Measurement of Asymmetry Parameters in ^{37}K

Optical Pumping of Alkali Atoms

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Spring 2013

Presented in partial fulfillment for the degree of Master of Science

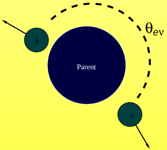
Outline

- Introduction
  - What are angular correlations and why are they interesting?
  - How do we measure them at TRINAT?
- Optical Pumping
  - How does it work?
  - How does my model improve our understanding?
  - What are the results from our December 2012 run?
- Outlook
  - Analysis of the completed A_β experiment
  - Description of the planned B_ν measurement (my Ph.D. project)
  - Time-line

Motivation - Fundamental Symmetries

- In the standard model (SM), all fermions are left-handed.
  - Weak interaction is strictly Vector − Axial-Vector or $(V - A)$
  - Parity is conserved in strong and EM interactions but violated in weak ones?
- $SU(2)_L \otimes U(1)_Y \xrightarrow{?} SU(2)_R \otimes SU(2)_L \otimes U(1)_Y$
- Angular correlations in β-decay are sensitive to new physics
  - Measure these angular correlations experimentally
  - Compare the results to the SM predictions

Unpolarized



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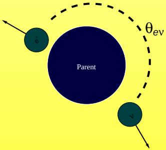
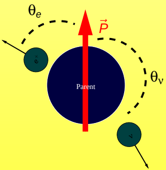


Polarized



Polarized Decay Rate

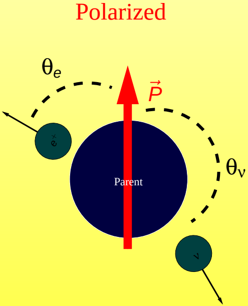
The polarized decay rate is given as:

$$\frac{d^5W}{dEd\Omega_e d\Omega_\nu} \sim 1 + P\left(A_\beta \frac{p_e}{E_e} cos\left(\theta_e\right) + B_\nu \frac{p_\nu}{E_\nu} \cos\left(\theta_\nu\right)\right)$$

A_β and B_ν are sensitive to right-handed currents through their dependencies on: $x = \frac{a_{RR}+a_{RL}}{a_{LL}+a_{LR}} \overset{SM}{\rightarrow} 0, \;\; y = \frac{a_{RR}-a_{RL}}{a_{LL}-a_{LR}} \overset{SM}{\rightarrow} 0$

$$A_\beta \overset{SM}{=} \frac{-2\lambda}{1+\lambda^2}\left(\sqrt{\frac{3}{5}} - \frac{\lambda}{5}\right) = -0.5702(6)$$

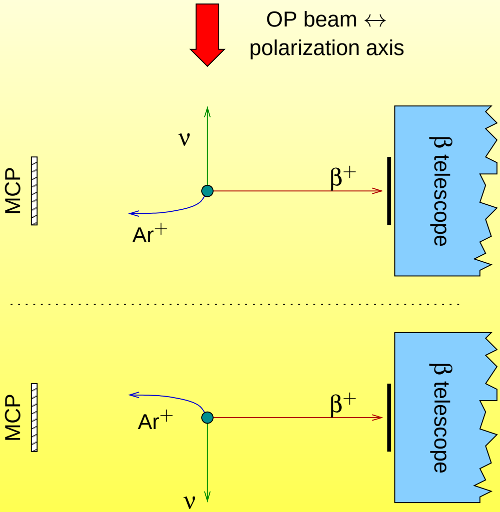
$$B_\nu \overset{SM}{=} \frac{-2\lambda}{1+\lambda^2}\left(\sqrt{\frac{3}{5}} + \frac{\lambda}{5}\right) = -0.7692(15)$$



$$\lambda = \sqrt{2\frac{\mathcal{F}t}{ft} - 1} = \frac{g_A M_{GT}}{g_V M_F}$$

$$= 0.5754(16)$$

Principle of the B_ν measurement



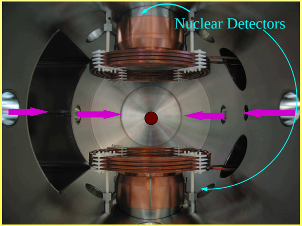
$$^{37}_{19}K \rightarrow ^{37}_{18}Ar + \beta^+ + \nu$$

$$I^\pi = \frac{3}{2}^+ \rightarrow \frac{3}{2}^+$$

- Mixed Fermi / Gamow-Teller Decay
- 98% branching ratio to ground state
- Isobaric analogue transition

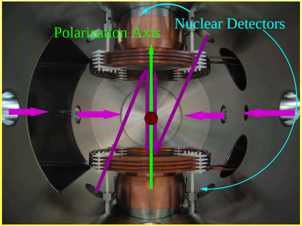
Overview

- Magneto-Optical Trap (MOT)
  - Provides a cold, localized source of atoms
  - Shallow trap so products emerge unperturbed
  - New AC-MOT design allows for an improved duty cycle



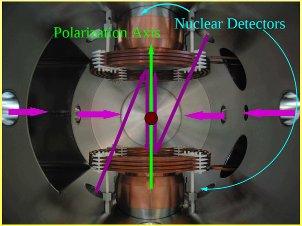
Overview

- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
  - σ^+ σ^- lasers drive biased random walk.
  - Have achieved $P > 95\%$ and expect improvements.
  - Measure P for the same atoms that are decaying.



Overview

- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
- Nuclear Detectors
  - DSSSD - Position Sensitive Si Detectors
  - Scintillator - Full energy of Positron
  - rMCP - Measure the asymmetry of the recoiling Ar^+
  - eMCP - Discern backgrounds in the experiment



Optical Pumping - Overview

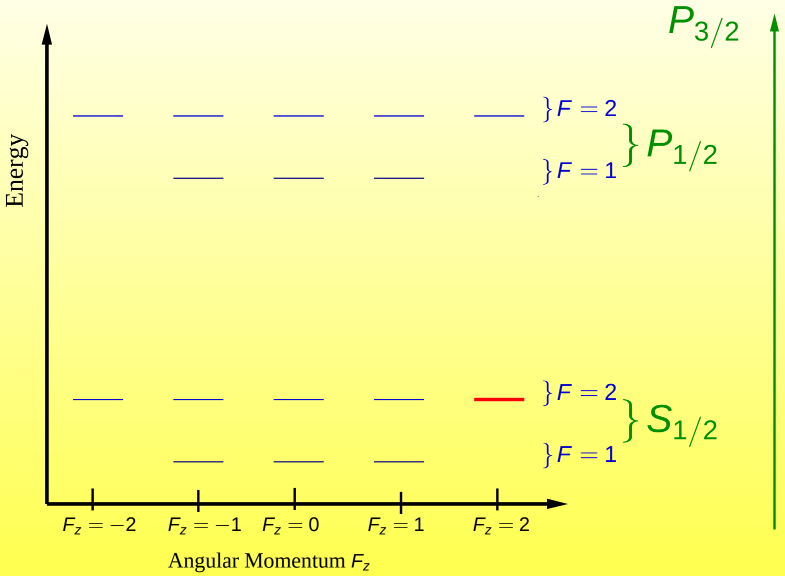
- Any asymmetry is directly proportional to the nuclear polarization
  - Need high polarization. $P > 95\%$ has been reached in the past.
  - Must have a good model to measure the polarization precisely
- Laser light pumps the atoms to a fully polarized state
  - Nucleus is polarized through the hyperfine interaction
- Use the excited state population as a probe of the polarization
- This is atomic physics in a nuclear physics experiment that has particle physics goals.

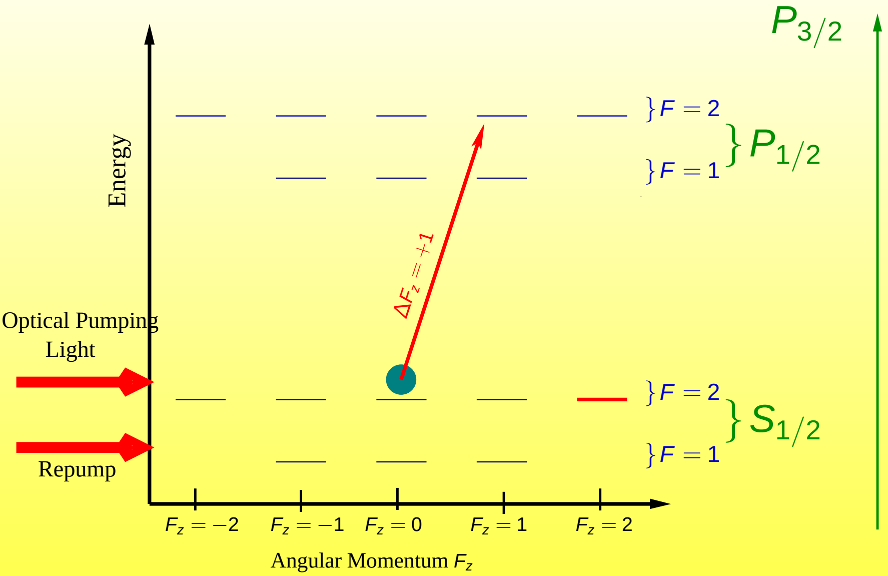
Atomic Structure of Alkali Atoms

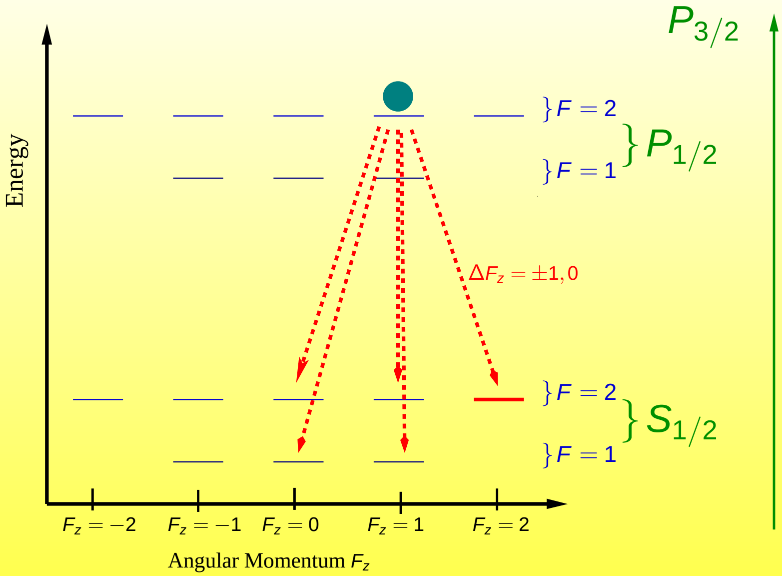
- Electronic configuration is $[Ar]4s$
- Treated as a single electron orbiting in a Coulomb potential

$$H = \underbrace{\underbrace{H_0}_{\text{Coulomb}} + \underbrace{H_{so}}_{\text{Spin-Orbit}} + \underbrace{H_{hf}}_{\text{Hyperfine}} + \underbrace{H_B}_{\text{Zeeman Shifts}}}_{\text{Atomic Hamiltonian}} \underbrace{- e\vec{d} \cdot \vec{E}(t)}_{\text{Laser Term}}$$

- $H_{SO} = \vec{L} \cdot \vec{S}$ splits levels into states with $\vec{J} = \vec{L} + \vec{S}$ ($\sim 1.6THz$)
- $H_{hf} = \vec{I} \cdot \vec{J}$ splits levels into states with $\vec{F} = \vec{J} + \vec{I}$ ($\sim 240MHz$)
- $H_B = g_F \mu_B B_z F_z$ removes degeneracy of F states ($\sim 2.8MHz$)


$P_{3/2}$
Energy
$\}F = 2$
$\}F = 1$
$\} P_{1/2}$
$\}F = 2$
$\}F = 1$
$\} S_{1/2}$
$F_z = -2$
$F_z = -1$
$F_z = 0$
$F_z = 1$
$F_z = 2$
Angular Momentum F_z


$P_{3/2}$
Energy
$\}F=2$
$\}F=1$
$\} P_{1/2}$
$\Delta F_z = +1$
Optical Pumping Light
$\}F=2$
$\}F=1$
$\} S_{1/2}$
Repump
$F_z=-2$
$F_z=-1$
$F_z=0$
$F_z=1$
$F_z=2$
Angular Momentum F_z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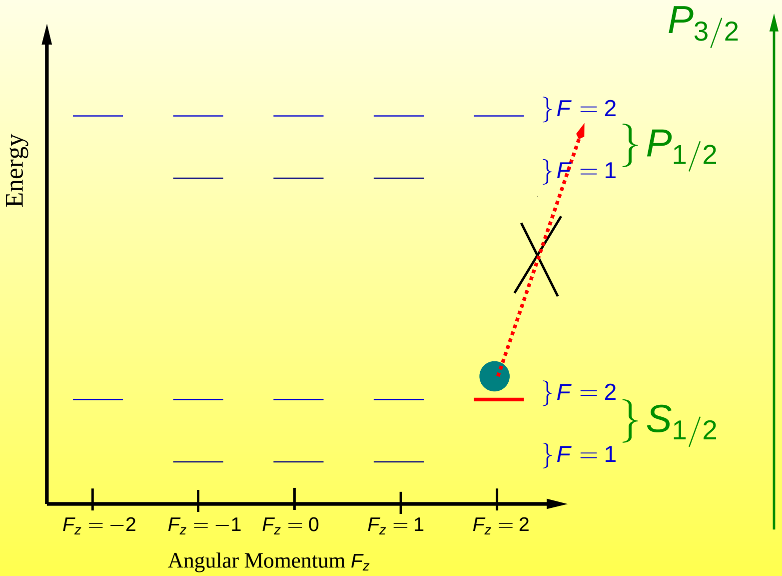
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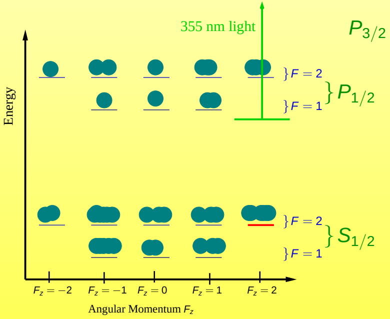
Stretched State

In ^{37}K: $\vec{I} = \frac{3}{2}$; $\vec{J} = \frac{1}{2}$; $\vec{F} = \vec{I} + \vec{J} = 1, 2$

- Stretched state has $F = 2$, $M_F = 2$ or equivalently $I_z = \frac{3}{2}$, $J_z = \frac{1}{2}$
- An atom in this state is dark to the laser light and is trapped
- This state corresponds to total atomic and nuclear polarization



Polarization

$$P = \frac{\langle \psi | I_z | \psi \rangle}{|\vec{I}|}$$

Alignment

$$T = \frac{I(I+1) - 3\langle \psi | I_z^2 | \psi \rangle}{I(2I-1)}$$

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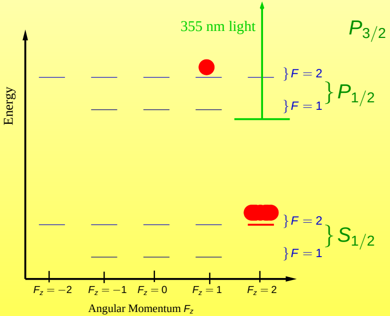

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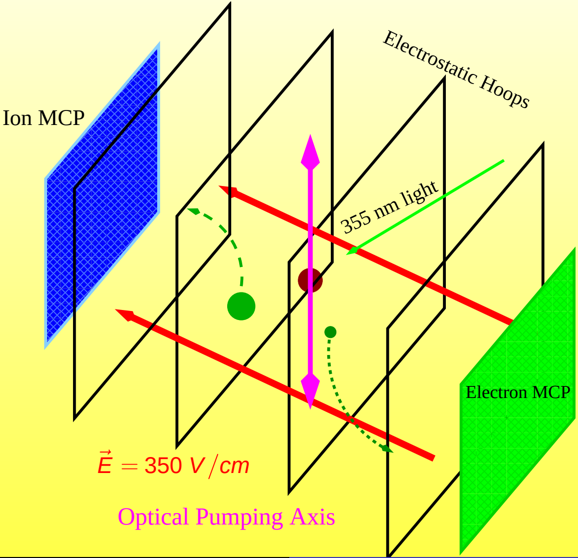
Optical Pumping Geometry



Classical Rate Equations

$W_{e,g} =$ Laser induced transition rate
$\gamma_{spon} =$ Natural line-width of excited state
$\mu_{e,g} =$ The transition strength between states e, g

$e =$ excited state
$g =$ ground state

$$\frac{dN_g}{dt} = -\sum_e W_{e,g} N_g + \sum_e W_{e,g} N_e + \gamma_{spon} \sum_e |\mu_{e,g}|^2 N_e$$

$$\frac{dN_e}{dt} = \underbrace{\sum_g W_{e,g} N_g}_{\text{absorption}} - \underbrace{\sum_g W_{e,g} N_e}_{\text{stimulated emission}} \underbrace{- \gamma_{spon} \sum_g |\mu_{e,g}|^2 N_e}_{\text{spontaneous emission}}$$

- Solve this set of $4(2I+1) \overset{^{37}K}{\rightarrow}$ 16 real coupled equations

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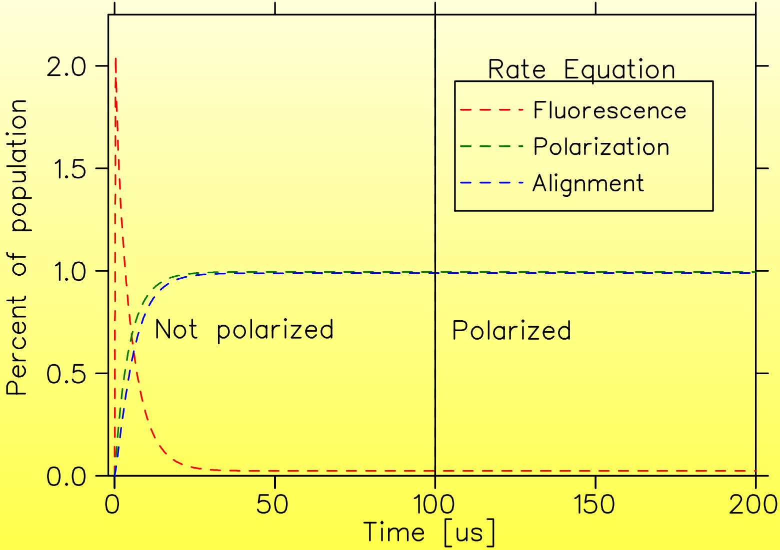
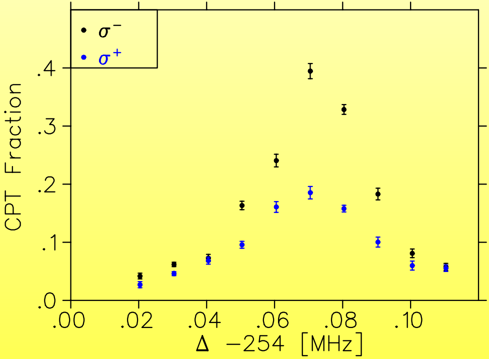
- Solve this set of $4(2I+1) \stackrel{^{37}K}{\rightarrow}$ 16 real coupled equations
- This classical theory neglects a number of quantum effects that can impact the degree of polarization.

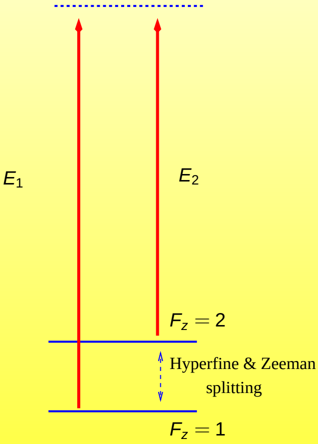
Rate Equation Results - Basic Features



Coherent Population Trapping

- A precisely tuned laser traps atoms in coherent dark states
- Mimics the decaying of fluorescence without polarizing atoms
- Classical model cannot reproduce these effects





Optical Bloch Equations - Density Matrix

Diagonal elements correspond to the probability to be in a given state

$$\rho = \begin{pmatrix} \rho_{00} & \rho_{01} \cdots & \rho_{0n} \\ \rho_{10} & \rho_{11} \cdots & \rho_{1n} \\ \vdots & \ddots & \vdots \\ \rho_{n0} & \rho_{n1} \cdots & \rho_{nn} \end{pmatrix} \qquad \rho_{ij} = \rho_{ji}^*$$

Time evolution of the density matrix is given by Louiville's Equation:

$$\frac{d\rho}{dt} = \frac{1}{i\hbar}[H(t), \rho]$$

Optical Bloch Equations - Density Matrix

Off-diagonal elements represent the correlation between the states

$$\rho = \begin{pmatrix} \rho_{00} & \rho_{01} \cdots & \rho_{0n} \\ \rho_{10} & \rho_{11} \cdots & \rho_{1n} \\ \vdots & \ddots & \vdots \\ \rho_{n0} & \rho_{n1} \cdots & \rho_{nn} \end{pmatrix} \qquad \rho_{ij} = \rho_{ji}^*$$

Time evolution of the density matrix is given by Louiville's Equation:

$$\frac{d\rho}{dt} = \frac{1}{i\hbar}[H(t), \rho]$$

Where the Hamiltonian is the sum of atomic and laser terms:

$$H = \underbrace{\underbrace{H_0}_{\text{Coulomb}} + \underbrace{H_{so}}_{\text{Spin-Orbit}} + \underbrace{H_{hf}}_{\text{Hyperfine}} + \underbrace{H_B}_{\text{Zeeman Shifts}}}_{\text{Atomic Hamiltonian}} \underbrace{- e\vec{d} \cdot \vec{E}(t)}_{\text{Laser Term}}$$

- Must now solve a set of

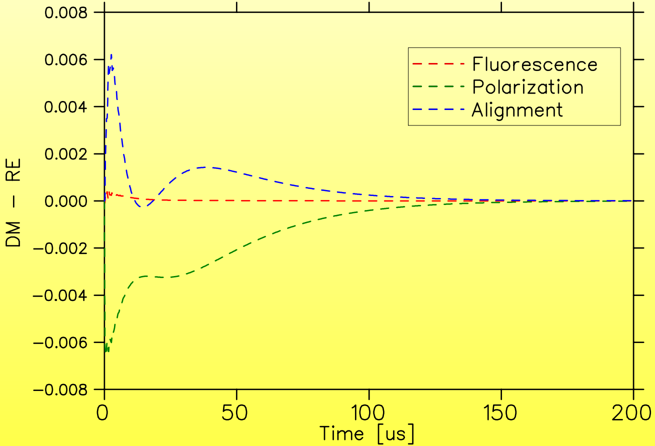
$$\frac{[4(2I+1)][4(2I+1)-1]}{2} \overset{^{37}K}{\rightarrow} 120$$

complex differential equations.

- With 18 potentially variable input parameters
- Capable of modeling any alkali atom
- Check it out!
`http://code.google.com/p/optical-bloch-equations`

Comparison to rate equation

Most parameters give results that are close to the classical model

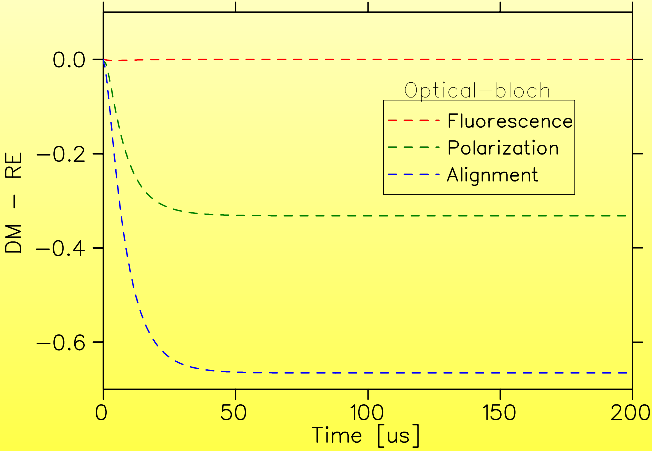


$\Delta_{2\to2} = 2.0\ MHz$
$\Delta_{1\to2} = 3.0\ MHz$

Comparison to rate equation

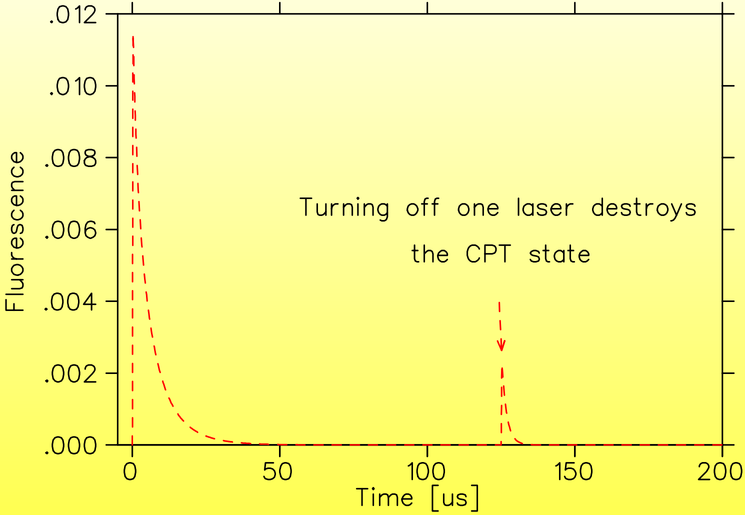
Parameters chosen to create CPT states show large differences

These states are included in the model and avoided in the experiment



$$\Delta_{2\to2} = 0.0\ MHz$$
$$\Delta_{1\to2} = 0.0\ MHz$$

Coherent Population trapping in the density matrix model

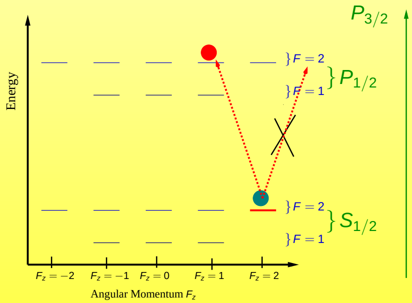


Depolarizing mechanisms - Stokes Parameter s_3

- s_3 characterizes the degree of circular polarization
- s_0 is equivalent to the total power contained in the beam

$$\frac{s_3}{s_0} = \frac{I_+ - I_-}{I_+ + I_-}$$

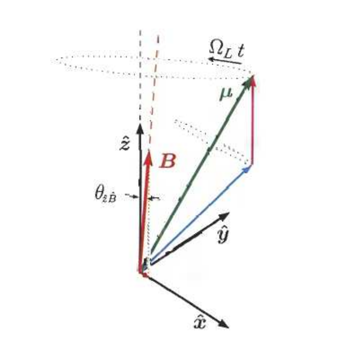
- If $|s_3| < 1.0$ then atoms can be pumped out of the stretched state



Equilibrium is reached with not all atoms in the fully stretched state

Depolarizing mechanisms - Transverse magnetic field

- Magnetic field perpendicular to polarization axis causes precession



Atoms in the stretched state precess to other ground states

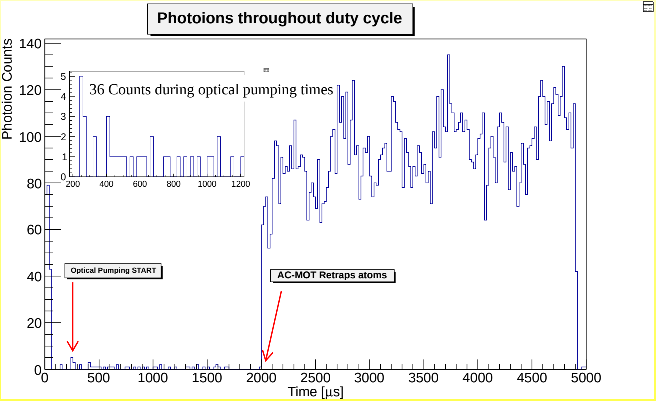
$\vec{B} = B_x\hat{x} + B_z\hat{z}$

$$H_{\vec{B}} = -\vec{\mu}\cdot\vec{B}$$
$$H_{B_x} = g_F\mu_B B_x F_x = g_F\mu_B B_x \frac{F_+ + F_-}{2}$$

B_x from apparatus: $B_x/B_z = 0.4\%$
Stray field from Earth, cyclotron, ...
Mechanical misalignment: $\theta_{\hat{z}\hat{\theta}} \leq 2^\circ$

^{37}K data

- Too few counts to extract polarization from fluorescence data
- Can use recoil asymmetry to deduce polarization
- Use stable ^{41}K to test model and compare to ^{37}K polarization



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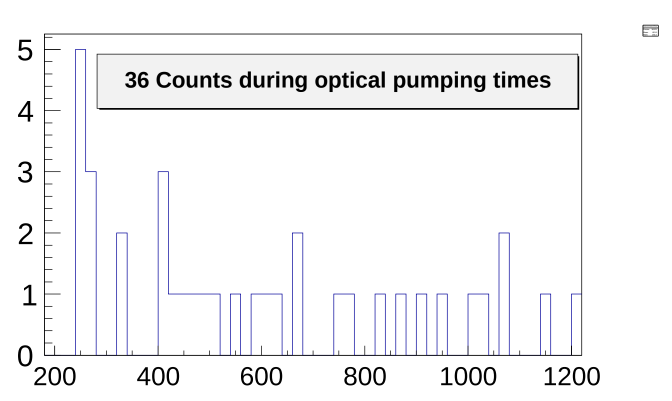
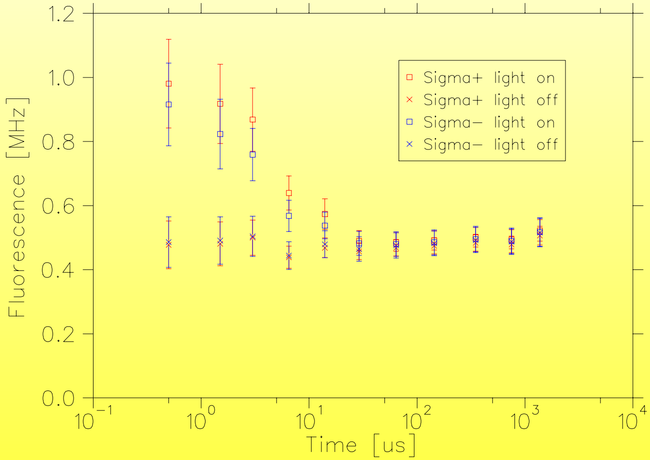


^{41}K data

- Stable ^{41}K has similar hyperfine structure to ^{37}K
- Can be produced and trapped off-line in large quantities!



Fitting details

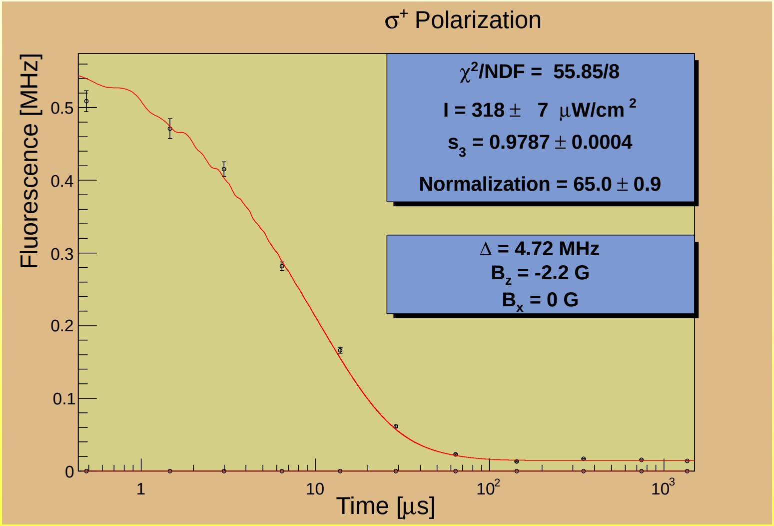
- Aligned field fixed by trapped population scans: $B_z = 2.2\ G$
- Relative detuning of lasers is fixed at $\Delta_{2\to2} - \Delta_{1\to1} = 3.6\ MHz$
- Relative laser intensity is fixed at 2:1
- s_3 is assumed to be the same for both lasers

Fitted parameters of interest are the

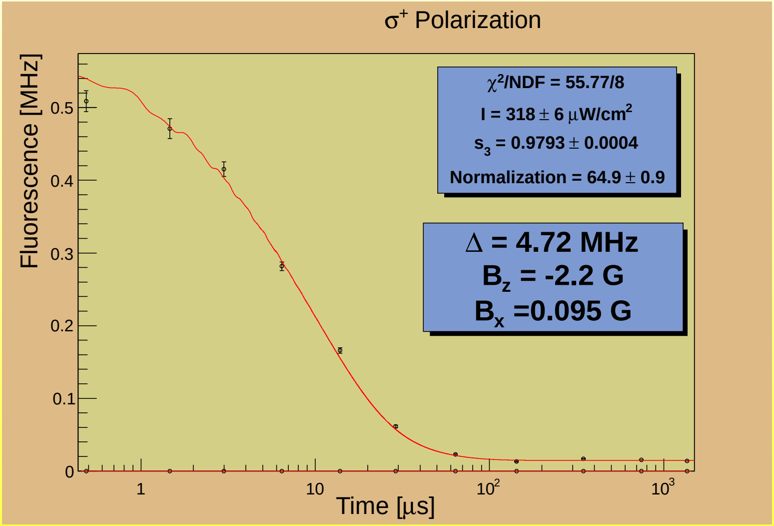
- Laser intensity at the trap position
- Background level
  - Residual fluorescence above background signals imperfect polarization
- A depolarizing mechanism

Stokes parameter s_3 and transverse field B_x are $> 99\%$ correlated

Fits to the fluorescence



Fits to the fluorescence



Results

- Errors scaled so that $\chi^2/NDF = 1.0$ acknowledges underestimate of systematics
- Depolarizing mechanisms s_3 and B_x are $> 99\%$ correlated
- ^{41}K data is fit and ^{37}K polarization is projected from the result

Fit results with $B_x = 0.0\ G$

	s_3	$P\left[^{41}K\right]$	$P\left[^{37}K\right]$
σ^-	0.9953(5)	0.9976(2)	0.9974(3)
σ^+	0.979(1)	0.9816(9)	0.9815(9)

Fit results with $B_x = 0.10\ G$ or $\theta_{\hat{B}\hat{z}} = 2^\circ$

	s_3	$P\left[^{41}K\right]$	$P\left[^{37}K\right]$
σ^-	0.9959(5)	0.9967(2)	0.9966(3)
σ^+	0.979(1)	0.9807(9)	0.9806(9)

Results

- Central value is chosen as average of two fits

Combined uncertainties for ^{41}K

	σ^-	σ^+
Fitting	0.0003	0.0012
$s_3 vs. B_x$	0.00045	0.0005
Sum	0.0005	0.0013

Combined fit results

	$P\left[^{41}K\right]$	$P\left[^{37}K\right]$
σ^-	0.9972(5)	0.9970(6)
σ^+	0.981(1)	0.981(1)

Conclusions

- New model of optical pumping has been developed and applied
  - Density matrix treats the atoms quantum mechanically
  - Coherent trapped populations are modeled in this picture
  - The transverse magnetic field is incorporated naturally
- Improved model allows for more accurate measure of polarization
- Photo-ions will have fewer systematics; allow for more reliable fits
- Future work
  - Establish better systematic uncertainties and improve fitting
  - Explore additional systematics including initial sub-level distribution
  - Use the improved model to recommend optimal optics settings

Status, Outlook

- Analysis of December 2012 run is continuing; results this year
- Will reconfigure apparatus to measure neutrino asymmetry B_ν
  - Take data in 2014?
  - Ph.D in 2015?
- Completed all required and elective coursework
- Completed teaching requirement

Acknowledgments

- TAMU:
  - Dan Melconian, Spencer Behling, Praveen Shidling, Mike Mehlman, Yakup Boran
  - All the committee members
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  - Daniel Ashery (Tel Aviv)

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Polarized Decay Rate

The polarized decay rate is given as:

$$\frac{d^5W}{dEd\Omega_e d\Omega_\nu} \sim 1 + P\left(A_\beta \frac{p_e}{E_e} cos\left(\theta_e\right) + B_\nu \frac{p_\nu}{E_\nu}\cos\left(\theta_\nu\right)\right)$$

A_β and B_ν are sensitive to right-handed currents through their dependencies on:

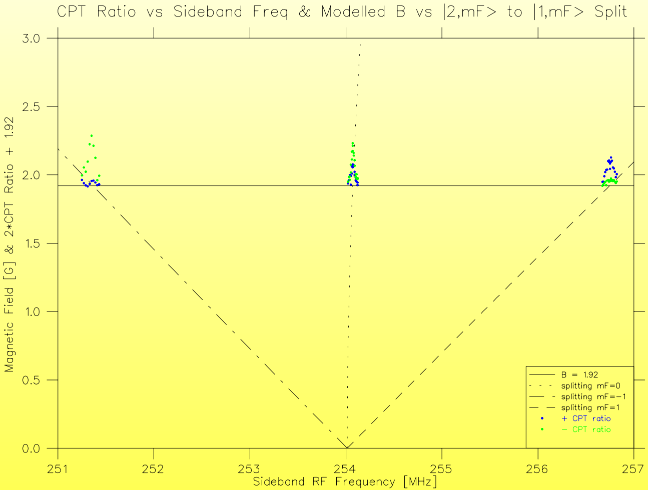
$$x = \frac{a_{RR}+a_{RL}}{a_{LL}+aLR} \stackrel{SM}{\rightarrow} 0, \;\; y = \frac{a_{RR}-a_{RL}}{a_{LL}-a_{LR}} \stackrel{SM}{\rightarrow} 0$$

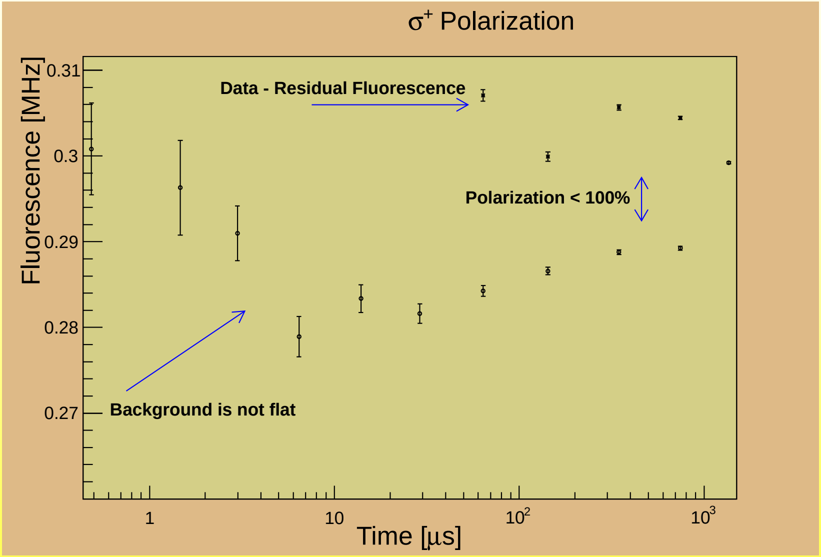
$$A_\beta = \frac{-2\lambda}{\left(1+x^2\right)+\lambda^2\left(1+y^2\right)}\left(\sqrt{\frac{3}{5}}\left(1-xy\right) - \frac{\lambda}{5}\left(1-y^2\right)\right)$$

$$B_\nu = \frac{-2\lambda}{\left(1+x^2\right)+\lambda^2\left(1+y^2\right)}\left(\sqrt{\frac{3}{5}}\left(1-xy\right) + \frac{\lambda}{5}\left(1-y^2\right)\right)$$

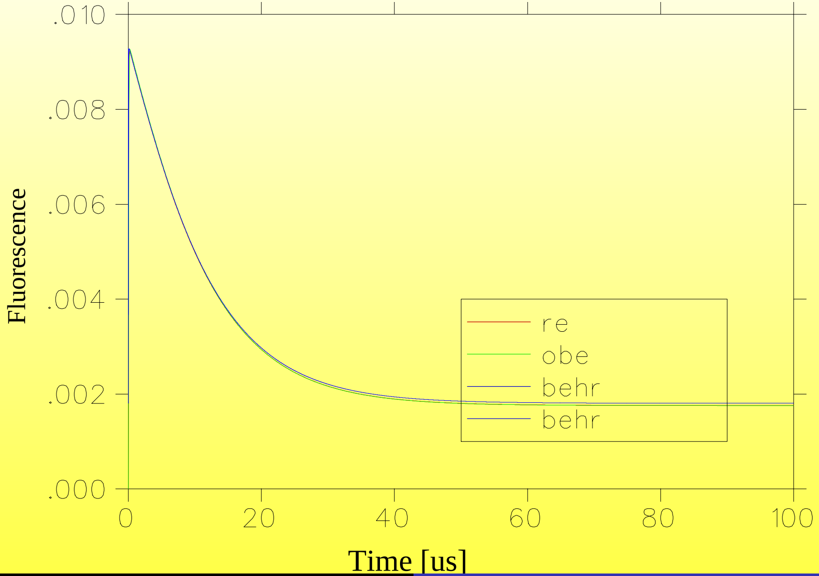
$$\lambda = \sqrt{\left(2\frac{\mathcal{F}t}{ft}-1\right)\frac{1+x^2}{1+y^2}}$$

All-optics magnetometry

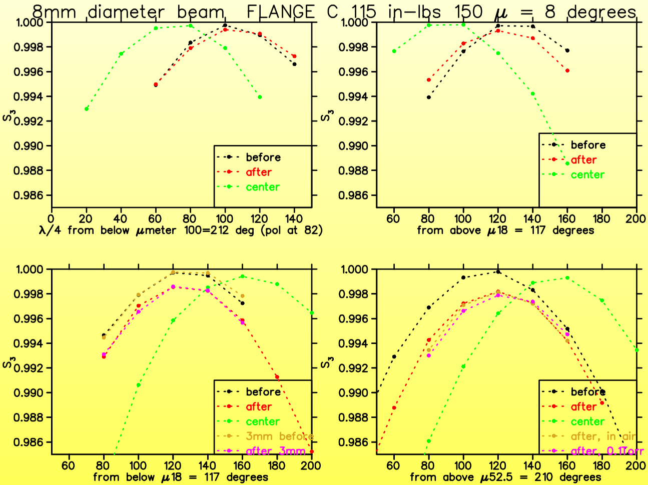



σ+ Polarization
Data - Residual Fluorescence
Polarization < 100%
Background is not flat
Fluorescence [MHz]
0.31
0.3
0.29
0.28
0.27
1
10
10^2
10^3
Time [µs]

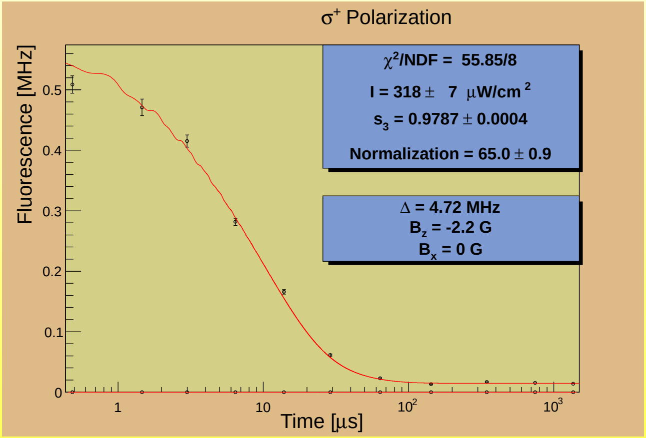
Comparison to existing models



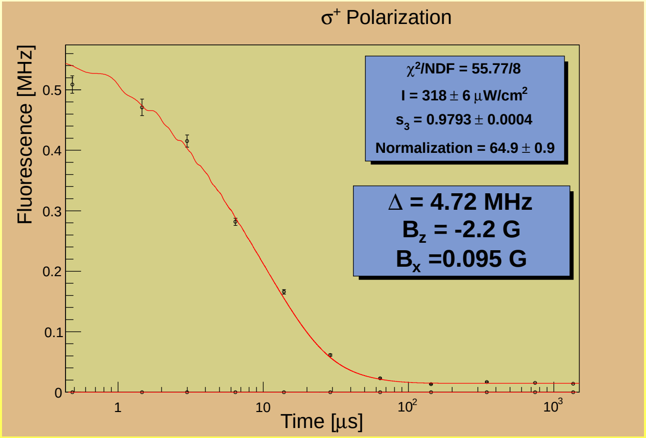
Measurements of s_3



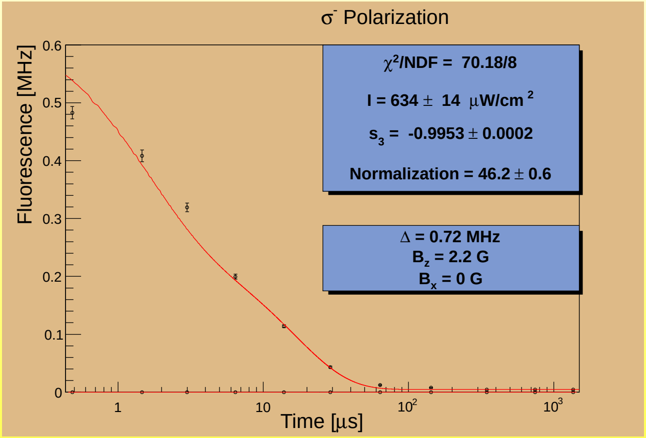
σ^+, $B_x = 0.0\ G$


σ+ Polarization
χ2/NDF = 55.85/8
I = 318 ± 7 μW/cm 2
s3 = 0.9787 ± 0.0004
Normalization = 65.0 ± 0.9
Δ = 4.72 MHz
Bz = -2.2 G
Bx = 0 G
Fluorescence [MHz]
0.5
0.4
0.3
0.2
0.1
0
1
10
102
103
Time [μs]

σ^+, $B_x = 0.095\ G$



$\sigma^{-}, B_x = 0.0\ G$


σ⁻ Polarization
Fluorescence [MHz]
Time [µs]
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
10²
10³
χ²/NDF = 70.18/8
I = 634 ± 14 µW/cm²
s₃ = -0.9953 ± 0.0002
Normalization = 46.2 ± 0.6
Δ = 0.72 MHz
B_z = 2.2 G
B_x = 0 G

σ^-, $B_x = 0.095\ G$