New Method for Large Scale Production of Hyperpolarized Xenon

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Introduction

Hyperpolarized xenon, due to its solubility in tissues, offers possibilities of imaging organs beyond the lung air space. Furthermore the limited supply and high cost of ^{3}He make xenon an attractive alternative for lung imaging. The low magnetic moment of xenon relative to ^{3}He, the 26% natural abundance of ^{129}Xe, and its anesthetic effect at high concentrations limit signal strength. Signal is further reduced for dissolved state studies, where T_1 relaxation continues during transport. Finally, spin-exchange techniques presently in use offer much lower xenon polarizations, between 2% and 20%, than either methods for producing hyperpolarized helium.

We report here on a new method for producing hyperpolarized xenon. We outline how a fundamental change in the dynamics of xenon flow in the polarization chamber allows the stages of the process to be isolated and optimized. We discuss a numerical simulation, supported by experimental measurements, that estimate the performance of our system. Finally we report progress implementing our design.

Existing Practice

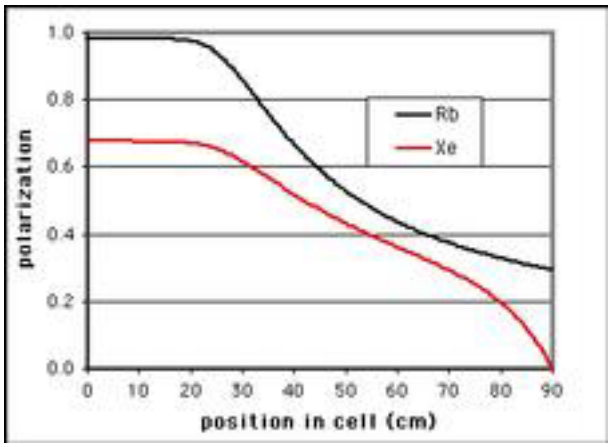
Hyperpolarized xenon production is accomplished using the alkali spin-exchange technique. High-power diode laser arrays can deliver as much as 100W light at the rubidium D1 absorption wavelength of 795 nm within a 2 nm linewidth. This light is transported through a fiber, circularly polarized, and directed on a warm glass cell containing rubidium vapor, approximately 100 torr of nitrogen to quench re-radiation, the xenon, and possibly helium buffer gas. An important difference between polarizing xenon and helium is the large rubidium-xenon electronic depolarization cross section. This depolarization alters, even dominates, the optimum polarization conditions. Increasing the pressure of xenon decreases the polarization of rubidium and the light absorption. Total gas pressure also has multiple impacts: pressure broadening of the rubidium line allows greater laser light absorption. On the other hand, lower pressure allows longer rubidium-xenon dimer lifetimes, providing more efficient spin exchange to the xenon nucleus than the contact interaction (which is pressure independent).

Existing polarizers of xenon are designed either for batch or flow-through mode operation. Batch mode polarizers[1] typically fill a spin-exchange cell with one or more atmosphere of xenon. At these xenon pressures, rubidium vapor pressure associated with 95°C can be polarized with a diode array. Polarization spin-up time constants around ten minutes are obtained. Coated cells minimize wall relaxation. Continuous flow-through systems operate in a different regime[2]. The partial pressure of xenon is reduced to 1% while the total pressure is increased to 10 atmospheres using 98% helium. The pressure broadening allows greater use of the 2 nm linewidth of the laser for polarizing rubidium, while the reduced xenon concentration allowed greater rubidium concentrations. At 150°C these systems have polarization spin-up time constants less than one minute. The gas mixture entering the polarization cell diffusively mixes with warm, rubidium-saturated gas in the cell, while mixed, polarized gas is drawn off from the other end. Both batch and flow through systems accumulate hyperpolarized xenon in the frozen phase in a permanent (>0.05 T) magnet due to its slow relaxation[3].

New Method

Our new system is designed to operate in the high-flow, diffusion-independent regime. The central idea is to flow the gas mixture in the direction opposite to the laser light. The unpolarized gas entering the polarization chamber is partially polarized by the attenuated laser light, while the most polarized gas about to exit the chamber is subjected to the highest intensity full laser spectrum. This multi-stage process has added benefits. The gas entering the cell is over heated and rubidium saturated. The polarization cell has higher rubidium density in the center than at the walls. The exit regions of the polarization cell can be maintained at room temperature, serving to finalize condensing the rubidium in the presence of the polarizing light. The glass laser-light entrance window is cold, eliminating the laser attenuation associated with the rubidium boundary dead layer. Since the exiting gas does not diffusively average the rubidium polarization over the polarization cell, the cell can be made quite long extracting the maximum polarization from the laser beam in the pre-polarization stage. The total gas pressure can be reduced and still efficiently use the laser light. At very low pressures the spin exchange cross section is dominated by Rb-Xe dimer formation. Spin-up time constants can be less than one second. Accumulating frozen xenon at low pressure may avoid the depolarizing effects of xenon snow formation.

We developed a numerical simulation of the polarization process. It includes cross sections and rate constants for rubidium polarization, light absorption, and Rb-Xe spin exchange, as well as rubidium and xenon depolarization mechanisms. It allows adjustment of flow rate, pressure, mixture, temperature distribution, laser wavelength profile, and cell geometry. We have used it to maximize a defined figure-of-merit by adjusting selected parameters and predict system performance.



Rb and Xe Polarization

Implementation

We have assembled a xenon polarizer based on these principles. Adjustable flow rates, concentrations, and temperatures allow us to explore the important process parameters. The polarizing cell is approximately 2 cm in diameter and over one meter in length. It has three temperature regions: a rubidium saturation (entrance) region, nominally above 200°C, a polarization region between 150°C and 180°C, and a condensation (exit) region at room temperature. Gas mixtures of total pressure around 100 mbar will be dominated by nitrogen, with around 10 torr of xenon. Previous studies have yielded polarizations as high as 70% with this mixture, reporting spin-up times of several seconds with 2 W laser power[4]. Our system could support flow rates as high as several liters per hour of xenon, depending on laser power. Polarizations, which will be measured in the chamber as well as at the exit, are calculated to reach 65-80%. Characterization of the system is presently underway.

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