Spin-Exchange Optical Pumping

gas atoms by spin exchange - metal atoms

A. van Wijngaarden, and X. Zeng
Isisatom, New Jersey 08544 9833

tall-metal atoms and noble-gas nuclei is
ed by interactions in long-lived van der
vbe the spin-rotation interactions $\gamma N \cdot S$
metal–noble-gas pair and the electron
interaction $\alpha R \cdot S$ between the nuclear
itary values for $K$ and for the nuclearar
al expressions for spin transfer coeffi-

$R(1+P_{ao})$

$R(1-P_{ao})$

$m = 1/2$

$1/2$

excited state relaxation
Spin-Exchange Optical Pumping
The Theoretical Minimum

University of Wisconsin-Madison

• The Theoretical Minimum (Expensive Photon Theory)
• SEOP with Cheap Photons

QUANTUM MECHANICS
THE THEORETICAL MINIMUM
WHAT YOU NEED TO KNOW TO START DOING PHYSICS

New York Times bestselling author
LEONARD Susskind & ART FRIEDMAN
Basic Spin-Exchange Apparatus

Frequency Synthesizer → NMR Bridge → Low-Noise Preamplifier → Lock-in Amplifier

$B_0 \sim 10 \text{ G}$

Circularly Polarized Pumping Light
$\lambda = 794.7 \text{ nm}$

GE180, $T_1 \sim 400 \text{ hrs}$
SEOP “Application”

Helmholtz Coils 21 G

RF Coils

EPR Photodiode

EPR Coil

Oven

Target Cell

Pickup Coils

794.7 nm Circularly Polarized Laser light

High Intensity Gamma Beam

1 m
Spin-Exchange w/ Noble Gases

Spin-Exchange: \[ \langle K \cdot S \rangle \]

\[
[Rb]k_{se} = 10^{14} \text{cm}^{-3} \times \begin{cases} 
6.8 \times 10^{-20} \text{cm}^3/\text{s} & \text{He} \\
1.8 \times 10^{-16} \text{cm}^3/\text{s} & \text{Xe}
\end{cases}

= \begin{cases} 
(40 \text{ hr})^{-1} & \text{He} \\
(1 \text{ min})^{-1} & \text{Xe}
\end{cases}
\]
Spin-Exchange Efficiency

\[ H = \gamma S \cdot N + \alpha S \cdot K \]

\[ \eta = \frac{\sigma_{SE}}{\sigma_{SE} + \sigma_{SR}} \]

1/25 for RbHe/Xe

1/4 for KHe
Hybrid Spin-Exchange

Idea: use Rb as spin-transfer agent to K

[Rb] << [K] suppresses this channel

>99% efficient

>95% (theory)

~30%
Hybrid Pumping II

Less alkali spin-relaxation → increase K density → faster SEOP
Nuclear Polarization

\[ \text{Flow out} = \text{Flow in} \]

\[ \mathcal{P} \mathcal{P} \mathcal{K} \mathcal{K} + \mathcal{G} \mathcal{S} \mathcal{S} \mathcal{S} \mathcal{S} + \mathcal{G} \mathcal{w} \mathcal{w} \mathcal{w} \mathcal{w} = \mathcal{G} \mathcal{S} \mathcal{S} \mathcal{S} \mathcal{S} \mathcal{P} \mathcal{P} \mathcal{A} \mathcal{A} \]

\[ \mathcal{P} \mathcal{P} \mathcal{K} \mathcal{K} = \mathcal{P} \mathcal{P} \mathcal{A} \mathcal{A} - \mathcal{G} \mathcal{w} \mathcal{w} \mathcal{w} \mathcal{w} \]

\[ \mathcal{G} \mathcal{S} \mathcal{S} \mathcal{S} \mathcal{S} + \mathcal{G} \mathcal{w} \mathcal{w} \mathcal{w} \mathcal{w} \]

\[ \mathcal{H} \mathcal{R} = 0.95 \]

\[ \mathcal{P} \mathcal{P} \mathcal{A} \mathcal{A} \]
The X-factor

Relaxation rate method
Slope $9.1 \times 10^{-20} \text{ cm}^3/\text{s}$

Direct Methods
average $6.8 \times 10^{-20} \text{ cm}^3/\text{s}$

Apparently,
\[
\frac{1}{T_{\text{wall}}} = \frac{1}{T_{\text{room}}} + X \Gamma_{SE} \quad \rightarrow \quad P_{He} \leq \frac{1}{1 + X} \approx 0.75
\]
Absolute Polarimetry

\[ B_K = \frac{8\pi}{3} \mu_K \kappa[\text{He}] P_K \]

Frequency-shift enhancement factor

\[ \kappa = \kappa_0 + \frac{3}{8\pi} C(z) - 1 \]

\[ \kappa_0(473K) = 6.39 \pm 1.5\% \quad (\text{He}) \]

\[ \kappa_0 = 493 \pm 6\% \quad (\text{Xe}) \]
Diagnostics

- EPR Spectroscopy/Imaging of Rb polarization
  (observe via transverse or longitudinal probe, transmission of pumping light, purple glow)

- Probe Faraday Rotation
  (Alkali density, Rb polarimetry)

- Diffraction grating spectrometer
  (monitor pump laser absorption vs freq, measure K:Rb density ratios)

- Calibrated external NMR methods
  (neutron transmission, p H₂O, magnetometry…)
Expensive Photon Source

5 W, 5 GHz, ~$100k
Optical Pumping

Efficiency - 2 photons/2 atoms = 100%

Light absorption rate $\Gamma P_{Rb}$
Alkali Spin-Relaxation

Photon demand \( \Phi = \Gamma P_{Rb}[Rb]V \)

\[ \Gamma(1 \text{ amg}) = \begin{cases} 
2.4 \times 10^5 /s & \text{Xe} \\
45 /s & \text{He} 
\end{cases} \]

Saam-Driehuys principle:
“The best way to polarize Xenon is to leave out the Xenon”
Light Propagation

\[
\frac{d\Phi}{dz} = -[Rb] \Gamma P_{Rb}
\]

Quality of “dark” state essential to pumping optically thick vapors (~50 O.D.)
Ideal Laser Power Reqs

\[ \eta = \eta_{OP} \eta_{SE} \left( 1 - \frac{P_K}{P_{Rb}} \right) \]

1 1/4 1/10 @ 90% pol

\[ \text{In[33]} := \frac{1000 \text{ cm}^3}{3600 \text{ sec}} \cdot \frac{2.69 \times 10^{19} \text{ He3}}{\text{cm}^3} \cdot \frac{4 \text{ photons}}{\text{He3}} \cdot \frac{15 \text{ Watt}}{6 \times 10^{19} \text{ photons / sec}} \cdot \frac{1}{1 - .9} \]

\[ \text{Out[33]} = 74.7222 \text{ Watt} \]
Spin-Exchange Optical Pumping with Cheap Photons

What I think we know
• Spin-exchange collision physics
• Optical pumping with narrowband light
• Hybrid SEOP of He-3
• Precision polarimetry
• How to make high performance cells
• Wall relaxation increases with temp

What we ought not think we know
• Optical pumping in multi-bar gases
• van-der-Waals molecules in multi-bar gases
• There is an X-factor
• The temperature inside our cells
• Why blue light comes out
• What happens to the photons

What we know we don’t know
• Why $T_1$ depends on cell orientation
• Where the X-factor comes from
• Is there a Xe X-factor?
• What the little particles are
XeNA: An automated ‘open-source’ $^{129}$Xe hyperpolarizer for clinical use

Panayiotis Nikolaou$^{a,b}$, Aaron M. Coffey$^{a,i}$, Laura L. Walkup$^{b,†}$, Brogan M. Gust$^{b}$, Nicholas Whiting$^{c,*}$, Hayley Newton$^{c}$, Iga Muradyan$^{g}$, Mikayel Dabaghyan$^{g}$, Kaili Ranta$^{d}$, Gregory D. Moroz$^{f}$, Matthew S. Rosen$^{a,h}$, Samuel Patz$^{g}$, Michael J. Barlow$^{c}$, Eduard Y. Chekmenev$^{a,i,j}$, and Boyd M. Goodson$^{b}$

200 W
1 l/hr
50% Pol
$125k$
Spin-Exchange: \[ \langle I \cdot S \rangle \]

Spin-Exchange w/ Noble Gases

\[
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interaction $\alpha \vec{K} \cdot \vec{S}$ between the nuclear
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al expressions for spin transfer coeffi-

\[ \Gamma_{se} = (3 - \text{body formation rate}) \times (\text{spin - transfer prob}) \]

\[ = \frac{1}{T_K \left( \frac{\alpha \tau}{\hbar} \right)^2} = \frac{k_{chem[Rb]}}{\tau} \left( \frac{\alpha \tau}{\hbar} \right)^2 \propto \frac{1}{\text{gas pressure}} \]
Pressure-dependence of RbXe Spin-Exchange

- Does 3-body formation/breakup model hold at $P_3 > 1 \text{ bar}$? Rb $^3\Sigma$ does not!
- Are there important other formation mechanisms such as $Rb + Xe_2 \rightarrow RbXe + Xe$?
Anisotropic Spin-Exchange

\[ H = \alpha S \cdot K + \beta (3S \cdot RR \cdot K - S \cdot K) \]

\[ P_{K,max} = \frac{k_\alpha - k_\beta / 2}{k_\alpha + k_\beta} \]

Estimates: few % effect in binary collisions
Hybrid Efficiency Measurements

Spin-Exchange eff.

Photon eff.

5% photon efficiency great, but still less than expected
Photon efficiency II

- 1 l/hr, 30-90%
- 200 W

\[
\text{In}[35] := \left( \frac{0.5 \times 1000 \text{ cm}^3 \times 2.69 \times 10^{19} \text{ pXe cm}^{-3}}{3600 \text{ sec} \times 100 \text{ Watt}} \right) \frac{15 \text{ Watt}}{6 \times 10^{19} \text{ photons / sec}}^{-1}
\]

\[
\text{Out}[35] = \frac{107.063 \text{ photons}}{\text{pXe}}
\]
Cheap Photon Sources

1000 GHz

50 GHz

50 GHz

15 GHz

1000 GHz
Diode Array Bars and SEOP

‘90s: replace expensive ion-laser pumped Ti:Sapphire or dye lasers with inexpensive (~$100/Watt) diode array bars, with ~2nm line widths. Mitigate broad laser profile by pressure broadening to several bar

Problem: He polarization < 60%
Xe typ. <30%
Circular Dichroism of Alkali Vapor

\[ \sigma(\nu) = \sigma_0(\nu)(1 - P_\infty P) \]
Fine-structure mixing

$m_j=3/2$ (pure $P_{3/2}$)

$m_j=1/2$ ($P_{3/2}$–$P_{1/2}$ mixture)
Quality of “dark” state essential to pumping optically thick vapors (~100 O.D.)
Leaky Dark State

If fully polarized atoms still absorb light at a small rate, equilibrium Rb polarization \(<1\)

Light absorption rate increases by factor

\[
\gamma = 1 + \frac{R}{\Gamma} \left(1 - P_\infty^2\right)
\]

Optically thick vapor requires \(\frac{R}{\Gamma} \gg 1\)

\[
\frac{R}{\Gamma} = 100 \quad P_\infty = 0.95 \quad \gamma = 11
\]

Small optical pumping imperfections are expensive!
Dichroism Spectrum

This is unknown for Xe
Spectral hole quickly reduces optical pumping rate at front of cell, thus reducing Rb polarization.

Light in the line wings contributes weakly to pumping rate but strongly to imperfect dichroism.
Narrowed vs Broad Laser Polarization

14 W Narrowed vs 42 W broadband
X-factor

\[ P_{He} < \frac{P_{Rb}}{1 + X} \]

NIST Data
X factor really is surface effect

\[ X = \chi \frac{S}{V} \]

- Fluctuations in cell wall properties?
- Small # of strongly relaxing sites?
Xe X-factor?

$X = 3.4$

RbH coated Pyrex
"the magnetic relaxation sites at the glass wall involved here may be the dominant cause of wall relaxation in SEOP cells at any field. "—Saam, Gentile, Chen,…

Betty @ UW 240 hr ↔ 50 hr

X-factor?
Cell Heating

Raman spectroscopy

Diffusion-weighted imaging
Temp dependence of $\kappa_0$
Other stuff I pretend doesn’t happen

• Alkali cluster formation (0.2-1 µm)  
  (in-situ neutron spin filters, high-power RbXe SEOP)

• Divots on cell walls near Rb particles

  “Together, these findings suggest that Rb particles do form during the SEOP process and at times can impart sufficient energy to locally alter the Pyrex surface”—Driehuys & gang

• Purple glow—Rb*+Rb* energy pooling—breakdown of N₂ quenching?
Progress!

(a) SEOP NSFs
- 2015: 2100 W VH G-narrowed, hybrid
- 2015: 2100 W VH G-narrowed, hybrid
- 2010: TAS, two 50 W grating narrowed, hybrid
- 2005: PNR, 20 W grating narrowed + 30 W broad
- 2000: SANS, 15 W broadband diode
- 1995: First NSF, 1 W dye laser

(b) SEOP targets
- 2010: Transversity, 2.4 K:Rb, 50 W 0.2 mm Diode
- 2010: GEN, 3.6 K:Rb, 72 W 2 mm Diode
- 2005: Duality, Rb, 72 W 2 mm Diode
- 2000: GDH, Rb, 84 W 2 mm Diode
- 1995: E142, Rb, 20 W Ti:Sapph

(c) MEOP NSFs and targets
- 2015: GEN, GDH (piston)
- 2010: GEN, GDH (piston), fill-up mode, 30 W Yb fiber
- 2005: GEN, Toeppler, filling mode, 8 W LMA
- 2000: GEN, Toeppler, filling mode, 8 W LMA
- 1990: GEN, Bates, cryo, Nd:YAP
- 1990: Toepler, continuous flow, 0.3 W LMA
S. Kadlecak
B. Chann
I. Nelson
E. Babcock
B. Lancor
B. Wyllie
Z. DeLand
A. Korver

D. Thrasher to present tomorrow

Collaborators
William Happer (Princeton)
Tom Gentile (NIST)
Wangchun Chen (NIST)
Michael Snow (Indiana)

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Optically Polarized $^3\text{He}$

T. R. Gentile, P. J. Nacher, B. Saam, T. G. Walker

This image contains a webpage with the title "Optically Polarized $^3\text{He}$" and a subtitle mentioning authors T. R. Gentile, P. J. Nacher, B. Saam, and T. G. Walker. The content of the page includes a diagram and a graph with data points for different elements such as Rb, Xe, and He. The webpage is from arXiv.org, under the category of physics, with the identifier arXiv:1612.04178.