Polarized \( \beta \) decay observables from laser-cooled atoms: progress and outlook for fundamental symmetry tests

Dan Melconian
Cyclotron Institute/Dept. of Physics & Astronomy
Texas A&M University

CAP Congress — June 14, 2012
1. Motivation

- the SM – nuclear $\beta$ decays
1. **Motivation**
   - the SM – nuclear $\beta$ decays

2. **TRINAT**
   - The TRINAT experiment
   - Past results
   - Current program
Long Range Plan:

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To answer these basic questions will require the pursuit of a select set of **sensitive experiments** involving electroweak interactions of nuclei, ..., experiments whose physics reach **compliments** - and in some cases **exceeds** - direct searches for new particles at high-energy colliders. Collectively, this set of experiments - the **New Standard Model Initiative** - represents a concerted effort to exploit the **unique opportunities at the low-energy precision frontier** to **discover key ingredients** of the New Standard Model.''
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Long Range Plan:

``To answer these basic questions will require the pursuit of a select set of sensitive experiments involving electroweak interactions of nuclei, ... experiments whose physics reach compliments – and in some cases exceeds – direct searches for new particles at high-energy colliders. Collectively, this set of experiments – the New Standard Model Initiative – represents a concerted effort to exploit the unique opportunities at the low-energy precision frontier to discover key ingredients of the New Standard Model.’’

The TRINAT program:

Probe fundamental symmetries of the weak interaction via precision measurements of $\beta$ decay
The gameplan

- perform a $\beta$ decay experiment on short-lived isotopes

$$\frac{A}{Z}X \rightarrow Z_{\mp 1}^A Y + e^{\pm} + \nu_e$$

$p_X = 0$
The gameplan

- perform a $\beta$ decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters

\[
\frac{A}{Z}X \rightarrow Z_{\mp 1}^A Y + e^{\pm} + \nu_e
\]

$P_X = 0$

$P_Y$
The gameplan

- perform a $\beta$ decay experiment on short-lived isotopes

- make a precision measurement of the angular correlation parameters

- compare the SM predictions to observations

$\frac{A}{Z}X \rightarrow Z_{\mp 1}^{A}Y + e^{\pm} + \nu_e$

$p_X = 0$
The gameplan

- perform a $\beta$ decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters
- compare the SM predictions to observations
- look for deviations as an indication of new physics
The rate of $\beta$-decay

The often-quoted expression from Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

$$\frac{d^5 W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2 \xi$$
The rate of $\beta$-decay

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$\beta-\nu$ correlation

Fierz term
The rate of $\beta$-decay

The often-quoted expression from Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

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Polarization $\rightarrow$ $\frac{\langle I \rangle}{I} \cdot \left[ A_\beta \frac{p_e}{E_e} + B_\nu \frac{p_\nu}{E_\nu} + D \frac{p_e \times p_\nu}{E_e E_\nu} \right]$

$\beta-\nu$ correlation

Fierz term

Basic decay rate

$\xi$ correlation
The rate of $\beta$-decay

The often-quoted expression from Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_o - E_e)^2 \xi \left( 1 + \frac{\beta-\nu \text{ correlation}}{E_e E_{\nu_e}} + \frac{\text{Fierz term}}{\Gamma m_e} \right)$$

polarization $\rightarrow$ $\frac{\langle I \rangle}{I} \cdot \left[ \begin{array}{c} A_{\beta \text{ asym}} \frac{p_e}{E_e} \\ B_{\nu \text{ asym}} \frac{p_{\nu}}{E_{\nu}} \\ D \frac{p_e \times p_{\nu}}{E_e E_{\nu}} \end{array} \right]$ [alignment $\rightarrow$ $\frac{p_e \cdot p_{\nu}}{3E_e E_{\nu}} - \frac{(p_e \cdot \hat{i})(p_{\nu} \cdot \hat{i})}{E_e E_{\nu}}$]

$$\left[ \frac{I(I+1) - 3\langle M_I^2 \rangle}{I(2I-1)} \right] + \ldots$$
The rate of $\beta$-decay

The often-quoted expression from Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi$$

The basic decay rate

$$= \left(1 + \frac{a_{\beta\nu}}{E_e E_{\nu_e}} \frac{p_e \cdot p_{\nu_e}}{E_e E_{\nu_e}} + \frac{b}{\Gamma m_e} \Gamma \right)$$

$p_e \cdot p_{\nu_e} / E_e E_{\nu_e}$

The correlation parameters depend on the currents mediating the weak interaction

$$\Rightarrow$$ sensitive to new physics

$$\left[ \beta - \nu \text{ correlation} \right]$$

$$\left[ \text{Fierz term} \right]$$

$$\left[ \beta - \nu \text{ asym} \right]$$

$$\left[ \nu - \text{ asym} \right]$$

$$\left[ \text{T-violating} \right]$$

$$\langle I \rangle \cdot \left[ A_{\beta} \frac{p_e}{E_e} + B_{\nu} \frac{p_{\nu}}{E_{\nu}} + D \frac{p_e \times p_{\nu}}{E_e E_{\nu}} \right] \left[ I(I+1) - 3\langle M_I^2 \rangle \right] / I(2I-1) + \ldots$$

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Simplest case: $0^+ \rightarrow 0^+$ decay of $^{38}\text{mK}$

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_\nu} \sim p_e E_e (A_0 - E_e)^2 \xi \left( 1 + a_{\beta\nu} \frac{p_e \cdot p_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e} \right)$$

Pure Fermi decay $\Rightarrow$ minimal nuclear structure effects
Simplest case: $0^+ \rightarrow 0^+$ decay of $^{38m}\text{K}$

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_\nu} \sim p_e E_e (A_0 - E_e)^2 \xi \left( 1 + a_{\beta\nu} \frac{p_e \cdot p_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e} \right)$$

Pure Fermi decay $\rightarrow$ minimal nuclear structure effects

$Q(^{38m}\text{K}) = 5.02234(12)$ MeV

- $E_x = 130.4(3)$ keV
- $T_{1/2} = 923.9(6)$ msec
- $\beta^+ \rightarrow 3^+$
- $\beta^+ \rightarrow 2^+$
- $\beta^+ \rightarrow 0^+$

$^{38m}\text{K} \rightarrow ^{38}\text{Ar}$

- $2^+ \rightarrow 0^+$: 0.151(12)$\%$, 5.88(3)$\%$
- $3^+ \rightarrow 0^+$: 99.849(12)$\%$, 4.97(2)$\%$

$^{38}\text{Ar}$

Simplest case: $0^+ \rightarrow 0^+$ decay of $^{38m}K$

$$\frac{d^5W}{dE_ed\Omega_e d\Omega_\nu} \sim p_e E_e (A_0 - E_e)^2 \xi \left( 1 + a_{\beta\nu} \frac{p_e \cdot p_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e} \right)$$

Pure Fermi decay $\implies$ minimal nuclear structure effects

$$Q(^{38m}_{19}K) = 5.02234(12) \text{ MeV}$$

$^{38m}_{19}K^{0^+} \rightarrow 38^+_1\text{Ar}^{0^+}$

A well-understood, clean decay

(if one can get rid of the ground state...!)
A closer look . . .

\[ \nu_e \]

\[ \frac{-ig_w}{\sqrt{2}} \gamma^\nu \left( C_V + C'_V \gamma_5 \right) \]

\[ Z^A X \]

\[ W^+ \]

\[ e \]

\[ Z^{-1}_A Y \]

vector propagator:

\[ \frac{-i(g_{\mu\nu} - k\mu k\nu / M^2_W)}{k^2 - M^2_W} \]

\[ k^2 \ll M^2_W \Rightarrow \frac{ig_{\mu\nu}}{M^2_W} \]

\[ a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2}{|C_V|^2 + |C'_V|^2} \equiv 1 \]

\[ b_F \equiv 0 \]
A closer look . . .


\[ \nu_e \]

\[ \frac{-i g_w}{2\sqrt{2}} \gamma^\nu (C_V + C'_V \gamma_5) \]

\[ e \]

\[ Z_{-1}^A Y \]

\[ W^+ \]

\[ -\frac{i g_w}{\sqrt{2}} \gamma^\mu T_+ \]

\[ Z_{-1}^A X \]

\[ \nu_e \]

\[ \frac{-i g_w}{2\sqrt{2}} (C_S + C'_S \gamma_5) \]

\[ e \]

\[ Z_{-1}^A Y \]

\[ W_{\text{scalar}} \]

\[ \frac{-i g_w}{\sqrt{2}} T^+ \]

vector propagator:

\[ \frac{-i (g_{\mu\nu} - k_{\mu} k_{\nu} / M_W^2)}{k^2 - M_W^2} \]

\[ \frac{k^2 \ll M_W^2}{i g_{\mu\nu} / M_W^2} \]

scalar propagator:

\[ \frac{-i}{k^2 - M_W^2} \]

\[ \frac{k^2 \ll M_W^2}{i M_W^2} \]

\[ a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} \]

\[ \frac{?}{1} \]

\[ b_F = \frac{-2 \Re(C'_S C_V + C'_S C'_V)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} \]

\[ \frac{?}{0} \]
Helicity and an $\alpha_{\beta\nu}$ measurement

$^{38m}\text{K}$ decay

in the back-to-back geometry:

“Fast”

“Slow”
Helicity and an $\alpha_{\beta\nu}$ measurement

$^{38m}\text{K}$ decay is $0^+ \rightarrow 0^+$

Helicity *enhances/suppresses* scalar (vector) currents in the back-to-back geometry:

“Fast”

$^{38}\text{Ar}$

$\nu_e$ $\rightarrow$ $e^+$, $\nu_e$

$I = 0$

“Slow”

$^{38}\text{Ar}$

$\nu_e$ $\rightarrow$ $e^+$

$I = 0$
Principle of a scalar search
Principle of a scalar search

Fit TOF projections as a function of $E_\beta$ to detailed MC simulations
How can we get such a beautiful spectrum?

Neutral Atom Traps!

Any type of trap requires a velocity-dependent force to cool an object . . . as well as a position-dependent force that defines $x = 0$.

Laser light $\rightarrow$ velocity-dependent force

Zeeman effect $\rightarrow$ position-dependent force

$magneto$-optical trap $=$ damped harmonic oscillator
Coupling a MOT to ISAC-I

E.L. Raab et al., PRL 59 (1987) 2631
Coupling a MOT to ISAC-I

yields with 40 $\mu$A on TiC:

$^{37}\text{K}$ $6 \times 10^7$/s
$^{38}\text{K}$ $133 \times 10^7$/s
$^{38m}\text{K}$ $7 \times 10^7$/s

E.L. Raab et al., PRL 59 (1987) 2631
TRINAT: A double-MOT system

- Ion beam
- Neutralizer
- Collection chamber

- MCP
- Electrostatic hoops
- DSSSD
- BC408
- β detector
- Detection chamber

15 cm
TRINAT: A double-MOT system

Traps provide a **backing-free, cold** (\( \sim 1 \) mK), **localized** (\( \sim 1 \) \( \text{mm}^3 \)) source of short-lived radioactive atoms

Detect \( p_\beta \) and \( p_{\text{recoil}} \) \( \Rightarrow \) deduce \( p_\nu \)!
The (old) detection chamber

- MCP
- electrostatic hoops
- push beam from 1st trap
- BC408 light guide
- DSSD
- Be foil
- trapping beams

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Analysis of $\alpha_{\beta\nu}$

Fit TOF projections as a function of $E_{\beta}$ to detailed MC simulations
Analysis of $\alpha_{\beta\nu}$

$\text{Ar}^{+1,+2,+3}$

TOF spectra

[Gorelov PRL 95 (2005)]

Fit parameter:

$\tilde{a}_{\beta\nu} \equiv \frac{a_{\beta\nu}}{1 + b \frac{m}{\langle E \rangle}}$

$< 1$ if there is a **scalar** current

$\tilde{a}_{\beta\nu} = 0.9981 \pm 0.0030 \pm 0.0037$

$\chi^2/789 = 0.997$ (52% CL)
Analysis of $\alpha_{\beta\nu}$

$\text{Ar}^{+1,+2,+3}$

TOF spectra

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$$\tilde{a}_{\beta\nu} = 0.9981 \pm 0.0030 \pm 0.0037$$

(stat) (syst)

$$\chi^2/789 = 0.997 \ (52\% \ CL)$$

Best general limits on scalar currents
TRINAT’s polarized program

\[ \frac{A}{Z} X \rightarrow Z_{\mp 1}^A Y + e^\pm + \nu_e \]

\[ p_X = 0 \quad p_Y \]

\[ p_\nu, p_\beta \]

\[ \theta_{e,\nu}, \theta_{e,\nu}, i \]

\[ I^{\pi} = 0^+ \rightarrow 0^+ \]

\[ a_{\beta\nu} = 1 \]

\[ ^{38}_{\text{m}} K: \quad I^{\pi} = 0^+ \rightarrow 0^+ \]

\[ a_{\beta\nu} = \frac{1 - \rho^2}{1 + \rho^2} \]

\[ ^{37} K: \quad I^{\pi} = \frac{3}{2}^+ \rightarrow \frac{3}{2}^+ \]
Almost as simple as $^{38m}\text{K}$:

$$^{37}\text{K}^{\beta^+}$$

- $3/2^+ \rightarrow 3/2^+$ with $0.022\%$ probability, $4.96$ MeV
- $5/2^+ \rightarrow 3/2^+$ with $2.07(11)\%$ probability, $3.79$ MeV

$^{37}\text{K}$ has an isobaric analogue decay to $^{37}\text{Ar}$ with $97.99(14)\%$ probability, $1.225(7)$ s.

$^{37}\text{Ar}$ has a strong branch to the ground state.
Almost as simple as $^{38\text{m}}\text{K}$:

$$
\begin{array}{c|c|c}
\text{State} & J^P & \% \\
\hline
^{37}\text{K} & 3/2^+ & 0.022\% \\
\hline
^{19}\text{Ar} & 3/2^+ & 97.99(14)\% \\
\hline
\end{array}
$$

Strong isobaric analogue decay

$$
\Rightarrow \text{need } \rho \equiv \frac{G_A M_{GT}^2}{G_V M_F}
$$

$$
\rho^2 = \frac{2\mathcal{F} t_{0^+ \rightarrow 0^+}}{\mathcal{F} t} - 1
$$
Almost as simple as $^{38m}\text{K}$:

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Level</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6020(7)</td>
<td>$3/2^+$</td>
<td>$0.022%$</td>
</tr>
<tr>
<td>2.7961(3)</td>
<td>$5/2^+$</td>
<td>$2.07(11)%$</td>
</tr>
</tbody>
</table>

$^{37}\text{K} ightarrow ^{37}\text{Ar}$

$1.225(7)\text{s} eta^+$

$Q_{EC}: \pm 0.003\%$
$BR: \pm 0.14\%$
$t_{1/2}: \pm 0.57\%$

$f_t = 4533(28)$ +

$\delta_{NS} - \delta_C: \pm 0.06\%$
$\delta': \pm 0.04\%$

$\rho^2 = \frac{2Ft^{0^+\rightarrow0^+}}{Ft} - 1$

$\rho = 0.5874(71)$

- isobaric analogue decay
- strong branch to g.s.
- polarization/alignment
  - mixed Fermi/Gamow-Teller
  - need $\rho \equiv G_A M_{GT} / G_V M_F$

$^{37}\text{K}$ isobaric analogue decay

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Almost as simple as $^{38m}{\text{K}}$:

$$\begin{align*}
^{37}\text{K} &\beta^+ \\
3.6020(7) &\quad 3/2^+ & 1.225(7) \text{s} &\quad 3/2^+ \\
2.7961(3) &\quad 5/2^+ & 0.022\% &\quad 4.96 \\
\end{align*}$$

$^{37}_{18}\text{Ar}$

The lifetime limits the $\mathcal{F}t$ value (and hence $\rho$):

$$\rho^2 = \frac{2\mathcal{F}t^{0+\rightarrow0^+}}{\mathcal{F}t} - 1$$

$$\begin{align*}
Q_{\text{EC}}: &\quad \pm 0.14\% \\
\text{BR}: &\quad \pm 0.57\% \\
\left\{ \begin{array}{c}
\delta^{'}_R: \quad \pm 0.04\% \\
\delta_{NS} - \delta_C: \quad \pm 0.06\%
\end{array} \right. \\
\text{ft} = 4533(28) &+ \text{ft} = 4562(28)
\end{align*}$$

$$\Rightarrow \rho = 0.5874(71)$$
Improved lifetime

$^{38}$Ar ($p$, $2n$)$^{37}$K at the Cyclotron Institute
Improved lifetime

Set #9: $t_{1/2} = 1238.8 \pm 1.8 \text{ ms}; \quad \chi^2/488 = 1.05$

Set #9: $t_{1/2} = 1237.9 \pm 2.0 \text{ ms}; \quad \chi^2/10288 = 1.03$
Improved lifetime

nearly a $10 \times$ improvement: $t_{1/2} = 1236.51 \pm 0.47 \pm 0.83$ ms

$\Rightarrow \mathcal{F}t = 4562(28)$ s $\longrightarrow$ 4605(8) s

and $\rho = 0.5874(71)$ $\longrightarrow$ 0.5766(21)

P. Shidling et al., in preparation
Angular distribution of $a \frac{3}{2}^+ \rightarrow \frac{3}{2}^+$ decay

$$dW \sim 1 + a_{\beta\nu} \frac{p_e \cdot p_\nu}{E_e E_\nu} + b \Gamma \frac{m}{E_e} + \frac{I}{I} \cdot \left[ A_{\beta} \frac{p_e}{E_e} + B_\nu \frac{p_\nu}{E_\nu} + D \frac{p_e \times p_\nu}{E_e E_\nu} \right]$$

$$+ c_{\text{align}} \left[ \frac{p_e \cdot p_\nu}{3E_e E_\nu} - \frac{(p_e \cdot \hat{i})(p_\nu \cdot \hat{i})}{E_e E_\nu} \right] \left[ \frac{I(I+1) - 3 \langle (I \cdot \hat{i})^2 \rangle}{I(2I-1)} \right]$$

<table>
<thead>
<tr>
<th>Correlation</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta - \nu$ correlation:</td>
<td>$a_{\beta\nu} = \frac{1-\rho^2/3}{1+\rho^2}$ = 0.6580(61)</td>
</tr>
<tr>
<td>Fierz interference parameter:</td>
<td>$b_{\text{Fierz}} = 0$ (sensitive to scalars and tensors)</td>
</tr>
<tr>
<td>$\beta$ asymmetry:</td>
<td>$A_{\beta} = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right) = -0.5739(21)$</td>
</tr>
<tr>
<td>$\nu$ asymmetry:</td>
<td>$B_\nu = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} + \frac{\rho}{5} \right) = -0.7791(58)$</td>
</tr>
<tr>
<td>Alignment parameter:</td>
<td>$c_{\text{align}} = \frac{4\rho^2/5}{1+\rho^2}$ = 0.2052(62)</td>
</tr>
<tr>
<td>Time-violating $D$ coefficient:</td>
<td>$D = 0$ (sensitive to imaginary couplings)</td>
</tr>
<tr>
<td>a $\beta-$recoil observable</td>
<td>$R_{\text{slow}} \sim \frac{1-a_{\beta\nu}}{1-a_{\beta\nu}} - \frac{2c_{\text{align}}}{3} - \frac{(A_{\beta} - B_\nu)}{3} + \frac{(A_{\beta} - B_\nu)}{3} = 0$</td>
</tr>
</tbody>
</table>

specific to our geometry
The **Standard Model**: $SU(2)_L \times U(1) \Rightarrow W_L^{\pm}, Z^0, \gamma$

Built upon **maximal** parity violation:

Vector $\hat{P}|\Psi\rangle = -|\Psi\rangle$

$$H_{SM} = G_F V_{ud} \left[ \bar{e}(\gamma_\mu - \gamma_\mu \gamma_5) \nu_e \right. \left. \bar{u}(\gamma^\mu - \gamma^\mu \gamma_5) d \right]$$

Axial vector $\hat{P}|\Psi\rangle = +|\Psi\rangle$
Eg: Right-handed currents

The **Standard Model**: $\text{SU}(2)_L \times \text{U}(1) \Rightarrow W_L^\pm, Z^\circ, \gamma$

Built upon **maximal** parity violation:

$$
\begin{align*}
\text{Vector: } \hat{P}|\Psi\rangle &= -|\Psi\rangle \\
H_{SM} &= G_F V_{ud} \overline{e} \left( \gamma_\mu - \gamma_\mu \gamma_5 \right) \nu_e \overline{u} \left( \gamma^\mu - \gamma^\mu \gamma_5 \right) d
\end{align*}
$$

Axial – vector: $$\hat{P}|\Psi\rangle = +|\Psi\rangle$$

low-energy limit of a **deeper** SU(2)$_R \times$ SU(2)$_L \times$ U(1) theory?
The **Standard Model**: \( SU(2)_L \times U(1) \Rightarrow W^\pm_L, Z^0, \gamma \)

Built upon **maximal** parity violation:

\[
\begin{align*}
H_{\text{SM}} &= G_F V_{ud} \left( \gamma_\mu - \gamma_\mu \gamma_5 \right) \nu_e \left( \gamma^\mu - \gamma^\mu \gamma_5 \right) d \\
\Rightarrow \text{low-energy limit of a deeper } SU(2)_R \times SU(2)_L \times U(1) \text{ theory?} \\
&\Rightarrow 3 \text{ more vector bosons: } W^\pm_R, Z'
\end{align*}
\]

**Simplest extensions**: *manifest left-right symmetric models*

→ only new parameters are the \( W_2 \) mass and a mixing angle, \( \zeta \):

\[
\begin{align*}
|W_L\rangle &= \cos \zeta |W_1\rangle - \sin \zeta |W_2\rangle \\
|W_R\rangle &= \sin \zeta |W_1\rangle + \cos \zeta |W_2\rangle
\end{align*}
\]
RHCs would affect correlation parameters

\[ A_\beta = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right) \]

\[ B_\nu = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} + \frac{\rho}{5} \right) \]

and \[ R_{\text{slow}} = 0 \]
In the presence of new physics, the angular distribution of $\beta$ decay will be affected.

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

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

and

$$R_{\text{slow}} = 0 \rightarrow y^2$$

where $x \approx (M_L/M_R)^2 - \zeta$ and $y \approx (M_L/M_R)^2 + \zeta$

are RHC parameters that are zero in the SM.
RHCs would affect correlation parameters

In the presence of new physics, the angular distribution of $\beta$ decay will be affected.

\[ A_\beta = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right) \rightarrow \frac{-2\rho}{1+\rho^2} \left[ (1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right] \]

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and \[ R_{\text{slow}} = 0 \rightarrow y^2 \]

where \( x \approx (M_L/M_R)^2 - \zeta \) and \( y \approx (M_L/M_R)^2 + \zeta \) are RHC parameters that are zero in the SM.

\[ \Rightarrow \text{Precision measurements test the SM} \]

Goal must be \( \lesssim 0.1\% \)

(see Profumo, Ramsey-Musolf and Tulin, PRD 75 (2007))
The $\beta$ asymmetry

$$A_\beta = -2\rho \left( \frac{\sqrt{3/5} - \rho/5}{1 + \rho^2} \right)$$

- recoil order corrections under control
- value sensitive to RHCs
- energy-dependence sensitive to SCCs
The new chamber

- Shake-off $e^-$ detection
- Better control of OP beams
- $B_{\text{quad}} \rightarrow B_{\text{OP}}$ quickly: AC-MOT (Harvery & Murray, PRL 101 (2008))
- Increased $\beta$/recoil solid angles
- Stronger $E$-field
- ...
The new chamber

- Shake-off
- Better control of $B_{\text{quad}}$ (Harvey & Murray, PRL 101 (2008))
- Increased $\beta$/recoil solid angles
- Stronger $E$-field

- 500 $\mu$m thick Be foil
- Electrostatic hoops (anti)Helmholtz coils
- BC408 recoil MCP
- 40x40mm 2x300 $\mu$m
- 100 $\mu$m thick Si-coated mirror
- BB1 Si-strip detector
Outline of polarized experiment

\[ F = I + J \]

\[ I = \frac{3}{2} \]

\[ J = \frac{1}{2} \]

\[ m = \sigma \pm S \]

355 nm
Outline of polarized experiment

\[ F = I + J \]

\[ I = \frac{3}{2} \]

\[ J = \frac{1}{2} \]

\[ \sigma \pm \frac{1}{2} \]

\[ 355 \text{ nm} \]

D\textsubscript{2} trapping light

anti-Helmholtz
Outline of polarized experiment

\[ F = I + J \]
\[ I = \frac{3}{2} \]
\[ J = \frac{1}{2} \]
\[ m_F = \pm \frac{3}{2} \]

D\textsubscript{1} pumping light

Helmholtz (2 G)

\[ P_{1/2} \]
\[ S_{1/2} \]
\[ 1 \]
\[ 2 \]

355 nm light pumping

Helmholtz (2 G)
Outline of polarized experiment

Dan Melconian

MCP

E-field

K⁺

F = I + J

I = \frac{3}{2}

J = \frac{1}{2}

m_F = -2 -1 0 1 2

P_{1/2}

S_{1/2}

D_1

light

photoionization

Helmholtz (2 G)

F = I + J

I = \frac{3}{2}

J = \frac{1}{2}

m_F = -2 -1 0 1 2

P_{1/2}

S_{1/2}

355 nm

σ^±
Atomic measurement of $P$

Deduce $P$ based on a model of the excited state populations:

$$\frac{\sigma^2}{\Delta} = \frac{1}{128} = 0.0078125$$

$$\Rightarrow P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$$
for MOT currents rapidly switched to zero, the induced eddy currents continue to produce $B$ fields until they too reduce to zero.

In practice the $B$ field due to the MOT takes $\sim 10$ ms to reduce to $<10^{-7}$ T, this time depending on the proximity of conductors to the coils, their shape, and resistivity. During this time, a large fraction of trapped atoms escape, resulting in a cold atom density that rapidly falls to zero. Losses can be reduced by leaving the cooling lasers on to create an optical molasses (if this does not interfere with the experiment); however, the loss problems remain. The comparatively long time taken for the $B$ field to decay also reduces data accumulation rates, since the repetition rate is then only $\sim 50$ Hz.

It is clearly advantageous to eliminate these constraints. Several methods have been attempted, including shaping the dc MOT driving current at switchoff to try to cancel fields due to eddy currents [10]. This technique is complicated and requires different currents when spectrometer

\[ \Rightarrow \langle P \rangle = -97.0 \pm 0.9\% \]

![Graph showing photon events vs. optical pumping time](image)

FIG. 1 (color online). The switching configuration for the ac MOT. The MOT is driven by an alternating supply, so that the net induced current in conductors surrounding the MOT coils is zero. The polarization of the six trapping laser beams is switched at the same rate as the MOT current, so as to maintain trapping. Experiments using charged particles are conducted during the time the MOT current is zero.

\[ \Rightarrow P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73} \]
Asymmetry = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) - N(\sigma^-)}

\sim P A_\beta \left\langle \frac{p_e}{E_e} \right\rangle

P = 0.967

finite vacuum

A = 81.3(1.0)\%

\begin{align*}
A_{\beta} & = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) - N(\sigma^-)} \\
& \sim P A_{\beta} \left\langle \frac{p_e}{E_e} \right\rangle
\end{align*}

P = 0.28(0.49)\%

(-0.87(0.61)\%)

A = -79.2(1.5)\%
Measuring $B_\nu$ (and $D$)

\[ dW \sim PB_\nu \hat{p}_\nu \cdot \hat{i} + PD \frac{\hat{i} \cdot (p_\beta \times \hat{p}_\nu)}{E_\beta} \]

\[ \hat{p}_\beta \approx \hat{z} \quad \Rightarrow \quad p_\nu \approx -p_{Ar} \]

OP beam
Measuring $B_\nu$ (and $D$)

\[ dW \sim PB_\nu \hat{p}_\nu \cdot \hat{i} + PD \frac{\hat{i} \cdot (p_\beta \times \hat{p}_\nu)}{E_\beta} \]

$\hat{p}_\beta \approx \hat{z} \Rightarrow p_\nu \approx -p_{Ar}$
Measuring $B_{\nu}$ (and $D$)

\[
dW \sim P B_{\nu} \hat{p}_{\nu} \cdot \hat{i} + P D \frac{\hat{i} \cdot (p_{\beta} \times \hat{p}_{\nu})}{E_{\beta}}
\]

\[
\hat{p}_{\beta} \approx \hat{z} \Rightarrow p_{\nu} \approx -p_{Ar}
\]

\[
\hat{x} \text{ asymmetry } \sim P B_{\nu} \quad \hat{y} \text{ asymmetry } \sim P D
\]
The neutrino asymmetry measurement

$$\beta\text{-telescope} - \text{MCP coincidences}$$

$$\begin{align*}
1\text{st}: & \quad \langle B_{\nu} \rangle = (0.995 \pm 0.040) B_{\nu}^{\text{SM}} \\
2\text{nd}: & \quad \langle B_{\nu} \rangle = (0.975 \pm 0.031) B_{\nu}^{\text{SM}} \\
\Rightarrow & \quad B_{\nu} = 0.981(26)(17) B_{\nu}^{\text{SM}}
\end{align*}$$

(Melconian, PLB 649 (2007) 370)
Expected limits if $A_\beta$, $B_\nu$ and $R_{\text{slow}}$ all measured to 0.1%

see Profumo, Ramsey-Musolf and Tulin, PRD 75 (2007) 075017
Beyond the minimal L-R symmetric model

(adapted from Thomas et al., Nucl Phys A 694; see also Severijns, Beck and Naviliat-Cuncic, Rev Mod Phys 78 (2006))

different experiments are complementary
Summary

- SM is fantastic, but **incomplete**
- many **exciting avenues** to find more complete model
- $t_{1/2}$ of $^{37}$K no longer limits $\mathcal{F}t$
- **needed:** precision measurement of correlation parameters
- (AC-)MOT + opt. pumping = *cool* physics

**Timeline:**

1. online test of AC-MOT, new detectors, new VME-DAQ, new coils, new... circa Oct (and throughout offline)
2. $A_\beta$ by the end of this year
3. analysis of $\lesssim 0.3\%$ this time next year
4. $B_\nu$ and $R_{\text{slow}}$ data Fall 2013
5. improve **scalar limits** with $^{38m}$K in 2014

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