Precision measurement of the nuclear polarization of laser-cooled, optically pumped $^{37}$K

- Motivation: spin-polarized $\beta$ decay
- Direct Optical pumping
  - Our polarization method also provides a continuous probe
  - Complication: Coherent population trapping. Easy to kill.
- Measurement of $^{37}$K polarization

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In support of our $^{37}$K $A_\beta$ result JH.00007 Ben Fenker et al.
TRIUMF

\[ ^{37}\text{K spin-polarized experiments} \]

\[ ^{37}\text{K} \ A_\beta \ \text{result JH.00007 Ben Fenker et al.} \]

- 10,000 atoms trapped
- \( P \) measured in-situ on \(^{37}\text{K}\) by atomic method
- ion + shakeoff e\(^{-}\) for \( A_{\text{recoil}} \)

Isobaric mirror decay has helicity-driven null

\[ W(\theta) \approx 1 + a \cos(\theta_{\beta\nu}) \]

\[ a = (A_\beta - B_\nu)P - a_{\beta\nu} + 2c/3 = 1 \text{ or } 0 \text{ indep. of } M_{GT}/M_F \]
AC MOT to turn off trap

MOT's 7 G/cm Bquad off to 1% of its value in 100 µs:

B=1% of MOT at 100 us

How to spin-polarize a nucleus with a laser: Part I

Polarize atom by Direct Optical Pumping

Biased random walk

Simple example:

\[ J' = 1/2 \]

\[ J = 1/2 \]

\[ m_J = -1/2 \quad m_J = +1/2 \]

\[ P(m=1/2) = 1 - \left(\frac{2}{3}\right)^N \] after \( N \) steps

Need 12 photons absorbed to get to 99% of maximum.
Direct Optical Pumping, $I=3/2$

- Biased random walk
- $\sigma^\pm$ light
- $4S_{1/2} \rightarrow 4P_{1/2}$ transition

- Optimize with $^{41}\text{K}$, almost same hyperfine splitting as $^{37}\text{K}$

\[ \vec{F} = \vec{J}_{\text{atom}} + \vec{I}_{\text{nucleus}} \]
\[ H_{\text{hyperfine}} = -\mu_N \cdot \vec{B}_e = A \vec{I} \cdot \vec{J} \]

Spin flips: $\sigma^+ \rightarrow \sigma^-$

Small frequency shift (-2 MHz) to compensate Zeeman shift
Fluorescence Diagnostic $^{41}\text{K}$

- Single-photon counting
- Burst of fluorescence as atoms are optically pumped
- Modelled with rate equations including stray $B_\perp$ field and imperfect $S_3$
- Used to optimize parameters for use in $^{37}\text{K}$
Coherent Population Trapping is bad

But easy to remove by counter-propagating beams and by RF detuning

\[ F=2 \quad \rightarrow \quad F=1 \]
\[ 4P_{1/2} \quad \Gamma = 6 \text{ MHz} \]
\[ \Delta m = \pm 1 \]

\[ m = -2 \quad -1 \quad 0 \quad 1 \quad 2 \]

\[ \Rightarrow B_z = 2.339(10) \text{ G} \]
Quantifying Polarization from excited state population

Tail \sim \text{few \% of peak} \Rightarrow \text{We need tail/peak to \sim 10\% accuracy to extract} \ P \text{ to \sim 0.1\%}

We can’t quite extract \( P \) by inspection: \( \Delta F = 0 \) for Larmor precession

Same centroid \( P \) from 2 approaches:

Rate eqs for classical populations

\[
\frac{dN_i}{dt} = -R_{ji}N_i + R_{ij}N_j + \lambda N_j
\]

Optical Bloch Eqs include \( B_\perp \) rigorously

\[
\frac{d\rho}{dt} = \frac{1}{i\hbar} [H, \rho] + \lambda
\]

We measure \( S_3 \) and float \( B_\perp \)

\( (S_3 = -0.9958(8), -0.9984(13), \text{+}0.9893(14), \text{+}0.9994(5)) \)
Optical pumping and probing $^{37}$K

- Photoionize
  - $\sim 1\%$
  - Does not change polarization

![Diagrams showing optical pumping and probing processes involving $^{37}$K.](image)
Polarization fit to all $^{37}$K data

Transverse field ($B_x$) common to all: 124(8) mG

$\sigma^-$ Polarization State

$S/N_A = 4.7(6)$

$\sigma^+$ Polarization State

$S/N_B = 4(1)$

$S/N_C = 6(3)$

$S/N_D = 4.6(7)$

$S/N_E = 6(3)$

Counts / 20 µs

Counts / 10 µs

Counts / 10 µs

Counts / 10 µs

Counts / 4.0 µs

Time [µs]

Time [µs]
# Uncertainty Budget for $^{37}$K Polarization

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta P \times 10^{-4}$</th>
<th>$\Delta T \times 10^{-4}$</th>
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<td>Initial $T$</td>
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<td>Cloud temp</td>
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<tr>
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<td>Initial $P$</td>
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<td>Require $\mathcal{I}<em>+ = \mathcal{I}</em>-$</td>
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<tr>
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<td>17</td>
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<tr>
<td><strong>STATISTICS</strong></td>
<td>7</td>
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</tr>
</tbody>
</table>

- $P(\sigma^+) = +0.9913(8)$
- $T(\sigma^+) = -0.9770(22)$
- $P(\sigma^-) = -0.9912(9)$
- $T(\sigma^-) = -0.9761(27)$

$\rightarrow$ B. Fenker

JH.00007 $^{37}$K $A_\beta$
Precision measurement of the nuclear polarization of laser-cooled, optically pumped $^{37}$K

- Direct Optical pumping provides a continuous probe
- Measurement of $^{37}$K vector polarization and tensor ‘alignment’

$$P(\sigma^+) = +0.9913(8) \quad T(\sigma^+) = -0.9770(22)$$
$$P(\sigma^-) = -0.9912(9) \quad T(\sigma^-) = -0.9761(27)$$

$1-P = 0.87\%$, known to $\approx 10\%$ of its value


In support of our $^{37}$K $A_\beta$ result JH.00007 Ben Fenker et al.
Improvements in progress

- trim stray B field gradients better
- improve $S_3$, flipping, ($S_3=-0.9958(8), -0.9984(13), +0.9893(14), +0.9994(5)$) and gradients.
- add flipping of $B_z$
- higher-power 355 nm photoionizing laser by 3x to improve statistics
- gentler RAC-MOT with lower-frequency half-sinusoid to dissipate 1/10 the power while maintaining confinement (L. Lawrence, McMaster, Poster EA.00150)

Lower $E_B$ threshold (0.5 MeV) by changing mirrors from 0.25 mm SiC to 0.012 mm mylar ‘pellicles’
Polarization by data set

Nuclear Polarization

A  B  C  D  E

Field [V cm\(^{-1}\)]

\(t_{OP}\) [\(\mu s\)]

\(\sigma^-\)  \(\sigma^+\)
Polarization time dependence

$^{41}$K data also suggest a 1 millisecond $B_{\text{quad}}$ component.

Materials: 316L, 316LN, Ti, glassy carbon electrodes.
What elements can be laser cooled?

- H
- Li
- Na
- K
- Rb
- Cs
- Fr
- He
- Ne
- Ar
- Kr
- Xe
- Mg
- Ca
- Sr
- Ba
- Dy
- Er
- Yb
- Al
- Cr
- Ag
- Hg

- Trapped in MOT
- Radioactives trapped
- Long–livedRad.
- Plans

Here Be slain Dragons

37 K polarization
Viewport birefringence

Characterizing viewport birefringence allows prediction of $S_3$ in center given $S_3$ in and out.
1/2-sinusoid dissipates less power and keeps confinement.

Liam Lawrence, McMaster U., poster CEU at DNP, Oct 14 downtown.
\(\beta\) decay geometry and optical pumping

- **AC MOT turns off Bquad fast**
  - \(< 1\% \) after 0.1 ms
- **Trap and optical pumping share Z axis**: Larger \(\beta^+ \ d\Omega\)
- **\(\beta^+\) passes through**
  - 0.25mm SiC mirror substrates
- **atomic \(e^-\) coincidences**: measure \(A_{\text{recoil}}\), remove backgrounds
Optics Techniques

- Combine 769.9nm D1 and 766.49 D2 with angle-tuned 780 nm laser-line filter
- Flip spin state with liquid crystal variable retarder
- Relieve stress-induced birefringence with PCTFE (Neoflon) viewport seals

\[ S_3 = -0.9958(8), -0.9984(13), +0.9893(14), +0.9994(5) \]