spectroscopic feedback, should also allow optimization of multieponential Xe polarization dynamics, pointing the way to multifold improvements in HP $^{129}$Xe production efficiency.
ASSOCIATED CONTENT

Supporting Information
Detailed information regarding the SEOP setup used, the preparation processes, and experimental parameters. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
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