Nuclear spin polarization of $^{37,41}K$ by optical pumping

Benjamin Fenker

Texas A&M University Cyclotron Institute

October 11, 2013
Angular correlations in nuclear $\beta$-decay 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: Improving polarization diagnostics
Motivation: Fundamental Symmetries

- Standard model (SM) weak interaction is strictly Vector – Axial-Vector ($V - A$)
  - Parity is conserved in strong and EM interactions but violated in weak ones?
  - $SU(2)_L \otimes U(1)_Y \rightarrow SU(2)_R \otimes SU(2)_L \otimes U(1)_Y$
- Angular correlations in $\beta$-decay are sensitive to new physics

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

Polarized

$A_\beta^{SM} = -0.5702(6)$
$B_\nu^{SM} = -0.7692(15)$

Benjamin Fenker  
Nuclear spin polarization of $^{37,41}K$ by optical pumping
Overview

- Magneto-Optical Trap (MOT)
  - Provides a cold, localized source of atoms
  - Shallow trap so products emerge unperturbed

Polarization Axis
Nuclear Detectors

Benjamin Fenker
Nuclear spin polarization of $^{37,41}K$ by optical pumping
Overview

- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
  - $\sigma^+ \sigma^-$ lasers drive biased random walk.
  - Measure $P$ for the same atoms that are decaying.

Benjamin Fenker

Nuclear spin polarization of $^{37,41}$K by optical pumping
Overview

- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
- Nuclear Detectors
  - $\beta$-telescopes measure position, energy along polarization axis

Benjamin Fenker

Nuclear spin polarization of $^{37,41}\text{K}$ by optical pumping
Optical Pumping

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

![Energy level diagram](image)
Optical Pumping

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

$355 \text{ nm light}$

$\begin{align*}
\{ F = 2 \} \quad \{ P_{3/2} \} \\
\{ F = 1 \} \quad \{ P_{1/2} \} \\
\{ F = 2 \} \quad \{ S_{1/2} \} \\
\{ F = 1 \}
\end{align*}$
Rate Equation Results: Basic Features

Excited state population [%]

Nuclear polarization

Not Polarized

Polarized

Time [µs]

Benjamin Fenker

Nuclear spin polarization of $^{37,41}K$ by optical pumping
Need a quantum mechanical model, at least for the atom:

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

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

\[
H = H_0 + H_{so} + H_{hf} + H_B - \vec{e} \cdot \vec{E}(t)
\]

- **Atomic Hamiltonian**
  - **Coulomb**
  - **Spin-Orbit**
  - **Hyperfine**
  - **Zeeman Shifts**
  - **Laser Term**

- **Must solve a set of**

\[
\left[ 4 (2I + 1) \right] \left[ 4 (2I + 1) - 1 \right] ^{37}_{2} K \rightarrow 120
\]

- **complex differential equations.**
- **With 18 potentially variable input parameters (power, freq, etc.)**
- **Capable of modeling any alkali atom**
Depolarizing mechanisms: Why $P < 100\%$

Imperfect light polarization
- Characterized by the Stokes parameter $s_3$

Transverse magnetic field
- $\vec{F}$ precesses around $\vec{B}$

Coherent population trapping
- Dark, not polarized
- Requires quantum theory

Angular Momentum $F_z$

Energy

CPT Fraction

Nuclear spin polarization of $^{37,41}K$ by optical pumping
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
Stable $^{41}K$ has similar hyperfine structure to $^{37}K$

Can be produced and trapped off-line in large quantities!
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 we expect $^{37}K$ results to be similar

<table>
<thead>
<tr>
<th></th>
<th>$\sigma^-$</th>
<th>$\sigma^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fitting</strong></td>
<td>0.0003</td>
<td>0.0012</td>
</tr>
<tr>
<td>$s_3$ vs. $B_x$</td>
<td>0.00045</td>
<td>0.0005</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td>0.0005</td>
<td>0.0013</td>
</tr>
</tbody>
</table>

Combined uncertainty for $^{41}K$ and $^{37}K$

<table>
<thead>
<tr>
<th></th>
<th>$\sigma^-$</th>
<th>$\sigma^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Combined fit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P[^{41}K]$</td>
<td>0.9972(5)</td>
<td>0.981(1)</td>
</tr>
<tr>
<td>$\sigma^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma^+$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
- Photoions will have fewer systematics; allow for more reliable fits
- Future work
  - Explore additional systematics including initial sub-level distribution
  - Use the improved model to recommend optimal optics settings
  - Purchase a triggered UV laser to get better statistics with $^{37}K$ data
Acknowledgments

➤ TAMU:
  ➤ Dan Melconian, Spencer Behling, Praveen Shidling, Mike Mehlman

➤ Elsewhere:
  ➤ TRIUMF: John Behr, Alexander Gorelov, Melissa Anholm, Scott Smales, Ioana Craiciu
  ➤ Daniel Ashery (Tel Aviv)
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

\[ \begin{align*}
F_z &= 2 \\
F_z &= 1
\end{align*} \]

Hyperfine & Zeeman splitting

\[ E_1 \]

\[ E_2 \]
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

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

\[ H_{\vec{B}} = -\vec{\mu} \cdot \vec{B} \]

\[ H_{B_x} = g_F \mu_B B_x F_x = g_F \mu_B B_x \frac{F_+ + F_-}{2} \]

\[ B_x \text{ from apparatus: } B_x / B_z = 0.4\% \]

Stray field from Earth, cyclotron…

Mechanical misalignment: \( \theta \leq 2^\circ \)
Fitting details

- Aligned field fixed by trapped population scans: $B_z = 2.2 \, G$
- Relative detuning of lasers is fixed at $\Delta_{2\rightarrow2} - \Delta_{1\rightarrow1} = 3.6 \, MHz$
- 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 $\geq 99\%$ correlated
Optical Pumping Geometry

Electrostatic Hoops

355 nm light

\[ \vec{E} = 350 \text{ V/cm} \]

Optical Pumping Axis

Electron MCP

Ion MCP

Benjamin Fenker

Nuclear spin polarization of $^{37,41}\text{K}$ by optical pumping
Measurements of $s_3$