QUALIFIER

Mark Limes April 1st, 2011

Introduction

- Outline of xenon storage cell project
- Optical pumping
- Brief interlude
- Gas-phase spin-exchange
- Relaxation
- Low-field nuclear magnetic resonance
- Preliminary results
- Discussion of results
- Current and future projects

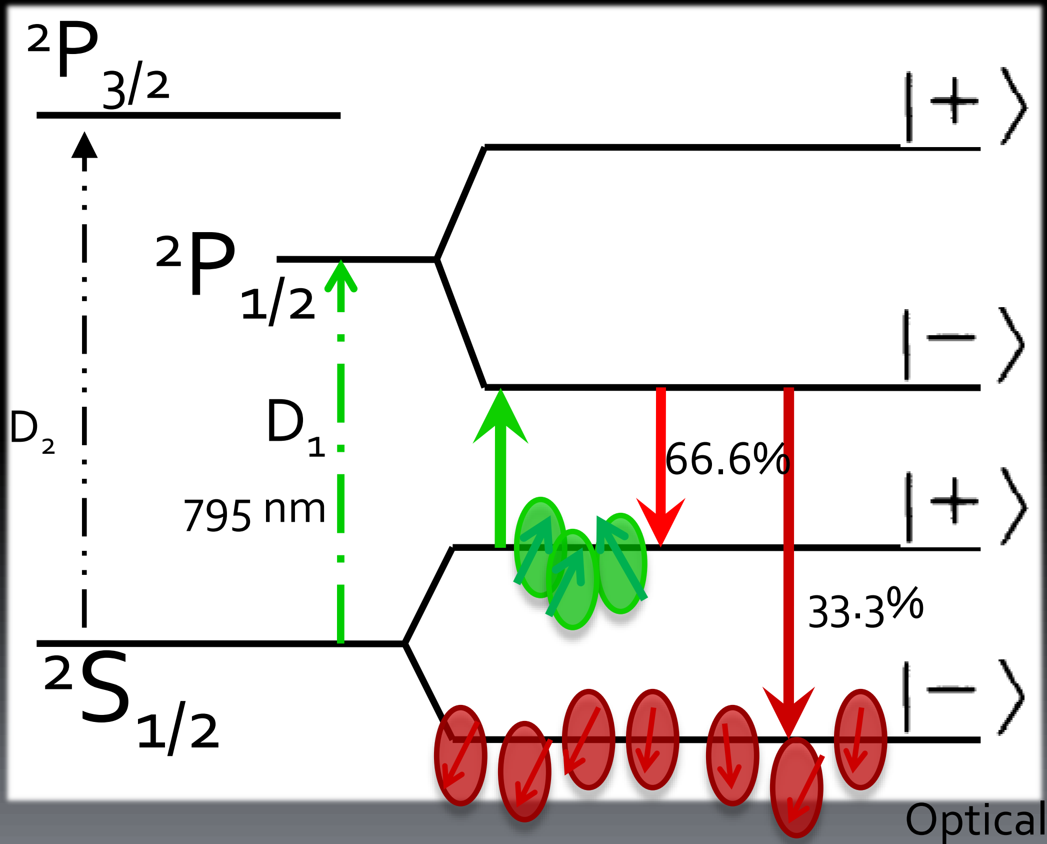
Project Purpose

- Find a holding method for (hyperpolarized) xenon that minimizes nuclear polarization relaxation rates

- Develop a consistent system of characterizing the quality of holding methods
- Collect data on and provide explanations for various intrinsic and extrinsic physical mechanisms causing relaxation

Optical Pumping

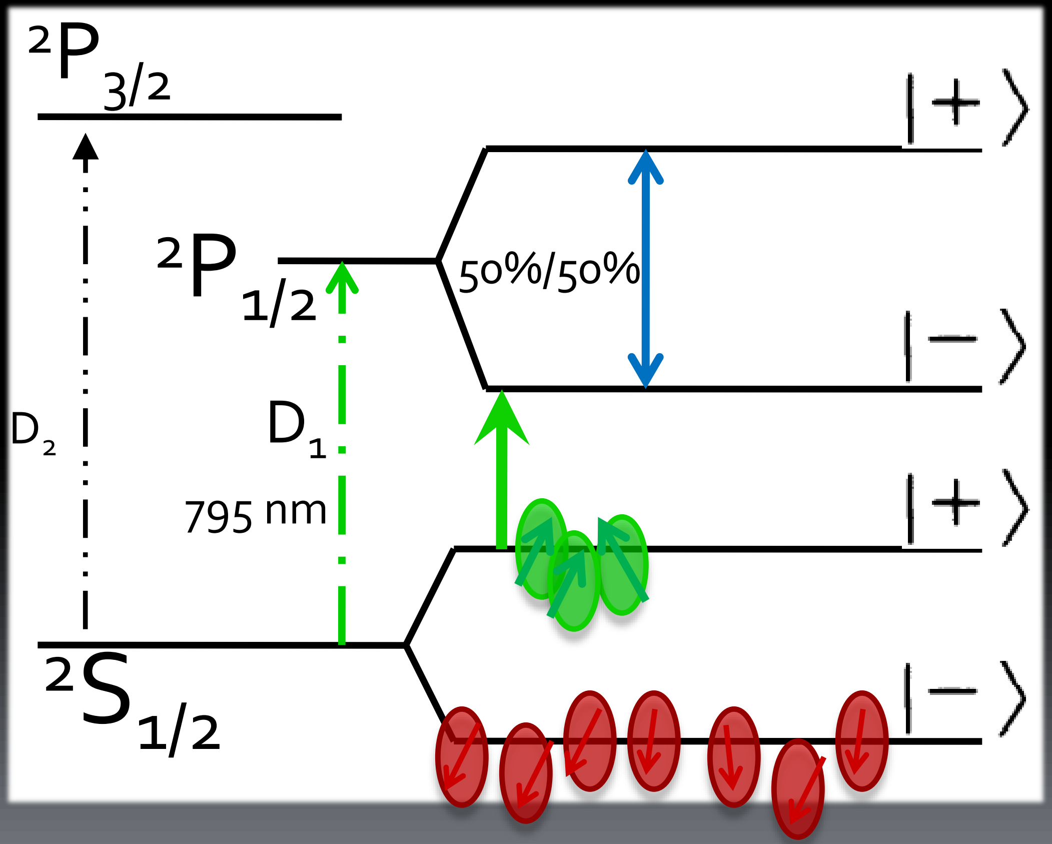
- Optically pumping an alkali-metal's valence electron state with circularly polarized light



Optically Pumped Atoms- Happer, 2010

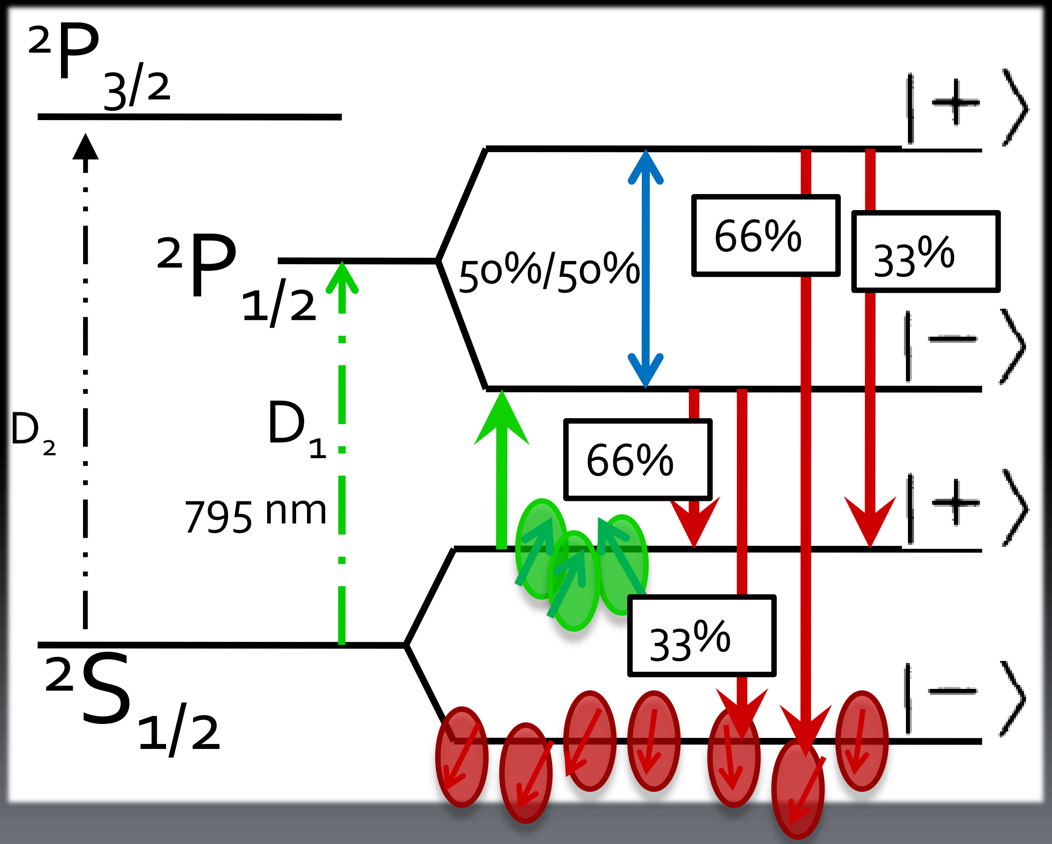
Optical Pumping

- Buffer gases depolarize the excited state and increase photon efficiency by collisional mixing



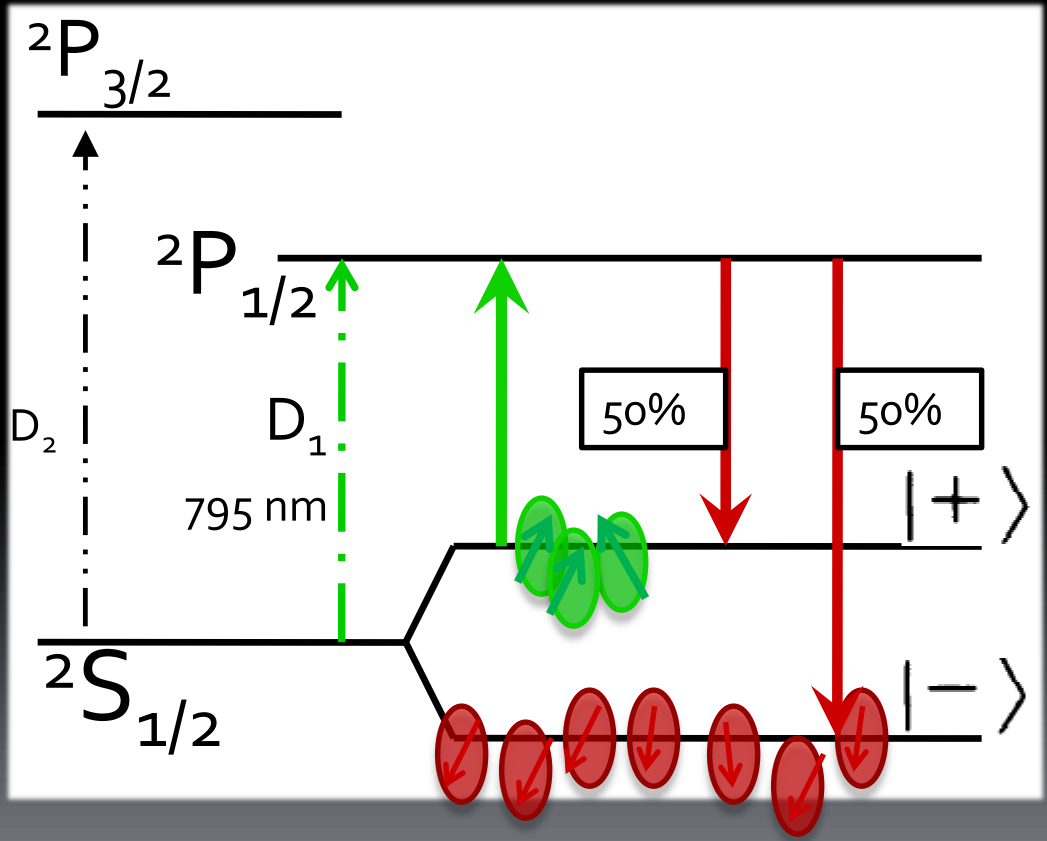
Optical Pumping

- Buffer gases depolarize the excited state and increase photon efficiency by collisional mixing



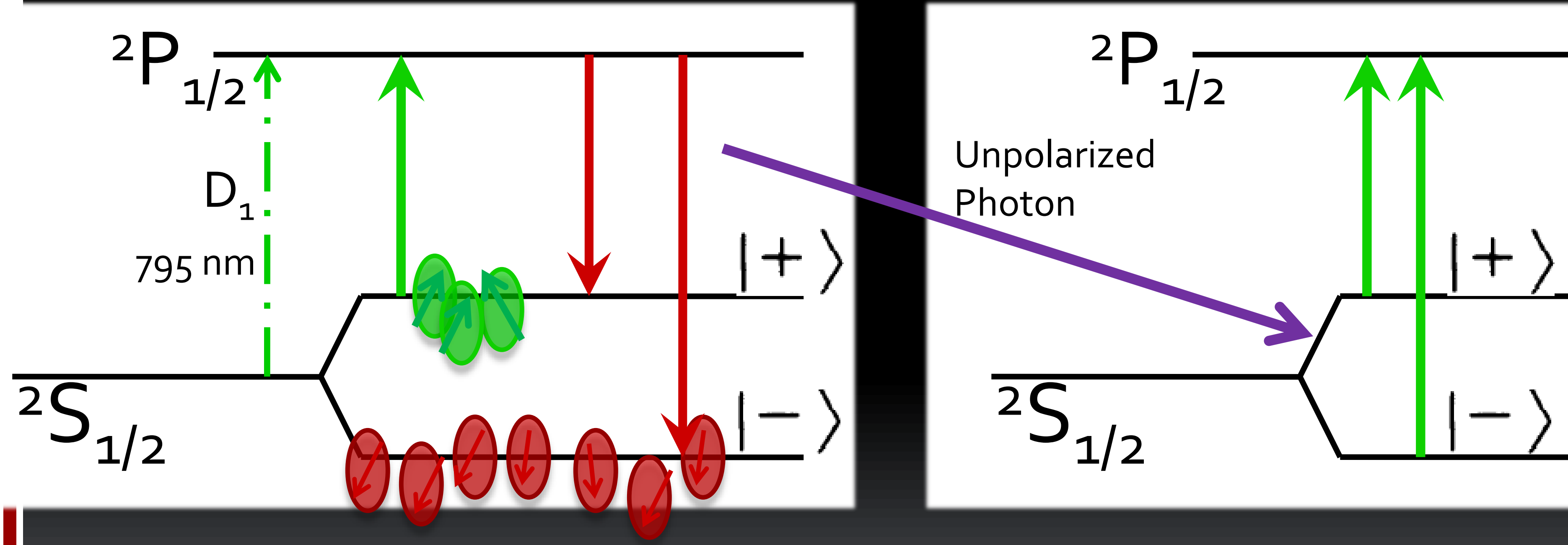
Optical Pumping

- Buffer gases depolarize the excited state and increase photon efficiency by collisional mixing



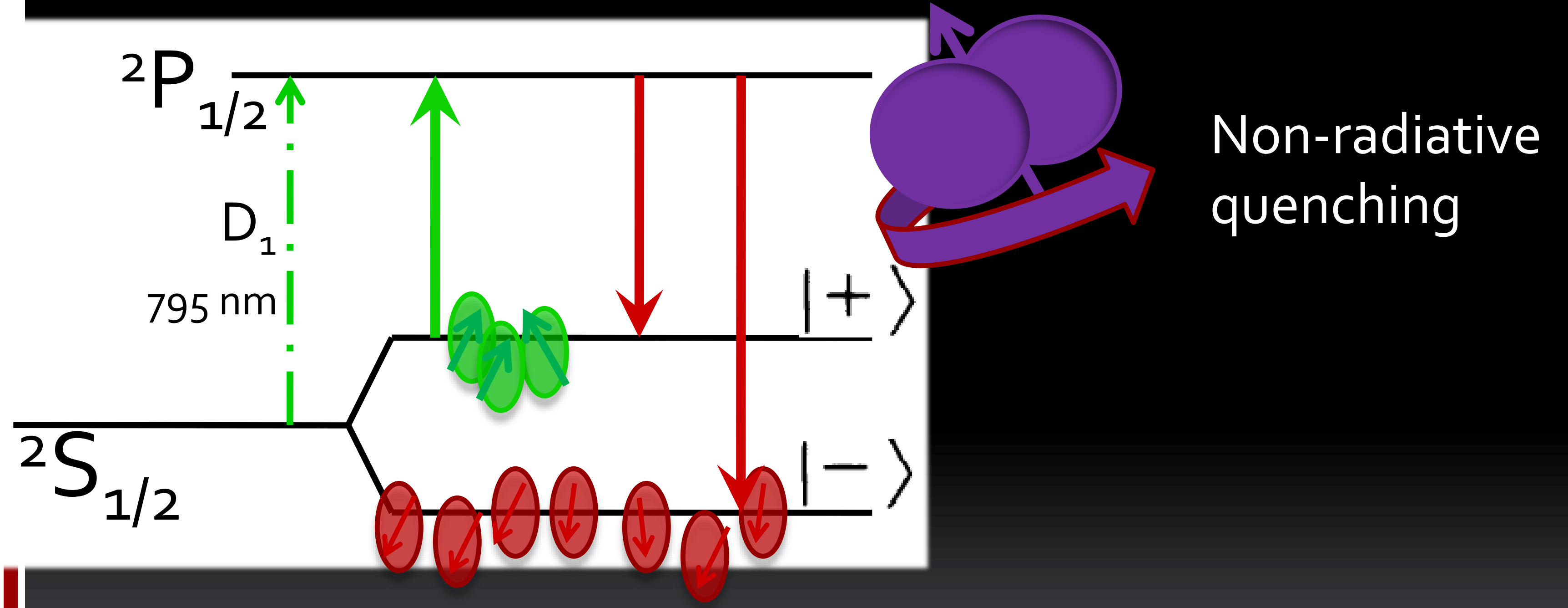
Optical Pumping

- Radiation trapping from spontaneity



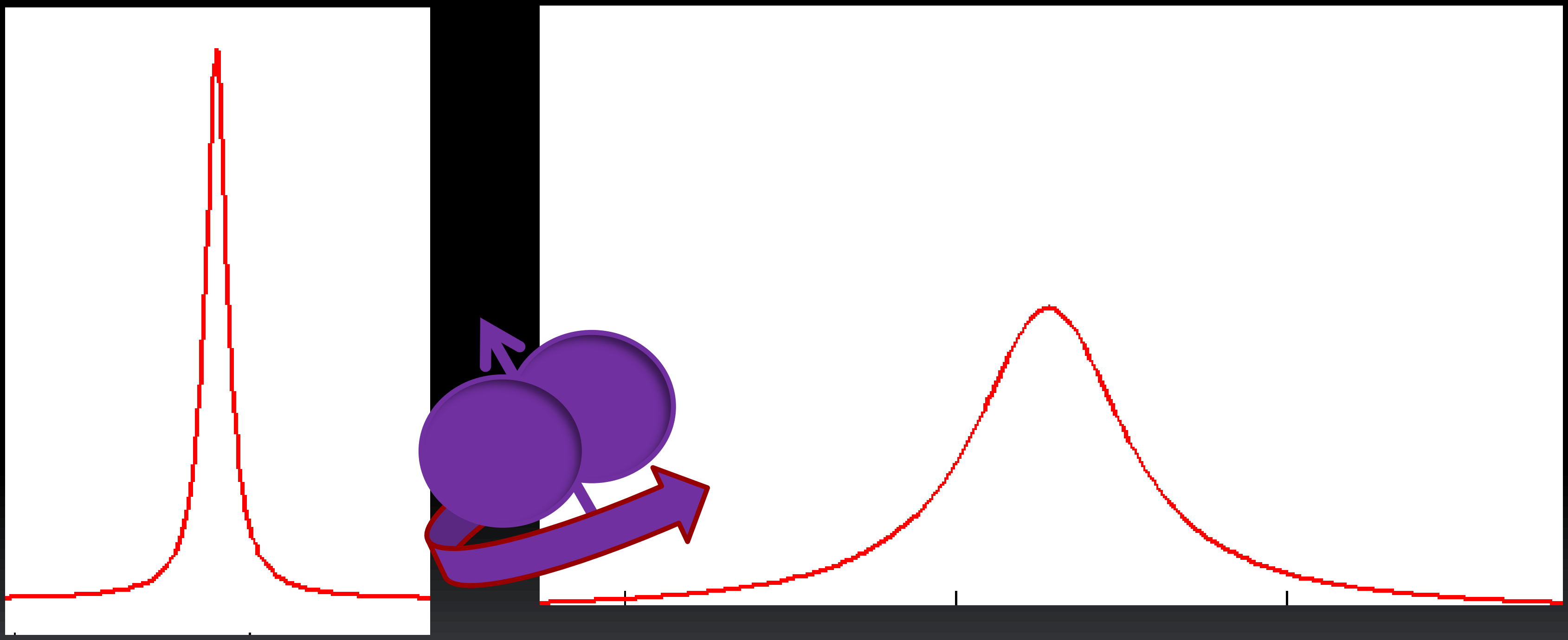
Optical Pumping

- Buffer gas prevents radiation trapping and takes away angular momentum



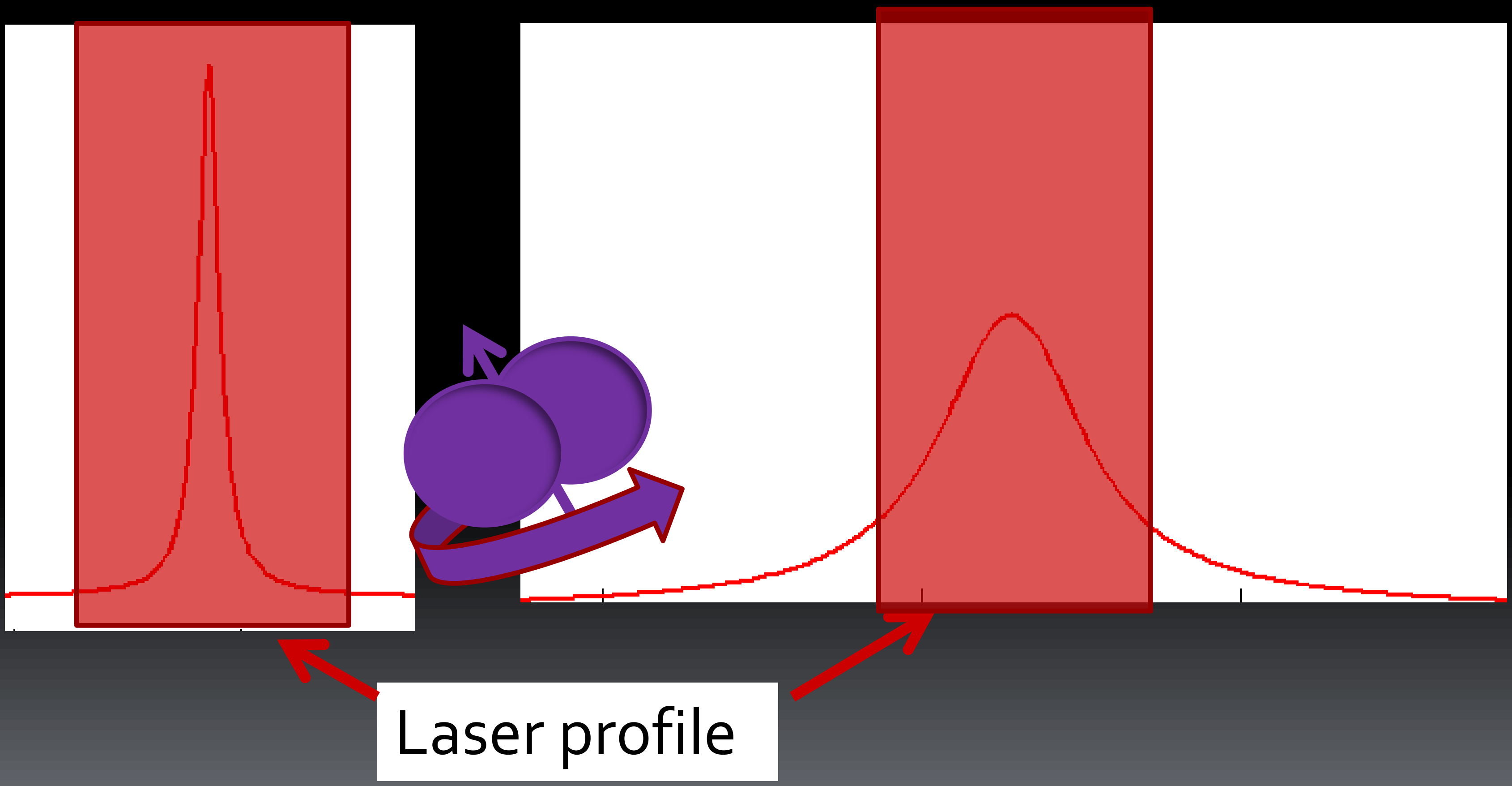
Optical Pumping

- Buffer gas also broadens absorption line



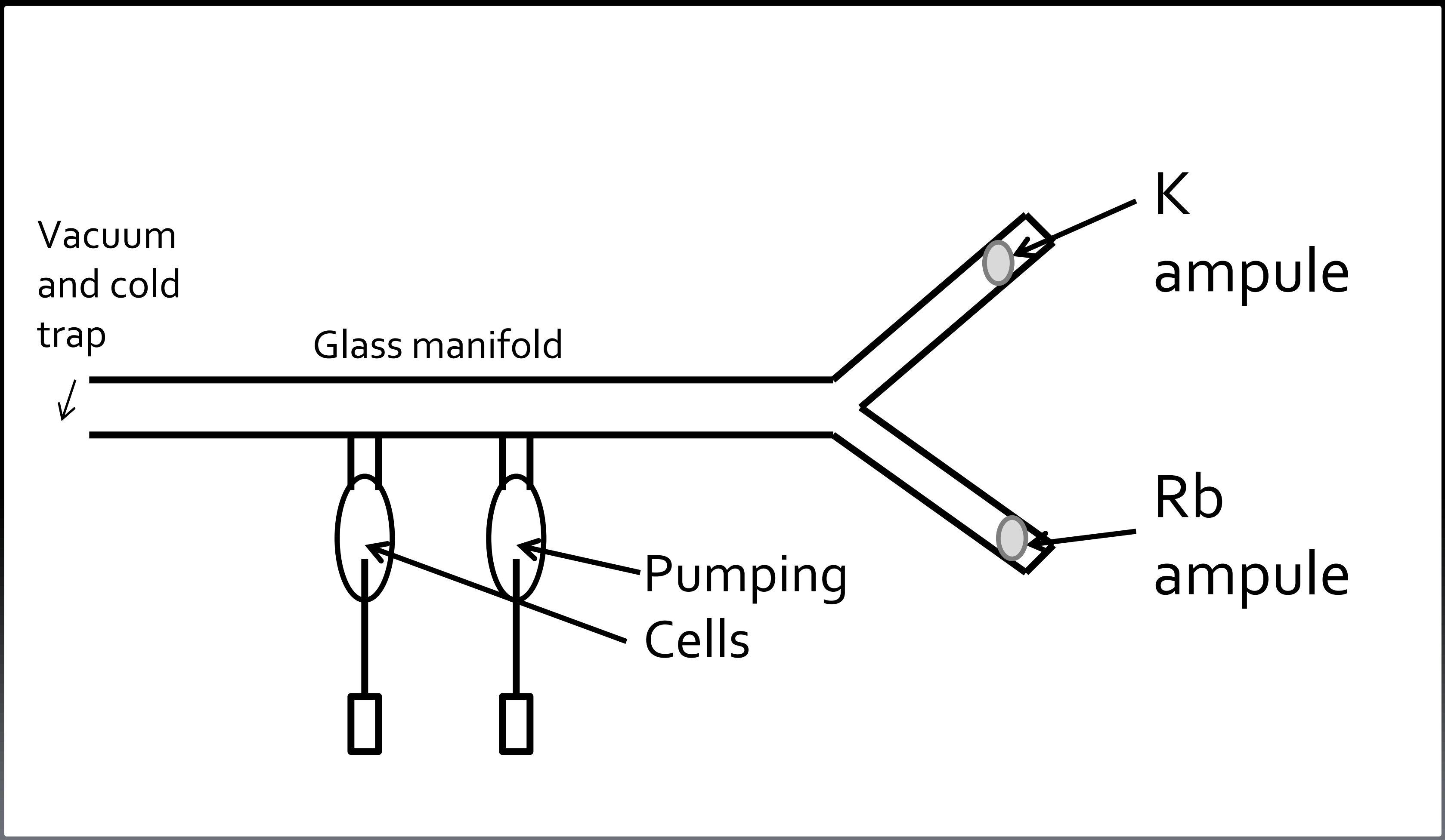
Optical Pumping

- Buffer gas also broadens absorption line



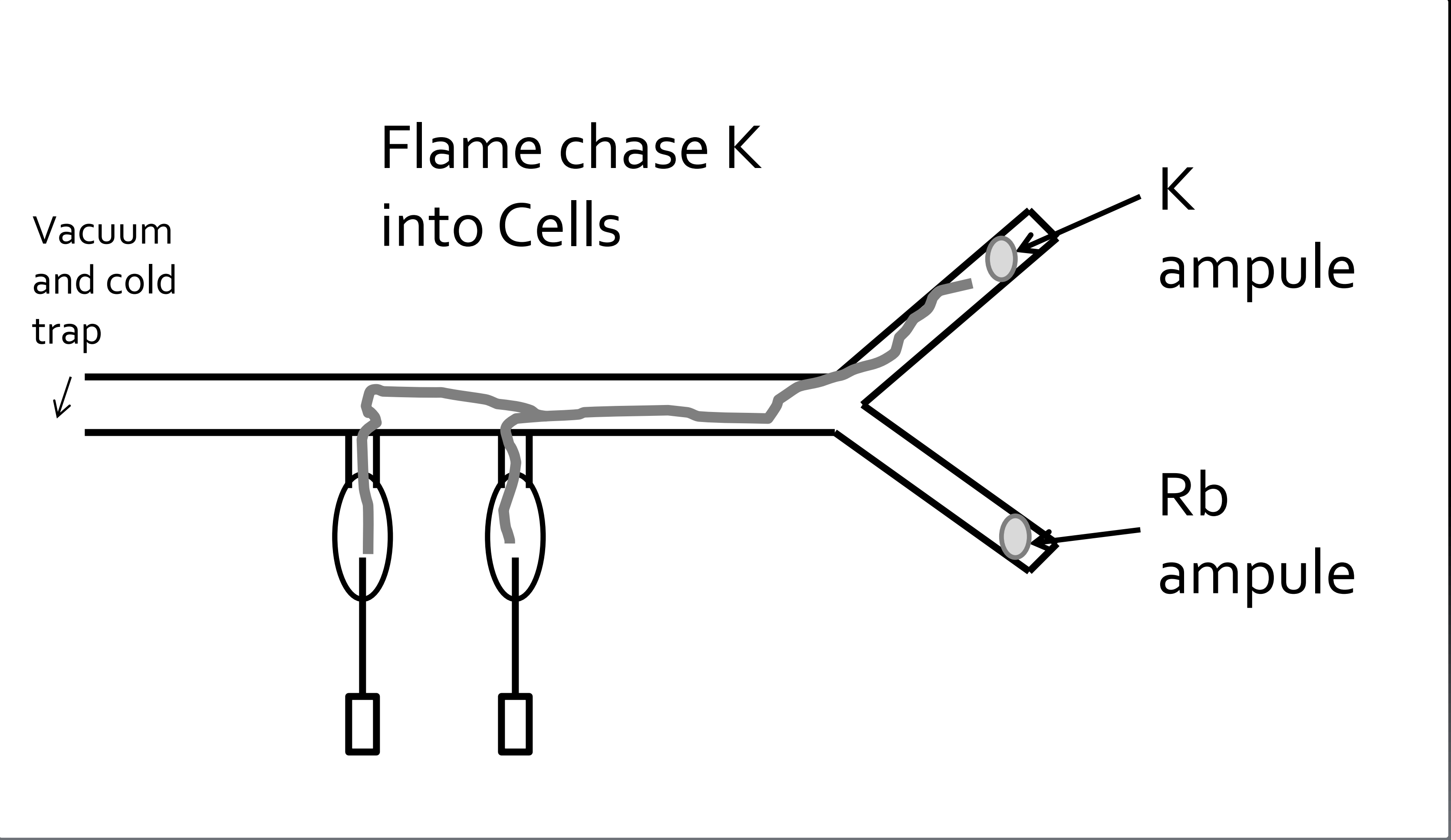
Brief Interlude

- Hybrid K-Rb cells



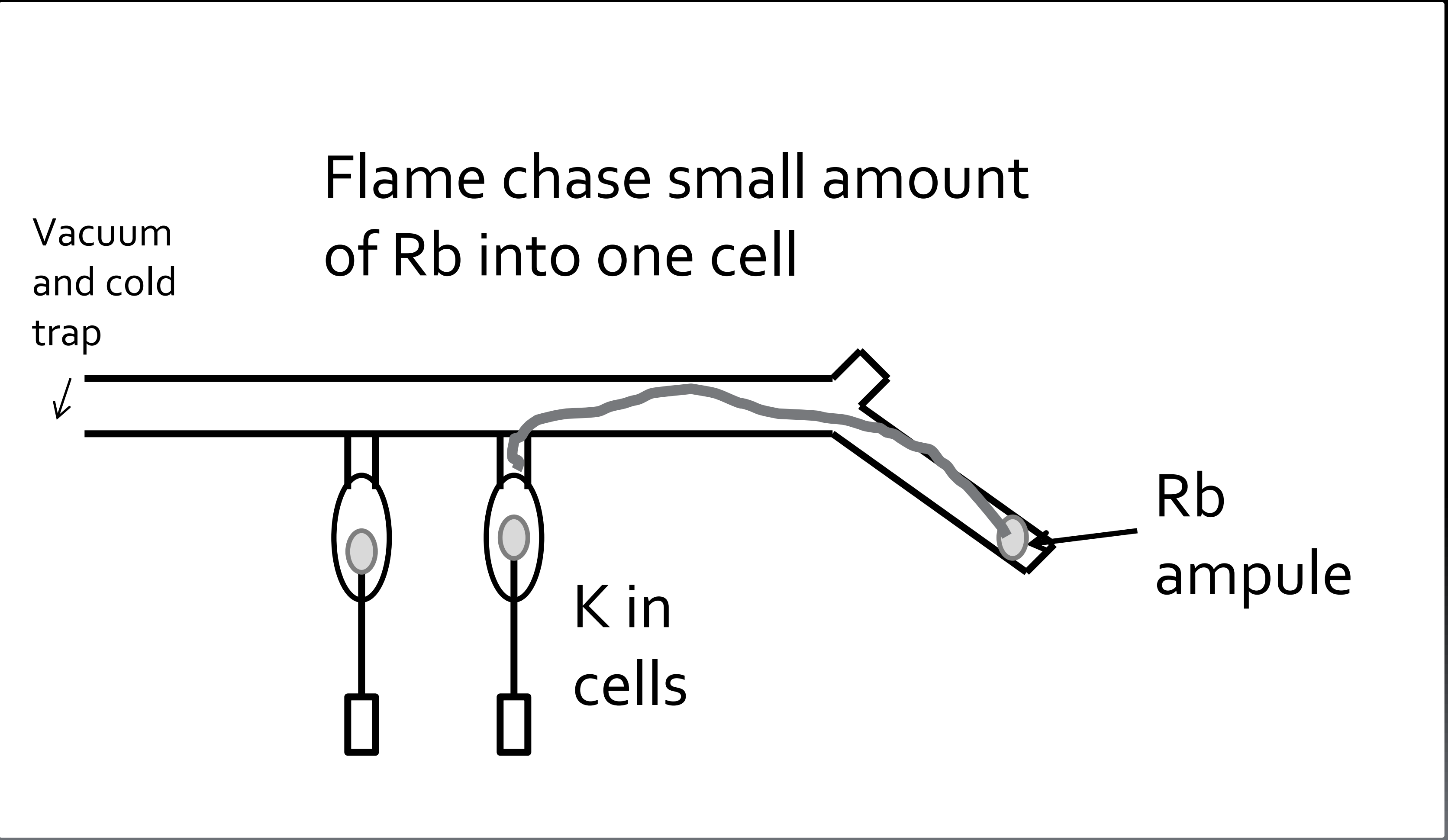
Brief Interlude

- Hybrid K-Rb cells



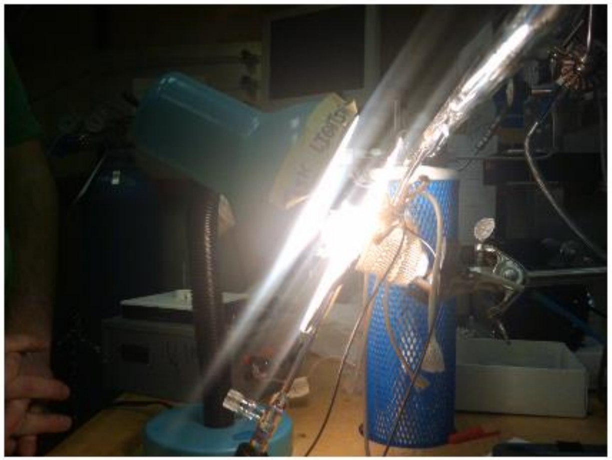
Brief Interlude

- Hybrid K-Rb cells

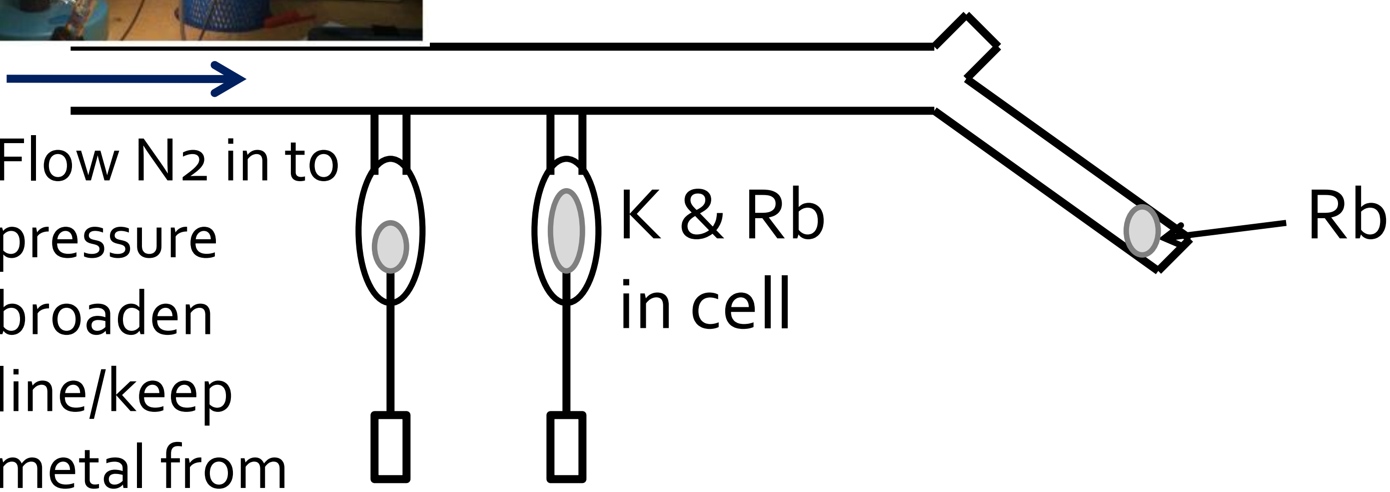


Brief Interlude

- Hybrid K-Rb cells



Run a white light absorption measurement, analyze, able to add more Rb



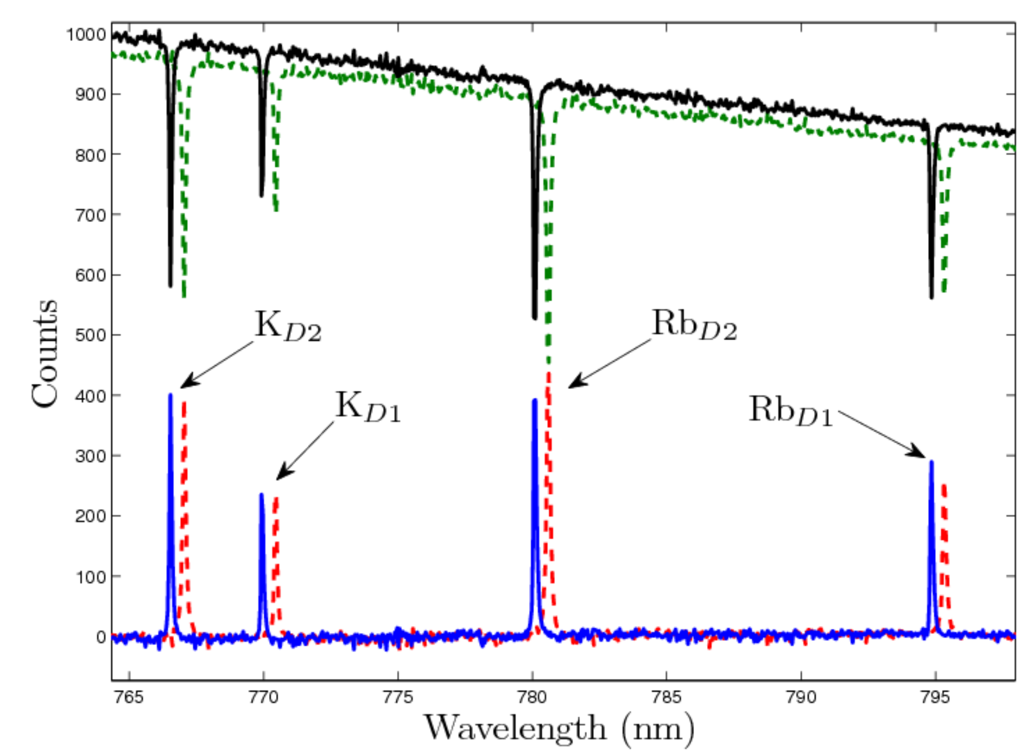
Flow N2 in to pressure broaden line/keep metal from escaping cell

Brief Interlude

- Hybrid K-Rb cells

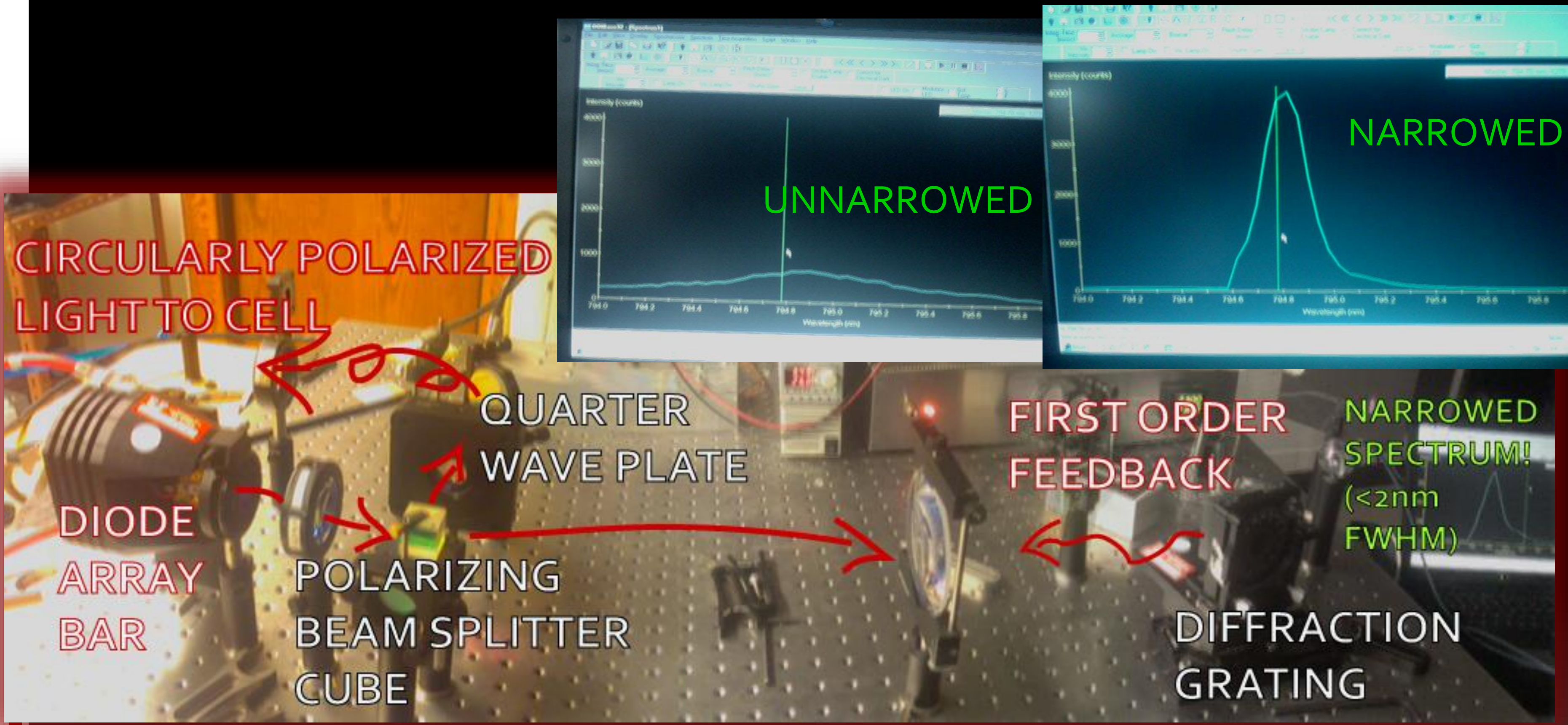
154B in situ at 105C	Lorentzian
K_{D1}/K_{D2}	.64± .04
Rb_{D1}/Rb_{D2}	.62± .04
$\mathcal{D}_{105C}$ (D2 lines)	.695± .03
$\mathcal{D}_{105C}$ (D1 lines)	.719± .05
$\mathcal{D}_{200C}$ (D2 lines)	1.15± .05
$\mathcal{D}_{200C}$ (D1 lines)	1.19± .09

154B Post pull-off at 100C	Lorentzian
K_{D1}/K_{D2}	.52± .02
Rb_{D1}/Rb_{D2}	.55± .02
$\mathcal{D}_{100C}$ (D2 lines)	.757± .02
$\mathcal{D}_{100C}$ (D1 lines)	.726± .03
$\mathcal{D}_{200C}$ (D2 lines)	1.30± .03
$\mathcal{D}_{200C}$ (D1 lines)	1.25± .04



Solid lines – in situ
Dash lines – post-pull off (shifted for clarity)
Raw data on top, bottom baseline corrected

Optical Pumping



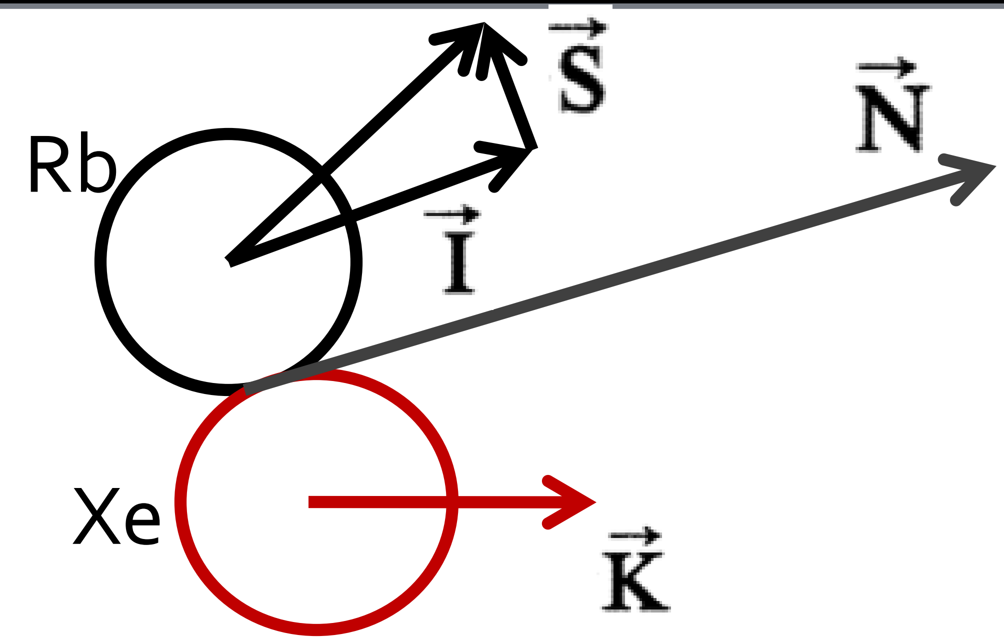
- One of our laser set-ups

(Chann et. al. 2000,

Gas-Phase Spin-Exchange

- Hamiltonian

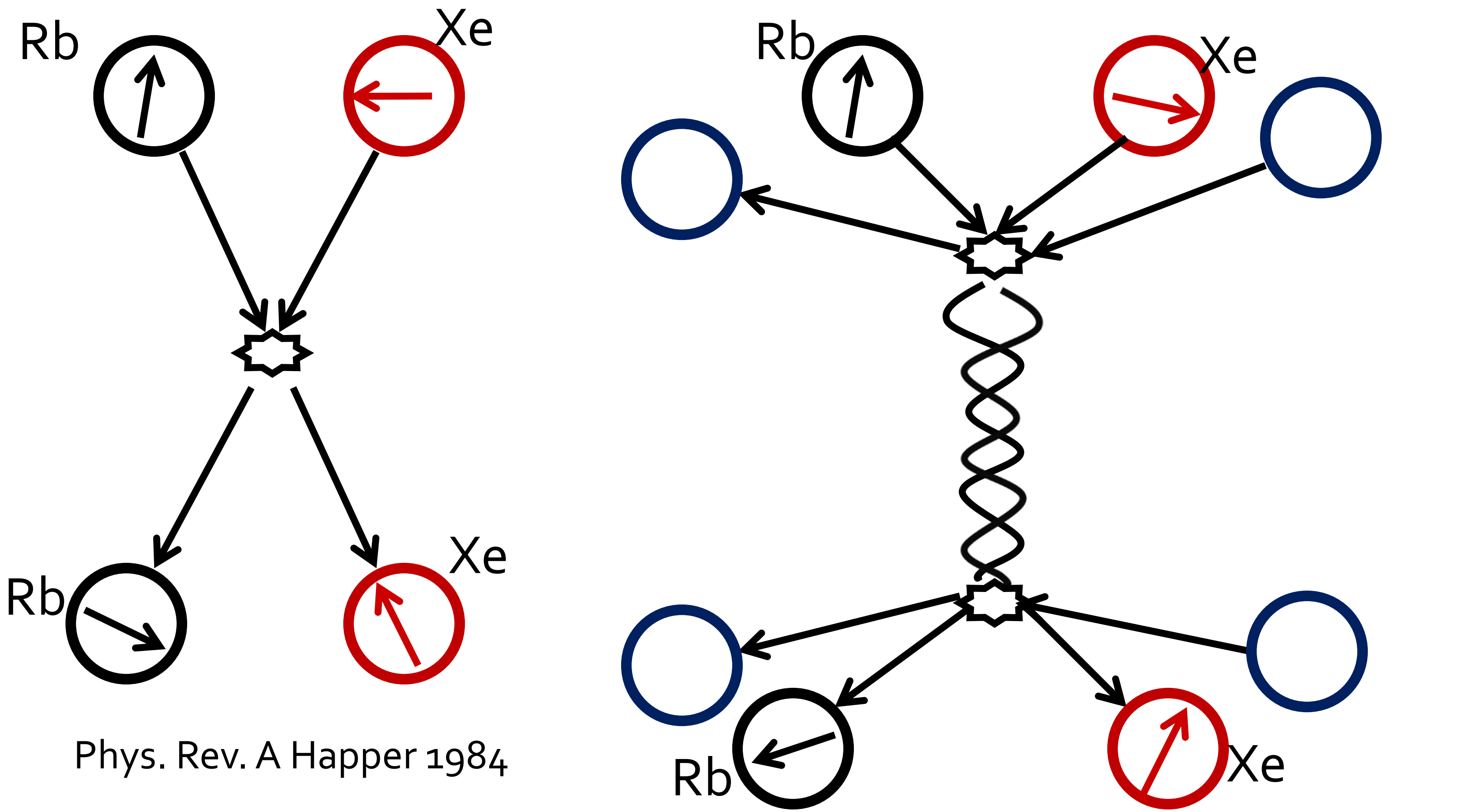
$$H = A\vec{I}\cdot\vec{S} + \gamma\vec{N}\cdot\vec{S} + \alpha\vec{K}\cdot\vec{S} + \cdots$$



Phys. Rev. A Happer 1984

Gas-Phase Spin-Exchange

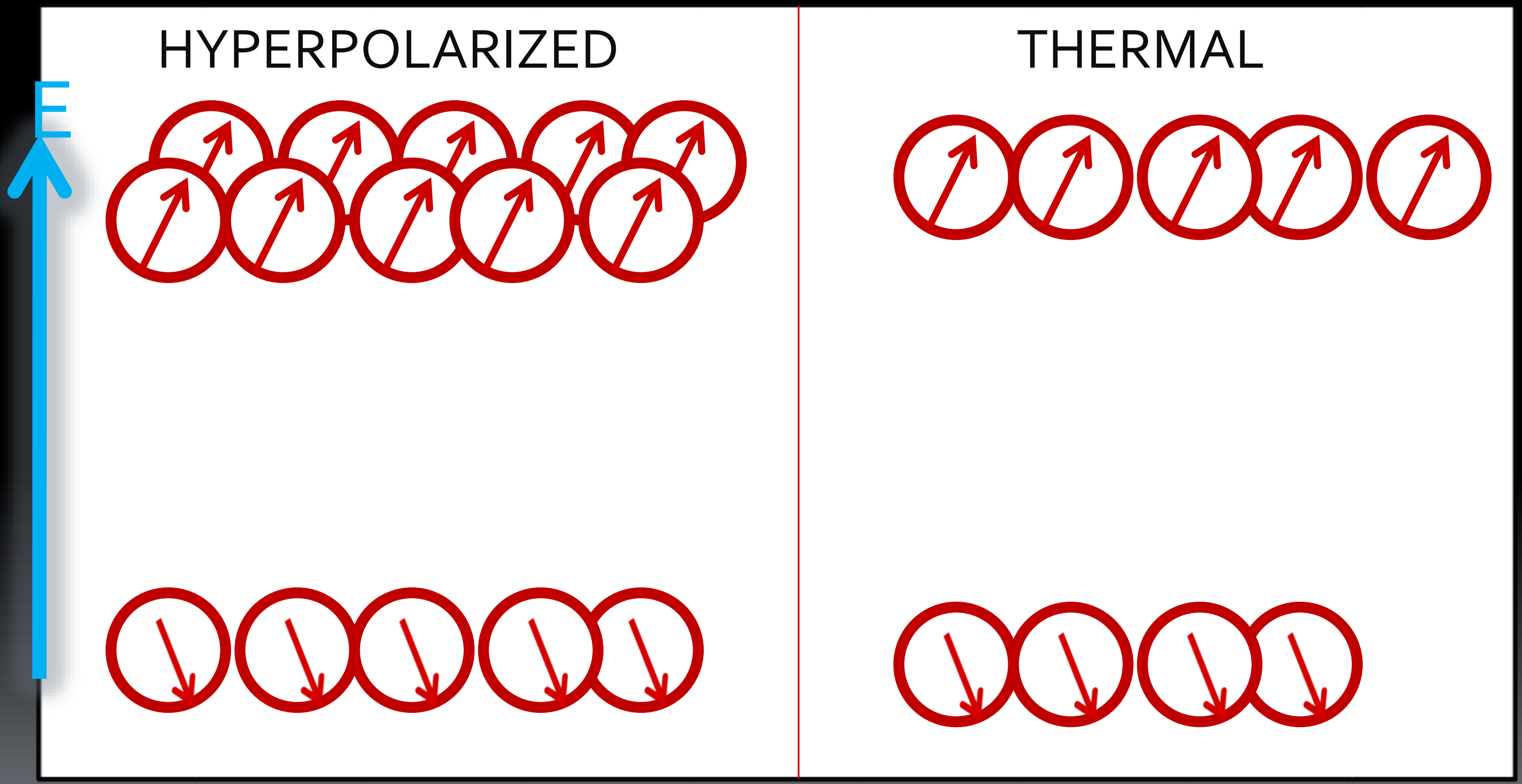
- Binary collisions and Van der Waals molecules



Phys. Rev. A Happer 1984

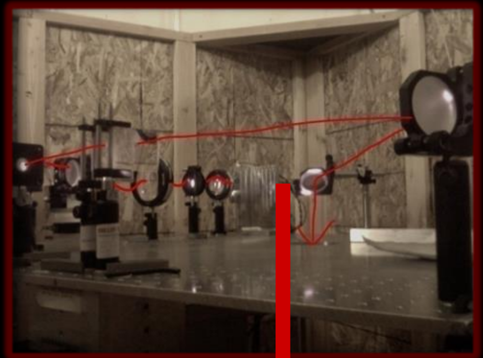
Gas-Phase Spin-Exchange

- Why go to all this trouble?



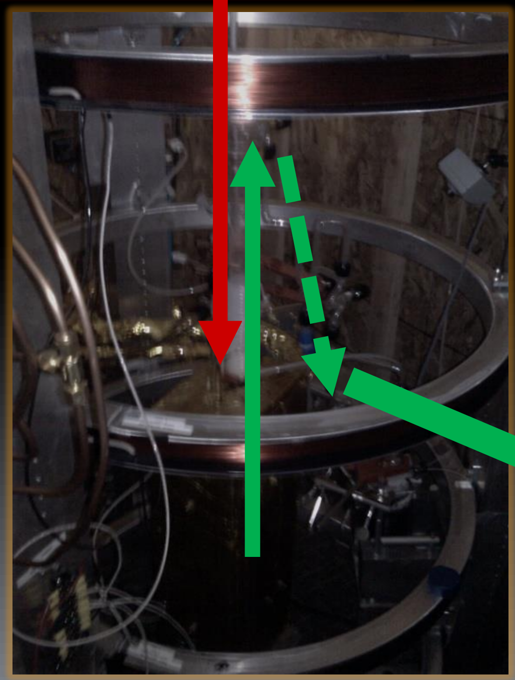
Polarizer

- Flow through Xenon polarizer – a useful tool

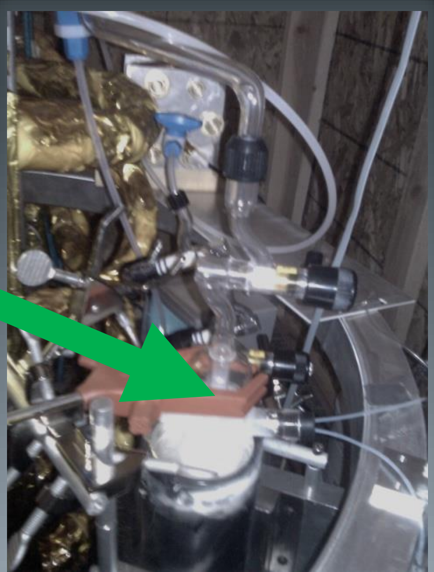


Rb Pump

Flow Xe



COLLECT XENON



Phys. Rev. A- Schrank et. al. 2009

Relaxation

- Longitudinal Nuclear Spin Relaxation

$$\frac{dn}{dt} = \frac{n_o - n}{T_1}$$

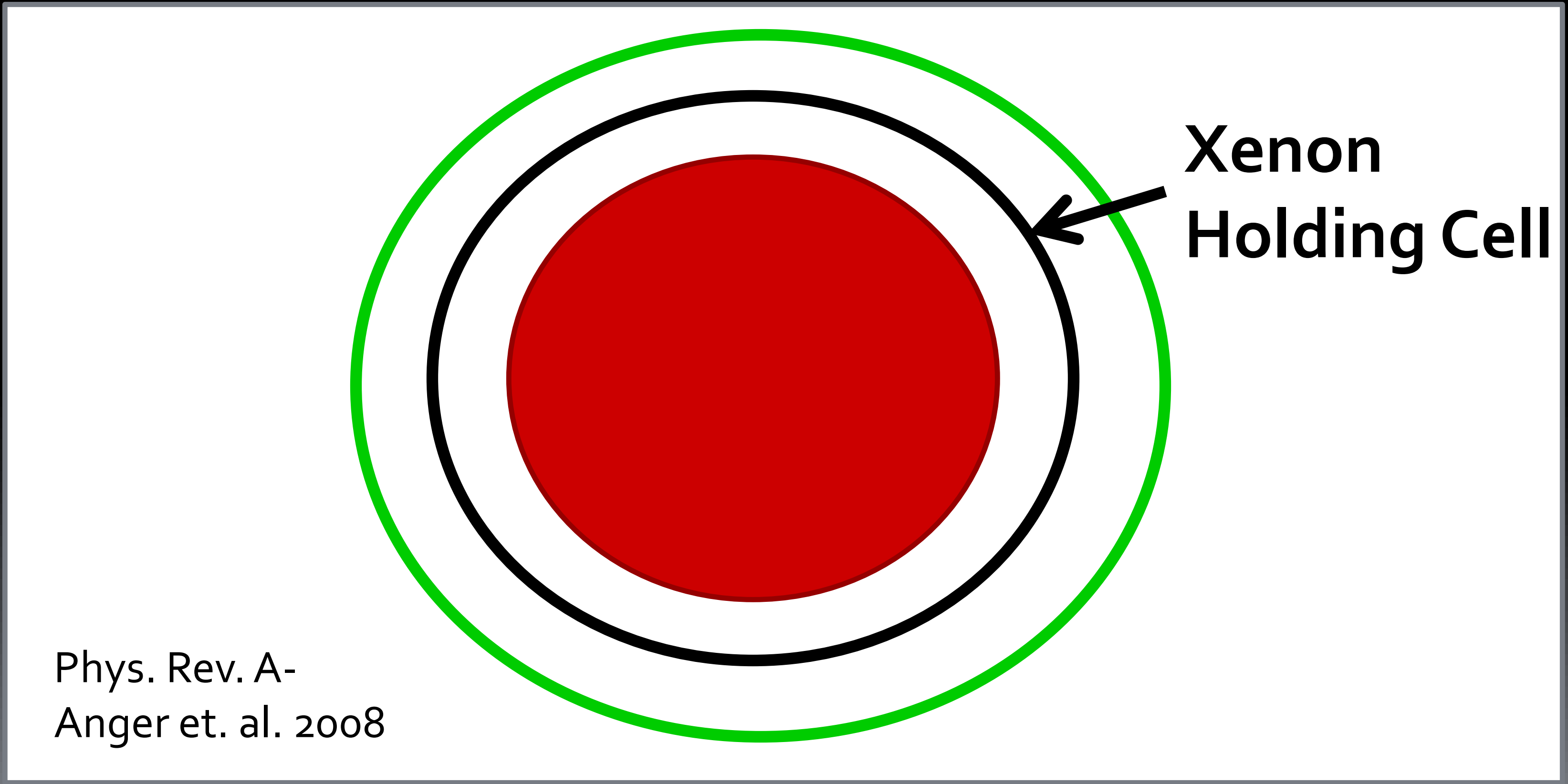
$$n = Ae^{-t/T_1}$$

where n is population difference

Relaxation

- Intrinsic and extrinsic

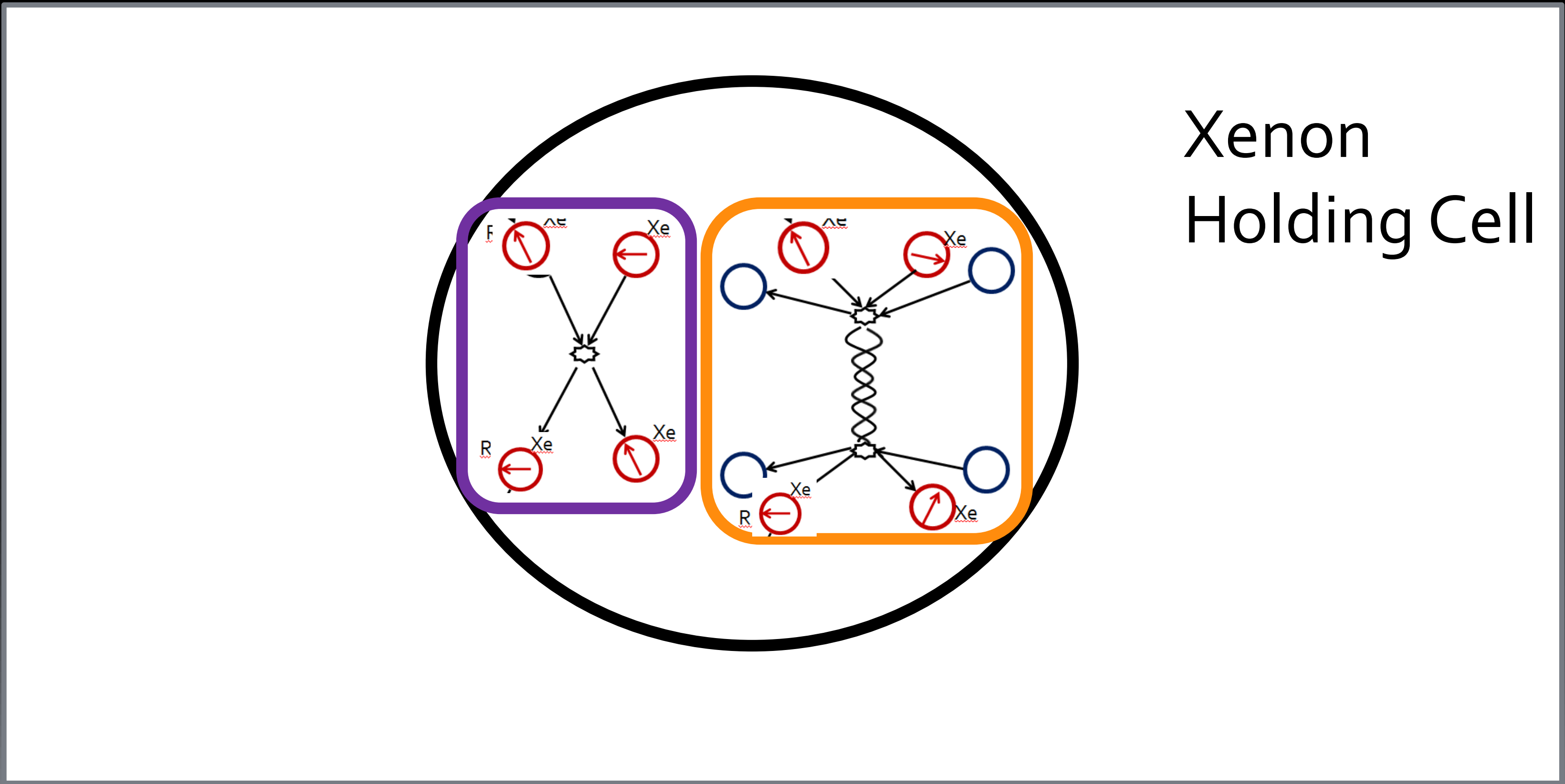
$$\Gamma = \Gamma_t + \Gamma_p + \Gamma_g + \Gamma_w$$



Relaxation

- Intrinsic: Transient and persistent

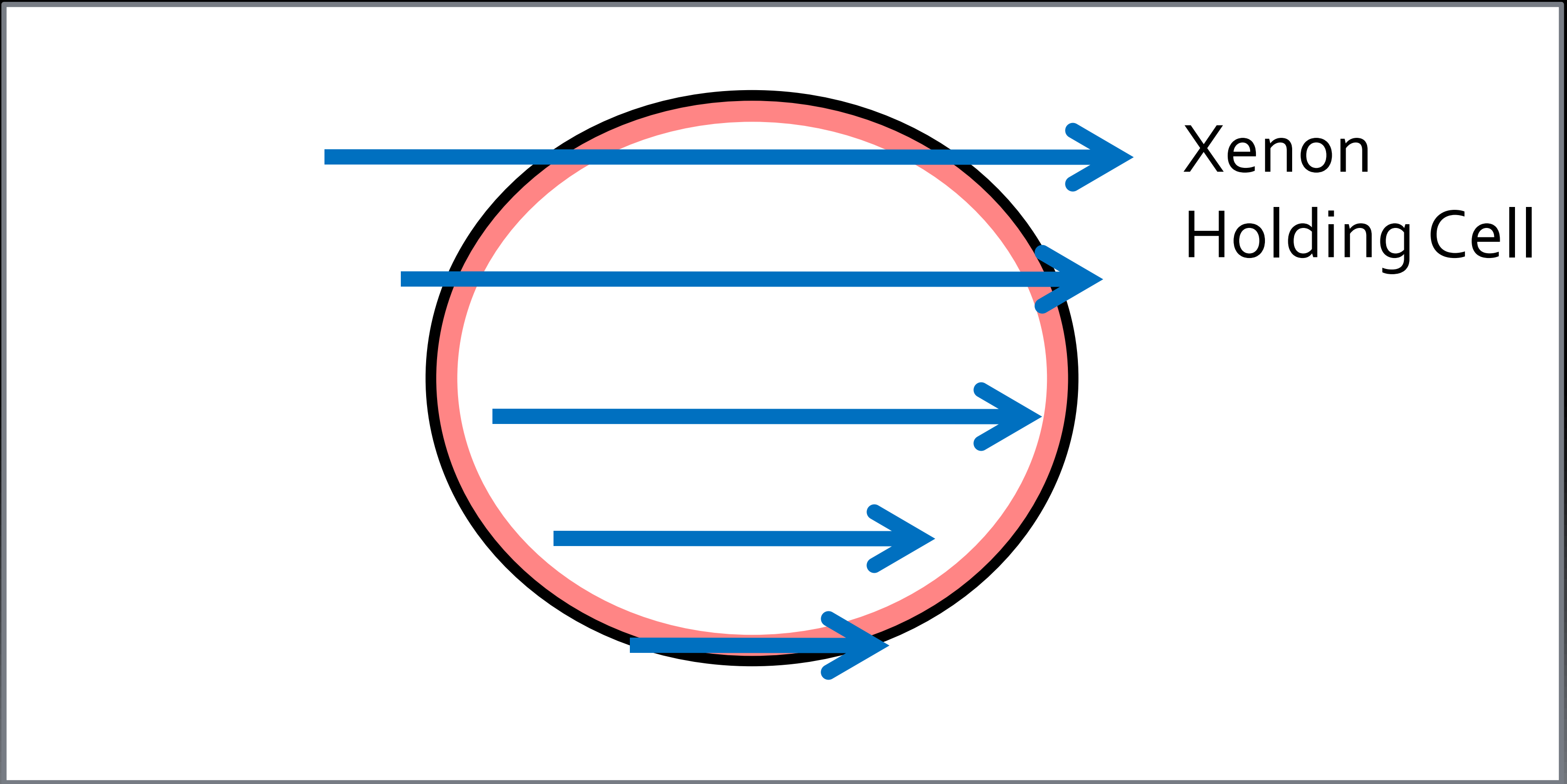
$$\Gamma = \Gamma_t + \Gamma_p + \Gamma_g + \Gamma_w$$



Relaxation

- Extrinsic: Magnetic field gradient and wall

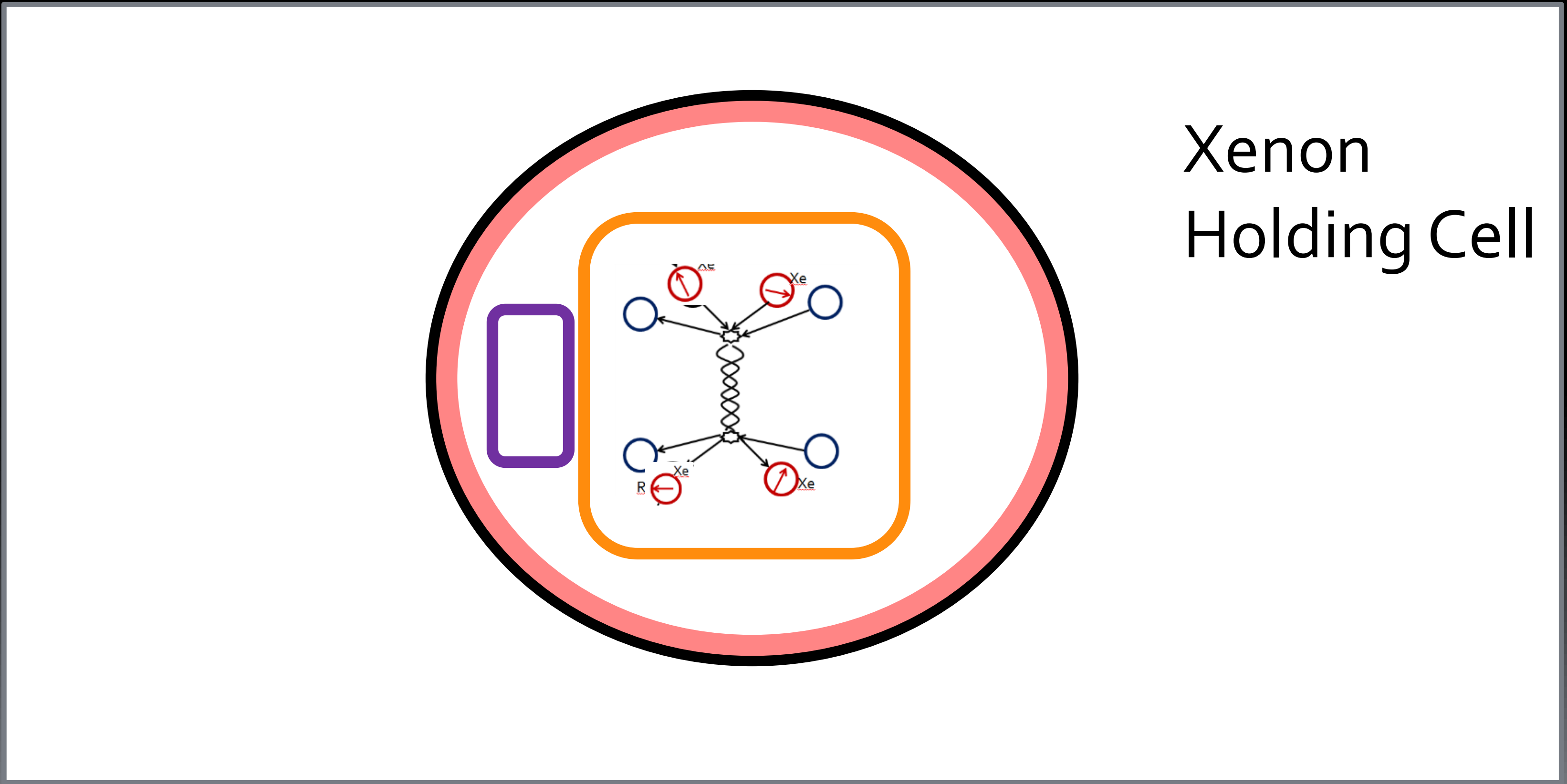
$$\Gamma = \Gamma_t + \Gamma_p + \Gamma_g + \Gamma_w$$



Relaxation

- This work is in the regime primarily dominated by persistent dimers and wall

$$\Gamma = \Gamma_t + \Gamma_p + \Gamma_g + \Gamma_w$$



Relaxation

- Semi-phenomenological equation for xenon nuclear spin relaxation rate

$$\Gamma = \frac{[Xe]}{56.1\ \mathrm{h}}\left(\frac{T_o}{T}\right)^{\frac{1}{2}} + \frac{1}{4.59\ \mathrm{h}}\left(1 + r\frac{[B]}{[Xe]}\right)^{-1}\left(\frac{T_o}{T}\right)^{2} + \Gamma_w$$

Persistent dimer term

Wall term

Transient dimer term

Gradient term ignored

Phys. Rev. A
Anger et. al. 2008

Relaxation

- Buffer gas helps yet again

$$\Gamma_p \propto \tau_B$$

$$\frac{1}{\tau_B} = k_{\mathbf{B}}[\mathbf{B}] + k_{\mathbf{Xe}}[\mathbf{Xe}]$$

$$\Gamma_p = \frac{\Gamma_p^{\mathbf{Xe}}}{1 + r\frac{[\mathbf{B}]}{[\mathbf{Xe}]}}$$

$$\text{where } r = \frac{k_{\mathbf{B}}}{k_{\mathbf{Xe}}}$$

Relaxation

- Unexpected temperature dependence

$$\Gamma_p = 2\mathcal{K}[\mathrm{Xe}]\frac{W}{\tau_B}$$

$$\Gamma_p \propto T^{\frac{1}{2}}\tau_B$$

$$\tau_B = (\overline{V}\sigma_o n)^{-1} \propto T^{-\frac{1}{2}}\sigma_o^{-\frac{1}{2}}$$

$$\Gamma_p \propto \sigma_o^{-\frac{1}{2}}$$

where W is fraction of polarization lost during lifetime τB of the molecule, $\mathcal{K}$ is the chemical equilibrium coefficient, $\overline{V}$ is the mean relative velocity, σ_o is the mean total cross section at this speed, and n is the mean number of molecules per unit volume.

Phys. Rev. A
Anger et. al. 2008

Phys. Rev. Lett.
Chann et. al. 2002

Phys. Rev. A
Walker et. al. 2001

Relaxation

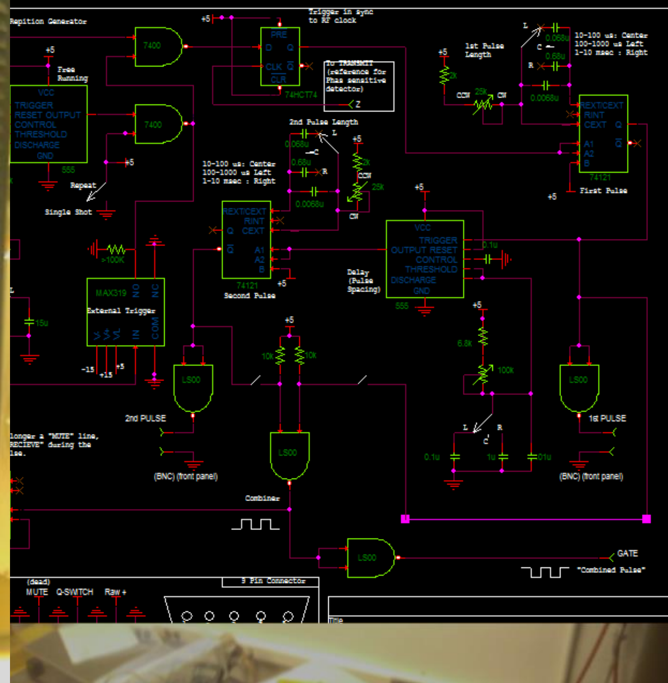
- Solutions? For binary cross sections

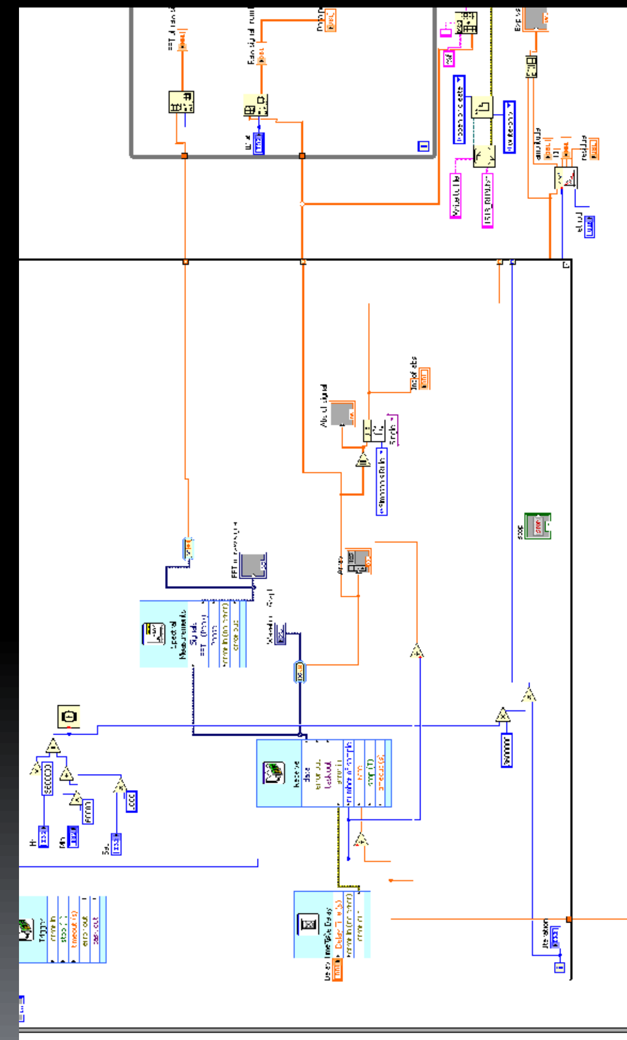
$$\sigma(T) = \frac{1}{(kT)^2} \int_0^\infty dE\, \sigma(E) E e^{-E/kT}.$$

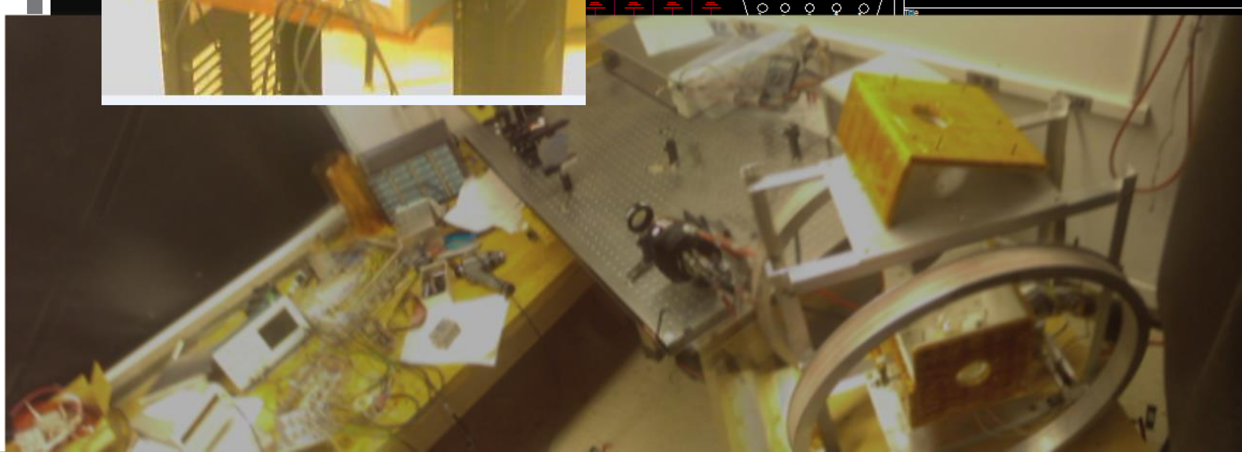
$$\sigma(E) = \frac{8\pi\mu^2}{3\hbar^4} \int_0^\infty b^3\, db \times \left| \int_{r_0}^\infty dR\, \frac{c_K(R)}{\sqrt{1 - b^2/R^2 - V(R)/E}} \right|^2$$

Low-field NMR

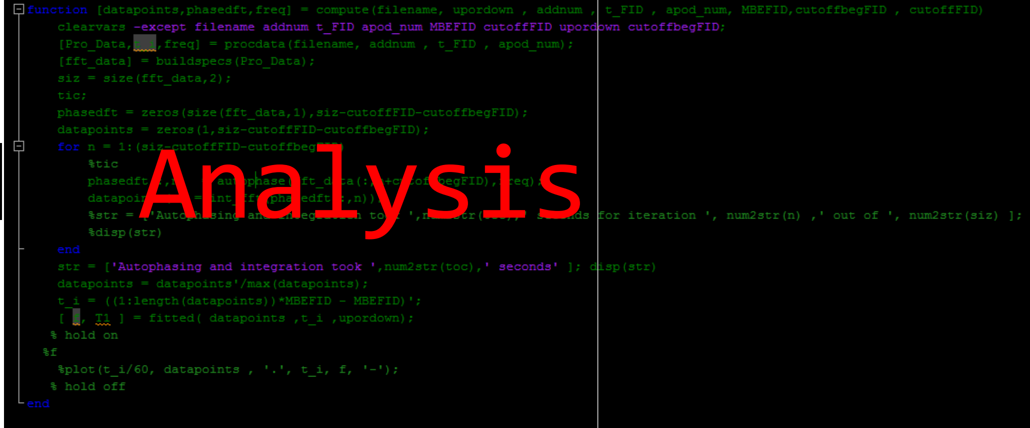
- Result of first project with group

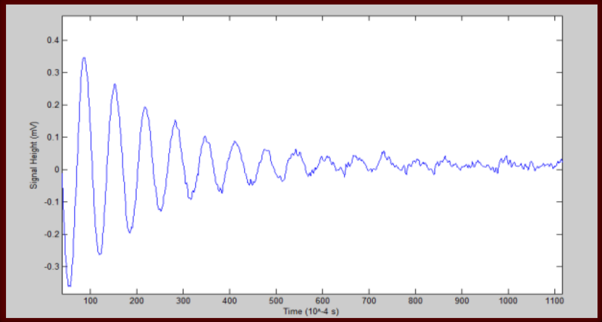






Analysis





Free Induction Decays (FID)

- Collect 20-120 FID's for a given T1 measurement
- Baseline correct and zerofill FID's
- FFT FID's
- Phase correct FFT'S
- Integrate phase corrected FFT's
- 2-parameter fit these to exponential decay
- T1 (or relaxation rate) comes from this

Preliminary Results

- Coatings from Geoff Schrank at PNNL

Cell 151A
8-member
fluorocarbon,
Pure xenon

Temp (deg C)	T1 (hrs)	T1_wall (hrs)
150	3.9 ± .7	9.7 ± 2.6
150	1.2 ± .5	1.5 ±.7
150	1.8 ± .1	2.4 ± .2

Cell 151B
18-member
hydrocarbon,
Pure xenon

Temp (deg C)	T1 (hrs)	T1_wall (hrs)
150	4.8 ± .7	15 ± 3
150	4.1 ± .4	9.6 ± 1.3
25	2.7 ± .4	8.6 ± 1.5
26	2.5 ± .4	6.9 ± 1.3
175	4.7 ± .1	12 ± 1.2

Preliminary Results

- In-house coatings

Cell 151C
8-member
hydrocarbon,
pure xenon

Temp (deg C)	T1 (hrs)	T1_wall (hrs)
150	3.3 ± .2	6.4 ± .7
150	3.2 ± .2	6.2 ± .7
150	2 ± 1	5.3± 2.7
150	2.7± 2	4 ± 3
150	3.2± .1	6.2 ± .6
Cell	Broken	

Preliminary Results

- Re-coated 151A & 151B with 18-member hydrocarbon in-house (OCD runs)

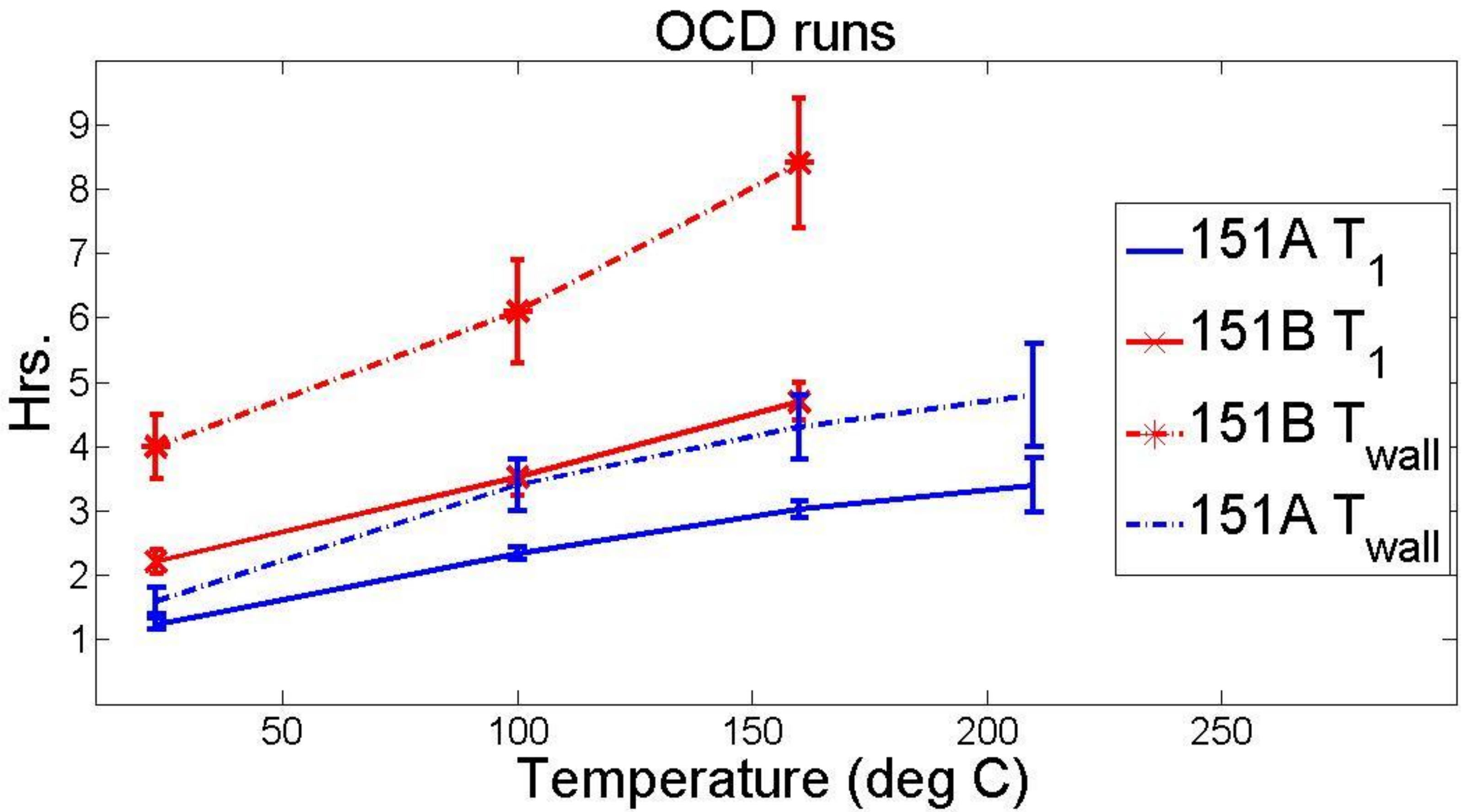
T1

Cell	Coating	23°C	100°C	160°C	210°C
151A	OCD(18)	1.24(.09)	2.33(.10)	3.02(.12)	3.39(.42)
151B	OCD(18)	2.21(.18)	3.52(.28)	4.69(.29)	
BL1	OCD(18)	.93(.05)			

Twall

Cell	Coating	23°C	100°C	160°C	210°C
151A	OCD(18)	1.6(.2)	3.4(.4)	4.3(.5)	4.8(.8)
151B	OCD(18)	4.0(.5)	6.1(.8)	8.4(1.0)	
BL1	OCD(18)				

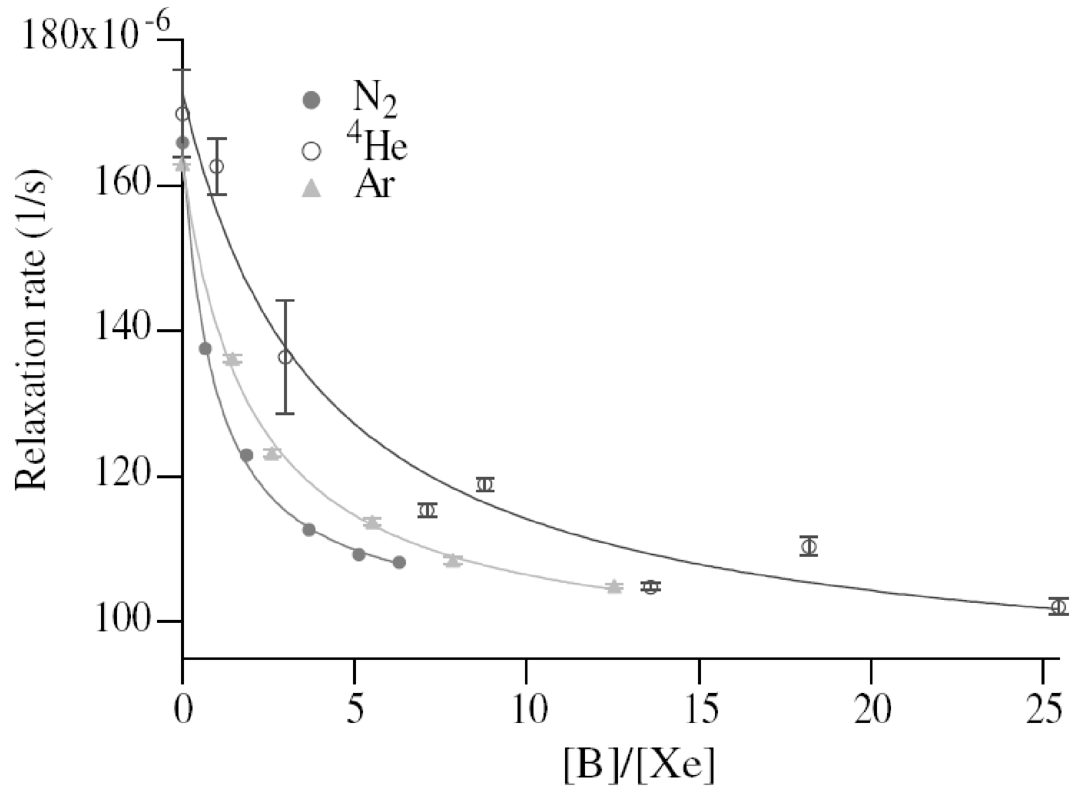
Preliminary Results



Introducing Nitrogen

- Buffer gas helps yet again

$$\Gamma_p = \frac{\Gamma_p^{\mathbf{Xe}}}{1 + r\frac{[\mathbf{B}]}{[\mathbf{Xe}]}}$$



Phys. Rev. Lett.
Chann et. al. 2002

FIG. 1. Xe spin-relaxation rate as a function of composition, for various buffer gases, at a fixed Xe density of 0.15 amagat.

Characterizing Coatings

- Find T1 in with pure xenon in cell at low-field
- Introduce high pressure of nitrogen into cell with pure xenon
- Sweep temperature range of coating
- Back out the wall relaxation
- Push temperature limit of coating
- Purposefully degrade coatings to test durability (haven't done… on purpose)

Current and Future Projects

- Surprising T_1 phenomenon seen in solid xenon, i.e. see a lengthening in T_1, seemingly dependent on passing through the liquid phase

Temp (K)	Snow T_1 (min)	Ice T_1 (min)
77	142 ±6	173 ± 6
122	45 ± 15	
132	36 ± 8	61 ± 9
147	35 ± 3	50 ± 3

Current and Future Projects

- Is it structural? FCC-HCP combinations or many broken lattices as some groups are claiming?

ATOMISTIC STUDY OF XENON CRYSTAL GROWTH VIA... PHYSICAL REVIEW B **82**, 115401 (2010)

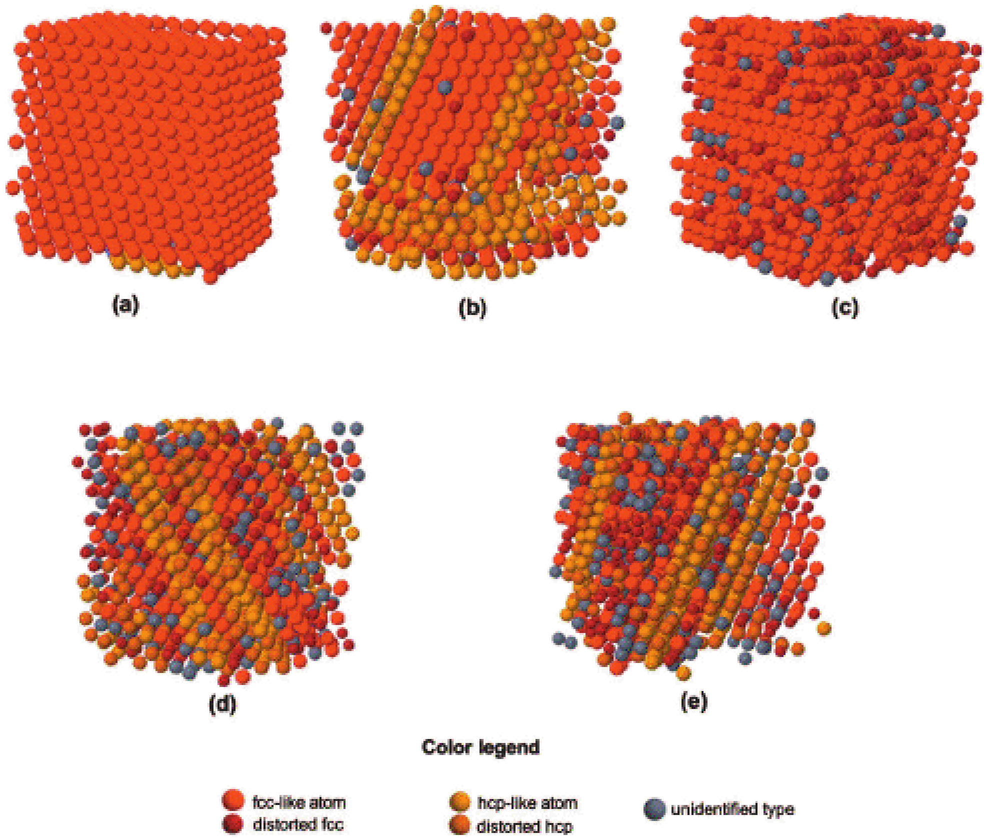


FIG. 6. (Color) Bond angle analysis performed on structures obtained as a result of tempering hot samples as obtained after a simulated deposition with a rate of 2×10^{11} atoms/s. Only 12-fold-coordinated Xe atoms are shown. Tempering temperatures and simulation times are as follows: (a) 10 K, 64 ns; (b) 25 K, 72 ns; (c) 50 K, 110 ns; (d) 75 K, 140 ns; and (e) 100 K, 56 ns.

Conclusion

- Hyperpolarized noble gases make unique systems for NMR study.
- Polarizer is a unique tool that gives us a way to isolate hyperpolarized xenon…
- But…
- Need to develop a way to store the gas for extended periods of time.
- Projects in Spintronics, Medical Physics, and Dilute Xenon Spins coming soon!

THE UNIVERSITY OF UTAH