**$\beta^+$ asymmetry in spin-polarized $^{37}$K decay**

- The most accurate $A_\beta$ measurement
  Agrees with theory prediction

- Constraints on:
  Weak interaction changes within nuclei
  Non-SM lepton helicities:
  Left-right symmetric models.
  4-fermi contact Lorentz ‘scalar’, ‘tensor’

TRIumf Neutral Atom Trap collaboration:

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Lepton helicity $\rightarrow$ angular distribution

$^{37}\text{K} \rightarrow ^{37}\text{Ar} + \nu$

$^{37}\text{K}$

$^{-}$

This decay pattern needs non-S.M. chirality

$I=3/2 \rightarrow I=3/2$:

Leptons can’t increase nuclear spin any further
One experimental discovery of parity violation

Wu, Ambler, Hayward, Hopper, Hobson, PR 105 (1957) 1413

Dilution
Refrigerator
to spin-polarize

$$^{60}\text{Co} \rightarrow ^{60}\text{Ni} + \beta^- + \bar{\nu}$$

$$W[\theta] = 1 + PA\hat{I} \cdot \frac{\vec{p}_\beta}{E_\beta}$$

$$= 1 + A\frac{\nu}{c} \cos[\theta]$$

$$A_{\beta^-} \approx -1.0$$

Followup $$^{58}\text{Co} \rightarrow ^{58}\text{Fe} + \beta^+ + \nu$$

$$A_{\beta^+} > 0$$

Wauters 2010 PRC $A_{^{60}\text{Co}} = -1.014 \pm 0.020$ [SM $-0.987 \pm 0.009$]
$^{37}$K isobaric mirror decay: a ‘heavy neutron’?

Here $A_\beta$ isn’t 1 or -1 or a clean fraction. There are 2 operators:

‘Fermi’ changes n to p

‘Gamow-Teller’ changes n to p and nucleon spin

$\tau$, $Q$, and branch $\Rightarrow$ decay strength $\mathcal{F}t$

We know the Fermi $\mathcal{F}t_0$ from the $0^+ \rightarrow 0^+$ decays, so from $\mathcal{F}t$ we can get the Gamow-Teller strength:

$$\mathcal{F}t \ (\text{Shidling PRC 2014}) \Rightarrow \rho = C_A M_{GT} / C_V M_F = 0.5768 \pm 0.0021$$

$\Rightarrow A_\beta [SM] = -0.5706 \pm 0.0007$

Main uncertainty is experimental branching ratio.
$^{37}$K isobaric mirror decay: a ‘heavy neutron’

$\Rightarrow A_\beta[SM] = -0.5706 \pm 0.0007$

Dominant uncertainty is exp. branching ratio

1st-order recoil-order from E&M moments:

- Induced tensor $d_1 \approx 0$,
- Small $\mu \Rightarrow$ small weak magnetism

Recoil-order + Coulomb + finite-size corrections $\Rightarrow$ $
\Delta A_\beta \approx -0.0028 \left( \frac{E_\beta}{E_0} \right)$
Holstein RMP 1975

Isospin mixing contributes 0.0004 uncertainty from shell model

DFT for isospin mixing has improved its functional

Using weighted average for $\delta_C$ would $\Rightarrow 0.0004 \rightarrow 0.0005$
TRIumf Neutral Atom trap at ISAC

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

$A_\beta$ physics

extras

j.a.behr triumf cap17

$^{37}\text{K} \ 8 \times 10^7 / \text{s}$

TiC target

1750°C

70 μA

protons

main TRIUMF cyclotron
‘world’s largest’

500 MeV H$^-$ (0.5 Tesla)
TRINAT lab: “tabletop experiment”

- **ISAC ion beam**
- **TRINA T lab**
- **“tabletop experiment”**
- **Detection trap 0.3 picoatmosphere**
- **Ring Laser**
- **Collection trap**
- **Beta detector**
- **Pb shielding**
- **CCD Camera**
- **Atom detector**
\( ^{37}K \) decay geometry

- \( \beta \), recoil nucleus
- shakeoff \( e^- \) for TOF trigger

This decay pattern is helicity-forbidden if the \( \nu \) goes straight up, independent of Gamow-Teller/Fermi ratio.
Optical pumping and probing $^{37}\text{K}$

Photoionize 1% in situ probe

$P_+ = +0.9913(8)$

$P_- = -0.9912(9)$

$\sigma \propto (1-P)$

Fenker NJP 2016
$\beta^+$ asymmetry $^{37}$K data

- Backscatter from scint agrees to $\sim$10%
Background

- $2.8 \times 10^{-3}$ of events in main peak are background from non-trapped atoms
- Conservatively assume polarized between 0 and 100%.
  $\rightarrow A_\beta \times (1.0014 \pm 0.0014)$
- These will be removed by MCP position info when we increase to design $E$ field
### $^{37}$K $A_\beta$+ Uncertainties

<table>
<thead>
<tr>
<th>Source $\times 10^{-4}$ [†: $\beta$ scattering]</th>
<th>$\Delta A_\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background (Correction 1.0014)</td>
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<tr>
<td>Trap Position</td>
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<td>BB1 Radius†</td>
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<td>Scintillator threshold</td>
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<td>GEANT4 physics list†</td>
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<td>Shakeoff electron t.o.f. region</td>
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<td>SiC mirror thickness†</td>
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<tr>
<td>Be window thickness†</td>
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<td>Scintillator or summed†</td>
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<td>Total systematics</td>
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<td>Statistics</td>
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<tr>
<td>Polarization</td>
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</tr>
<tr>
<td>Total uncertainty</td>
<td>18</td>
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</tbody>
</table>

$A_\beta = -0.5707 \pm 0.0013 \text{ (stat)} \pm 0.0012 \text{ (syst)} \pm 0.0005 \text{ (pol)}$

$= -0.5707 \pm 0.0018$

$A_\beta[\text{SM}] = -0.5706 \pm 0.0007$

Better relative uncertainty than

$^{19}$Ne $-0.0360 \pm 0.0008$

[Calaprice 1975]

and neutron

$0.1197 \pm 0.0006$

[PERKEO II PRL 2013, UCNA PRCr 2013]
Weak interaction: same strength, all nuclei?

\[ A_\beta \Rightarrow GT/F \]

Then \( \mathcal{F}t \) of \( ^{37}K \Rightarrow V_{ud} \)

- An isospin mixing test useful for
- \( 0^+ \rightarrow 0^+ \) determination of \( V_{ud} \) i.e. \( \psi[n] \neq \psi[p] \)

- Salam and Strathdee
  Nature 1974: phase transitions at very high B fields could drive \( V_{ud} \rightarrow 1 \)

Hardy Towner PLB 1975 applied to the \( ^{35}Ar A_\beta \) controversy.

\( ^{19}Ne \) Broussard DNP 2016
Why the weak interaction is ‘weak’ at low energy

‘more massive virtual particles are created for shorter times’

Propagator+vertices:

\[ T \propto \frac{G_X(-g^{\mu\nu} + p^\mu p^\nu / M_X^2)G_X}{p^2 - M_X^2} \quad p << M_X \]

\[ T \propto \frac{G_X^2}{M_X^2} \Rightarrow \]

- **Decay rates** \( \propto \frac{G_X^2 G_X'^2}{M_X^4} \)
  or \( \propto \frac{G_X^2}{M_W^2} \frac{G_X G_X'}{M_X^2} \) if process interferes with W
  (couples to SM-handed \( \nu \))
  e.g. Fierz term \( \propto \frac{m}{E_\beta} \)

- **IF** \( G_X \sim \) electroweak coupling, then 0.1% sensitivity in angular correlations \( \rightarrow M_X \sim 6 \) or 30 \( M_W \)
Left-Right Symmetric model

Extra $W'$ with heavier mass, couples to $\nu_R$

Otherwise same coupling strength, so parity is a good symmetry at very high energy

$\delta \equiv (M_1/M_2)^2$

$M'_{W_R} > 352$ GeV 90%

$37^K$: $M'_{W_R} > 3.7$ TeV 90%

$\nu_\mu^R > \nu_\mu$ but LHC $M'_{W_R} > 3.7$ TeV 90%
\( g_R > g_L : \)

\[ ^{37}\text{K} \Rightarrow g_R \lesssim 7.7 \text{ at } 4 \text{ TeV} \]

(or \( g_R < 4 \), at 2 TeV but LHC7 2 TeV ‘bump’ had \( g \sim 0.5 \))

\[ V_{ud}^R < V_{ud}^L \]

For \( M'_W < 70 \text{ GeV} \), nuclear \( \beta \) decay constrains \( V_{ud}^R \)
$A_\beta \ [E_\beta]$ agrees with S.M.

New interactions that make normal-helicity $\nu$'s 'interfere' with S.M. Fierz term $\propto \frac{m_\beta}{E_\beta}$

CMS PRD 91 92005

Bhattacharya PRD 94 054508 (2016) combined ATLAS, CMS:
future $A_{\text{recoil}} \propto A_\beta + B_\nu$

Technique demonstrated in $^{80}\text{Rb}$ Pitcairn PRC 2009

$A_{\text{recoil}}$ depends on $\rho$; $p$ dependence doesn’t

$37\text{K} A_\beta$ physics extras j.a.behr triumf cap17
Helicity-driven null in mirror decay

\[ W(\theta_{\beta\nu i}) \approx 1 + A_{\beta\nu i} \cos(\theta_{\beta\nu i}) \]

\[ A_{\beta\nu i} = \frac{a + PB - 2cT/3}{1 + PA} \]

For \( P = -1 \), \( A_{\beta\nu i} = 1 \), independent of \( M_{GT}/M_F \)

2014 data under analysis
TRIUMF Neutral Atom Trap: Near Future

We have measured the $\beta$ asymmetry of $^{37}$K decay to be $A_\beta = -0.5707 \pm 0.0018$

Agrees with theory $-0.5706 \pm 0.0007$, complements the best $\beta$ decay measurements

We plan to measure $A_\beta[E_\beta]$ 3-5 x better, and $A_{\text{recoil}}$ with sensitivity to ‘4-fermion contact’ interactions complementary to $\pi \rightarrow e\nu\gamma$, $\pi \rightarrow e\nu$, and $\text{LHC } p + p \rightarrow e + E_\perp$

We also plan a TRV $\beta\nu\gamma$ 3-momentum correlation, first of its type in 1st-generation particles
the Fierz term is ‘easier’ to constrain but has more competition.

For scalars coupling to wrong-chirality $\nu$, we compete with our own $^{38mK} \beta-\nu$ Gorelov 2005.
# Polarization Improvements

**SYST** $\times 10^{-4}$

<table>
<thead>
<tr>
<th></th>
<th>$\Delta P$</th>
<th>$\Delta T$</th>
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</thead>
<tbody>
<tr>
<td>$\sigma^-$</td>
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<td>10</td>
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<tr>
<td>$\sigma^+$</td>
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<td>8</td>
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<td>$\sigma^-$</td>
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<tr>
<td>$\sigma^+$</td>
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Initial $T$

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<td>$B_z$ Uncertainty</td>
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Initial $P$

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<td>Total SYSTEMATIC</td>
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<tr>
<td>STATISTICS</td>
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<td>21</td>
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</tbody>
</table>


$P(\sigma^+) = +0.9913(8)$ \hspace{1cm} $T(\sigma^+) = -0.9770(22)$

$P(\sigma^-) = -0.9912(9)$ \hspace{1cm} $T(\sigma^-) = -0.9761(27)$

- pellicle mirrors: less $\beta^+$ scattering
- define $T$ by OP
- trim B gradients
- improve $S_3$ flipping and gradients
- add flipping of $B_z$
- higher-power photoionizing laser
- gentler RAC-MOT

**Uncertainty** $\propto (1-P)$
MSSM and $\beta$ decay correlations

Profumo, Ramsey-Musolf, Tulin
PRD 75 075017 2017

$C_S + C'_S$ can be 0.001 in MSSM in 1-loop order including mixing

Include mixing of:
- left and right sfermions (this is where $\beta$ decay can help; constraints are said to be few)
- sfamily mixing (already tightly constrained, e.g. by $\mu \rightarrow e \gamma$...)

Effective 4-fermi scalar and tensor couplings are generated that contribute to $b_{\text{Fierz}}$ and spin correlation observables like $B_\nu$ as large as 0.001.
Weakly-coupled $W'$ still has electric charge

Does $\sigma \ e^+ + e^- \rightarrow W^+ + W^-$ double for $W'$?

Depends on the cut for $W$: typically this cut (explicitly listed in PDG) excludes low-mass $W$ because of serious background
nucleon form factors

Herczeg Prog Part Nucl Phys 46 (2001) 413 pointed out need for form factors

\[ \langle p|\bar{u}d|n\rangle = g_s(q^2)\bar{u}_p u_n \]

\[ \langle p|\bar{u}\sigma_{\lambda\mu}d|n\rangle = g_T(q^2)\bar{u}_p \sigma_{\lambda\mu} u_n \]

2001: “0.25 < g_s < 1” depressing to the experimentalist

\( g_T \) related to transverse spin structure function

Bhattacharya, Cirigliano, et al. PRD 85 05412 (2012) first lattice gauge calculations,

\( g_s = 0.8 \pm 0.4, \quad g_T = 1.05 \pm 0.35 \)

\( \rightarrow \) (2016) PRD 94 054508

\( g_s = 0.97 \pm 0.12 \pm 0.06, \quad g_T = 0.987 \pm 0.051 \pm 0.020 \)

\( g_s = 1.02 \pm 0.10 \) Gonzalez-Alonso, Camalich PRL 112 042501 (2014) isospin symmetry
“2nd-class” weak interactions would violate isospin symmetry when quarks are combined by QCD into nucleons. “Induced tensor” $d$ is near zero in isobaric mirror decay.

This result is complementary to other nuclear $\beta$ decay (Sumikama PRC 2011) in models where 2nd-class currents change with system (Wilkinson EPJA 2000)

Babar set best 3-generation constraints PRL 2009

$\tau^- \rightarrow \omega \pi^- \nu_\tau$
What elements can be laser cooled?

- H
- Li
- Na
- K
- Ca
- Rb
- Cs
- Fr
- Mg
- Al
- Cr
- Ag
- Ba
- Dy
- Er
- Yb
- He
- Ne
- Ar
- Kr
- Xe
- ANL
- LANL, TRIUMF
- LANL
- Stony Brook, JILA, Legnaro

Trapped in MOT
Radioactives trapped
Long-lived Rad.
Plans
Super-ratio

\[
A_{\text{obs}}^{\text{SR}}(E_e) = \frac{1 - s(E_e)}{1 + s(E_e)} = A_{\text{obs}}
\]

\[
s(E_e) = \sqrt{\frac{r_1^{-}(E_e)r_2^{+}(E_e)}{r_1^{+}(E_e)r_2^{-}(E_e)}}
\]

B. Plaster et al. PRC 86 (2012) 055501