Correlation measurements in nuclear $\beta$ decays

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Main collaborators/thanks


TRIUMF: J.A. Behr, A. Gorelov, M.R. Pearson, K.P. Jackson, P. Bricault, M. Dombsky

Tel Aviv: D. Ashery, I. Cohen

UCNA Collaboration: (too many to list)

Others: A. García, G. Savard, J. Dilling

Funding: TAMU and DOE
Overview

- Motivation
NSAC 2007 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.’’
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```

Probe fundamental symmetries of the weak interaction via precision measurements of $\beta$ decay.
Overview

- **Motivation** ✓
- $\beta$ decay and correlations
- $0^+ \rightarrow 0^+$ decays and scalar currents
- Neutron decay and $|V_{ud}|$
- Polarized decay and RHCs
Overview

- Motivation
- $\beta$ decay and correlations
- $0^+ \rightarrow 0^+$ decays and scalar currents
- Neutron decay and $|V_{ud}|$
- Polarized decay and RHCs

→ perform a precision $\beta$ decay experiment
→ compare the SM predictions of correlation parameters to observations
→ look for deviations as an indication of new physics
The rate of $\beta$-decay

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

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

polarization $\rightarrow$

\[
+ \left( \frac{\langle \vec{I} \rangle}{I} \right) \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_{\nu}}{E_{\nu}} + D \frac{\vec{p}_e \times \vec{p}_{\nu}}{E_e E_{\nu}} \right]
\]

$\beta$ asym $\quad$ $\nu$ asym $\quad$ $T$-violating
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polarization $\rightarrow$ $$+ \frac{\langle \vec{I} \rangle}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_{\nu}}{E_{\nu}} + D \frac{\vec{p}_e \times \vec{p}_{\nu}}{E_e E_{\nu}} \right]$$

alignment $\rightarrow$ $$+ c \left[ \frac{\vec{p}_e \cdot \vec{p}_{\nu}}{3 E_e E_{\nu}} - \frac{(\vec{p}_e \cdot \hat{i})(\vec{p}_{\nu} \cdot \hat{i})}{E_e E_{\nu}} \right] \left[ \frac{I(I+1) - 3\langle(\vec{I} \cdot \hat{i})^2\rangle}{I(2I - 1)} \right]$$
The rate of $\beta$-decay

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$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_o - E_e)^2 \xi \left( 1 + \frac{a_{\beta\nu}}{E_e E_{\nu_e}} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e} + \frac{b}{E_e} \Gamma m_e \right)$$

polarization → $\frac{\langle \vec{I} \rangle}{I} \cdot \begin{bmatrix} A_{\beta} \frac{\vec{p}_e}{E_e} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \end{bmatrix}$

alignment → $+ c \left[ \frac{\vec{p}_e \cdot \vec{p}_\nu}{3E_e E_\nu} - \frac{(\vec{p}_e \cdot \hat{i})(\vec{p}_\nu \cdot \hat{i})}{E_e E_\nu} \right] \left[ \frac{I(I+1) - 3\langle (\vec{I} \cdot \hat{i})^2 \rangle}{I(2I - 1)} \right] + \ldots$
$0^+ \rightarrow 0^+ \text{ decay: } ^{38\text{m}}\text{K}$

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

$E_x = 130.4(3) \text{ keV}$

$\frac{d^5 W}{dE_e d\Omega_e d\Omega_\nu} \sim p_e E_e (A_o - E_e)^2 \left( 1 - \frac{A_o - 3(E_e - \vec{p}_e \cdot \vec{p}_\nu)}{M} \right)$

$\times \xi \left( 1 + a_{\beta \nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e} \right)$
A closer look . . .

\[ \frac{-ig_w}{\sqrt{2}} \gamma^\mu \tau_+ \]

\[ Z_{AX} \]

\[ W^+ \]

\[ e \]

\[ Z^{-1}_{AY} \]

vector propagator:

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

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

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

(a) vector propagator:

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

(b) scalar propagator:

\[ \frac{-i g_w}{\sqrt{2}} \gamma^\mu \gamma_5 \]

\[ a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C'_S|^2 - |C''_S|^2 + \frac{2\alpha Z m_e}{p_e} \delta m (C_S C^*_V + C''_S C''^*_V)}{|C_V|^2 + |C'_V|^2 + |C'_S|^2 + |C''_S|^2} \]

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

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Helicity and an $\alpha_{\beta\nu}$ measurement

$^{38m}$K decay

in the back-to-back geometry:

“Fast”

$^{38}$Ar

$^{38}$Ar

“Slow”

$\nu_e$ $\nu_e$ $e^+$ $e^+$
Helicity and an $\alpha_{\beta\nu}$ measurement

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

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

```
Vector
```

```
Scalar
```

"Fast"

```
$^{38}$Ar
\[ I = 0 \]
\[ e^+ \]
\[ \nu_e \]
```

"Slow"

```
$^{38}$Ar
\[ I = 0 \]
\[ e^+ \]
\[ \nu_e \]
```
Principle of a scalar search

Fit TOF projections as a function of $E_\beta$ to detailed Monte Carlo 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 $\vec{x} = 0$

Laser light $\rightarrow$ velocity-dependent force

Zeeman effect $\rightarrow$ position-dependent force

$\rightarrow$ magneto-optical trap = damped harmonic oscillator
But ... 

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

⇒ need many absorptions ...
But . . .

(×30 000)

cycling transition ⇒ not everything trappable
But …

(×30 000)

and still the trap is shallow …
- isomerically selective!
- point-like source! ($\lesssim 1$ mm$^3$ FWHM)
- cold atoms! ($\lesssim 1$ mK)
- backing-free source!

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

\[
\sigma^+ + \sigma^- + K^+ \text{ ion beam} \\
\sigma^- + \sigma^+ + E.L. Raab \text{ et al.}, \text{PRL 59 (1987) 2631}
\]
Coupling a MOT to ISAC-I

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

\[ \text{E.L. Raab et al., PRL 59 (1987) 2631} \]

yields with 40 \( \mu \)A on TiC:

\[ ^{37}K \quad 6 \times 10^7/s \]
\[ ^{38}K \quad 133 \times 10^7/s \]
\[ ^{38m}K \quad 7 \times 10^7/s \]
Double-MOT system

Ion beam

Push beam

Neutralizer

Collection chamber

15 cm

MCP

Electrostatic hoops

DSSSD

β detector

Detection chamber

BC408

Collection chamber Detection chamber
Traps provide a backing-free, cold (∼ 1 mK), localized (∼ 1 mm³) source of short-lived radioactive atoms

Detect \( \vec{p}_\beta \) and \( \vec{p}_{\text{recoil}} \) \( \Rightarrow \) deduce \( \vec{p}_\nu \)!
Over-determined kinematics

- test response

\[ \langle E_\beta \rangle = 2.66 \text{ MeV} \]

\[ 800 < TOF < 1200 \]

Gaussian peak

511 Compton summing

low-energy tail
Over-determined kinematics

- measure $\vec{p}_\nu$
- event-by-event
- test response

$\beta$
$\theta_{\beta\nu}$
$\nu$

$\langle E_\beta \rangle = 2.66$ MeV

Ar$^{40}$ recoil TOF [ns]

$800 < TOF < 1200$

511 Compton summing

Gaussian peak

low-energy tail

$E_\beta^{\text{meas}} - E_\beta^{\text{reconstruct}}$ [MeV]
The (old) detection chamber

- MCP
- DSSSD
- BC408 light guide
- Be foil
- Electrostatic hoops
- Push beam from 1st trap
- Trapping beams

\[ \hat{x}_{\text{chmbr}} \]
\[ \hat{z}_{\text{chmbr}} \]
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: $\hat{\alpha}_{\beta\nu} \equiv \frac{\alpha_{\beta\nu}}{1 + b \frac{m}{\langle E \rangle}}$

$\hat{\alpha}_{\beta\nu} = 0.9981 \pm 0.0030 \pm 0.0037$

(stat) (syst)

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

\[ 0^+, T=2 \]

\[ \beta^+ \]

\[ p \leftarrow \gamma \]

\[ \beta^- - \nu \] correlations

\[ Z \]

\[ N \]

Stable

\( T = 1 \)

\( T = 2 \)
\[ T = 2 \text{ superallowed decays} \]

- $\beta^+ \rightarrow 0^+, T=2$ 
- $\beta^+ \rightarrow p, \gamma$ 

- $\beta - \nu$ correlations 
- Model-dependence of $\delta_C$ calc seems to depend on $T$ ... 
- New cases for $V_{ud}$
Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of $^{32}\text{Ar}$

E. G. Adelberger,¹ C. Ortiz,² A. García,² H. E. Swanson,¹ M. Beck,¹ O. Tengblad,³ M. J. G. Borge,³ I. Martel,⁴ H. Bichsel,¹ and the ISOLDE Collaboration⁴

¹Department of Physics, University of Washington, Seattle, Washington 98195-1560
²Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556
³Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain
⁴EP Division, CERN, Geneva, Switzerland CH-1211

(Received 24 February 1999)

The positron-neutrino correlation in the $0^+ \rightarrow 0^+$ $\beta$ decay of $^{32}\text{Ar}$ was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the standard model prediction. For vanishing Fierz interference we find $a = 0.9989 \pm 0.0052 \pm 0.0039$, which yields improved constraints on scalar weak interactions.

Doppler shape of delayed proton depends on $\vec{p}_e \cdot \vec{p}_\nu$!
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(Received 24 June 2001)

The positron-neutrino correlation in the $0^+ \rightarrow 0^+$ decay depends on the effect of lepton recoil on the proton shape. Our result is consistent with the standard model and allows us to determine the parameters $a$ and $b$ of the $\bar{p}_e \cdot \bar{p}_\nu$ relationship.

Doppler shape of delayed proton depends on $\vec{p}_e \cdot \vec{p}_\nu$!

![Graph showing $dn/dE$ versus $E-E_0$](image)

FIG. 1. Intrinsic shapes of the $0^+ \rightarrow 0^+$ delayed proton group for $a = +1$, $b = 0$ (heavy curve) and $a = -1$, $b = 0$ (light curve). The daughter’s 20 eV natural width is not visible on this scale.
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(Received 24

Fig. 2. Sketch of apparatus used at Isolde.

IG. 1. Intrinsic shapes of the $0^+ \rightarrow 0^+$ delayed proton group or $a = +1, b = 0$ (heavy curve) and $a = -1, b = 0$ (light curve). The daughter’s 20 eV natural width is not visible on its scale.
How to improve $a_{\beta\nu}$ in $^{32}$Ar

- Must keep separation of $\beta$ and proton
How to improve $\alpha_{\beta\nu}$ in $^{32}\text{Ar}$

- Must keep separation of $\beta$ and proton

Diagram showing the process and separation of particles.
How to improve $\alpha_{\beta\nu}$ in $^{32}\text{Ar}$

- Must keep separation of $\beta$ and proton

**ISOLDE** vs **NSCL**
How to improve $\alpha_{\beta\nu}$ in $^{32}$Ar

- Must keep separation of $\beta$ and proton

**ISOLDE** vs **NSCL**

```
but why throw away $E_\beta$ information?!?

How can we keep it ... ?
```
Why not an open-geometry Penning trap?
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Gabrielse  
Why not an open-geometry Penning trap?

- Larmor radii of $\beta$ and $p$; pixelation $\Rightarrow$ separation

Why not an open-geometry Penning trap?

- Larmor radii of $\beta$ and $p$; pixelation ⇒ separation
- Compare parallel vs opposite hemispheres ⇒ enhance signal

Why not an open-geometry Penning trap?

- Larmor radii of $\beta$ and $p$; pixelation $\Rightarrow$ separation
- Compare parallel vs opposite hemispheres $\Rightarrow$ enhance signal
- Similar to other studies measuring recoiling nucleus

A Penning trap at CI/TAMU
A Penning trap at CI/TAMU

- ANL gas-catcher – close collaboration with Savard
- 15 keV transport from multi-RFQ
- 6 mm opening to 24 segment, $10^{-2}$ mbar RFQ
- 1.5 – 2.5 $\mu$s, $\sim$ 5 eV FWHM to trap
- grad student starting design of trap (7 Tesla, 210 mm bore)
### Estimated rates at T-REX

Estimated rate of $T = 2$ superallowed proton emitters from T-REX at the trap ($^3$He target, overall $\sim 10\%$ efficiency)

<table>
<thead>
<tr>
<th>RIB</th>
<th>$t_{1/2}$ [ms]</th>
<th>projectile</th>
<th>beam energy [MeV/u]</th>
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<tr>
<td>$^{36}$Ca</td>
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</tr>
<tr>
<td>$^{40}$Ti</td>
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- All have similar decay schemes $\Rightarrow$ $^{32}\text{Ar}$ proof-of-principle
- Very small backgrounds $\Rightarrow$ sufficient rates
- Many branches, lifetimes and correlations to measure $\Rightarrow$ fruitful program
The rate of $\beta$-decay

$$
\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_o - E_e)^2 \xi 
\left( 1 + \frac{a_{\beta\nu}}{\frac{E_e E_{\nu_e}}{E_e}} \right) + b \frac{\Gamma m_e}{E_e}
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\]

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

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

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

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

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

and

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

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

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

Gamow-Teller component $\Rightarrow$ have to measure \(\lambda \equiv G_A/G_V\)
The comparative half-life of $\beta$ decay is:

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

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theoretically simpler 3-quark system:

$\rightarrow$ no isospin corrections
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$$ft = \frac{K}{G_F^2 |V_{ud}|^2 (1 + 3\lambda^2)}$$

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

theoretically simpler 3-quark system:

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The rate of $\beta$-decay

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\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_o - E_e)^2 \xi \left( 1 + \frac{a_{\beta\nu}}{E_e E_{\nu_e}} \vec{p}_e \cdot \vec{p}_{\nu_e} + \frac{b}{E_e} \right)
\]

Polarization $\rightarrow$

\[\sigma_n \cdot \left[ \begin{array}{c}
A_{\beta} \frac{\vec{p}_e}{E_e} \\
B_\nu \frac{\vec{p}_\nu}{E_\nu} \\
D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}
\end{array} \right] \]

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

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

$\Leftrightarrow \lambda = -1.2694(28)$

PDG2010
Advantages of ultracold neutrons

\[ V_{58\text{Ni}} = 335 \text{ neV} \Rightarrow 8 \text{ m/s} \]

\[ V_{\text{grav}} = mgh = 102 \text{ neV/m} \]
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\[ \Rightarrow \text{Reduced backgrounds:} \]

- more decays/neutron
- no production source bkgds
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⇒ Reduced backgrounds:
- more decays/neutron
- no production source bkgd

\[ V_{\text{mag}} = \vec{\mu} \cdot \vec{B} = 60 \text{ neV/T} \]
Advantages of ultracold neutrons

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⇒ Reduced backgrounds:

● more decays/neutron
● no production source bkgds

\[ V_{\text{mag}} = \vec{\mu} \cdot \vec{B} = 60 \text{ neV/T} \]

⇒ 100% polarization!
Area B at LANSCE

800 MeV proton beam

7 T polarizing magnet

AFP spin flipper

SD$_2$ UCN source

Decay volume and detection chamber
Asymmetry extracted from super-ratio:

\[
S(E) \equiv \frac{R(E)_1^{↑} R(E)_2^{↓}}{R(E)_1^{↓} R(E)_2^{↑}}
\]

\[
A_{\text{exp}}(E) = \frac{1 - \sqrt{S(E)}}{1 + \sqrt{S(E)}}
\]

\[
A_\circ = \frac{A_{\text{exp}}(E)}{\langle \beta \cos \theta \rangle}
\]

Data taken in “pulse pair” cycles:

- 720 s bkgd
- 3600 s asymmetry
- 720 s depolarization

- solenoidal magnet with 1 T central field
- field expansion (supress backscatter)
- MWPC + scintillator $\beta$ detection
\begin{itemize}
  \item S/N over ROI (275–625 keV) \approx 40
  \item Lower limit for initial UCN polarization: \( P > 99.48\% \)
  \item Liu \textit{et al.}, PRL \textbf{105}, 181803 (2010)
\end{itemize}
The rate of $\beta$-decay

$$\frac{d^5 W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi \left( 1 + \frac{a_{\beta\nu}}{E_e E_{\nu_e}} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}} + b \frac{\Gamma m_e}{E_e} \right) \beta - \nu \text{ correlation}$$

Fierz term

The basic decay rate

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

Polarization $\rightarrow$$$

$$+ \vec{\sigma}_n \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right]$$

$\beta$ asym $\nu$ asym $T$-violating

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

$$A_{\beta} = -2 \left[ |\lambda|^2 + \Re e(\lambda) \right] \frac{1 + 3|\lambda|^2}{1 + 3|\lambda|^2}$$

$$= -0.1173(13)$$

$\Leftrightarrow \lambda = -1.2694(28)$

PDG2010
The rate of $\beta$-decay

$$\frac{d^5 W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2 \xi \left( 1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}} + b \frac{\Gamma m_e}{E_e} \right)$$

polarization $\rightarrow$ + $\vec{\sigma}_n \cdot \left[ A_\beta \frac{\vec{p}_e}{E_e} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right]$ $\beta$ asym $\nu$ asym $T$-violating

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

$$A_\beta = -2 \frac{\left| \lambda \right|^2 + \Re e(\lambda)}{1 + 3 \left| \lambda \right|^2}$$

$$= -0.1173(13) \iff \lambda = -1.2694(28)$$

$$= -0.1138(46)(21) \iff \lambda = -1.2603(134)$$

$\Rightarrow$ UCNA

PRL 102 (2009)
The rate of $\beta$-decay

$$\frac{d^5W}{dE_e d\Omega_{e} d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi \left( 1 + a_{\beta\nu} \frac{\vec{p_e} \cdot \vec{p_{\nu_e}}}{E_e E_{\nu_e}} + b \frac{\Gamma m_e}{E_e} \right)$$

polarization $\rightarrow$ + $\vec{\sigma}_n \cdot \left[ A_\beta \frac{\vec{p_e}}{E_e} + B_\nu \frac{\vec{p_\nu}}{E_\nu} + D \frac{\vec{p_e} \times \vec{p_\nu}}{E_e E_\nu} \right]$ (Fierz term $T$-violating)

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

$$A_\beta = -2 \frac{|\lambda|^2 + \Re e(\lambda)}{1 + 3|\lambda|^2}$$


$$= -0.1173(13) \quad = -0.1138(46)(21) \quad = -0.1197(9)(^{+12}_{-14})$$

$\Leftrightarrow \lambda = -1.2694(28) \quad = -1.2603(134) \quad = -1.2759(^{+41}_{-45})$

UCNA

Continue to beat down the errors

Plans for $b, B_\nu \ldots$
The $\beta^+$-decay of $^{37}\text{K}$

$$ft = (\text{phase space}) (\text{partial half-life}) = \frac{K}{G_V^2|M_F|^2 + G_A^2|M_{GT}|^2}$$
The $\beta^+$-decay 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 $\rho \equiv G_A M_{GT}/G_V M_F$

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

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

$B.R. = 0.9799(14)$

and $t_{1/2} = 1.225(7) \text{ s}$
Present status of $^{37}$K’s $f t$ value

\[
\begin{align*}
Q_{EC} & : \pm 0.003\% \\
BR & : \pm 0.14\% \\
t_{1/2} & : \pm 0.57\%
\end{align*}
\]

\[
\begin{align*}
ft & = 4533(28) + \delta'_{NS} - \delta'_{C} : \pm 0.06\% \\
Ft & = 4562(28)
\end{align*}
\]

Lifetime limits the $Ft$ value
Present status of $^{37}$K’s $f_t$ value

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

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

$$\mathcal{F}t = 4562(28)$$

Lifetime limits the $\mathcal{F}t$ value

$^{38}$Ar($p$, $2n$)$^{37}$K at CI:

Produces $\approx 20,000$ pps
Present status of $^{37}$K's $ft$ value

\[ Q_{EC}: \pm 0.003\% \]
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\[ ft = 4533(28) + \delta'_{R} : \pm 0.04\% \]
\[ \delta'_{NS} - \delta'_{C} : \pm 0.06\% \]
\[ \mathcal{F}t = 4562(28) \]

Lifetime limits the $\mathcal{F}t$ value

$^{38}$Ar($p$, $2n$)$^{37}$K at CI:

Production limit the $\mathcal{F}t$ value

- $t_{1/2} = 1.2325(20)$ s
- $\chi^2/495 = 1.015$
- CL = 40%

Produces $\approx 20,000$ pps; $t_{1/2}$ measurement 2 months ago
A measurement of $|V_{ud}|$?

Not yet ... to get $V_{ud}$, still need $\rho \equiv \frac{G_A M_{GT}}{G_V M_F}$

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

see Naviliat-Cuncic and Severijns, PRL 102, 12302 (2009)
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see Naviliat-Cuncic and Severijn, PRL 102, 12302 (2009)

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

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

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

Just like the neutron, need to measure a correlation parameter (e.g. $A_\beta$) to determine $\rho$
A measurement of $|V_{ud}|$?

Not yet ... to get $V_{ud}$, still need $\rho \equiv G_A M_{GT} / G_V M_F$

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

see Naviliat-Cuncic and Severijns, PRL 102, 12302 (2009)

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

$$dW \sim 1 + a \beta \nu \hat{p}_e \cdot \hat{p}_\nu E_e E_\nu + b \Gamma_{m} E_e + D \hat{p}_e \times \hat{p}_\nu E_e E_\nu + c \langle (\hat{I} \cdot \hat{i})^2 \rangle$$

FIG. 1. $\mathcal{F}t_0$ values deduced for five mirror transitions as a function of the mass number of the mirror nuclei. The horizontal band shows the $\pm 1\sigma$ limits of the result from the fit.
### Present correlation parameter values

<table>
<thead>
<tr>
<th>Correlation</th>
<th>SM prediction</th>
</tr>
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<tbody>
<tr>
<td>$\beta - \nu$ correlation:</td>
<td>$a_{\beta\nu} = \frac{1-\rho^2/3}{1+\rho^2} = 0.6580(61)$</td>
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<td>Fierz interference parameter:</td>
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<td>Alignment parameter:</td>
<td>$c_{\text{align}} = \frac{4\rho^2/5}{1+\rho^2} = 0.2052(62)$</td>
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<td>Time-violating $D$ coefficient:</td>
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- **$R_{\text{slow}}$** specific to our geometry

\[ R_{\text{slow}} \sim \frac{1-a_{\beta\nu}-2c_{\text{align}}/3 - (A_\beta-B_\nu)}{1-a_{\beta\nu}-2c_{\text{align}}/3 + (A_\beta-B_\nu)} = 0 \]

\[ \mathcal{F}t + |V_{ud}^{0\rightarrow0}| \text{ give } \rho \]
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$\mathcal{F}t + |V_{ud}^{0\rightarrow0}| \text{ give } \rho \rightarrow \text{ SM predictions for correlation params}$
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\[
\mathcal{F}t + |V_{ud}\rangle^0 \rightarrow 0 | \text{ give } \rho \rightarrow \text{ SM predictions for correlation params} \\
\rightarrow \text{ search for new physics}
\]

(see Severijns, et al., PRC 78, 055501 (2008))
New physics would affect values

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))
The $\beta$ asymmetry

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

- **recoil order corrections** under control
- **value sensitive to RHCs**
- **energy-dependence sensitive to SCCs**

\[ \pm 1.2\% \text{ in } \rho \]

\[ \delta = \zeta = 0.04 \]

\[ \pm 12\% \text{ in } g \]

\[ \delta = -\zeta = 0.04 \]

\[ d/A_c = 0.0 \pm 0.3 \pm 0.3 \]
Polarizing the cloud

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

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

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

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

\[ m_F = -2 \quad -1 \quad 0 \quad 1 \quad 2 \]
\[ \vec{B}_{op} = 2.5 \text{ G} \]
Polarizing the cloud

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

can monitor atomic fluorescence via photoions

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

\begin{align*}
I &= \frac{3}{2} \\
J &= \frac{1}{2}
\end{align*}

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

\[ \vec{B}_{\text{op}} = 2.5 \text{ G} \]
Atomic measurement of $P$

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

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

$$\text{Asymmetry} = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) + N(\sigma^-)}$$

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

- $P = 1$
- $P = 0.967$
- finite vacuum
- $A = 81.3(1.0)\%$
- $P = (0.28\pm0.49)\%$
- $(-0.87\pm0.61)\%$
- $A = -79.2(1.5)\%$

**Diagram:***
- 355 nm laser
- CaF$_2$ trap laser
- CaF$_2$ “A”
- CaF$_2$ “B”
- mirror
- Be foil
- photoionization
- MCP
- push beam
- $D_1$ optical pumping
- $D_2$ trap laser
- BC408 $\Delta E$
Asymmetry = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) + N(\sigma^-)} \\
\sim P A_\beta \left\langle \frac{p_e}{E_e} \right\rangle

atoms can get sprayed onto the thin mirrors and walls . . .
recoil coincidences cleaner!
Measuring $B_\nu$ (and $D$)

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

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

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

\[ \hat{x} \text{ asymmetry} \sim PB_\nu \]
\[ \hat{y} \text{ asymmetry} \sim PD \]
1\textsuperscript{st}: \langle B_\nu \rangle = (0.995 \pm 0.040) B^{\text{SM}}_\nu \\

2\textsuperscript{nd}: \langle B_\nu \rangle = (0.975 \pm 0.031) B^{\text{SM}}_\nu \\

\Rightarrow B_\nu = 0.981(26)(17) B^{\text{SM}}_\nu \\

(Melconian, PLB 649 (2007) 370)
# $B_\nu$ error budget

<table>
<thead>
<tr>
<th>Source</th>
<th>$\langle \Delta B_\nu \rangle / B_\nu^{\text{SM}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1$^{\text{st}}$</td>
</tr>
<tr>
<td>Asymmetry fit</td>
<td>±4.0</td>
</tr>
<tr>
<td>Polarization ${ $</td>
<td>stat</td>
</tr>
<tr>
<td>cloud position/velocity</td>
<td>+1.5</td>
</tr>
<tr>
<td>cloud size/temperature</td>
<td>−1.0</td>
</tr>
<tr>
<td>binning</td>
<td>+0.5</td>
</tr>
<tr>
<td>MCP efficiency/calibration</td>
<td>−0.0</td>
</tr>
<tr>
<td>MCP rotation</td>
<td>+0.4</td>
</tr>
</tbody>
</table>

With $B_\nu^{\text{SM}} = −0.7791$

$$B_\nu = −0.765 \pm 0.020 \pm 0.013$$

(stat) (syst)
The new chamber

- Shake-off $e^-$ detection
- Better control of OP beams
- AC-MOT . . . ? (Harvery & Murray, PRL 101 (2008))
- Increased $\beta$/recoil solid angles
- Stronger $E$-field
- . . .
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

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.
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
Conclusions

- $\beta$ decay correlations continue to test the SM:
  - $0^+ \rightarrow 0^+$ decays: scalar currents, CVC, $|V_{ud}|$/CKM unitarity
  - (ultra-cold) neutron decay: $g_A$, $|V_{ud}|$, RHCs, $T$-violation, ...
  - polarized mirror transitions: ditto

- Elegant (and fun!) tools of the trade:
  - MOTs: textbook $\beta$ decay
  - ion traps: more than just alkalis
  - polarized, laser-cooled atoms: very promising next generation of expts

Mille Grazie!