Design of a Hybrid $^3$He Polarizer: Measurement Techniques and Construction

Karen Mooney
University of Virginia
March 25, 2008
Polarizer Basics
New Polarizer Advancements

More Gas
• 3.0L/day Vs 1.0L/day

Higher Polarization
• 60% Vs 40%
• Rb-K Hybrid Cell
• Narrowed Diode Lasers

Enhanced Diagnostics
• AFP NMR w/ EPR calibration
  Vs
• Pulse NMR w/ Water calibration
Nuclear Magnetic Resonance (NMR)

• Polarized $^3$He nuclei are aligned with an external magnetic field
• He Nuclear Spins are “flipped” by applying a transverse RF Field
• Faraday Induction signal detected in mutually perpendicular coils
• Signal detected is proportional to $^3$He polarization
Measuring Polarization

Nuclear Magnetic Resonance (NMR)

• Polarized $^3$He nuclei are aligned with an external magnetic field
• He Nuclear Spins are “flipped” by applying a transverse RF Field
• Faraday Induction signal detected in mutually perpendicular coils
• Signal detected is proportional to $^3$He polarization
Adiabatic Fast Passage

\[ \vec{H}_{eff} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x} \]

\[ H_0 = \gamma \omega_{RF} \]

\( \omega_{RF} \) is fixed, \( H \) is swept through \( H_0 \)

Field Sweep

12.6 \( \leftrightarrow \) 21.5 Gauss
Adiabatic Fast Passage

\[ \vec{H}_{eff} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x} \]

\[ H_0 > H \]
Measuring Polarization

AFP

\[ \vec{H}_{\text{eff}} = (H(t) - H_0) \hat{z} + H_1(\omega_{RF}) \hat{x} \]

\[ H_0 > H \]
Measuring Polarization

\[^{\vec{H}}_{eff} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x}\]

\[H_0 > H\]
\[ \vec{H}_{eff} = (H(t) - H_0) \hat{z} + H_1(\omega_{RF}) \hat{x} \]

\[ H_0 > H \]

\[ H_0 = H \]

**Typical Lab Values**

\[ \omega_{RF} = 56.6 \text{ kHz} \]

\[ B_0 \approx 17 \text{ Gauss} \]
\[ \vec{H}_{\text{eff}} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x} \]

- \( H_0 > H \)
- \( H_0 = H \)
- \( H_0 < H \)

- RF Field \( H_1 \)
- Holding Field \( H \)
- Helium Spin \( \omega_{RF} \)
Measuring Mooney
Measuring Polarization

\[ \vec{H}_{\text{eff}} = (H(t) - H_0) \hat{z} + H_1(\omega_{RF}) \hat{x} \]

- \( H_0 > H \)
- \( H_0 = H \)
- \( H_0 < H \)

RF Field \( H_1 \)
Holding Field \( H \)
Helium Spin \( \omega_{RF} \)
\[ \vec{H}_{eff} = (H(t) - H_0) \hat{z} + H_1(\omega_{RF}) \hat{x} \]

- \( H_0 > H \)
- \( H_0 = H \)
- \( H_0 < H \)
\[ \vec{H}_{eff} = (H(t) - H_0) \hat{z} + H_1(\omega_{RF}) \hat{x} \]

- $H_0 > H$
- $H_0 = H$
- $H_0 < H$

RF Field $H_1$

Holding Field $H$

\[ \omega_{RF} \]

Helium Spin
Measuring Mooney

Measuring Polarization

\[ \vec{H}_{eff} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x} \]

\[ H_0 > H \]

\[ H_0 = H \]

\[ H_0 < H \]

RF Field \( H_1 \)

Holding Field \( H \)

Helium Spin \( \omega_{RF} \)
\[
\vec{H}_{\text{eff}} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x}
\]

- \(H_0 > H\)
- \(H_0 = H\)
- \(H_0 < H\)
Measuring Mooney Measuring Polarization

\[ \vec{H}_{\text{eff}} = (H(t) - H_0) \hat{z} + H_1(\omega_{RF}) \hat{x} \]

- $H_0 > H$
- $H_0 = H$
- $H_0 < H$
- $H_0 = H$

Helium Spin

RF Field $H_1$

Holding Field $H$

$\omega_{RF}$
\[ \vec{H}_{eff} = (H(t) - H_0) \hat{z} + H_1(\omega_{RF})\hat{x} \]
\[ \vec{H}_{\text{eff}} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x} \]
Measuring Polarization

**AFP**

\[ P_f \approx 0.99 \times P_i \]

\[ \vec{H}_{eff} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x} \]

Adiabatic- Field is swept slowly so that the spin can follow it

\[ D \frac{|\nabla H\hat{z}|^2}{H_1^2} \ll \frac{\dot{H}}{H_1} \ll \omega_{RF} \]

Fast- The Field is swept quickly enough so that the spins do not relax in the low field region.

Holding Field

H

Helium Spin
Measuring Polarization

AFP Schematic

- Holding Field (H)
- RF Field $H_1(\omega)$
- Pick Up Coils
- EPR Coil
- EPR Photo Diode
Measuring Polarization

AFP Schematic

- Holding Field \((H)\)
- RF Field \(H_1(\omega)\)
- Pick Up Coils
- EPR Coil
- EPR Photo Diode
Measuring Polarization

AFP Schematic

- Holding Field (H)
- RF Field $H_1(\omega)$
- - Pick Up Coils
- - EPR Coil
EPR Photo Diode
Measuring Polarization

AFP Signal

Lock-In Signal

A “Spin Up” Fit

Sample NMR Signal

Sample Spin Up Taken 01/2008
Electron Paramagnetic Resonance

Mooney
EPR - Measuring Frequency Shift

\[ \nu(B) \]

- \( F=3 \) to \( mF = -3 \ldots 3 \)
- \( 3035 \text{ MHz} \)
- \( 10 \text{ MHz (~22 gauss)} \)
- \( F=2 \) to \( mF = -2 \ldots 2 \)

Hyperfine

Zeeman
EPR - Measuring Frequency Shift

\[ \nu(B) \]

\[ \overrightarrow{B}_{Tot} = \overrightarrow{B}_{other} + \overrightarrow{B}_{He} \]

\[ B_{Tot} \approx 13 \text{ G}, B_{He} \approx 20 \text{ mG} \]
EPR- Measuring Frequency Shift

\[ \nu(B) \]

\[ \overrightarrow{B_{Tot}} = \overrightarrow{B_{other}} + \overrightarrow{B_{He}} \]

\[ B_{Tot} \approx 13 \, \text{G}, \quad B_{He} \approx 20 \, \text{mG} \]

\[ \Delta \nu \approx 20 \, \text{kHz} \]
EPR- Monitoring Frequency

Mooney Measuring Polarization
Measuring Polarization

EPR- Reversing $^3$He Polarization

\[ \vec{H}_{eff} = (H(t) - H_0)\hat{z} + H_1(\omega_{RF})\hat{x} \]

\[ H_0 = \gamma \omega_{RF} \]

$H_0$ is fixed, $\omega$ is swept through $\omega_{RF}$

$^3$He RF Sweep

56.6 kHz ↔ 30 kHz

Typical Lab Values

\[ B_0 = 12.6 \text{ Gauss} \]

\[ \omega_{RF} \approx 42 \text{ kHz} \]
EPR Schematic

- Holding Field (H)
- RF Field $H_1(\omega)$
- - Pick Up Coils
- EPR Coil
- EPR Photo Diode

Mooney

Measuring Polarization
EPR Schematic

- Holding Field (H)
- RF Field $H_1(\omega)$
- Pick Up Coils
- EPR Coil
- EPR Photo Diode
Measuring Polarization

Main Optical Pumping Oven
Mooney

Measuring Polarization

Main Optical Pumping Oven
Main Optical Pumping Oven
Main Optical Pumping Oven
Calculating Polarization

Calibration Procedure

• Take NMR
• Do EPR
• Take NMR
• Calculate $P_{He}$
• Average NMR Signals
• Get %/mV Calibration

$$P_{He} = \frac{3}{8\pi} \frac{(2I + 1)}{\mu_B \mu_{He} g_e [1 - 4I(\nu_{epr}/\nu_{hfs})k_0[He]V_{pc}]^{\Delta \nu_{epr}}}$$
Calibrated Data

- Calibration usually performed once per cell installation
- Changes with cell movement, coil movement, gain adjustments, etc.
- Recommended every few months for new Hybrid Polarizer.
Initial Proposal: 07/07

Optics System in protective enclosure

Gas Control including dispensing

Instrumentation cart - 2 meters

Polarization cart: 1 meter
Construction

Initial Proposal: 07/07

Optics System in protective enclosure

- Laser temperature control
- Laser current driver

A/Phi Box
- AR 10LA Amp
- Wavetek 80 MHz
- Feedback box
- HP 5334B Frequency Counter
- SR 530 Lock-in amplifier
- HP 3325A Mod FG

Tektronics Oscilloscope
- Agilent 33250A FG
- Keithley Multimeter
- SR 830 Lock-in amplifier
- HP 3325A Function Generator
- ENI 1040L RF Amplifier

Temperature Monitoring and Oven control
- SR 560 Preamp
- Kepco DC Power Supply

Gas Control including dispensing

Instrumentation cart - 2 meters
Polarization cart: 1 meter

Output
Optics System in protective enclosure

Gas Control including dispensing

Instrumentation cart - 2 meters

Polarization cart: 1 meter
Cart Constructed: 12/07
Laser Comparison: 11/07

- COMET
- FAP
- Rb D1

Simone T=235C

- COMET
- FAP

Wavelength (nm)

RMS Current (mA)

Spectral Density (W/nm)
Construction

Lower Gas System: 02/08

Lasers
Reduces Pressure from 3000 psi to 150 psi
Upper Gas System: 02/08

Laser

$^3$He fill  N$_2$ / Vacuum
Upper Gas System: 02/08

Laser

$^3$He fill  N$_2$ / Vacuum
Upper Gas System: 02/08

Laser

\(^3\)He fill  \(\text{N}_2 / \text{Vacuum}\)
"Upper Gas System: 02/08"

Diagram showing gas system components:
- Laser
- To Bag
- \(^3\text{He fill}\)
- \(\text{N}_2 / \text{Vacuum}\)
Implementation

Operational Target: 04/2008
Acknowledgements

Gordon Cates
Peter Dolph
Wilson Miller
Vladimir Nelyubin
Scott Rohrbaugh
Jaideep Singh
Al Tobias
Spin Exchange Optical Pumping (SEOP)

Rubidium energy level diagram which details optical pumping. Source: Singh, 2004

Collisional Mixing

m\(_J\) = -\(\frac{1}{2}\) → m\(_J\) = +\(\frac{1}{2}\)

Collisional Mixing

Nonradiative Quenching

\(\sigma_+\)

Spin Relaxation

\(5S_{1/2} \rightarrow 5P_{1/2}\)

m\(_J\) = -\(\frac{1}{2}\)

D\(_1\) Light

m\(_J\) = +\(\frac{1}{2}\)

\(\gamma_{SE}/(\gamma_{SE} + \Gamma)\)

\[ P_{3\text{He}} = \langle P_{Rb} \rangle \left( \frac{\gamma_{SE}}{\gamma_{SE} + \Gamma} \right) \]

Polarizing

Mooney

Polarizing

Spin Exchange Optimal Pumping (SEOP)

Collisional Mixing

m\(_J\) = -\(\frac{1}{2}\) → m\(_J\) = +\(\frac{1}{2}\)

Collisional Mixing

Nonradiative Quenching

\(\sigma_+\)

Spin Relaxation

\(5S_{1/2} \rightarrow 5P_{1/2}\)

m\(_J\) = -\(\frac{1}{2}\)

D\(_1\) Light

m\(_J\) = +\(\frac{1}{2}\)

\(\gamma_{SE}/(\gamma_{SE} + \Gamma)\)

\[ P_{3\text{He}} = \langle P_{Rb} \rangle \left( \frac{\gamma_{SE}}{\gamma_{SE} + \Gamma} \right) \]
Cell Performance

Simone - Previous Performance

Predicted [K]/[Rb]

Maximum Polarization

Al
Anna
Barbara
Dolly
Edna
Eva
Gloria
Simone

Mooney