Physics Challenges for Spin-Exchange Optical Pumping of He-3

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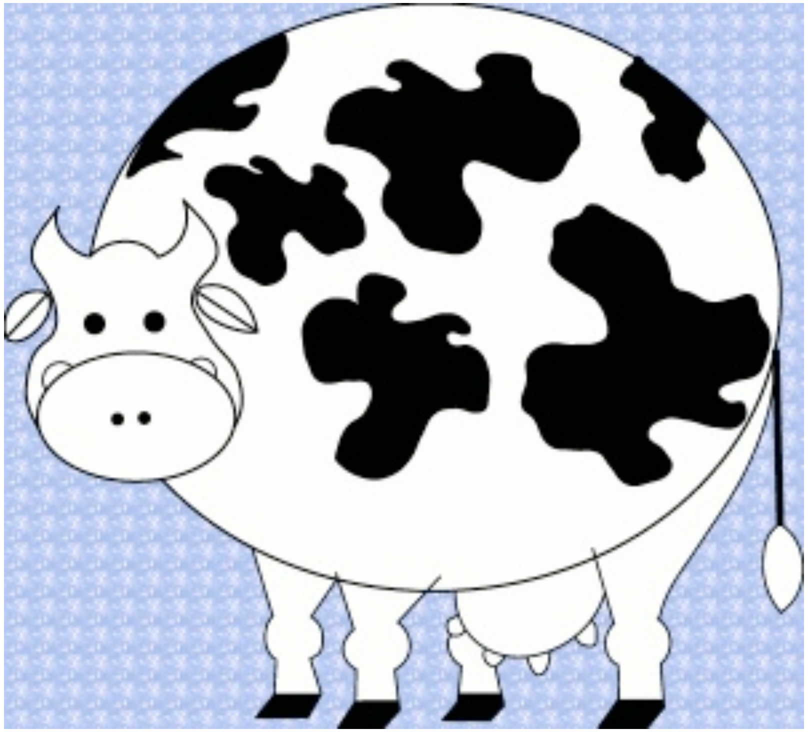
The Spherical Cow Model of SEOP

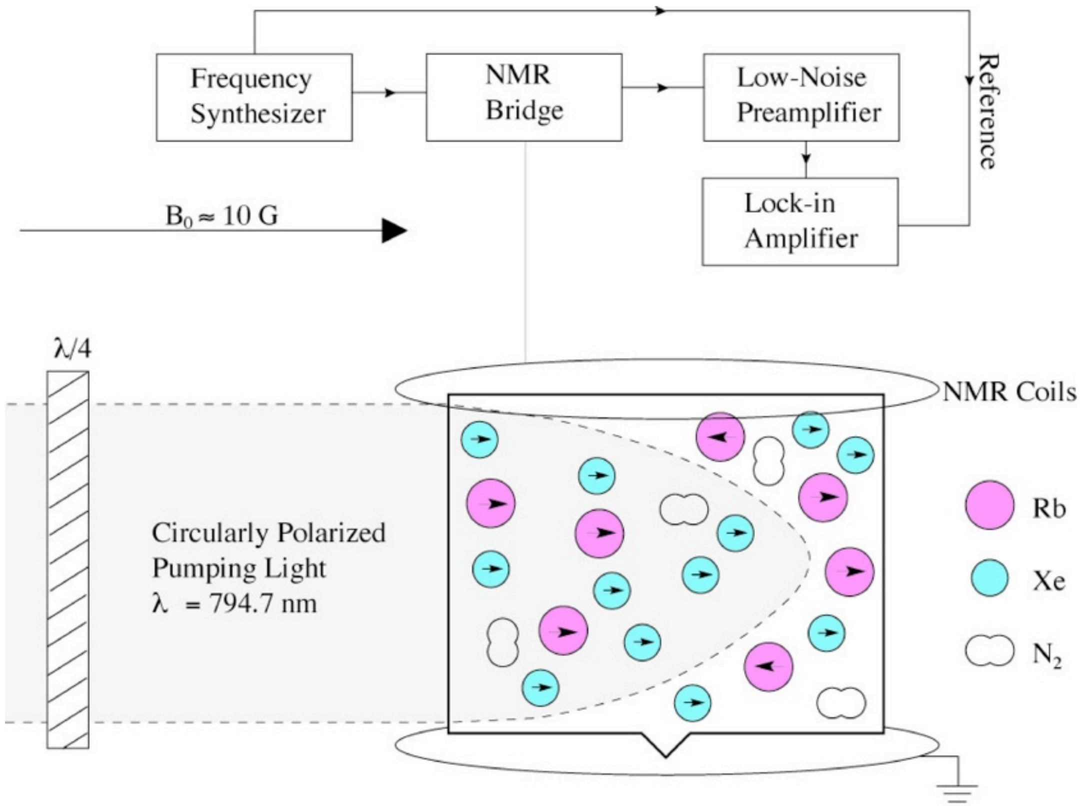


From Wikipedia:

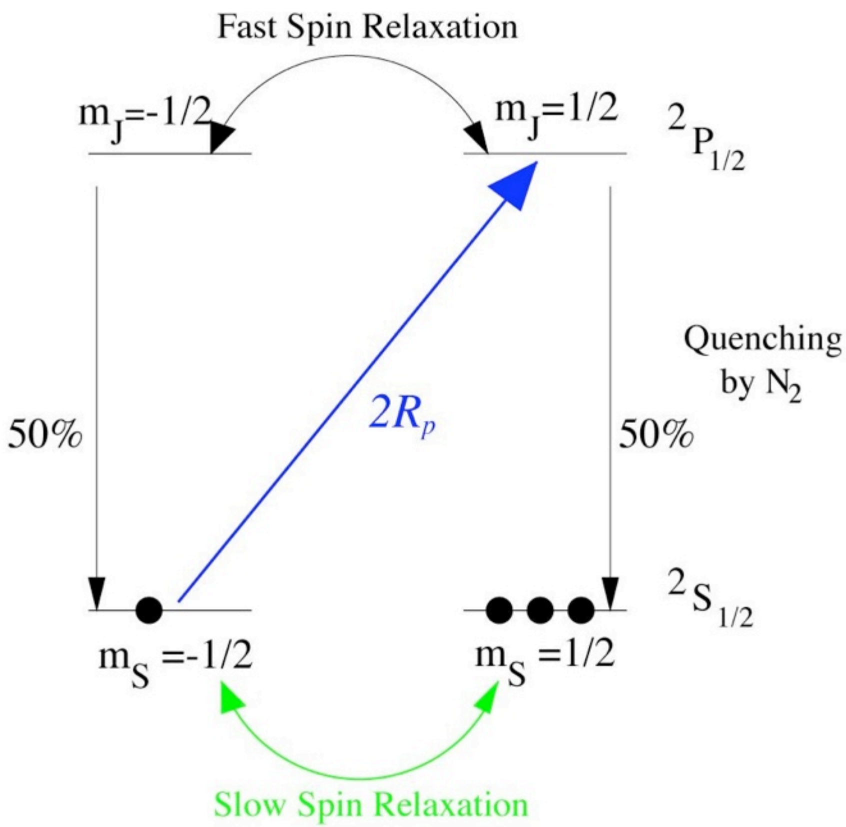
Spherical cow is a metaphor for highly simplified scientific models of reality.

T.W. and W. Happer, Rev. Mod. Phys. **69**, 629 (1997). Note: assumptions clearly stated.

Hyperpolarized Nuclei



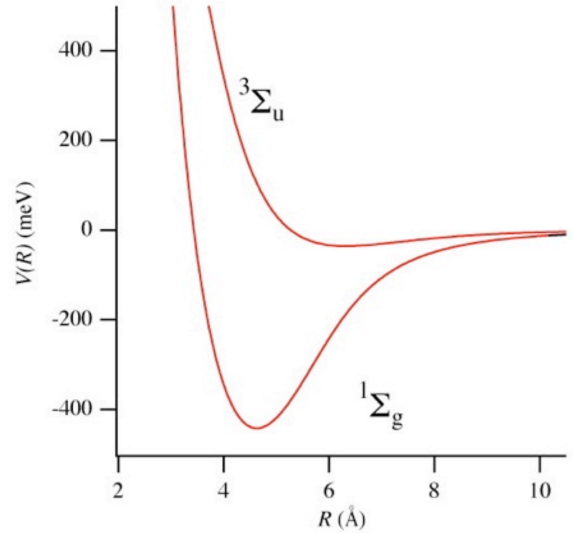
Optical Pumping

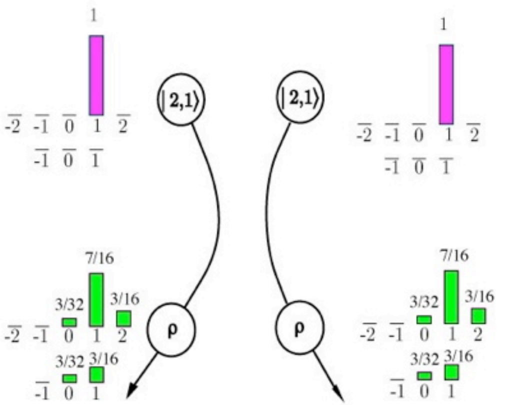


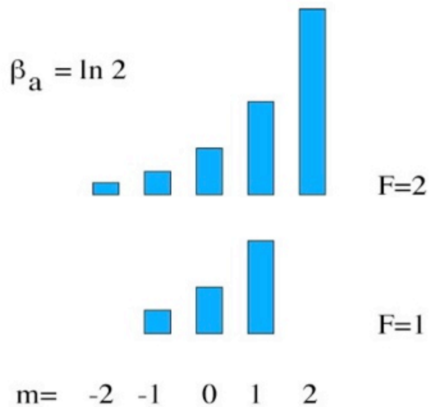
Efficiency-2 photons/2 atoms=100%

Light absorption rate = ΓP_{Rb}

Rb-Rb Spin-Exchange





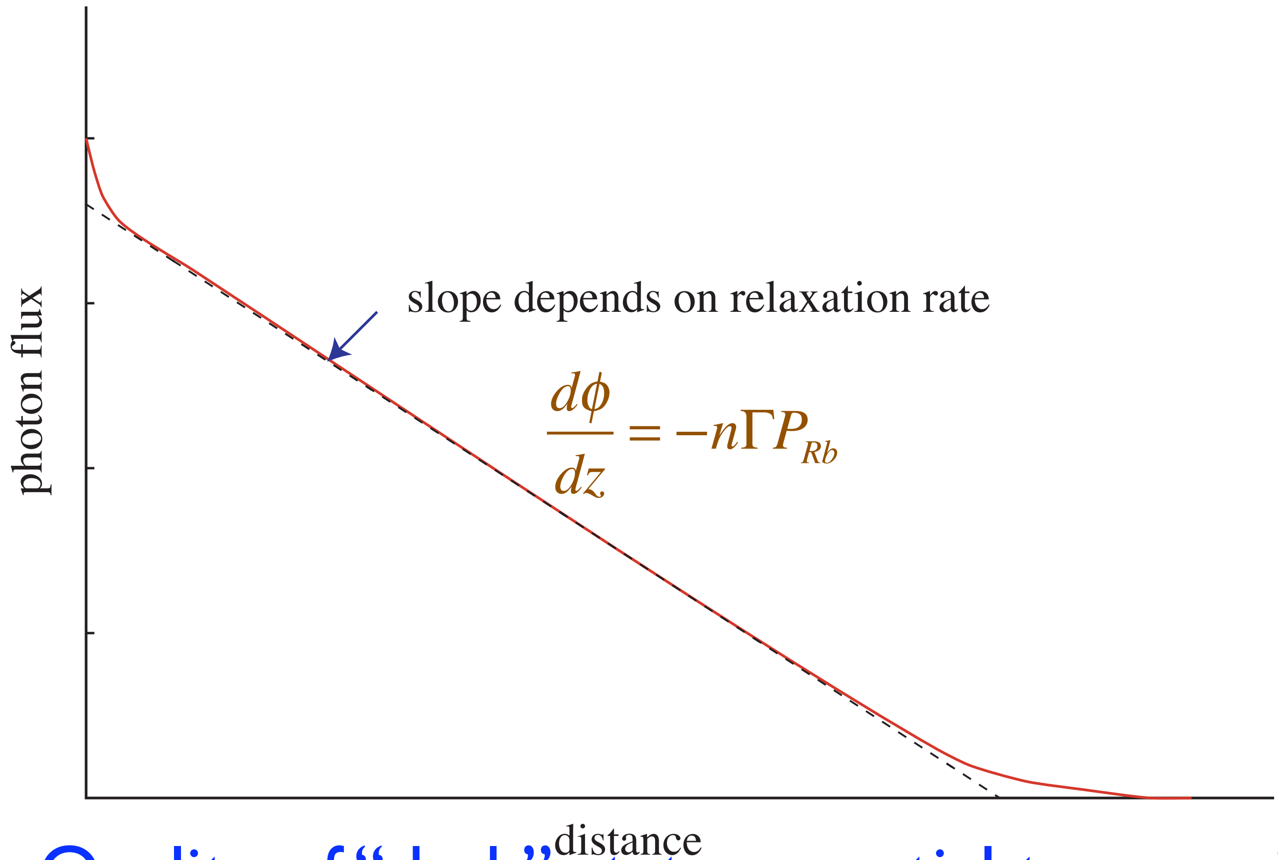


Cons. of Angular Momentum
maximize entropy
spin-temperature

Weak spin-axis coupling
important relaxation
mechanism

PRL **80**, 5512 (1998)
PRL **85**, 4237 (2000)

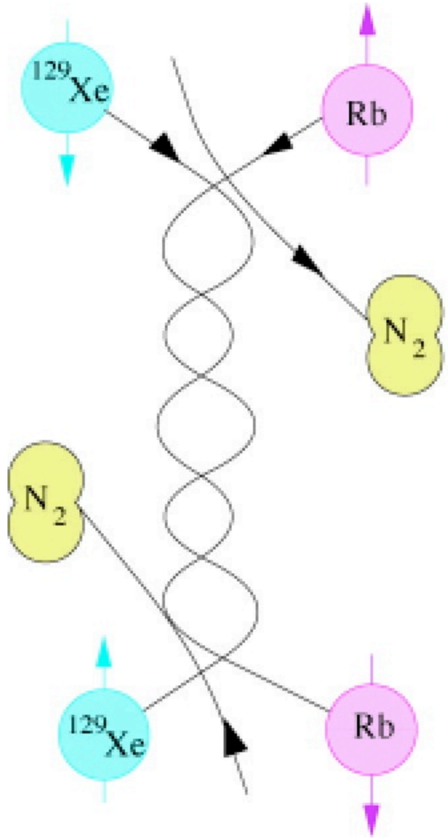
Light Propagation



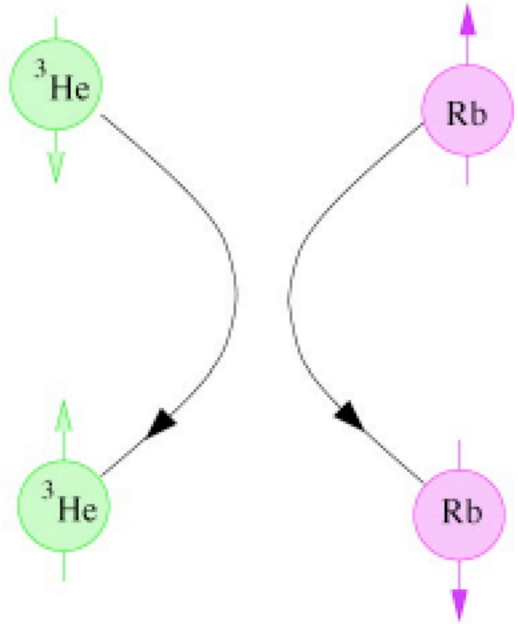
Quality of "dark" state essential to pumping optically thick vapors (~100 O.D.)

Wave-front velocity R/nσ=2.4 m/s Happer/Tam '77

Spin-Exchange w/ Noble Gases



Molecular Formation

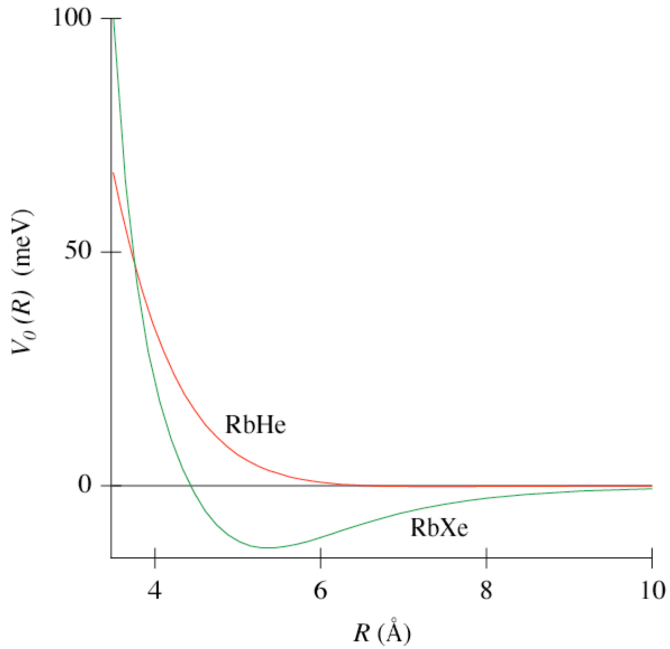


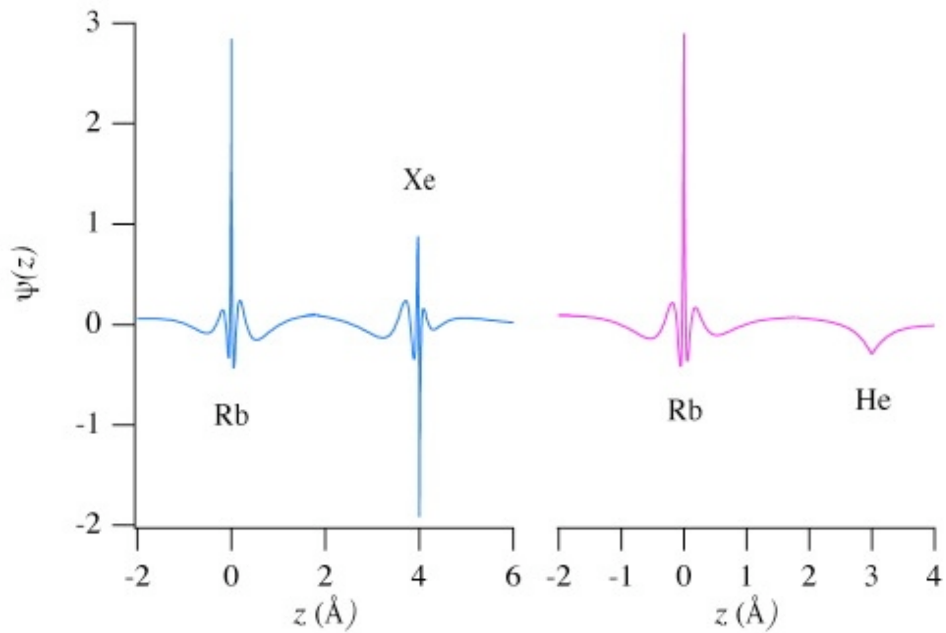
Binary Collisions

Spin-Exchange: $\alpha \ \boldsymbol{I} \cdot \boldsymbol{S}$

Spin-Relaxation: $\gamma \ \boldsymbol{N} \cdot \boldsymbol{S}$

Alkali-Noble Gas Molecules



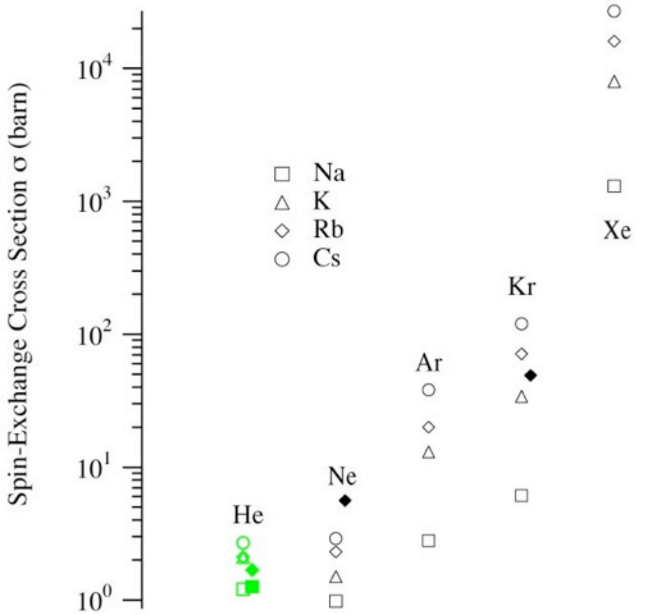


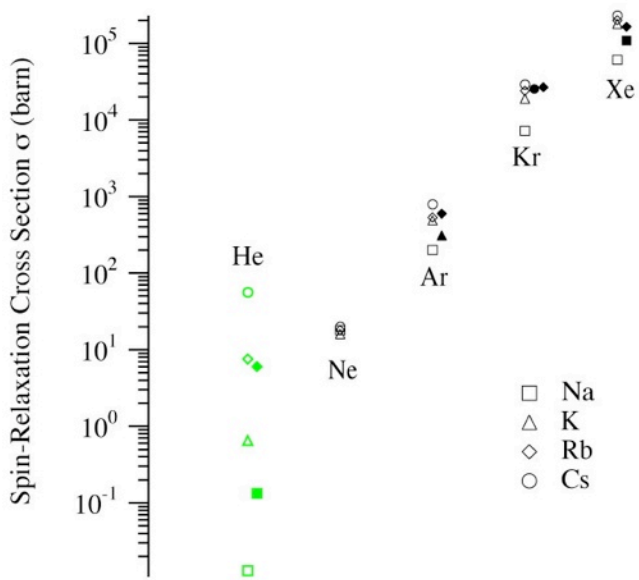
s-wave: $\alpha\ \boldsymbol{I}\cdot\boldsymbol{S}$ (Fermi contact hyperfine)

p-wave: $\gamma\ \boldsymbol{N}\cdot\boldsymbol{S}$ (Spin-orbit+Coriolis)

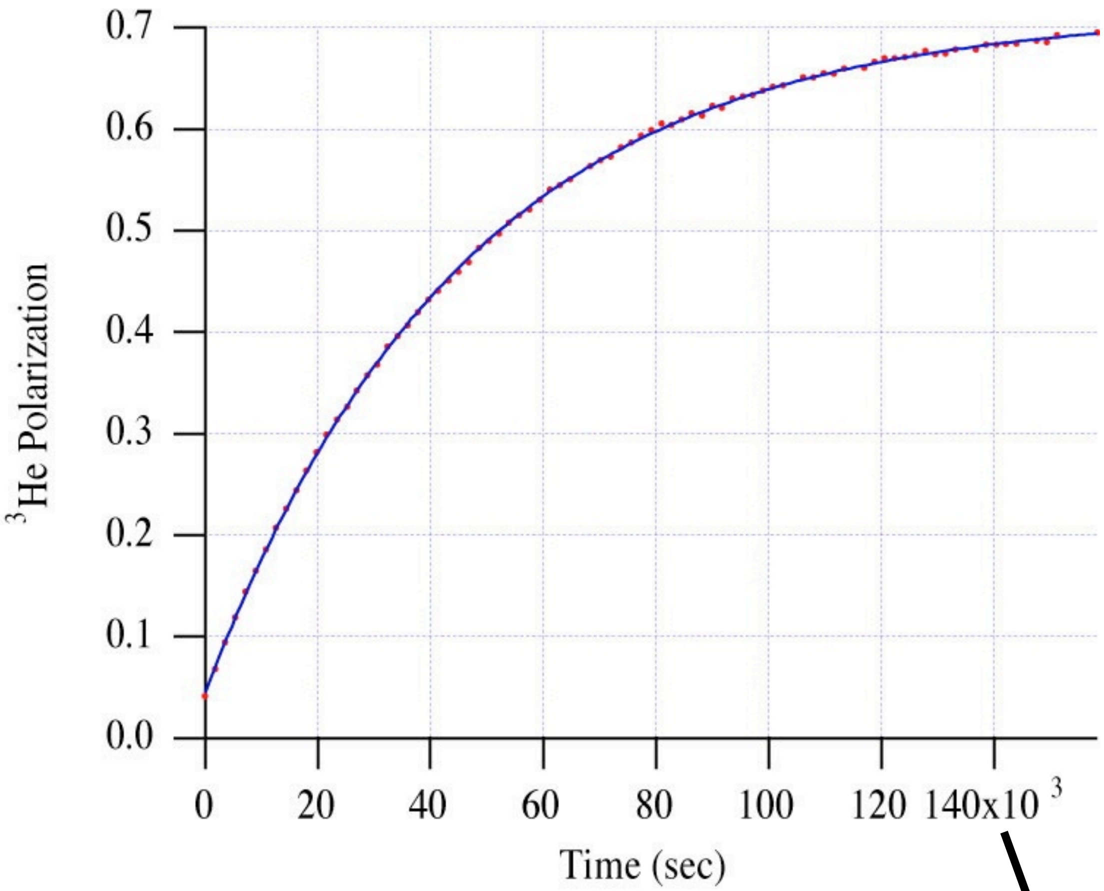
Spin-Exchange Efficiency

$$\eta = \frac{\sigma_{SE}}{\sigma_{SE} + \sigma_{SR}}$$ 1/50 for RbHe, 1/3 for KHe





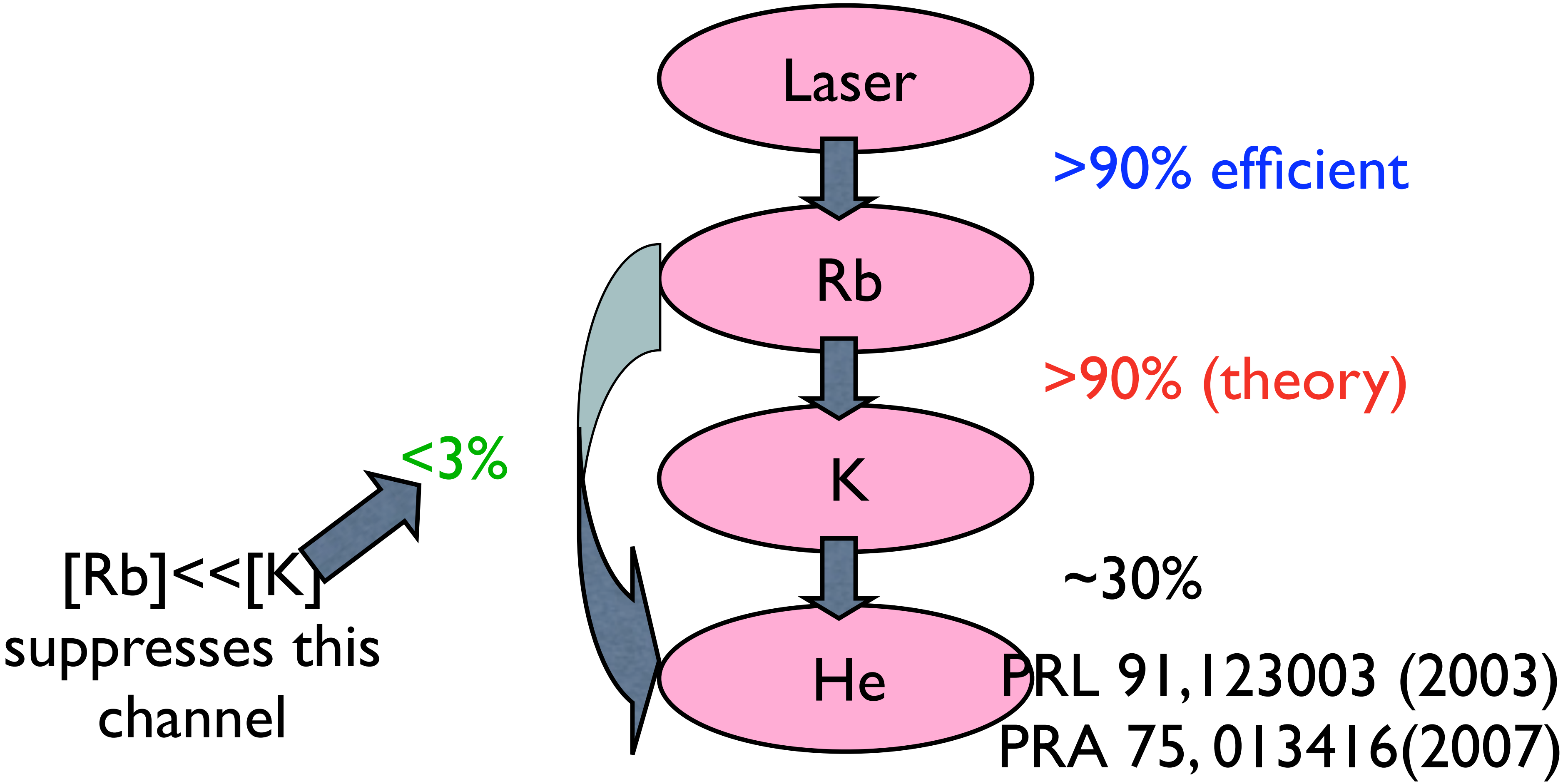
Rb-He pumping is SLOW



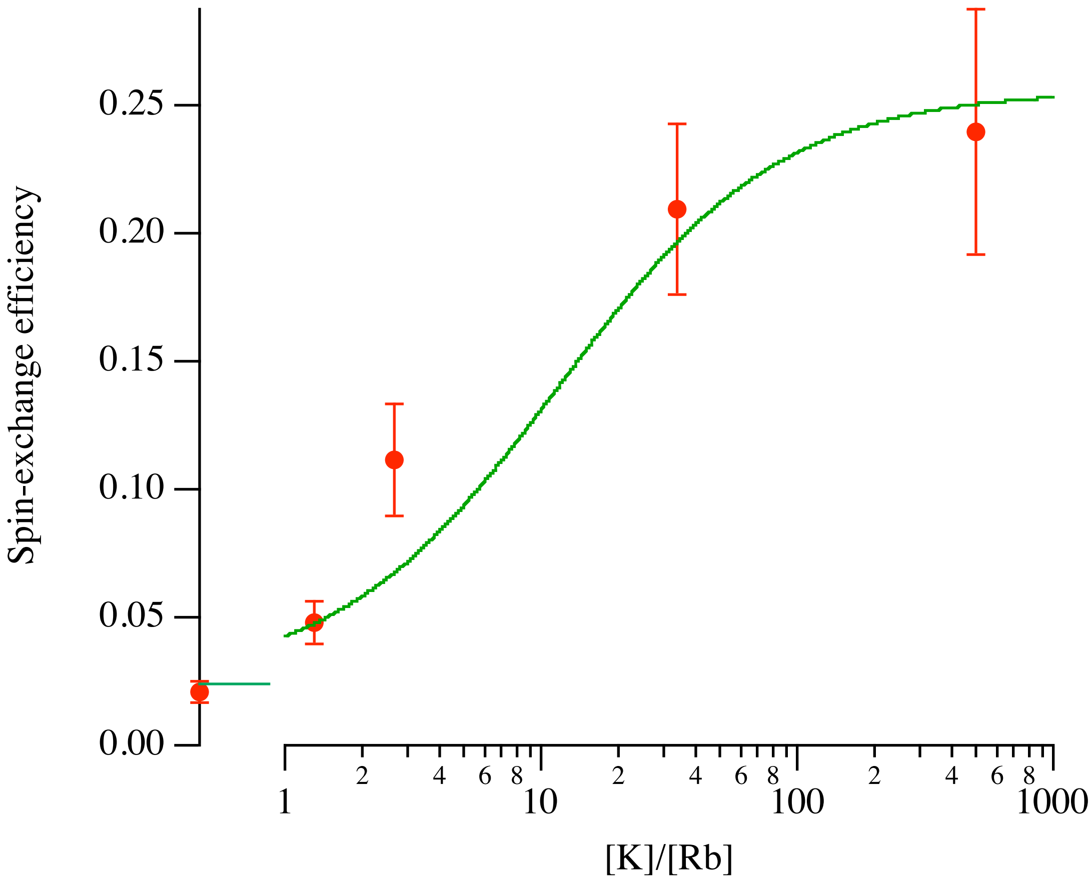
39 hours

Hybrid Spin-Exchange

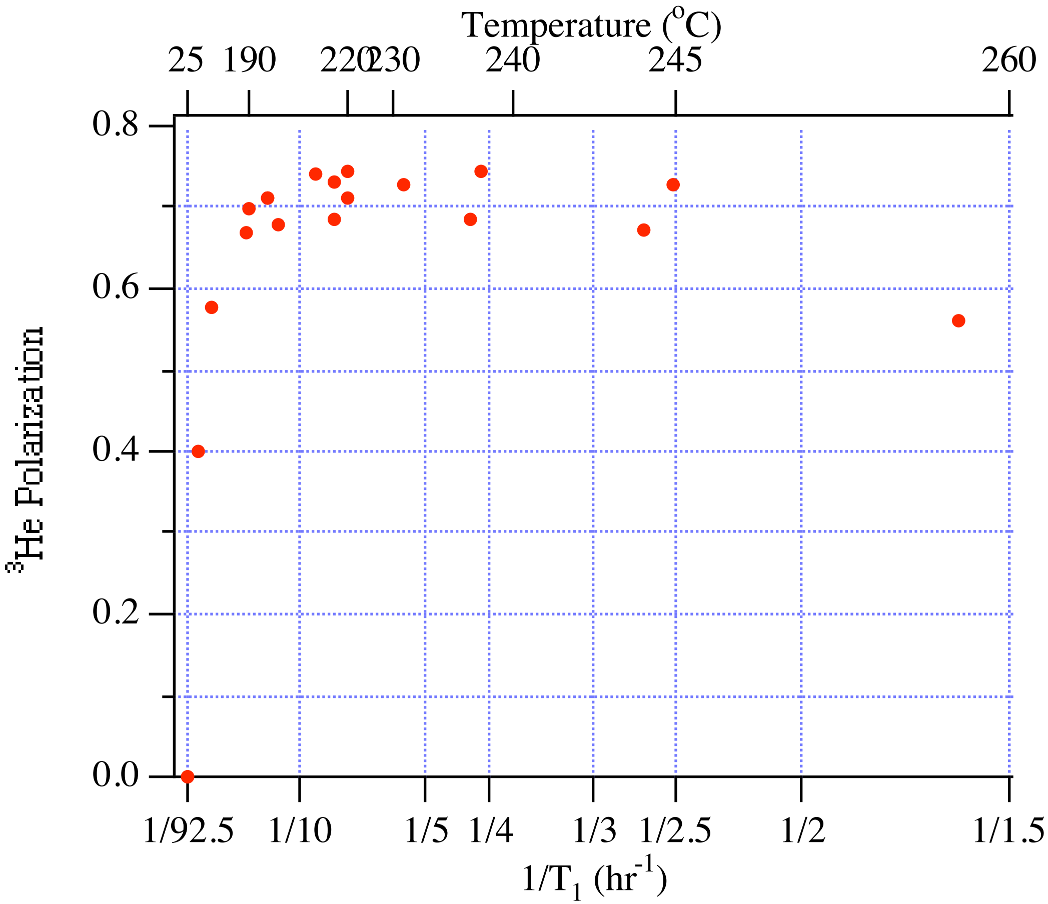
Idea: use Rb as spin-transfer agent to K



Hybrid Spin-Exchange Efficiency



Showing Off



Very fast (2.5 hrs), high polarization (76%)
w/ only 12 W pumping power

Summary

Spent photons to get
This ~100%

Spin-exchange rate

$$P_{\mathrm{He}} = P_{\mathrm{Rb}} \frac{k_{\mathrm{se}}[\mathrm{Rb}]}{k_{\mathrm{se}}[\mathrm{Rb}] + \Gamma_{\mathrm{He}}}$$

100's hours @ room temp
T. Gentile & others

$$\frac{dP_{He}[\mathrm{He}]}{dt} = \eta\phi$$

A More Realistic Cow

Artists:
Helen Croft
Sally Behncke

X-factor

Is there a fundamental limit?
Or should we find better walls?

Excess photon demand

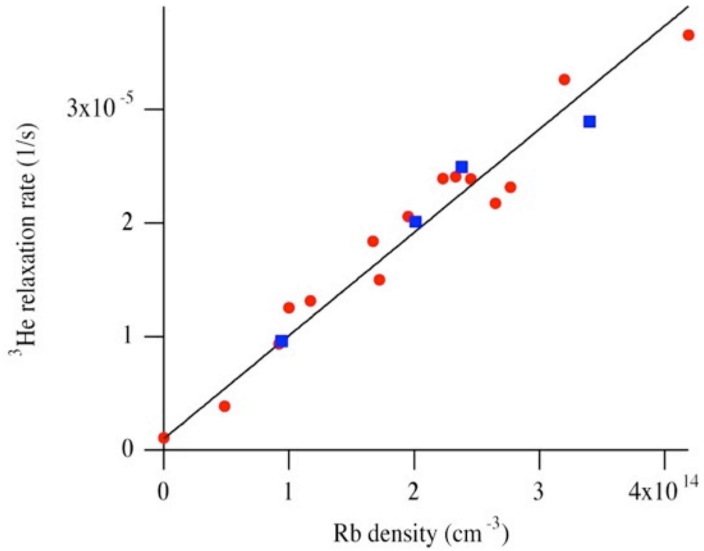
Imperfect Circular Dichroism

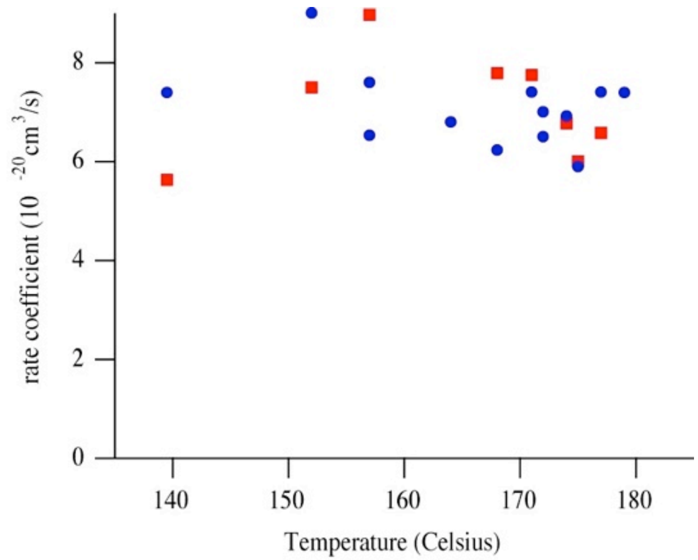
Excited-state nuclear spin non-conservation

Hybrid polarization puzzle

Neutron-induced relaxation

The X-factor

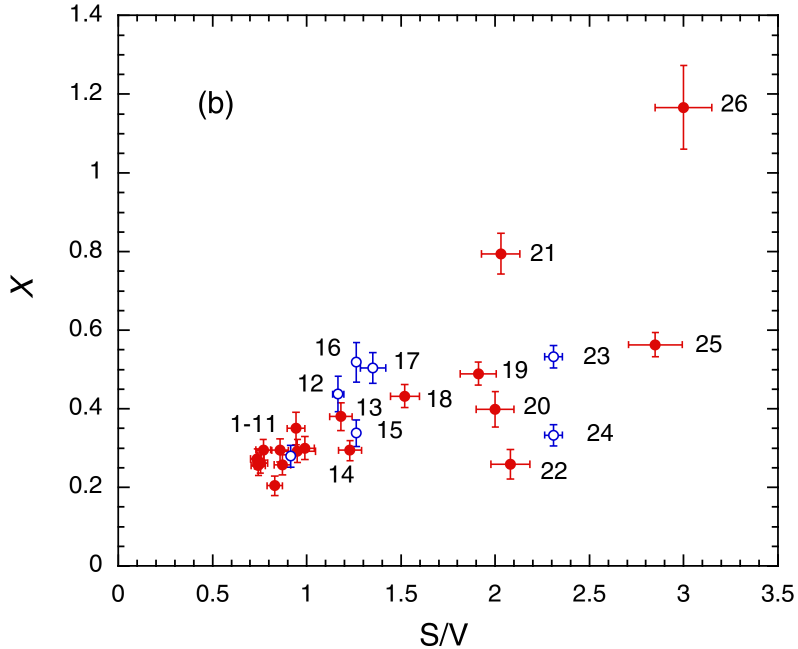




Relaxation rate method
spin-up & spin-down
Slope 9.1×10^{-20} cm^3/s

Repolarization and
rate balance
average 6.8×10^{-20} cm^3/s

X-Factor S/V Dependence



PRL **96,** 083003 (2006)

$$P_{He} = \frac{P_{Rb}}{1+X}$$

$$X = X_0 + \chi \frac{S}{V}$$

χ random

Is the "X-Factor" limited by fundamentals?

Anisotropic Spin-Exchange

$$H = \alpha \mathbf{S}\cdot\mathbf{K} + \beta(3\mathbf{S}\cdot\mathbf{RR}\cdot\mathbf{K} - \mathbf{S}\cdot\mathbf{K})$$

Independent of cell

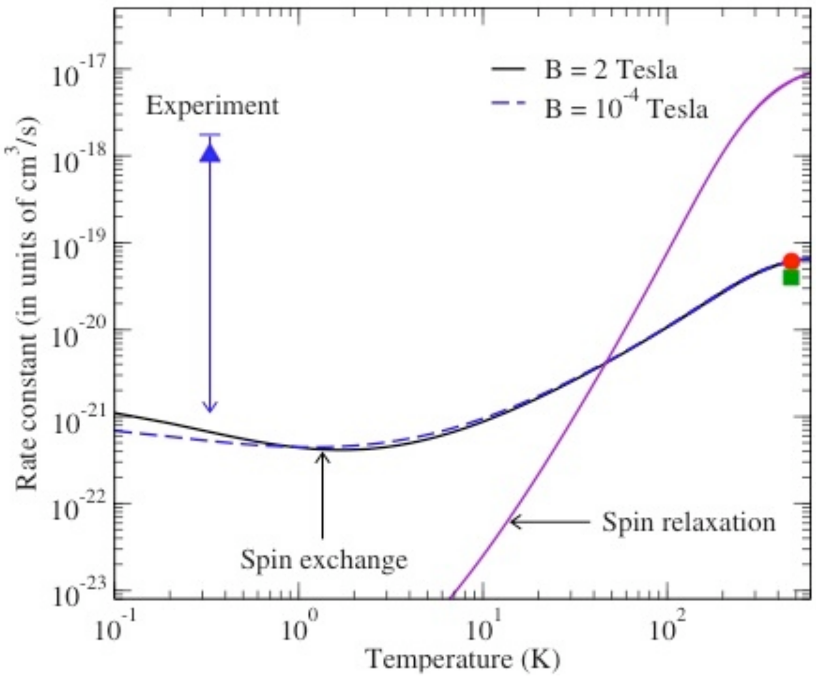
β Polarizes opposite to α $X = 3k_\beta / 2k_{SE}$

Walter et al. estimates β small

PRA **48**, 3642 (1998)

New Theory Input

PHYSICAL REVIEW A **78**, 060703 R 2008



Tscherbul (ITAMP)
new ab-initio calculations
of KHe

$\eta = 2.5$

old estimates 6.5

Need method to measure anistropic spin-exchange

Efficiency of Spin-Exchange

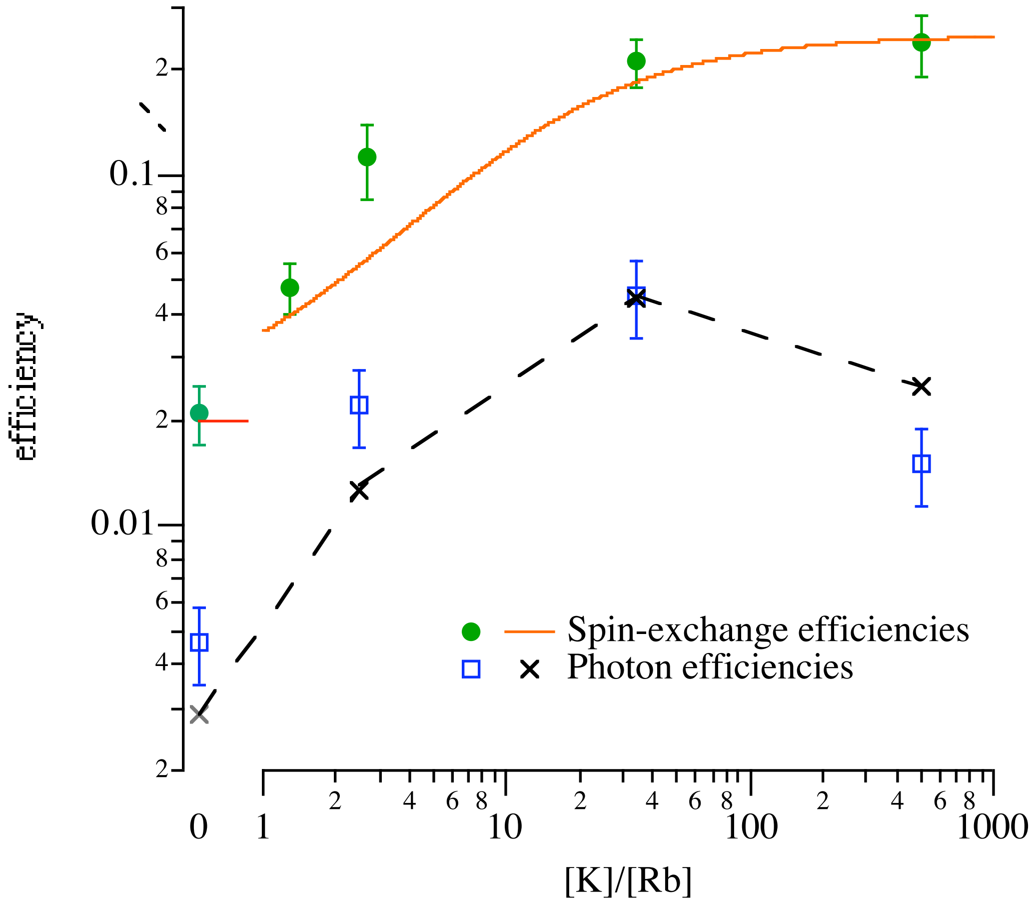
Photon efficiency

Polarization Rate

$$\eta_\gamma = \frac{[^3\mathrm{He}]V\,dP_{\mathrm{He}}/dt}{\Delta\phi}$$

Photon absorption rate

Hybrid Efficiency Measurements



Spin-Exchange eff.

Photon eff.

5% photon efficiency great, but still less than expected

Leaky Dark State

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

Light absorption rate increases by factor

$$\Upsilon = 1 + \frac{R}{\Gamma}\left(1 - P_\infty^2\right)$$

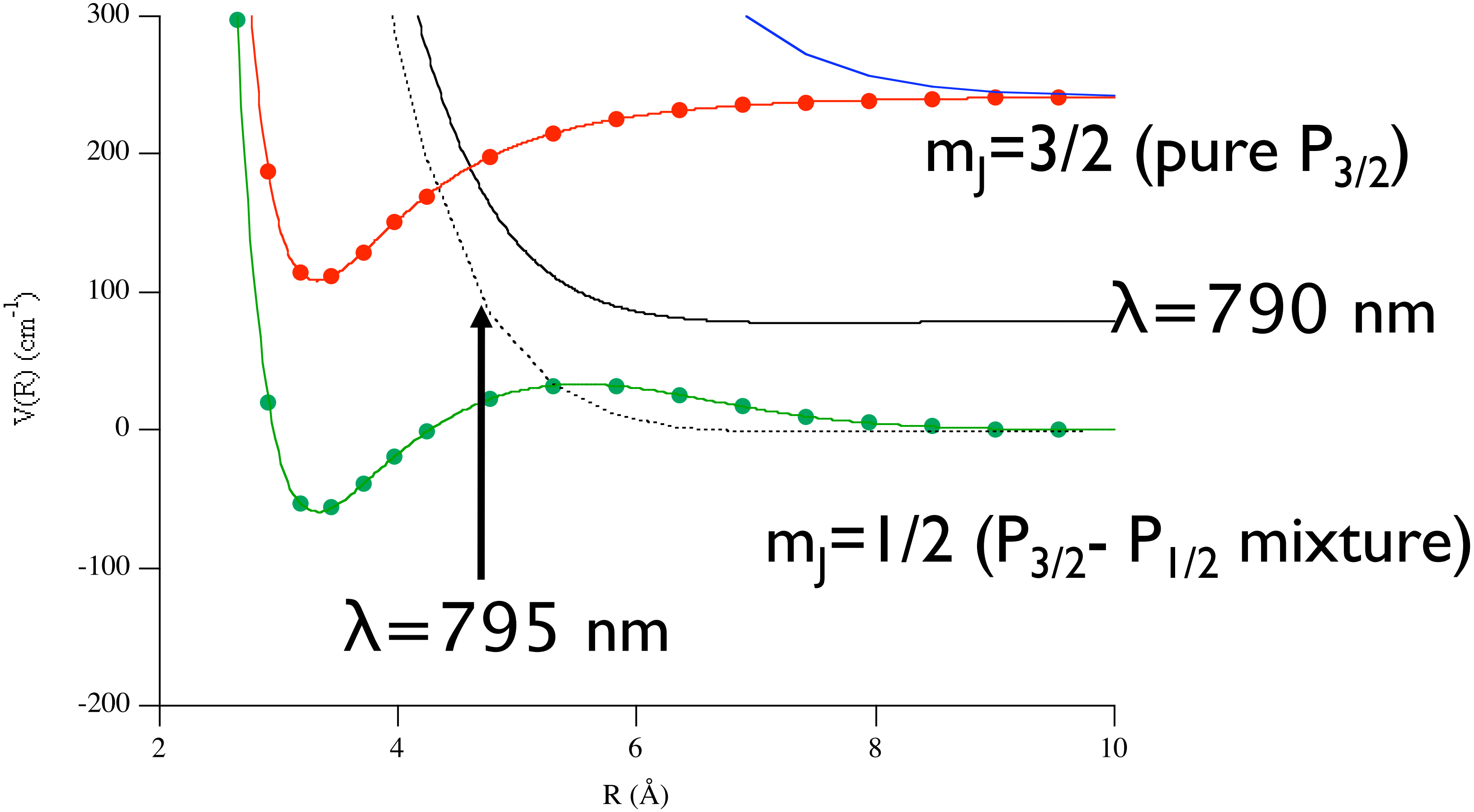
Optically thick vapor requires $\frac{R}{\Gamma} \gg 1$

$$\frac{R}{\Gamma} = 100 \quad P_\infty = 0.95 \quad \Upsilon = 11$$

Small optical pumping imperfections are expensive!

Why is $P_{inf}<1$?

Fine-structure mixing in Rb-He collisions?

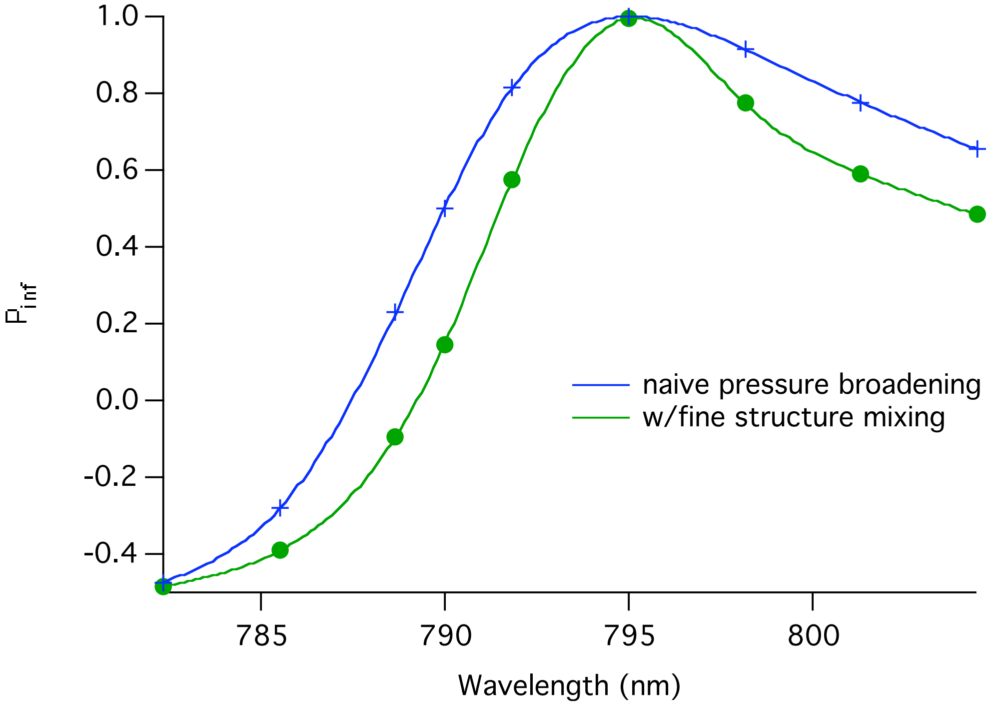


Pascale (PRA 28, 632 (1983)) potential curves modified to account for spin-orbit splitting

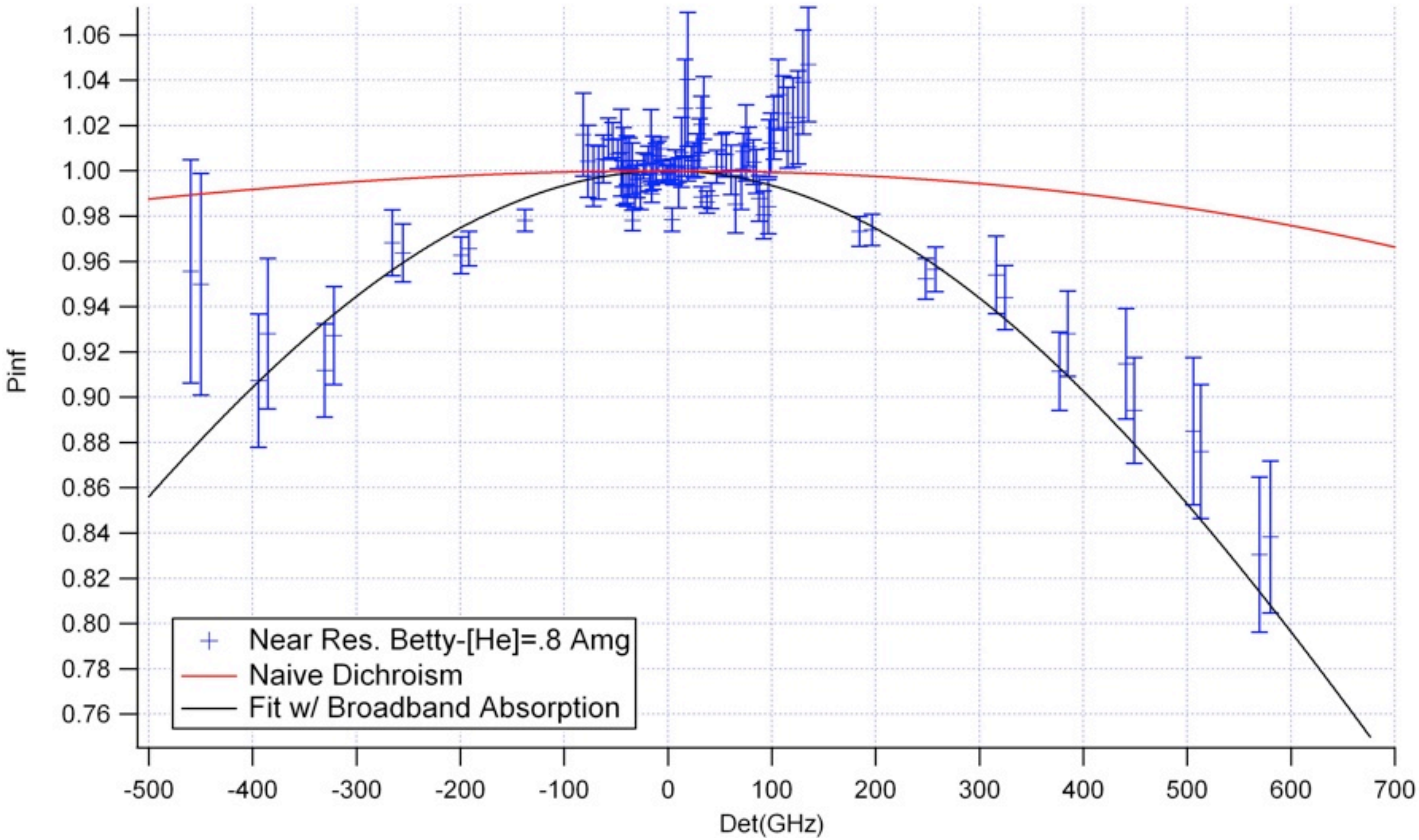
Landau-Zener estimate of P_{inf}

$$R_2 = [\mathrm{He}]\frac{8\pi R^2 \hbar \varepsilon^2}{\left| d\Delta V \big/ dR \right|}\exp\left(-V_g(R) \big/ kT \right)$$

$$P_\infty = \frac{P_{1\infty}R_1 + P_{2\infty}R_2}{R_1 + R_2}$$

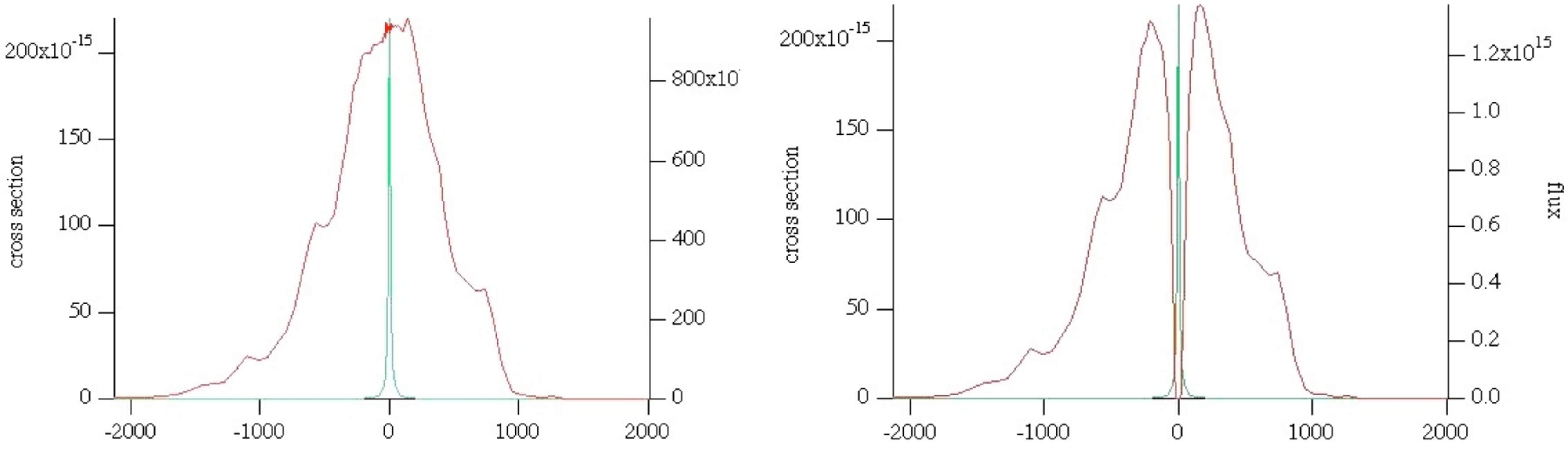


Dichroism Measurements



Brian Lancor, Bob Wyllie B4.9

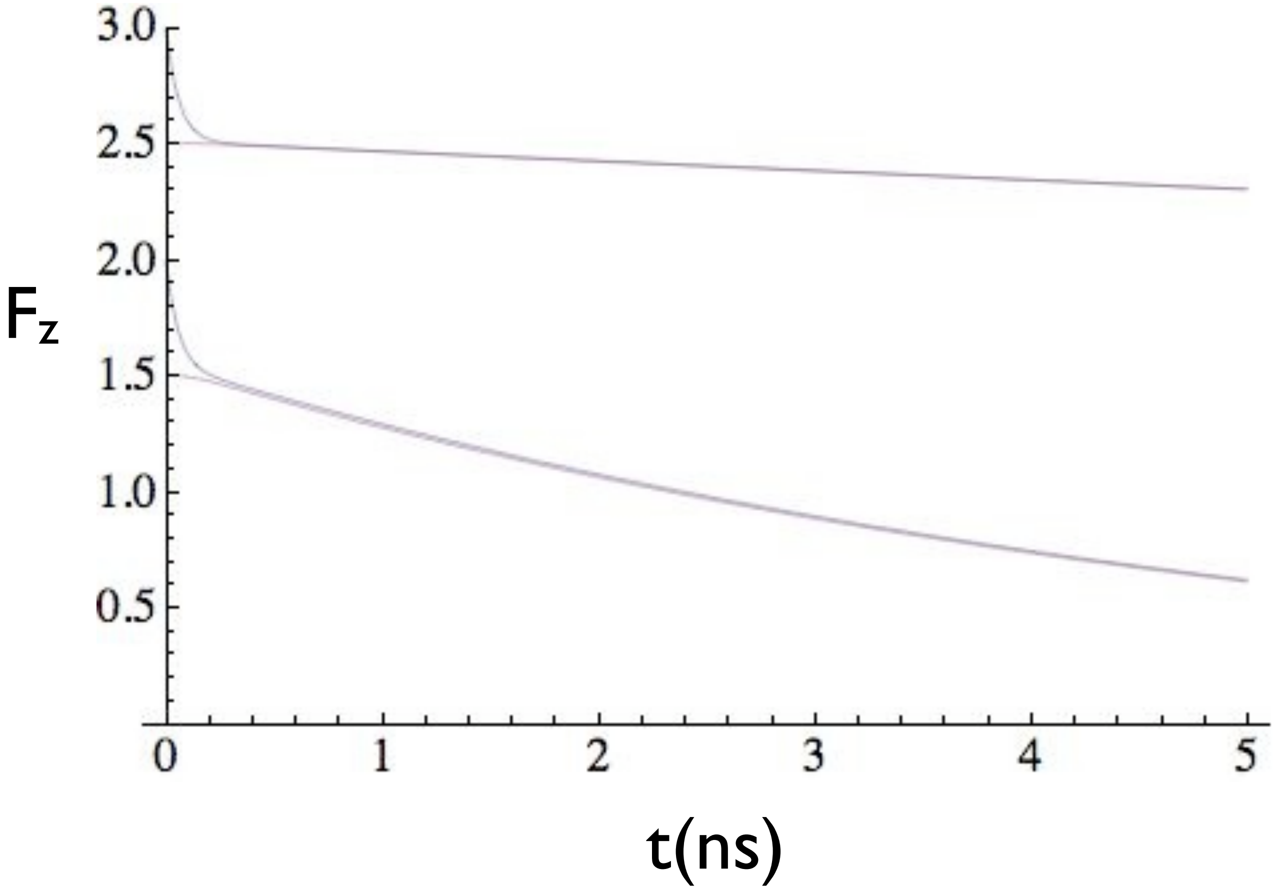
Broad-band pumping



Spectral hole quickly reduces optical pumping rate at front of cell, thus reducing Rb polarization.

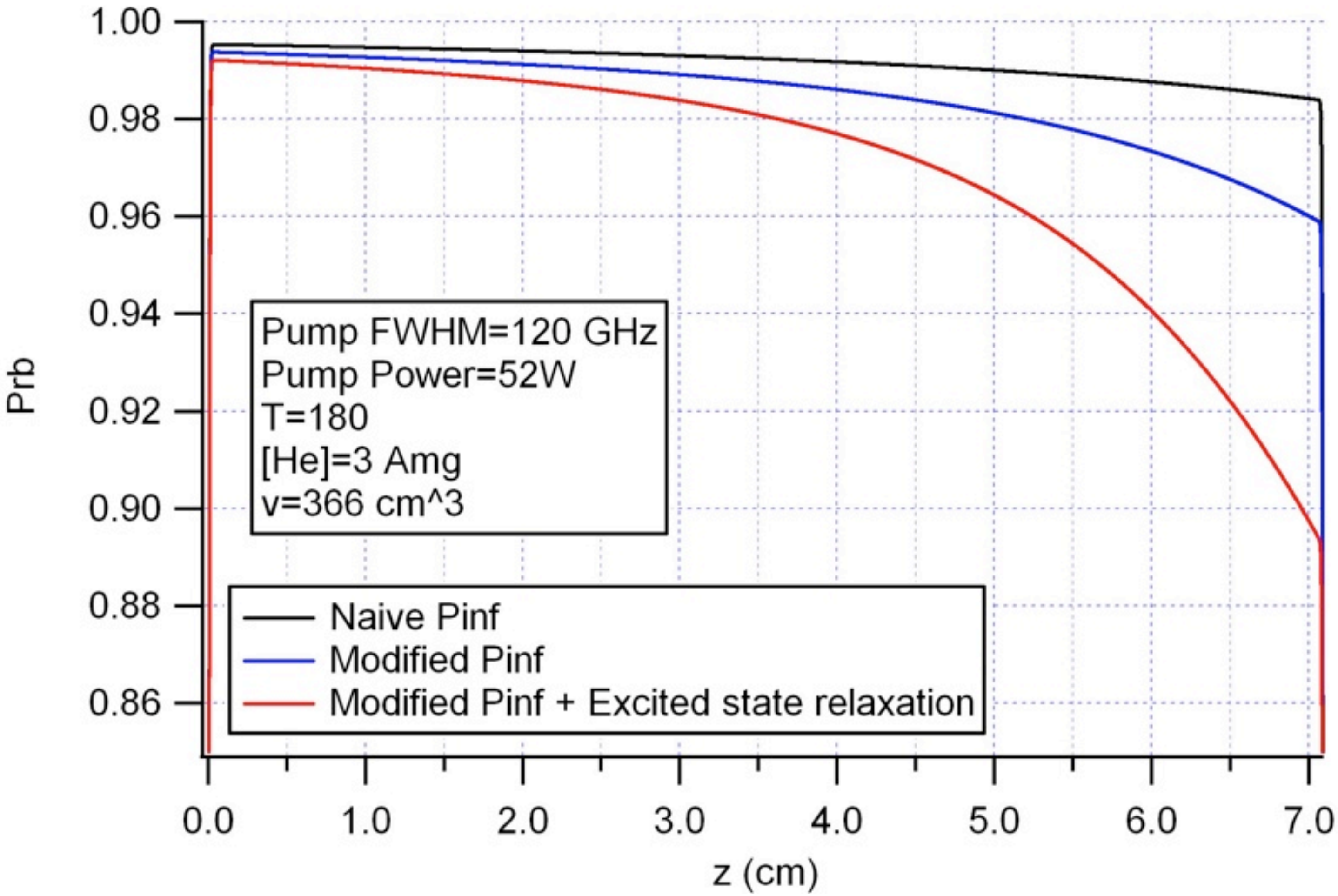
Light in the line wings contributes weakly to pumping rate but strongly to imperfect dichroism

Excited-state Nuclear Spin Relaxation

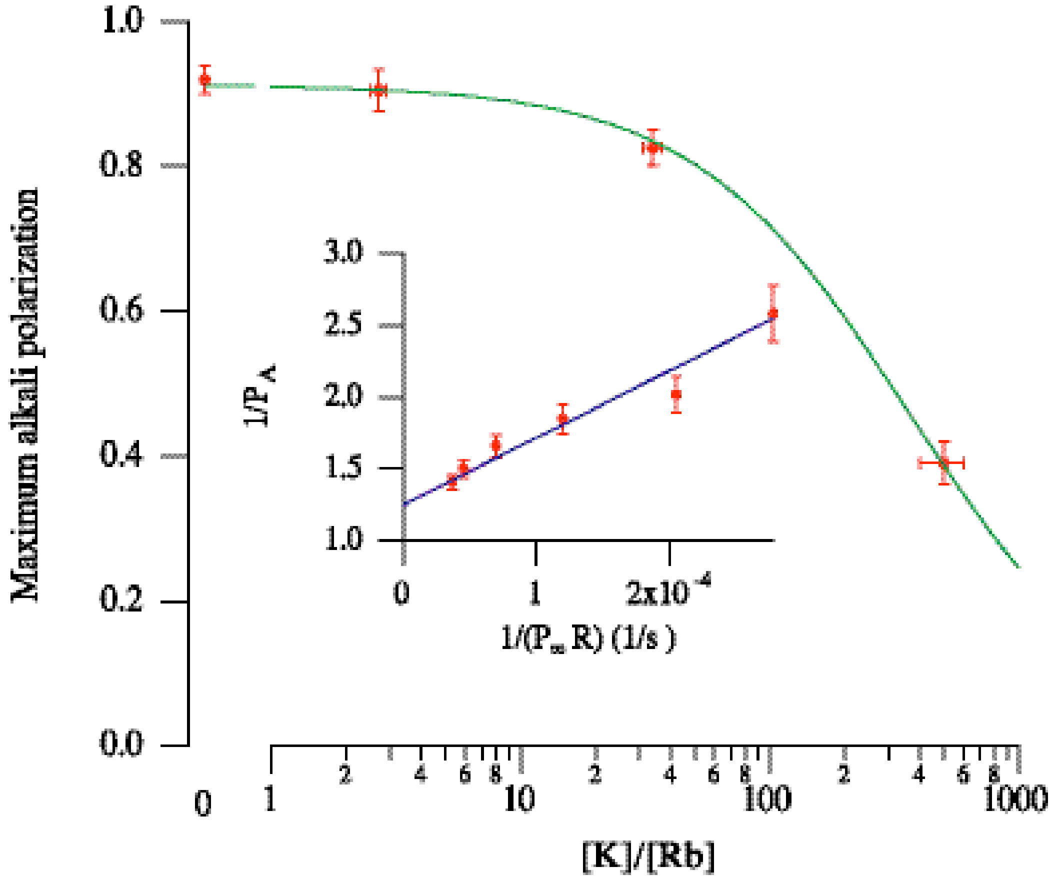


t=1.2 ns @ 75 Torr N_2

Effects on SEOP



Impure pumping problem



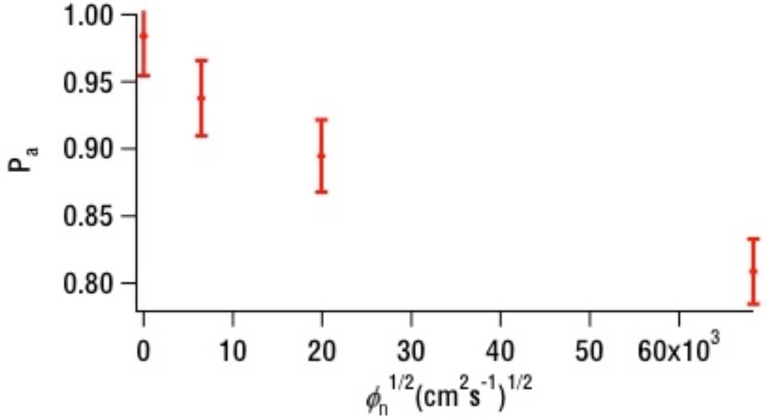
Rb pumping only 90% w/ broadband laser

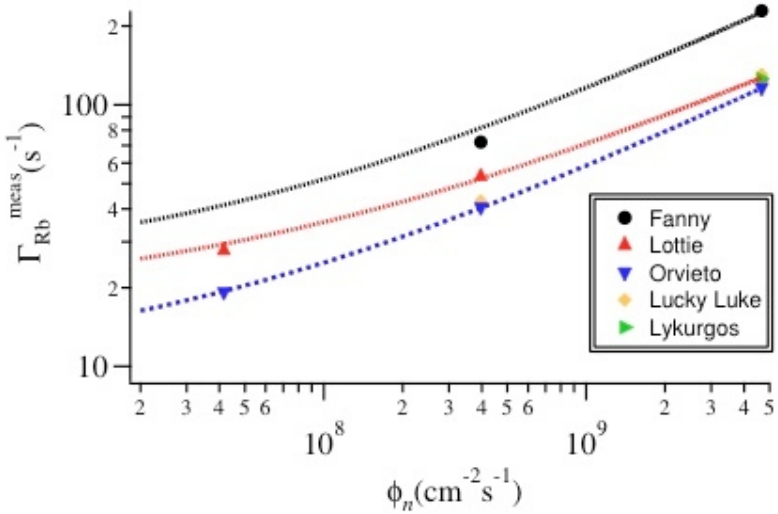
Fit assumes Rb laser directly pumps K at 0.3% rate

Increases for narrow band pumping

Neutron-induced Rb relaxation

E. Babcock et al B4.6





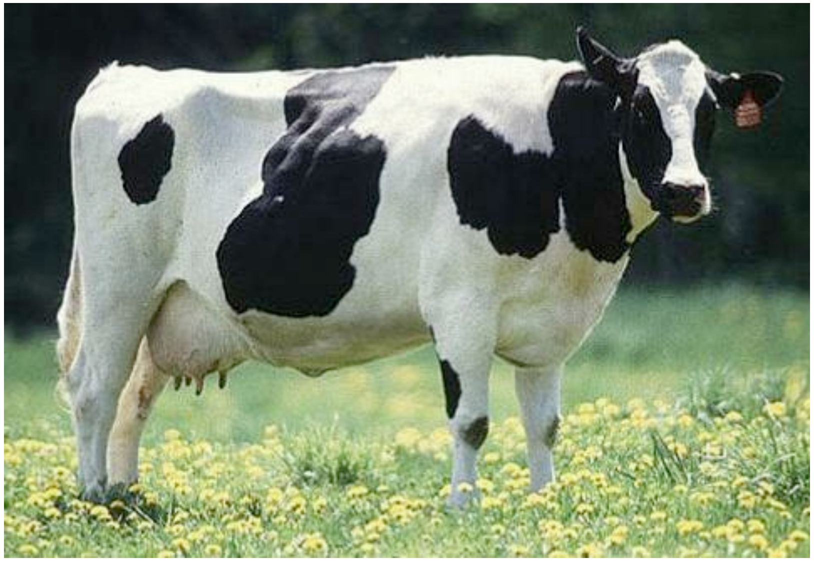
Stable species:

Rb^+, Rb_2^+, N

$N + Rb + X \rightarrow NRb + X$

$NRb + N_2 + X \rightarrow RbN_3 + X$

Summary



To make our SEOP cow as productive as a good Wisconsin dairy cow, we've got some work ahead of us!