Precision measurement of the positron asymmetry of laser-cooled, spin-polarized $^{37}$K

D. Melconian – April APS 2017
Introduction

Goal:
- To complement high-energy experiments by pushing the precision frontier
- Angular correlations in $\beta$ decay: values sensitive to new physics

Global gameplan:
- Measure the $\beta$-decay parameters
- Compare to SM predictions
- Look for deviations $\Leftrightarrow$ new physics
- Precision of $\lesssim 0.1\%$ needed to complement other searches (LHC)

Beautiful nucleus to test the standard model:

- Alkali atom ⇒ “easy” to trap with an atom trap and polarize with optical pumping
- Isobaric analogue decay ⇒ theoretically clean; recoil-order corrections under control
- Lifetime, Q-value and branches (i.e. the $F_t$ value) well known
- Strong branch to the g.s.

But there are challenges…

- Can’t calculate $M_{GT}$ or even $C_A$ ⇒ need to measure $\rho \equiv C_A M_{GT} / C_V M_F$
- Nuclear spin 3/2 ⇒ need to polarize the atoms, and especially know how polarized they are (also alignment)

### Isobaric analogue decay of $^{37}$K

- $Q_{EC} = 6.14746(23)$ MeV
- $^{37}$K $\beta^+$
- $1.2365(9)$ s $3/2^+$

<table>
<thead>
<tr>
<th>State</th>
<th>Energy (keV)</th>
<th>Branch (%)</th>
<th>Width (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/2^-</td>
<td>2490</td>
<td>29(4)</td>
<td>6.88</td>
</tr>
<tr>
<td>7/2^-</td>
<td>1611</td>
<td>25(20)</td>
<td>7.51</td>
</tr>
<tr>
<td>1/2^+</td>
<td>1410</td>
<td>42.2(75)</td>
<td>7.39</td>
</tr>
<tr>
<td>5/2^-</td>
<td>2796</td>
<td>2.07(11)%</td>
<td>3.79</td>
</tr>
<tr>
<td>5/2^+</td>
<td>3170</td>
<td>27(2)</td>
<td>6.35</td>
</tr>
<tr>
<td>3/2^+</td>
<td>3602</td>
<td>224(13)</td>
<td>4.96</td>
</tr>
<tr>
<td>3/2^-</td>
<td>3938</td>
<td>11.6(13)</td>
<td>5.78</td>
</tr>
</tbody>
</table>

- $^{37}$Ar
The $F_t$ is measured well enough  (for now)

$$dW = dW_0 \left[ 1 + a \frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu} + b \frac{\Gamma m_e}{E_\beta} + \frac{\langle \vec{I} \rangle}{I} \left( A_\beta \frac{\vec{p}_\beta}{E_\beta} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_\beta \times \vec{p}_\nu}{E_\beta E_\nu} \right) + \text{alignment term} \right]$$

<table>
<thead>
<tr>
<th>Correlation</th>
<th>SM expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta - \nu$ correlation</td>
<td>$a_{\beta \nu} = 0.6668(18)$</td>
</tr>
<tr>
<td>Fierz interference</td>
<td>$b = 0$</td>
</tr>
<tr>
<td>$\beta$ asymmetry</td>
<td>$A_\beta = -0.5719(7)$</td>
</tr>
<tr>
<td>$\nu$ asymmetry</td>
<td>$B_\nu = -0.7703(18)$</td>
</tr>
<tr>
<td>Time-violating correlation</td>
<td>$D = 0$</td>
</tr>
</tbody>
</table>

$\implies$ Data is in hand for improved branching ratio (currently limits $F_t$)
Outline of $\beta$ asym & polarization measurements

Not shown:

- Recoil MCP detector into page
- Shake-off $e^-$ MCP out of page
- The $\beta$ telescopes within the re-entrant flanges (top and bottom)
Outline of $\beta$ asym & polarization measurements

MOTs provide a source that is:

- Cold ($\sim 1 \text{ mK}$)
- Localized ($\sim 1 \text{ mm}^3$)
- In an open, backing-free geometry

Allows us to detect $\vec{p}_\beta$ and $\vec{p}_{rec}$

$\Rightarrow$ deduce $\vec{p}_\nu$

event-by-event!
Outline of $\beta$ asym & polarization measurements

Optical pumping:

- Polarized light transfers angular momentum to atom
- Nuclear and atomic spins are coupled

$$\vec{F} = \vec{I} + \vec{J}$$
Outline of $\beta$ asym & polarization measurements

\[ E - field \quad K^+ \]

355 nm

MCP

\[ \sigma^{\pm} \]

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

\[ P_{1/2} \]

\[ S_{1/2} \]

\[ F = \bar{F} + J \]

photoionization

D$_1$ OP

Helmholtz

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April APS 2017
Optical pumping is fast and **efficient**!

No time to go into details, but basically:

- Measure the rate of photions ($\leftrightarrow$ fluorescence) as a function of time
- Model sublevel populations using the optical Bloch equations
- Determine the average nuclear polarization: $\langle|P_{\text{nuc}l}|\rangle = 0.9913(9)$

![Graph showing photions per microsecond over time](image)
The $\beta$ asymmetry measurement

$E_\beta$ detectors:
Plastic scintillator

$\Delta E_\beta$ detectors:
Double-sided Si-strip

Use all information via the super-ratio:

$$A_{\text{obs}}(E_e) = \frac{1 - s(E_e)}{1 + s(E_e)}$$

with $s(E_e) = \sqrt{\frac{r_1^\uparrow(E_e) r_2^\uparrow(E_e)}{r_1^\downarrow(E_e) r_2^\downarrow(E_e)}}$
Two detectors and polarization states: reduce systematics

Blind analysis: remove small subset of one data set until all cuts defined

\( ^{37}K \ \beta \) Asymmetry
37K $\beta$ Asymmetry

Energy spectrum – *great agreement* with GEANT4 simulations:

\[ \chi^2 / 235 = 1.1 \]
Energy spectrum – **great agreement** with GEANT4 simulations:

- Backscattering too!
Asymmetry as a function of $\beta$ energy (*no background subtraction!)*:

Set D

$\chi^2/41 = 0.92$
(Dominant) Error budget and $A_\beta$ result

<table>
<thead>
<tr>
<th>Source</th>
<th>Correction</th>
<th>Uncertainty, $\Delta A_\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>−0.0007</td>
<td>$7 \times 10^{-4}$</td>
</tr>
<tr>
<td>Trap position</td>
<td>$4 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Trap movement</td>
<td>$5 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta E$ position cut</td>
<td>$4 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>GEANT4 physics list</td>
<td>$4 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Shake-off $e^-$ TOF region</td>
<td>$3 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>TOTAL SYSTEMATICS</td>
<td>$12 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>STATISTICS</td>
<td>$13 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>POLARIZATION</td>
<td>$5 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>TOTAL UNCERTAINTY</td>
<td>$18 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

$A_{\beta}^{\text{meas}} = -0.5707(18)$  
$A_{\beta}^{\text{SM}} = -0.5706(7)$  
$\rightarrow$ recoil-order corrections  
$- 0.5715(7)$

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April APS 2017
Comparison of $Ft$ values of:

- Mirror nuclei (including $^{37}$K)
- The neutron
- Pure Fermi decays

Also other physics to probe:

- Right-handed currents
- 2$^{nd}$ class currents
- Scalar and tensor currents

Recently awarded 16 additional shifts at high priority by TRIUMF’s EEC

0.1% is in sight… Stay tuned!
Collaboration and support

B. Fenker
S. Behling
M. Mehlman
D. Melconian
P.D. Shidling

J.A. Behr
I. Craiciu
A. Gorelov
S. Smale
C.L. Warner

M. Anholm
G. Gwinner
D. Ashery
I. Cohen
J. McNeil

Support provided by:
- The DOE and State of Texas
- NSERC, NRC through TRIUMF
- Israel Science Foundation