The $\beta^+$ decay of $^{37}$K as a multi-faceted probe of fundamental physics

Dan Melconian

Cyclotron Institute/Texas A&M University
Overview

1. Fundamental symmetries
   - what is our current understanding?
   - what lies beyond?

2. $V_{ud}$ and CKM unitarity
   - $0^+ \rightarrow 0^+$ decays
   - neutron decay: a complementary test
   - $^{37}K$ is like a “heavy neutron”

3. Angular correlations using laser-cooled atoms
   - probe Lorentz structure of weak interaction
   - example: polarized decay of $^{37}K$
Scope of fundamental physics

from the very smallest scales ...
Scope of fundamental physics

from the very smallest scales . . .

. . . to the very largest

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All of the known elementary particles and their interactions are described within the framework of

THE NEW STANDARD MODEL
All of the known elementary particles and their interactions are described within the framework of the Standard Model. This description is based on quantum mechanics and special relativity, leading to quantum field theory. The diagram illustrates the progression from classical mechanics to special relativity, through quantum mechanics, and finally to general relativity, with the ultimate goal being a unified theory that explains all these phenomena.
The Standard Model

All of the known elementary particles and their interactions are described within the framework of the new STANDARD MODEL

- quantum + special rel \(\Rightarrow\) quantum field theory
- Noether’s theorem \(\Leftrightarrow\) conservation laws

Maxwell’s eqns invariant under changes in vector potential \(\Leftrightarrow\) conservation of electric charge, \(q\)

and there’s other symmetries:

- time \(\Leftrightarrow\) energy
- space \(\Leftrightarrow\) momentum
- rotations \(\Leftrightarrow\) angular momentum
- ...
The Standard Model

All of the known elementary particles and their interactions are described within the framework of

**THE **SUPERMODERN **STANDARD MODEL**

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether’s theorem $\iff$ conservation laws
  - electroweak
- $SU(3) \times SU(2)_L \times U(1)$
  - strong
  - weak
  - E & M
- (classical general rel)
  - gravity
The Standard Model

All of the known elementary particles and their interactions are described within the framework of

THE NEW STANDARD MODEL

- **quantum + special rel** \(\Rightarrow\) **quantum field theory**
- Noether’s theorem \(\Leftrightarrow\) conservation laws
- **12 elementary particles** and **4 fundamental forces**

<table>
<thead>
<tr>
<th></th>
<th>1st</th>
<th>2nd</th>
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<th>(Q)</th>
<th>mediator</th>
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<tr>
<td><strong>leptons</strong></td>
<td>(\nu_e)</td>
<td>(\nu_\mu)</td>
<td>(\nu_\tau)</td>
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<td>(e)</td>
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<td>(W^\pm)</td>
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<td><strong>quarks</strong></td>
<td>(u)</td>
<td>(c)</td>
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<td>+2/3</td>
<td>(Z^0)</td>
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<td></td>
<td>(d)</td>
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<td>(b)</td>
<td>-1/3</td>
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Does the Standard Model work?

- **predicted** the existence of the $W^\pm$, $Z_0$, $g$, $c$ and $t$

- is a **renormalizable** theory

- GSW $\Rightarrow$ **unified** the **weak** force with **electromagnetism**

- QCD **explains** quark confinement
Does the Standard Model work?

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\[
a_\mu \equiv \frac{1}{2} (g - 2)
\]
\[
a_\mu (\text{exp}) = 11 659 208(6) \times 10^{-10}
\]
\[
a_\mu (\text{SM}) = 11 659 181(8) \times 10^{-10}
\]

±1 part-per-million!!

(PRL 92 (2004) 161802)
Does the Standard Model work?

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$a_\mu(\text{SM}) = 11659181(8) \times 10^{-10}$

$\pm 1$ part-per-million!

(PRL 92 (2004) 161802)

Wow ... this is

the most precisely tested theory ever conceived!
But there are still questions . . .

- **values of parameters**: does our “ultimate” theory *really* need 25 arbitrary constants? Do they change with time?

- **dark matter**: SM physics makes up only 4% of the energy-matter of the universe!

- **baryon asymmetry**: why more matter than anti-matter?

- **strong CP**: do axions exist? Fine-tuning?

- **neutrinos**: Dirac or Majorana?

- **fermion generations**: why three families?

- **weak mixing**: Is the CKM matrix unitary?

- **parity violation**: is parity maximally violated in the weak interaction? No right-handed currents?

- **EW symmetry breaking**: how do the fermions acquire mass? Mass hierarchy?

- **gravity**: of course can’t forget about a quantum description of gravity!
At our energy scales, we see four distinct forces...
But these coupling ‘constants’ aren’t really constant …

\[ \alpha_i \rightarrow \alpha_i(Q) \]

→ electromagnetic and weak strengths equal at \( \approx 10^{13} \) GeV

→ strong force gets weaker, but doesn’t unify with EW . . . .
Beyond the Standard Model

But what if there is **new physics** we haven’t seen yet?

the running of the coupling constants would be affected; maybe they converge at some GUT scale?

Are the three theories of **E & M, weak** and **strong** interactions all **low-energy limits** of **one unifying** theory?
How do we test the SM?

colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, . . . .

direct search for new particles

go big or go home

• large multi-national collabs
• billion $ price-tags
How do we test the SM?

**nuclear physics**: radioactive ion beam facilities (ISOL/frag)

- smaller collaborations
- contribute to all aspects
- “table-top” physics
How do we test the SM?

- **colliders**: CERN, SLAC, FNAL, BNL, KEK, DESY . . .
- **nuclear physics**: traps, exotic beams, neutron, EDMs, $0\nu\beta\beta$, . . .
- **cosmology & astrophysics**: SN1987a, Big Bang nucleosynthesis, . . .
- **muon decay**: Michel parameters: $\rho$, $\delta$, $\eta$, and $\xi$
- **atomic physics**: anapole moment, spectroscopy, . . .

All of these techniques are **complementary** and **important**
- different experiments probe different (new) physics
- if signal seen, cross-checks crucial!

**often they are interdisciplinary**

(fun and a great basis for graduate students!)
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What is the CKM matrix?

Cabibbo

flavour mixing

\[
|d'\rangle = \cos \theta_C |d\rangle + \sin \theta_C |s\rangle \\
|s'\rangle = - \sin \theta_C |d\rangle + \cos \theta_C |s\rangle
\]

mass eigenstates \( \neq \) weak eigenstates

purely leptonic

\[
\sqrt{G_F} = \text{strength of lepton coupling to } W
\]

semi-leptonic

\[
\sqrt{G_F \cos \theta_C} = \text{strength of quark coupling to } W
\]
What is the CKM matrix?

**Cabibbo**

mass eigenstates ≠ weak eigenstates

**Kobayashi**

generalized Cabibbo’s theory to three generations

**Maskwawa**

\[ \sqrt{G_F} \]

\[ \sqrt{G_F \cos \theta_C} \]

\[ u \rightarrow d' \]

\[ W^+ \rightarrow e^+ \nu_e \]

\[ V_{ud} = \frac{G_V}{G_F} \]

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Pure Fermi $0^+ \rightarrow 0^+$ decays

The comparative half-life of $\beta$ decay is:

$$ft = \left( \frac{\text{phase space}}{\text{partial half-life}} \right) = \frac{K}{G_V^2 |M_F|^2 + G_A^2 |M_{GT}|^2}$$

$$K/(\hbar c)^6 = 2\pi^3 \hbar \ln 2/(m_e c^2)^5$$ and $$G_V = G_F V_{ud}$$

For pure Fermi

$T = 1$ decays

$$T_3 \equiv \frac{1}{2} (N - Z) = \text{"isospin"}$$

$M_F = \sqrt{2}$, $M_{GT} = 0$
Pure Fermi $0^+ \rightarrow 0^+$ decays

The comparative half-life of $\beta$ decay is:

$$f_t = \left( \frac{\text{phase space}}{\text{partial half-life}} \right) = \frac{K}{G_V^2 |M_F|^2 + G_A^2 |M_{GT}|^2}$$

$$K/(\hbar c)^6 = 2\pi^3 \hbar \ln 2/(m_e c^2)^5$$

and by CVC, $G_V = G_F V_{ud}$

For pure Fermi $T = 1$ decays

$$M_F = \sqrt{2}$$

$$M_{GT} = 0$$

$Q_{EC}$ ⇒ $f$

$BR$

t$_{1/2}$

$0^+ \ T = 1$

should be constant

$Q_{EC}$

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Are they constant?

The most precisely measured $0^+ \rightarrow 0^+$ $ft$ values
Are they constant?

The most precisely measured $0^+ \rightarrow 0^+$ $ft$ values

![Graph showing $ft$ values vs Z of parent elements]
We must account for the fact that the decay occurs within the nuclear medium. 

\[ \mathcal{F} t \equiv ft \left( 1 + \delta'_R \right) \left( 1 + (\delta_{NS} - \delta_C) \right) = \frac{K}{G_F^2 |V_{ud}|^2 |M_F|^2 \left( 1 + \Delta^V_R \right)} \]

(really should be constant)

- \( \delta'_R = E_e^{\text{max}} \) and \( Z \) dependent radiative correction
- \( \delta_{NS} = \) nuclear structure dependent radiative correction
- \( \delta_C = \) isospin symmetry-breaking correction
- \( \Delta^V_R = \) transition independent radiative correction
$Ft$ values of $0^+ \rightarrow 0^+$ decays

![Graph showing $Ft$ values vs Z of parent for different elements]
\( \mathcal{F}_t \) values of \( 0^+ \rightarrow 0^+ \) decays

\[
\langle \mathcal{F}_t \rangle = 3072.1(8) \text{ s}
\]

\[
\chi^2/12 = 0.28
\]

Corrected \( \mathcal{F}_t \) values constant to 3 parts in \( 10^4 \)!

Hardy and Towner, PRC 79, 055502 (2009)
The comparative half-life of $\beta$ decay is:

$$ft = \left( \text{phase space} \right) \left( \text{partial half-life} \right) = \frac{K}{G^2_V |M_F|^2 + G^2_A |M_{GT}|^2}$$

$$K/(\hbar c)^6 = 2\pi^3 \hbar \ln 2/(m_e c^2)^5$$ and $$G_V = G_F V_{ud} \text{ (CVC)}$$
$$G_A \approx -1.27 G_F V_{ud} \text{ (PCAC)}$$

Theoretically simpler 3-quark system:

- no isospin corrections
- smaller radiative corrections
The comparative half-life of $\beta$ decay is:

$$ft = \left( \frac{\text{phase space}}{\text{partial half-life}} \right) = \frac{K}{G_V^2 |M_F|^2 + G_A^2 |M_{GT}|^2}$$

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and

$$G_V = G_F V_{ud} \text{ (CVC)}$$

$$G_A \approx -1.27 G_F V_{ud} \text{ (PCAC)}$$

For neutron decay: $M_F = 1$ and $M_{GT} = \sqrt{3}$

Gamow-Teller component $\Rightarrow$ have to measure $\lambda \equiv G_A/G_V$

$$ft = \frac{K}{G_F^2 |V_{ud}|^2 (1 + 3\lambda^2)} \iff |V_{ud}|^2 = \frac{4903.7 \pm 3.8 \text{ s}}{\tau_n (1 + 3\lambda^2)}$$

theoretically simpler 3-quark system:

- no isospin corrections
- smaller radiative corrections
How to get the Gamow-Teller part?

\[
\frac{d^5 W}{dE_\beta d\Omega_\beta d\Omega_\nu} = \frac{G_F^2}{(2\pi)^5} |V_{ud}|^2 p_e E_e (E_e - E_\nu)^2 \xi \left[ 1 + a_{\beta\nu} \frac{p_\beta \cdot p_\nu}{E_\beta E_\nu} + b \frac{m_e}{E_\beta} \right]
\]

\[
+ \sigma_n \cdot \left( A_\beta \frac{p_\beta}{E_\beta} + B_\nu \frac{p_\nu}{E_\nu} + D \frac{p_\beta \times p_\nu}{E_\beta E_\nu} \right)
\]

Within the Standard Model and in terms of \(\lambda \equiv G_A/G_V\):

\[
A_\beta = -2 \frac{|\lambda|^2 + \Re(\lambda)}{1 + 3|\lambda|^2} = -0.1173(13)
\]

\(\Leftrightarrow \lambda = -1.2695(29)\) \{PDG 2008\}

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How to get the Gamow-Teller part?

\[
\frac{d^5W}{dE_\beta d\Omega_\beta d\Omega_\nu} = \frac{G_F^2}{(2\pi)^5} |V_{ud}|^2 p_e E_e (E_\circ - E_e)^2 \xi \left[ 1 + a_{\beta\nu} \frac{p_\beta \cdot p_\nu}{E_\beta E_\nu} + b \frac{m_e}{E_\beta} \right] \]

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\]

\[
= -0.1173(13) \quad \text{PDG 2008}
\]

\[\Leftrightarrow \lambda = -1.2695(29) \quad \text{arXiv:1007.3790v1 [nucl-ex]}
\]

\[= -0.1197(9)(^{+12}_{-14}) \quad \text{PDG 2008}
\]

\[= -1.2759(^{+41}_{-45}) \quad \text{UCNA 2010}
\]
The $\beta^+$ of $^{37}\text{K}$

$$ft = \left( \text{phase space} \right) \left( \text{partial half-life} \right) = \frac{K}{G_V^2 |M_F|^2 + G_A^2 |M_{GT}|^2}$$

For isobaric analogue decay: $M_F = 1$ and $M_{GT} = ???$

GT component $\Rightarrow$ have to measure $\rho \equiv G_A M_{GT} / G_V M_F$

$$ft = \frac{K}{G_F^2 |V_{ud}|^2 (1 + \rho^2)}$$

$Q_{EC} = 6.14746(20)$ MeV

$B.R. = 0.9799(14)$

and $t_{1/2} = 1.225(7)$ s

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Corrections have been calculated!

\[ \mathcal{F}_t^{\text{mirror}} \equiv f_V t (1 + \delta'_R) (1 + (\delta^V_{NS} - \delta^V_C)) = \frac{2 \mathcal{F}_t^{0^+\rightarrow 0^+}}{1 + \frac{f_A}{f_V} \rho^2} \]

Severijns, Tandecki, Phalet and Towner, PRC 78, 055501 (2008)
surveys all \( T = 1/2 \) mirror transitions from \(^3\text{He}\) to \(^{83}\text{Mo}\)

\[ \delta'_R = 1.43(4)\% \]
\[ \delta^V_{NS} - \delta^V_C = 0.79(6)\% \]
\[ \frac{f_A}{f_V} = 1.00456(91) \]
Present status of $^{37}\text{K}'s$ $ft$ value

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

$$\begin{align*}
ft &= 4533(28) + \\
\delta'_{R}: \pm 0.04\% \\
\delta_{NS}^{V} - \delta_{C}^{V}: \pm 0.06\% \\
\end{align*}$$

Lifetime limits the $ft$ value

$^{38}\text{Ar}(p, 2n)^{37}\text{K}$ at the Cyclotron Institute, Texas A&M:

- **MARS beamline**
- **RIB**
- **Aluminum degraders**
- **Aluminized Mylar tape**
- **BC404 scintillator**
- **$4\pi$ gas prop chmbr**
- **70\% HPGe shielding**
- **35 FEET**

**Produces $\approx 10,000$ pps; $t_{1/2}$ measurement in 3 weeks**
A measurement of $|V_{ud}|$?

Not yet ... to get $V_{ud}$, still need $\rho$

$$|V_{ud}|^2 = \frac{5831.3 \pm 2.3 \text{ secs}}{F(t)_{\text{mirror}}(1 + \frac{f_A}{f_V} \rho)}$$

Angular distribution of an $I^\pi = \frac{3}{2}^+ \rightarrow \frac{3}{2}^+$ decay:

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

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

Just like the neutron, need to measure a correlation parameter (e.g. $A_{\beta}$) to determine $\rho$
The $\beta$ asymmetry

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

- recoil order corrections under control
- value sensitive to RHCs
- energy-dependence sensitive to SCCs
Correlation parameter values using present $\mathcal{F} t$ value $\Rightarrow \rho = 0.5874(71)$

<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>$R_{\text{slow}} \sim \frac{1-a_{\beta \nu}-2c_{\text{align}}/3 - (A_\beta-B_\nu)}{1-a_{\beta \nu}-2c_{\text{align}}/3 + (A_\beta-B_\nu)} = 0$</td>
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Electroweak unification . . .

The **Standard Model**: SU(2)$_L \times$ U(1) $\Rightarrow$ $W^\pm_L$, $Z^\circ$, $\gamma$

Built upon **maximal** parity violation:

$$H_{SM} = G_F V_{ud} \overline{e}(\gamma_\mu - \gamma_\mu \gamma_5) \nu_e \overline{u} \gamma^\mu - \gamma^\mu \gamma_5 d$$

**Vector** $\hat{P}|\Psi\rangle = +|\Psi\rangle$

**Axial-vector** $\hat{P}|\Psi\rangle = -|\Psi\rangle$
**Electroweak unification ... and beyond**

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

Built upon **maximal** parity violation:

$$H_{\text{SM}} = G_F V_{ud} \ e (\gamma_\mu - \gamma_\mu \gamma_5) \nu_e \ u (\gamma^\mu - \gamma^\mu \gamma_5) d$$

low-energy limit of a **deeper** $\text{SU}(2)_R \times \text{SU}(2)_L \times U(1)$ theory?
**Electroweak unification ... and beyond**

The **Standard Model**:

\[
\text{SU}(2)_L \times \text{U}(1) \Rightarrow W^\pm_L, Z^0, \gamma
\]

Built upon **maximal** parity violation:

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

- **Vector**: \( \hat{P} |\Psi\rangle = + |\Psi\rangle \)
- **Axial–vector**: \( \hat{P} |\Psi\rangle = - |\Psi\rangle \)

**low-energy limit of a deeper SU(2)_R \times SU(2)_L \times \text{U}(1) theory?**

\[ \Rightarrow 3 \text{ more vector bosons: } W^\pm_R, Z' \]

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

\[ \rightarrow \text{only new parameters are the } W_2 \text{ mass and a mixing angle, } \zeta: \]

\[
|W_L\rangle = \cos \zeta |W_1\rangle - \sin \zeta |W_2\rangle \\
|W_R\rangle = \sin \zeta |W_1\rangle + \cos \zeta |W_2\rangle
\]
RHCs would affect correlation parameters

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

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

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

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.

\[\Rightarrow\] Precision measurements test the SM

Goal must be $\lesssim 0.1\%$

(see Profumo, Ramsey-Musolf and Tulin, PRD 75 (2007))
Many groups around the world realize the potential of using traps for precision weak interaction studies.
Neutral Atom Traps

Any type of trap requires a velocity-dependent force to cool an object.
Neutral Atom Traps

Any type of trap requires a *velocity-dependent* force to cool an object

\[ x = 0 \]

... as well as a *position-dependent* force that defines \( x = 0 \)
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

$\Rightarrow$ atom trap = damped harmonic oscillator
but ....

\[ \hbar k \sim 0.0015 \text{ keV/c} \quad \text{vs.} \quad Mv \sim 45 \text{ keV/c} \]

\[ \Rightarrow \text{need many absorptions ...} \]

and still the trap is shallow ...
but . . . .

(\times 30 000)

cycling transition \Rightarrow \text{not everything trappable}

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\begin{align*}
\text{cycling transition} & \Rightarrow \text{not everything trappable} \\
\end{align*}
• isomerically selective!
• point-like source! $(\lesssim 1 \text{ mm}^3 \text{ FWHM})$
• cold atoms! $(\lesssim 1 \text{ mK})$
• backing-free source!

an ideal source of radioactives for $\beta$-decay experiments!
Coupling a MOT to ISAC-I

$^{37}$K yield with 40 $\mu$A on TiC #1: $6 \times 10^7$/s

E.L. Raab et al., PRL 59 (1987) 2631
Double-MOT system

Ion beam

Push beam

Neutralizer

Collection chamber

15 cm

MCP

Electrostatic hoops

DSSSD

β detector

Detection chamber
Double-MOT system

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

Detect $p_\beta$ and $p_{\text{recoil}} \Rightarrow$ deduce $p_\nu$!
...and Here is Reality
Optical pumping

\[ \hat{z} = \text{MCP} - \beta\text{-telescope axis} \]

\[ \hat{x} = \text{phoswich detector axis} \]
Optical pumping

\[ \hat{z} = \text{MCP} - \beta\text{-telescope axis} \]
\[ \hat{x} = \text{phoswich detector axis} = \text{polarization axis} \]

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

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

\[ B_{\text{op}} = 2.5 \text{ G} \]
Optical pumping

\[ \hat{z} = \text{MCP} - \beta\text{-telescope axis} \]

\[ \hat{x} = \text{phoswich detector axis} \]

\[ = \text{polarization axis} \]

can monitor

atomic fluorescence \[ \Rightarrow \]

via photoions

\[ F = I + J \]

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

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

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

\[ B_{op} = 2.5 \text{ G} \]
Atomic measurement of $P$

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

$$\Rightarrow P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$$
\[ A_\beta - \text{Phoswich asymmetries} \]

Asymmetry \[ = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) + N(\sigma^-)} \]

\[ \sim PA_\beta \left\langle \frac{p_e}{E_e} \right\rangle \]
Asymmetry \equiv \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) + N(\sigma^-)} 
\sim PA_\beta \left\langle \frac{p_e}{E_e} \right\rangle 

atoms can get sprayed onto the thin mirrors and walls . . .
recoil coincidences cleaner!
Geometry with shakeoff $e^-$ detector

- high-statistics!
- *know* decay occurred from trap!
- S1188 approved with high priority
- goal is 0.1% in $A_\beta$ (and $B_\nu$ and $R_{\text{slow}}$)
Measuring $B_\nu$ (and $D$)

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

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

UBC 2010 Dan Melconian July 26, 2010
Measuring \(B_\nu\) (and \(D\))

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

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

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

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

\[ \hat{x} \text{ asymmetry} \sim PB_\nu \]
\[ \hat{y} \text{ asymmetry} \sim PD \]
The neutrino asymmetry measurement

\[ \langle B_\nu \rangle = (0.995 \pm 0.040) B_\nu^{\text{SM}} \, \text{(stat)} \]

\[ \langle B_\nu \rangle = (0.975 \pm 0.031) B_\nu^{\text{SM}} \, \text{(stat)} \]

\[ B_\nu = 0.981(26)(17) B_\nu^{\text{SM}} \]

(Melconian, PLB 649 (2007) 370)
$B_\nu$ measurement and current limits

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
Conclusions

Physics Goals:

- $V_{ud}$: $^{37}$K is like a “heavy neutron”
- Right-handed currents: is parity \textit{maximally} violated?
- Second-class currents: is $G$-parity conserved?
- Time-reversal: does Nature care about the direction of time?

Experimental tools:

- RIB facilities (TRIUMF, TAMU, . . . , FRIB)
- fast tape-transport for lifetime and BR
- atom traps + optical pumping $\Rightarrow$ ideal polarized source
- ultra-cold neutrons
- ion traps, $T = 2$ decays
nuclear spin $I = 0$ case: $^{38}\text{mK}$

$F' = 3/2$ \hspace{2cm} $F = I + J$ \hspace{2cm} $F = 1/2$

$\Delta \omega_L$
1D Magneto-Optical Trap

$F' = \frac{3}{2}$

$\sigma^+$

$\omega_L$

$\sigma^-$

$F = \frac{1}{2}$

$B(z)$

$z, B < 0$

$z = B = 0$

$z, B > 0$

$m_{F'} = \frac{3}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}$

$m_F = \frac{-1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}$

m_{F'} = \frac{3}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}$

m_F = \frac{-1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}$

no net force

Force

Force
Trap/optical pumping cycle

- re-trap atoms before they expand too far
- MCP–laser coinc. and position cuts
  \(\Rightarrow\) high \(S/N\)
- Gaussian fits \(\Rightarrow \hat{x}, \hat{y}, \hat{z}\) characterization

![Graph showing number of photoions over cycle time with position and width characterization plots.]