A 3-Liter Capacity, Hybrid Spin-Exchange ^{3}He Polarizer for Medical Imaging

K. E. Mooney[1], G. W. Miller[2], P. A. Dolph[1], W. A. Tobias[1], V. Nelyubin[1], J. Singh[1], J. P. Mugler III[2], and G. D. Cates[1,2]

[1]Physics, University of Virginia, Charlottesville, Virginia, United States, [2]Radiology, University of Virginia, Charlottesville, Virginia, United States

Introduction: The original commercial ^{3}He polarizer (Model 9600, Magnetic Imaging Technologies, Inc) is capable of producing 1L of ^{3}He per day at up to 40% polarization, by using collisional spin exchange with an optically pumped rubidium vapor. Recent technical developments such as hybrid spin-exchange optical pumping (SEOP) [1] and commercially available high-power line-narrowed diode lasers [2] offer the promise of higher ^{3}He polarization, faster spin up times, and larger production volumes. In the present work we describe the performance of a new hybrid ^{3}He polarizer incorporating these developments.

Polarization Methods: Hybrid SEOP utilizes a vapor of two different alkali metals to spin-exchange with the ^{3}He, typically rubidium and potassium. The valence electron of rubidium is optically pumped by the circularly polarized laser light tuned to the D1 transition wavelength (~795nm), and readily transfers its spin to the potassium valence electron. Both metals can spin-exchange with the ^{3}He nuclei, but the spin-exchange cross section is nearly an order of magnitude higher for potassium than for rubidium [1]. Thus hybrid SEOP allows one to benefit from the more efficient spin-exchange between potassium and ^{3}He, while still using commercial lasers tuned to the rubidium optical pumping wavelength.

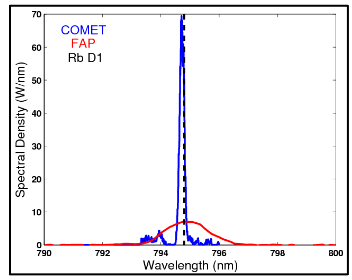

Figure 1: Spectral Density of Comet and FAP Lasers. The area under each curve is 25W, the total power output of the laser.

Equipment: The lasers which pump our rubidium vapor are VBG locked Comet line-narrowed diode lasers (Newport Corp.) centered at 794.8nm with a linewidth of 0.2nm. Fig. 1 compares the spectrum of a Comet to that of a Fiber Array Package (FAP) laser (Coherent, Inc.) used in our MITI polarizer. Both diodes output ~25W; however the Comet generates much more power at the rubidium D1 transition. Our polarizer is equipped with 3 Comet lasers (total laser power ~75W) merged into a single beam line by a fiber-optic combiner (Avantes).

The cell that is used to polarize the gas is a 3.5" ID sphere made of alumino-silicate glass with a 4" capillary stem and a glass valve. The cell can hold 3L of room temperature ^{3}He when it is pressurized to ~9atm. The alkali metal mixture was prepared in our lab with a target potassium to rubidium ratio of 5:1. The cell is heated in a ceramic oven to approximately 225ºC, which preliminary tests have shown to be the optimum temperature for our laser power. The oven is located at the center of a Hemholtz coil pair (Walker Scientific), which generates a holding field of 25G.

Measurement Techniques: During pumping, the growth of ^{3}He polarization towards its saturation value is monitored using adiabatic fast passage (AFP) NMR [3]. A set of transmit coils are driven at a fixed frequency (100kHz), then the holding field is swept up and down through the resonant field value causing the ^{3}He nuclei to flip 180º and then back again. The transverse magnetization is detected in separate receive coils. This procedure provides excellent SNR with minimal polarization loss per measurement (~1% relative). AFP measurements are performed at specified intervals during pumping and the integrated signal is plotted versus time and fit to an exponential curve. This is referred to as a "spin up", and the fit gives the saturation value and a spin up time constant, both of which are important in characterizing system performance.

The size of the AFP signal is periodically calibrated to the absolute ^{3}He polarization by measuring the alkali metal electron paramagnetic resonance (EPR) frequency [4]. A dedicated set of RF coils is used to drive a Zeeman transition (~20MHz) in one of the metals, the frequency of which depends on total magnetic field seen by the metal, which is a combination of the holding field (25G) and the field produced by the ^{3}He magnetization (~20mG). Using an AFP frequency sweep to flip the ^{3}He spins, the EPR frequency is measured with the ^{3}He nuclei oriented both parallel and anti-parallel to the holding field (see Fig. 2). The change in alkali transition frequency between the different ^{3}He spin orientations is proportional to the ^{3}He polarization, which can be calculated if the ^{3}He density is known. This technique provides a direct measurement of the ^{3}He polarization in situ, without relying on a calibration to a comparable water NMR signal.

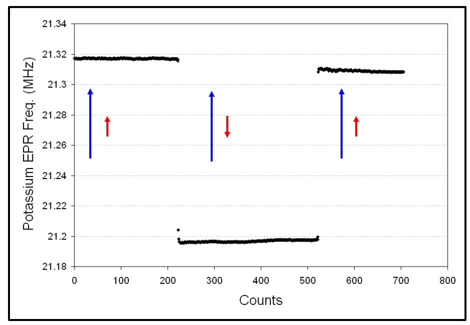

Figure 2: EPR Measurement Data. The blue arrows show the direction of the holding field, the red arrows represent the ^{3}He field.

Experimental Tests: Initial polarizer performance was characterized by filling the cell with 3 STP-liters of a 99% ^{3}He/ 1%N_2 mixture and setting the oven temperature to 225ºC. Three separate spin ups were acquired using 1, 2, or 3 lasers. Immediately following each spin up, the absolute polarization of the ^{3}He was measured using EPR.

Results: The results of the laser power test are shown in Fig. 3. With three Comets, the ^{3}He polarization saturated at 59.4 ± 3%, with a spin up time constant of 3.7hrs. The results for two and one Comet were P_{sat} = 55.6 ± 2.8% T_{up} = 4.1hrs and P_{sat} = 27.6 ± 1.4% T_{up} = 3.25hrs, respectively.

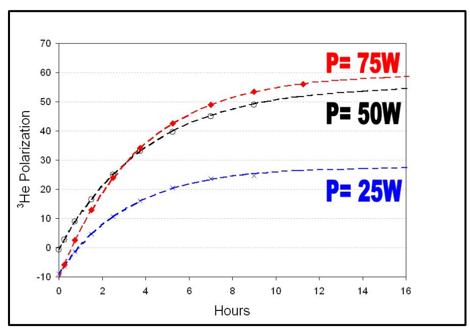

Figure 3: Laser Power Spin Ups. The data are shown with the fitted curves. The red points represent 3 lasers (75W), the black 2 lasers (50W), and the blue 1 laser (25W).

Conclusion: The combination of more efficient optical pumping (resulting from higher laser power concentrated at the rubidium D1 absorption line) and more efficient spin exchange (due to the hybrid alkali mixture) yields substantially higher ^{3}He polarization than previous-generation systems. Based on these results, we expect the Hybrid Polarizer to produce 3L of ^{3}He per day for use in both animal and human studies, with polarization levels approaching or exceeding 60%. In addition, the spin up time constant $T_{up} < 4$hrs means that after dispensing an overnight polarization run in the morning, a second batch of 3L at 40% polarization could be dispensed in the afternoon if desired.

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References: [1] W. C. Chen et al., Phys. Rev. A 75, 013416 (2007). [2] B. Chann et al., J. Appl. Phys. 94, 6908 (2003). [3] A. Abragam, (Oxford University Press, New York, 1996). [4] M. V. Romalis et al., NIM A 402, pp 260-267 (1998).