

Contents

Acknowledgements	iv
Abstract	vi
1 Introduction	1
2 Hyperpolarized Gas Production and Polarimetry	4
2.1 Background	4
2.2 Hyperpolarized Gas Production	6
2.2.1 Optical Pumping	6
2.2.2 Spin Exchange	9
2.2.3 Experimental Setup	10
2.2.3.1 Vacuum System and Cell Production	10
2.2.3.2 Optical Pumping Setup	13
2.3 Hyperpolarized Gas NMR Polarimetry	15
2.3.1 NMR Polarimetry Principles	15
2.3.1.1 Adiabatic Fast Passage	17
2.3.2 NMR Electronics	20
2.3.3 Water NMR Signals and Water Thermal Polarization	22
2.3.4 ^3He and ^{129}Xe NMR Polarimetry	23
2.4 Hyperpolarized Gas EPR Polarimetry	27
2.4.1 EPR Polarimetry Principles	27
2.4.2 EPR Electronics	29
2.4.3 ^3He and ^{129}Xe EPR Polarimetry	34
2.5 Concluding Remarks	38

3	The Pulsed Resistive Low-Field MR Scanner	39
3.1	Background	39
3.2	Signal-to-Noise Ratio in MRI, PMRI and Hyperpolarized Gas MRI	42
3.2.1	MR Signal	42
3.2.2	Noise in MRI	43
3.2.3	SNR in PMRI and Hyperpolarized Gas Imaging	45
3.3	PMRI Pulse Sequence	48
3.4	Electronics of the Pulsed Low-Field Resistive System	51
3.4.1	Readout Magnet and Power Supply	51
3.4.2	Polarizing Magnet and Power Supply	53
3.4.3	Transmit-Receive Circuit	54
3.4.4	Gradients	57
3.4.5	Techmag Console System - Data Acquisition and Control System	57
3.5	Hyperpolarized Gas Pumping Setup at Stanford	58
3.6	Concluding Remarks	59
4	T₂ Relaxation and Diffusion Measurements of Hyperpolarized ¹²⁹Xe and ³He in the Pulsed Low-Field Resistive MR Scanner	60
4.1	Background	60
4.2	Theory of Transverse (T ₂) Relaxation	64
4.3	Reversible T ₂ Decay	68
4.3.1	Magnet Inhomogeneities and Spin Echoes	68
4.4	Irreversible T ₂ Decay	71
4.4.1	Diffusion	71
4.4.1.1	Statistical Approach to Signal Decay due to Diffusion in Constant Gradients	71
4.4.1.2	Signal Decay due to Diffusion in an Arbitrary Gradient Waveform Based on the Bloch Equation	73
4.4.2	Spin-Spin Interaction	75
4.5	Measurements of Reversible Transverse Relaxation with Free-Induction-Decay	77
4.5.1	Determination of Gas Polarization	79
4.5.2	Adiabatic Condition for Spin Transition in the Pulsed Scanner	83

4.6	Measurements of Irreversible Transverse Relaxation Using CPMG Sequence	89
4.6.1	Errors in RF Pulse Calibration and Stimulated Echoes	91
4.6.2	Heating of the Magnet and Off-Resonance Effects	93
4.7	Measurements of Diffusion Using PGSE Sequence	96
4.7.1	Uncertainties in Determining Diffusion Coefficients of Hyperpolarized ^{129}Xe and ^3He	101
4.8	Measurement of Intrinsic (Spin-Spin) T_2 Relaxation Using CPMG Sequence with Variable Interecho Times	103
4.8.1	Uncertainties in Determining Inherent T_2 Relaxation of Hyperpolar- ized ^{129}Xe and ^3He	105
4.9	Conclusions	109
5	Hyperpolarized Gas Imaging on a Low-Field Pulsed Resistive System	111
5.1	Background	111
5.2	Basic Principles of MR Imaging	114
5.3	Theoretical Model of Signal Decay during Hyperpolarized Gas Imaging . . .	118
5.3.1	Flip-Angle Effect	118
5.3.2	Signal Decay due to T_1 and T_2 Relaxation	119
5.3.3	Signal Decay due to Diffusion	121
5.3.4	K-Space Weighting	121
5.4	Gradient Echo Imaging	124
5.4.1	Gradient Echo Pulse Sequence	124
5.4.2	K -Space Weighting for Gradient Echo Imaging	126
5.4.3	2-D Gradient Echo Imaging Experiments and Simulations	127
5.4.3.1	Centrally and Sequentially Ordered Phase-Encode Gradi- ents during Gradient Echo Imaging	131
5.5	Spin Echo Imaging	139
5.5.1	Spin Echo Pulse Sequence	139
5.5.2	K -Space Weighting for Spin Echo Imaging	140
5.5.3	1-D Spin Echo Imaging Experiments and Simulations	141
5.5.3.1	Centrally and Sequentially Ordered Phase-Encode Gradients	141
5.6	Conclusions	147

6 Future Work	149
6.1 Hyperpolarized Gas Polarimetry	149
6.2 Hyperpolarized Gas Imaging	150
A Theoretical Estimation of Diffusion Coefficients for Binary Gas Mixtures	152
A.0.1 Observable Diffusion Constant for a Mixture of Xe-129 and Nitrogen	154
A.0.2 Observable Diffusion Constant for a Mixture of He-3 and Nitrogen .	155
B Supplement on Fourier Transforms	156
C Imaging Parameters	157
C.1 Bibliography	159
Bibliography	159

List of Figures

2.1	Electron levels in ^{85}Rb atom, assuming $I_{Rb} = 0$. The vertical axis is not drawn to scale.	6
2.2	^{85}Rb magnetic sublevels. Taken from a paper by W. Happer [1].	7
2.3	Spin transfer between the rubidium electron and the noble gas nucleus.	9
2.4	^{129}Xe cell used for NMR and EPR polarimetry studies.	12
2.5	A schematics of the vacuum system used for Xe-cell production.	12
2.6	A photograph of the Ti-Sapphire lasers which were used for optical pumping at Caltech.	13
2.7	A schematics of the optical pumping setup.	14
2.8	A photograph of the Helmholtz electromagnet at Caltech.	14
2.9	Magnetization precessing like a spinning top around the effective magnetic field \mathbf{B} with a characteristic frequency ω	16
2.10	Schematics of spin-flip using the technique of the adiabatic fast passage.	18
2.11	Electronic circuitry for NMR detection.	21
2.12	Water AFP signals used for calibration of ^3He polarization (left) and ^{129}Xe polarization. Left: $A_1 = 3.9 \times 10^{-5}$, $B_{res} = 21.8$ G, $\Delta B_1 = 0.15$ G; $A_2 = -3.8 \times 10^{-5}$, $B_{res} = 21.6$ G, $\Delta B_2 = 0.10$ G. Right: $A_1 = 4.6 \times 10^{-5}$, $B_{res} = 21.6$ G, $\Delta B_1 = 0.1$ G; $A_2 = -5.0 \times 10^{-5}$, $B_{res} = 21.8$ G, $\Delta B_2 = 0.15$ G.	23
2.13	Left: ^3He AFP signal as a function of time. Right: AFP resonance during the ramp-up time and best fit to the data, $A_1 = -0.1639$, $B_{res} = 28.6$ G, $\Delta B_1 = 0.11$ G.	25
2.14	Left: ^{129}Xe AFP signal as a function of time. Right: AFP resonance during the ramp-up time and best fit to the data, $A_1 = -1.08 \times 10^{-4}$, $B_{res} = 27.8$ G, $\Delta B_1 = 0.15$ G.	26
2.15	Electronic circuitry for EPR detection.	29

2.16	Modulation of the Zeeman resonance produces a dispersion curve.	30
2.17	Proportional-integral feedback and mixer circuitry.	33
2.18	Schematics of EPR frequency before and after AFP flip.	33
2.19	Helium EPR frequency shifts after AFP flip.	35
2.20	A preliminary xenon EPR frequency shift after one AFP flip.	36
3.1	SNR as a function of readout frequency for PMRI and hyperpolarized gas MR. The transitional frequency, ω_T , is defined as the frequency at which the coil and the body contribute equal amount of noise. Well below ω_T , the SNR grows as a function of $\omega_o^{3/4}$, while well above ω_T , the SNR approaches its asymptotic limit.	46
3.2	Timing diagram illustrating a typical PMRI sequence. B_p is the waveform of the polarizing pulse and B_o is the waveform of the readout magnet.	48
3.3	Photograph of the homebuild 24 cm bore, 23 mT, 1 kW homogeneous readout magnet for PMRI of extremities. This magnet was used in the hyperpolarized gas experiments.	51
3.4	Photograph of the 13 cm bore, 0.4 T, 10 kW polarizing magnet used for polarizing protons in water in the PMRI experiments.	53
3.5	The pulsing/switching circuit. The circuit was used to transfer power stored in the conductor into the capacitor.	54
3.6	Dual transmit-receive circuit. The cross diodes present a short circuit in the transmit mode and an open circuit in the receive mode.	56
3.7	Saddle coil and the receiver-transmit circuitry used for hyperpolarized gas and water imaging at 1.1 MHz.	57
3.8	Solenoid coil and receiver-transmit circuitry used for hyperpolarized gas and water imaging at 397 kHz.	57
3.9	The pumping setup at Stanford.	58
4.1	Creation of a spin echo.	69
4.2	Pulse sequence used to generate free-induction-decay, or FID.	77
4.3	Free-induction-decay (FID) signal of water taken on the low-field pulsed resistive scanner (top) and its Fourier transform (bottom).	78
4.4	Xenon and water spectra used to calibrate xenon polarization levels.	82

4.5	Helium and water spectra used to calibrate helium polarization levels.	82
4.6	A schematic representation of the hyperpolarized gas magnetization alignment during imaging on the low-field pulsed resistive scanner. Left: magnetization alignment before the application of B_0 field. Right: magnetization alignment after the application of B_0 field. An adiabatic transition between the two states is required to prevent polarization loss.	84
4.7	A vectorial representation of the hyperpolarized gas magnetization transition during the ramping of the readout field. Left: Without the background field. Right: With small background field, \mathbf{B}_{low} , along z-direction.	85
4.8	Timing diagram of a typical PMRI pulse sequence with a modified B_0 waveform. Unlike in the diagram of Figure 3.2, the B_0 is now on a low-field setting before the application of the B_p pulse.	86
4.9	Pulse sequence used for demonstrating the non-adiabatic ramp-up of B_0 pulse in the absence of the low-field setting.	87
4.10	Creation of spin echoes demonstrating the existence of transverse magnetization before the ramp-up of the B_0 pulse: without the background field, with background field = 25 μT and with background field = 100 μT	87
4.11	Pulse sequence used to generate a Carr-Purcell-Meiboom-Gill echo train. . .	89
4.12	^3He (left) and ^{129}Xe (right) spin echo trains obtained with the CPMG sequence.	90
4.13	A logarithmic plot of the average measured ^{129}Xe spin echo magnitude as a function of time and best fit to the data. Number of echoes=4096, TE=7.29 ms, T2 extracted from the plot=49.5 s.	91
4.14	Measurement of FID magnitude as a function of B_1 pulse duration.	92
4.15	An example of the occurrence of stimulated echoes during a CPMG spin echo train. Number of echoes=256, TE=27.03 ms.	93
4.16	Pulse sequence used for measuring diffusion coefficients of hyperpolarized gases and water. First n_1 loops: no gradients used; last n_2 loops: bipolar gradients with amplitude = g , width = δ , separation = Δ	96
4.17	Bipolar gradient waveform used in the diffusion sequence as a function of time.	97

4.18	Left: ^3He spin echo train obtained with diffusion sequence from Figure 4.16. Right: Average echo amplitude from (right) plotted on a log scale as a function of time and best fit to data. $n_1=4$: $g=0$; $n_2=8$: $g=0.368$ mT/m; TE=105.35 ms, $\Delta=10.09$ ms, $\delta=5$ ms.	100
4.19	Left: ^{129}Xe spin echo train obtained with diffusion sequence from Figure 4.16. Right: Average echo amplitude from (right) plotted on a log scale as a function of time and best fit to data. $n_1=4$: $g=0$; $n_2=8$: $g=2.76$ mT/m; TE=135 ms, $\Delta=25.22$ ms, $\delta=5$ ms.	100
4.20	Left: Water spin echo train obtained with diffusion sequence from Figure 4.16. Right: Average echo amplitude from (right) plotted on a log scale as a function of time and best fit to data. $n_1=8$: $g=0$; $n_2=8$: $g=13.8$ mT/m; TE=75.55 ms, $\Delta=35.13$ ms, $\delta=15$ ms.	100
4.21	^3He T_2^{CPMG} data as a function of interecho time, TE, for two shimming values, and a fit to the data according to Eq 4.84. $g \approx 0.06$ mT/m, $T_2 = 23.7$ s; $g \approx 0.01$ mT/m, $T_2 = 14.7$ s.	106
4.22	^{129}Xe T_2^{CPMG} data as a function of interecho time, TE, for three shimming values, and a fit to the data according to Eq 4.84. $g \approx 0.02$ mT/m, $T_2 = 47.2$ s; $g \approx 0.13$ mT/m, $T_2 = 46.5$ s; $g \approx 0.38$ mT/m, $T_2 = 46.3$ s.	106
4.23	Distilled water T_2^{CPMG} data as a function of interecho time, TE, and a fit to the data according to Eq 4.84. $g = 0.005$ mT/m, $T_2 = 1.04$ s.	106
5.1	A typical gradient waveform used for collecting k -space data. Data acquisition occurs during the application of the positive G_x lobe. The magnitude of G_y is decremented with each excitation, while the magnitude of G_x is kept constant.	116
5.2	A schematic representation of k -space data collection. A line of k -space is acquired during each data acquisition; multiple acquisitions with varying k_y values are required to scan the entire plane.	117
5.3	Projection of magnetization onto the longitudinal and transverse axis.	118
5.4	Overview of r-space and k-space functions used in modelling the effects of signal decay on the image of a 2-D sphere.	122

5.5	Schematic representation of the model used to obtain the effect of diffusion, relaxation and finite flip-angle on the image. Top left: projection of a sphere onto the z-axis. Top right: Fourier transform of the sphere's projection—the jinc-function. Middle right: k -space weighting for centric (l) and sequential (r) encoding schemes. Bottom right: weighted projection of a sphere in k -space displayed in image mode. Bottom left: weighted projection of a sphere in r -space displayed in image mode.	123
5.6	Pulse sequence used in gradient echo imaging. RF = excitation pulse, α = flip-angle, G_x = gradient waveform along x-direction, G_y = gradient waveform along y-direction, Signal = gradient echo.	124
5.7	A schematic representation of k -space data collection in gradient echo sequence.	125
5.8	Schematic representation of signal decay during gradient echo sequence. Diffusion and T_2^* relaxation cause signal loss along the readout direction, while flip-angle and diffusion cause signal loss along the phase-encode direction. . .	127
5.9	Diffusion and T_2^* losses along the readout direction. Top: Experimental raw k -space data. Middle: Simulation of k -space data. Bottom: K -space weighting used in the simulation. Acq.time=42.6 ms, BW=1502 Hz, $\alpha = 8^\circ$, $FOV_x = FOV_y = 27.8$ cm, $\Delta x = 2.17$ mm, $\Delta y = 4.34$ mm, $T_2^* = 40$ ms, sequentially ordered phase-encode gradients.	128
5.10	Flip-angle effects along the phase-encode direction. Top: Experimental raw k -space data. Middle: Simulation of k -space data. Bottom: K -space weighting used in the simulation. Acq.time=10.8 ms, BW=5952 Hz, $\alpha = 19.6^\circ$, $FOV_x = FOV_y = 27.8$ cm, $\Delta x = 2.17$ mm, $\Delta y = 4.34$ mm, $T_2^* = 40$ ms, sequentially ordered phase-encode gradients.	129
5.11	A schematic representation of k -space trajectories using a Cartesian spiral (left) and concentric circles (right) encoding scheme that can significantly reduce diffusion losses during imaging.	132
5.12	A schematic representation of centrally (left) and sequentially (right) ordered phase-encoding scheme using 2DFT sampling of k -space. By acquiring central phase-encodes first, diffusion losses are reduced.	133

5.13	Gradient echo image of a 2.5 cm sphere filed with hyperpolarized ^3He obtained with sequentially ordered phase-encode gradients. Acq.time=4 ms, BW=8 kHz, $\alpha = 12.7^\circ$, $FOV_x = FOV_y = 10.5$ cm, $\Delta x = \Delta y = 1.64$ mm, $t_{pump} = 2$ h, T_2^* relaxation negligible.	136
5.14	Simulation of the experiment displayed in the Figure 5.13.	136
5.15	Gradient echo image of a 2.5 cm sphere filed with hyperpolarized ^3He obtained with centrally ordered phase-encode gradients. Acq.time=4 ms, BW=8 kHz, $\alpha = 12.7^\circ$, $FOV_x = FOV_y = 10.5$ cm, $\Delta x = \Delta y = 1.64$ mm, $t_{pump} = 2$ h, T_2^* relaxation negligible.	137
5.16	Simulation of the experiment displayed in the Figure 5.15.	137
5.17	Gradient echo image (left) and projection (right) onto the y-axis of a 2.5 cm sphere filed with hyperpolarized ^3He using centrally ordered phase-encode gradients. $t_{OP} = 10$ h; $f_{RF} = 398$ kHz; $\alpha = 13^\circ$; $\Delta x = \Delta y = 1.64$ mm; $FOV_x = FOV_y = 10.5$ cm; $T_{AcqTime} = 4$ ms; $BW = 8$ kHz; $G_x = 4.7$ mT/m; $G_y^{max} = 9.41$ mT/m.	138
5.18	Gradient echo image (left) and projection (right) onto the y-axis of a 2.5 cm sphere filed with doped water . $B_p \approx 0.3$ T; $f_{RF} = 398$ kHz; $\alpha = 90^\circ$; $\Delta x = \Delta y = 0.94$ mm; $FOV_x = FOV_y = 6$ cm; $T_{AcqTime} = 4$ ms; $BW = 8$ kHz; $G_x = 6.26$ mT/m; $G_y^{max} = 12.5$ mT/m.	138
5.19	Pulse sequence used in spin echo imaging.	139
5.20	A schematic representation of k -space data collection in spin echo sequence. .	140
5.21	Schematic representation of signal decay during spin echo sequence. The main mechanism of signal loss in both readout and phase-encode directions is diffusion.	141
5.22	Pulsed gradient spin echo sequence.	142
5.23	K -space weighting for ^{129}Xe using PGSE sequence with centric and sequential ordering - experimental data (circles), simulation (crosses). Predicts a $\times 2$ SNR gain using centric ordering. T_2 used in simulation = 6.5 s, $g_{max} = 1.32$ mT/m, $\Delta g = 0.04$ mT/m, $\delta = 5$ ms, $\Delta = 10.36$ ms, $TE = 54.2$ ms, $\Delta y = 0.58$ cm, $FOV_y = 40.7$ cm.	143

- 5.24 Diffusion k -space weighting–simulation for ^{129}Xe . Predicts a $\times 20$ SNR increase for a 2 mm target resolution using centric encoding. No T_2^{CPMG} relaxation. $\Delta y = 2$ mm, $FOV_y = 12.8$ cm, $G_{max} = 4.2$ mT/m, $\Delta G = 0.13$ mT/m, $\delta = 5$ ms, $\Delta = 10$ ms, $TE = 20$ ms. 145
- 5.25 Diffusion k -space weighting–simulation for ^3He . Predicts a $\times 20$ SNR increase for a 5 mm target resolution using centric encoding. No T_2^{CPMG} relaxation. $\Delta y = 5$ mm, $FOV_y = 32$ cm, $G_{max} = 1.54$ mT/m, $\Delta G = 0.05$ mT/m, $\delta = 2$ ms, $\Delta = 5$ ms, $TE = 10$ ms. 145
- 5.26 A 1-D spin echo image of a 2.5 cm sphere filled with hyperpolarized ^3He taken with centrally and sequentially ordered phase-encode gradients. Acquisition time = 4 ms, $FOV_y = 10.5$ cm, $\Delta y = 1.64$ mm, $G_{y,max} = 9.4$ mT/m, $\Delta G_y = 0.29$ mT/m. 146

List of Tables

2.1	The gas content of ^{129}Xe and ^3He cells used at Caltech. All pressures measured at room temperature. ^3He cell parameters taken from [2].	11
2.2	Dimensions of ^3He cell (taken from [2]) and ^{129}Xe cell.	11
2.3	Parameter values during the NMR-AFP experiment.	20
2.4	Parameters related to water AFP signal.	22
2.5	Parameters related to helium AFP signal.	25
2.6	Parameters related to xenon AFP signal.	26
2.7	Experimental and theoretical values of κ_o for Rb-He and Rb-Xe interaction. Rb-He experimental value taken from [3]; Rb-He theoretical value taken from [4]; Rb-Xe experimental and theoretical values taken from [5].	28
2.8	Parameter values during the EPR-AFP experiment.	32
2.9	Parameter values related to EPR Polarimetry.	34
2.10	Helium and xenon parameters used in EPR polarimetry. ⁽ⁱ⁾ Uncertainty related to κ_o measurement. ⁽ⁱⁱ⁾ Uncertainty due to the non-spherical shape of the cell.	34
4.1	The gas content of ^{129}Xe and ^3He cells used at Stanford. All pressures measured at room temperature.	80
4.2	Table of experimental and theoretical values of diffusion coefficients for ^{129}Xe , ^3He and distilled water.	102
4.3	Results of simple qualitative experiments testing the hypothesis of gas flow.	108