Measurement of the nuclear polarization in optically-pumped $^{37}\text{K}$: Progress towards a measurement of the $\beta$-asymmetry parameter

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TRIUMF Neutral Atom Trap
Symmetries in Subatomic Physics
Victoria, BC

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The TRINAT Collaboration

- TRIUMF - John Behr, Alexandre Gorelov, Konstantin Olchanski, Ioana Craiciu, Claire Warner, Claire Preston
- Texas A & M - Spencer Behling, Michael Mehlman, Dan Melconian, Praveen Shidling, Eames Bennett
- U of Manitoba - Melissa Anholm, Gerald Gwinner
- Tel Aviv - Daniel Ashery, Iuliana Cohen

TRIUMF & ISAC Target & Beam Delivery Group

Funding Agencies

- USA: DOE DE-FG02-93ER40773 & Early Career ER41747
- Canada: NSERC, NRC through TRIUMF, WestGrid
- Israel: Israel Science Foundation
Outline

- Motivation - Testing the SM with nuclear physics
- TRINAT - TRIUMF’s Neutral Atom Trap
- Polarization through optical pumping
- Systematics in the polarization measurement
- Outlook and future plans
Motivation: Fundamental Symmetries

- Search for possible right-handed currents
  - $SU(2)_L \otimes U(1)_Y \rightarrow SU(2)_R \otimes SU(2)_L \otimes U(1)_Y$
- Contribute to independent check on the value of $V_{ud}$
- Energy dependence tests recoil-order corrections, weak magnetism, second-class currents

Angular correlations in $\beta$-decay are sensitive to new physics

- $10^{-3}$ precision constrains SM extensions, while $10^{-4}$ has discovery potential

$$\frac{d^5 W}{dEd\Omega_e d\Omega_\nu} \sim 1 + a_{\beta\nu} \frac{p_e p_\nu \cos(\theta_{e\nu})}{E_e E_\nu} + b \frac{m_e}{E_e} +$$

$$P \left( A_{\beta} \frac{p_e}{E_e} \cos(\theta_e) + B_{\nu} \frac{p_\nu}{E_\nu} \cos(\theta_\nu) \right) + \ldots$$
Magneto-Optical Trap (MOT)
- Provides a cold (∼ 1 mK), localized (∼ Ø1 mm) source of atoms
- Shallow trap so products emerge unperturbed

Overview
Overview

- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
  - $\sigma^\pm$ lasers drive biased random walk towards $P_{\text{nucl}} = \pm 1$
Overview

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

- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
- Nuclear Detectors
  - β-telescopes measure position, energy along polarization axis
- Scintillators record full energy; backgrounds from untrapped atoms, annihilation
- Shake-off electron MCP tags events that decay from the trap
- Silicon $\Delta E$ detectors suppress background from $\gamma$s
- Collected statistics for 0.2% measurement of $A_{\text{obs}}$

![Energy spectrum graph](attachment:image.png)
Optical Pumping

- Stretched state has $F = 2$, $M_F = 2$ or equivalently $I_z = \frac{3}{2}$, $J_z = \frac{1}{2}$
- Zeeman sublevels feel $B_z = 2\, \text{G}$ along quantization axis
- Stretched state corresponds to atomic and nuclear polarization
- Photoionization is a monitor of excited state population
- Use this to monitor trap size, position, temperature, polarization

\[\vec{F} = \vec{I} + \vec{J}\]
Optical Pumping

- Stretched state has $F = 2$, $M_F = 2$ or equivalently $l_z = \frac{3}{2}$, $j_z = \frac{1}{2}$
- Zeeman sublevels feel $B_z = 2\, \text{G}$ along quantization axis
- Stretched state corresponds to atomic \textbf{and} nuclear polarization
- Photoionization is a monitor of excited state population
- Use this to monitor trap size, position, temperature, polarization

![Diagram showing energy levels and transitions](image)

Note: $\vec{F} = \vec{l} + \vec{j}$
Optical Pumping

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- Zeeman sublevels feel $B_z = 2$ G along quantization axis
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Note: \( \vec{F} = \vec{I} + \vec{J} \)
Photoions monitor trap parameters

- Polarized measurements must be done with MOT off
- With MOT off, cloud expands; alternate counting/trapping
With time-of-flight \textit{and} position cuts, this signal is \textit{very} clean.
This strong signal allows clean measurement of polarization

- Initial peak proportional to number of atoms, laser power, provides normalization
- Tail region provides information about the degree of polarization

- Directly measure non-stretched population, but
- Polarization depends on how this small population is distributed amongst sublevels
- Small tail measures deviation from unity
Polarization Signal

This strong signal allows clean measurement of polarization.

- Initial peak proportional to number of atoms, laser power, provides normalization
- Tail region provides information about the degree of polarization

\[ \mathcal{H} = H_0 + H_{SO} + H_{hf} + H_B - e \mathbf{d} \cdot \mathbf{E}(t) \]

Atomic Hamiltonian

- Coulomb
- Spin-Orbit
- Hyperfine
- Magnetic Field
- Laser Term

\[ H_{SO} = \mathbf{L} \cdot \mathbf{S} \]
\[ H_{hf} = \mathbf{I} \cdot (\mathbf{L} + \mathbf{S}) \]
\[ \mathbf{E}(t) = E_0 \cos(kz - \omega_L t) \hat{\varepsilon}_q \]

\[ \langle P \rangle = Tr(\hat{\rho} \hat{P}) = Tr(\hat{\rho} \hat{I}_z) \]

Density Matrix:
- \( \rho_{ii} \) - population of state \( i \)
- \( \rho_{ij} \) - correlation between \( i, j \)

\[ \langle T \rangle \sim Tr(\hat{\rho} \hat{I}_z^2) \]

Time evolution:
\[ \frac{d\hat{\rho}}{dt} = \frac{1}{i\hbar} [\mathcal{H}(t), \hat{\rho}] + \mathcal{R}(t) \]

Tremblay, P. and Jacques C. PRA 41(9), 4989 (1990)
Renzoni, F. et al. PRA 63(6), 065401 (2001)
Systematics in the polarization measurement

- Photoionization signal is an **indirect** measure of the polarization
- Light ellipticity and a transverse magnetic field affect the photoionization curve similarly but result in different polarization

![Graph showing nuclear polarization and steady state population](image)

- Off-line studies: $B_x \leq 66 \text{ mG}$
- Stokes parameter:
  
  $$\langle s_3 \rangle = \frac{I_+ - I_-}{I_+ + I_-}$$

  
  $\geq +0.9893$

  
  $\leq -0.9983$

- CPT “dark” states are minimized
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
  
  \[
  \frac{s_3}{s_0} = \frac{l_+ - l_-}{l_+ + l_-}
  \]

- If $|s_3|/s_0 < 1.0$, atoms can be pumped out of the stretched state

Equilibrium is reached with not all atoms in the fully stretched state.
Depolarizing mechanisms - Stokes Parameter $s_3$

\[ s_3 = -0.9980 \]

\[ s'_3 = -0.9959 \]

\[ s' = -0.9938 \]

\[ s_3 = -0.9950 \]

Warner et al. RSI 85, 113106 (2014).
Magnetic field perpendicular to polarization axis causes precession

Atoms in the stretched state precess to other ground states

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

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

\[
H_{Bx} = g_F \mu_B B_x F_x = g_F \mu_B B_x \frac{F_+ + F_-}{2}
\]
Depolarizing mechanisms - Transverse magnetic field

Trim coils minimize transverse magnetic field
Scan current and minimize optical pumping tail to find $I_{\text{ideal}}$

- Compare $I_{\text{ideal}}$ and $I_{\text{actual}}$, find $B_x = 33\, \text{mG}$.
- Conservatively assign 100% uncertainty $\rightarrow B_x \leq 66\, \text{mG}$
Preliminary Results

- Depolarizing mechanisms are almost 100% correlated
- Perform separate fits with either $s_3$ or $B_\perp$ fixed

\[ B_x = 66 \text{ mG} \]
\[ B_x = 4(36) \text{ mG} \]

\[
I(\sigma^-) = 2.2(3) \text{ Wm}^{-2} \quad I(\sigma^+) = 2.1(2) \text{ Wm}^{-2} \quad I(\sigma^-) = 2.0(2) \text{ Wm}^{-2} \quad I(\sigma^+) = 2.0(2) \text{ Wm}^{-2}
\]
\[
s_3(\sigma^-) = -0.9967(9) \quad s_3(\sigma^+) = +0.9915(16) \quad s_3(\sigma^-) = -0.9938 \quad s_3(\sigma^+) = +0.9893
\]
\[
P = -0.994(1)_{\text{stat}} \quad P = +0.990(2)_{\text{stat}} \quad P = -0.9916(4)_{\text{stat}} \quad P = +0.9890(3)_{\text{stat}}
\]
**Preliminary Results - Global Fit**

Vary delay-time after AC-MOT

Fit with common $s_3$ and $B_x$

\[ \sigma^- \quad \sigma^+ \]

- $E = 395 \text{ V/cm}$
  - 8.4 hours
  - $-2\log L/d.o.f. = 5617/8028$

- $E = 535 \text{ V/cm}$
  - 15.2 hours

- $E = 395 \text{ V/cm}$
  - 2.8 hours

- $E = 415 \text{ V/cm}$
  - 7.6 hours

- $E = 415 \text{ V/cm}$
  - 1.6 hours
### Preliminary Results

<table>
<thead>
<tr>
<th>Uncertainties / $10^{-4}$</th>
<th>$\sigma^+$</th>
<th>$\sigma^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polarization</td>
<td>Alignment</td>
</tr>
<tr>
<td>Depolarizing Mechanism</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Global Fit vs. Average</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Fit $\Delta$ vs. Fit $I$</td>
<td>3</td>
<td>6</td>
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<tr>
<td>Uncertainty in $B_z$</td>
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<td>Initial Alignment ($T_0 = -1$)</td>
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<td><strong>42</strong></td>
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<td>Hyperfine Pumping</td>
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<td>Sum Systematics</td>
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<tr>
<td>Central Value</td>
<td>0.9898</td>
<td>-0.9761</td>
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\[
\bar{P} = \frac{\langle M_i \rangle}{I} = 0.991(2)
\]

\[
\bar{T} = \frac{I(I+1)-3\langle M_i^2 \rangle}{I(2I-1)} = -0.978(5)
\]
Conclusions

- Nuclear polarization gives access to more $\beta$-decay observables
- Optical pumping achieves high polarization in an open geometry
  \[
  \bar{P} = 0.991 \pm 0.002
  \]
  - Will not dominate the uncertainty for present data set
  - We expect $\frac{dA_\beta}{A_\beta} \leq 0.5\%$ ($A_{\beta}^{SM} = -0.5706(7)$)
- Future plans include modeling our MOT to reduce uncertainty from initial sublevel distribution
- Polarization measurement at $10^{-4}$ precision requires more systematic studies

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<thead>
<tr>
<th>Source</th>
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<tr>
<td>2012</td>
<td>2014</td>
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<tr>
<td>Asymmetry (Stat.)</td>
<td>62</td>
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<td>Polarization (Systematics)</td>
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<td>Detector Response</td>
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<td>Asymmetric Number of Trapped Atoms</td>
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<td>Timing Errors</td>
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THANK YOU

Backup slides . . .
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Comparison with Geant4

\[ \chi^2 / \nu = 1.6 \]
Preliminary Results

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Future work: Initial sublevel distribution?

- Has little effect on equilibrium state but can affect the shape of the initial peak
- Polarization is limited by “unpolarized” β-asymmetry
- Alignment (T) unconstrained (for now)
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Future work: Initial sublevel distribution?

- Has little effect on equilibrium state but can affect the shape of the initial peak
- Polarization is limited by “unpolarized” $\beta$-asymmetry
- Alignment ($T$) unconstrained (for now)
- Model MOT dynamics to limit initial alignment

- Work in progress
Optics Layout

30 mW, 770 nm Laser

AOM for ON/OFF

Polarization Maintaining Fiber

Polarizing beam-splitter

High quality polarizer

LCVR - 1/2-wave plate or zero

Polarizing beam-splitter

Defects poorly polarized light

High quality polarizer

LCVR - 1/2-wave plate or zero

SiC Mirror

High quality 1/4-wave plate

UHV Viewport w/ PCTFE Gasket

Control Computer

Controls Optical Pumping ON/OFF

Controls Polarization State

TRAP
Why $^{37}$K?

- Atomic structure allows for laser-trapping AND optical pumping
- Isobaric analogue decay simplifies nuclear structure corrections
- Strong branch to ground state is a very clean decay
- $I^\pi = \frac{3}{2}^+ \rightarrow \frac{3}{2}^+$ is a mixed Fermi-Gamow Teller decay

$\Delta t_{1/2} = 0.08\%$
(Shidling et al. 2014)
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\[
A_\beta(0) = -0.5706(7) \\
\rightarrow \Delta A_\beta = 0.12\% \\
\]
Photoionization Events

- **BC408 Plastic Scintillator**
- **Silicon Strip Detector**

- Monitor of trap position, size, temperature
- Ultra-clean measure of nuclear polarization $P$
Measure $V_{ud}$ with mirror nuclei
TRINAT’s x2-MOT System

- Collection trap is coupled to TRIUMF-ISAC beam line
- Transfer atoms to second trap for precision measurement
Atoms can be polarized in a MOT if beams are unbalanced. We avoid this.

Use $\beta$-asymmetry of trapped (unpolarized) atoms to constrain initial polarization.

Correlation measurements with polarized nuclei

- Brute-force alignment of nuclear spin
- $P$ calculated knowing the temperature
- Backscattering from source holder

- Physically separate polarized atoms
- Very high polarization, but inefficient

- State selection; very high $P$
- Open geometry minimizes backscattering
- Must measure polarization