Superallowed Fermi Beta Decay Studies at TRIUMF-ISAC

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The Cabibbo-Kobayashi-Maskawa (CKM) matrix

The CKM matrix plays a central role in the Standard Model and underpins all quark flavour-changing interactions: weak interaction eigenstates $\neq$ quark mass eigenstates.

\[
\begin{pmatrix}
b' \\ s' \\ b'
\end{pmatrix} =
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}\begin{pmatrix}
d' \\ s \\ b
\end{pmatrix}
\]

In the Standard Model the CKM describes a unitary transformation.

\[V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1\]

The first row of the CKM matrix provides, by far, the most demanding experimental test of this unitarity condition.
CKM Unitarity

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.00008(43)V_{ud}(36)V_{us} \]

New Lattice QCD Form Factor Calculations for $V_{us}$


$K^+ \rightarrow l\nu / \pi^+ \rightarrow l\nu$  \hspace{1cm} (HPQCD Collaboration)

$|V_{us}| = 0.22564(53)$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.00009(43) V_{ud}(24) V_{us}$


$K^+ \rightarrow \pi^+ l\nu$  \hspace{1cm} (Fermilab Lattice and MILC Collaborations)

$|V_{us}| = 0.22290(90)$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99885(43) V_{ud}(40) V_{us}$
To first order, $\beta$ decay $ft$ values can be expressed as:

$$ft = \frac{K}{|M_{fi}|^2 g^2}$$

constants

Weak coupling strength

matrix element

phase space ($Q$-value)

half-life, branching ratio

For the special case of $0^+ \rightarrow 0^+$ (pure Fermi) $\beta$ decays between isobaric analogue states (superallowed) the matrix element is that of an isospin ladder operator:

$$|M_{fi}|^2 = (T - T_Z)(T + T_Z + 1) = 2 \quad \text{(for } T=1\text{)}$$

Strategy: Measure superallowed $ft$-values, deduce $G_V$ and $V_{ud}$:

$$G_V^2 = \frac{K}{2 \ ft}$$

$$|V_{ud}| = \frac{G_V}{G_F}$$

Vector coupling constant

Fermi coupling constant
Superallowed $ft$-values

$$ft \approx \frac{K}{2G_v^2} = \text{constant (CVC)}$$
Superallowed Fermi $\beta$ Decay: Corrections

\[ \mathcal{F}_t = ft \left( 1 + \delta'_R \right) \left( 1 + \delta_{NS} - \delta_C \right) = \frac{K}{2G_V^2 \left( 1 + \Delta_R^V \right)} = \text{constant} \]

$\Delta_R^V = \text{nucleus independent inner radiative correction: } 2.361(38)\%$

$\delta'_R = \text{nucleus dependent radiative correction to order } Z^2 \alpha^3: \sim 1.4\%$

- depends on electron’s energy and $Z$ of nucleus

$\delta_{NS} = \text{nuclear structure dependent radiative correction: } -0.3\% - 0.03\%$

$\delta_C = \text{nucleus dependent isospin-symmetry-breaking correction: } 0.2\% - 1.5\%$

- strong nuclear structure dependence
Corrected Superallowed $\mathcal{F}t$ Values

$$\mathcal{F}t_{WS} = 3072.38(75)$$
$$\chi^2/\nu = 0.32$$

Theoretical Treatment of $\delta_C$

Many recent approaches to ISB corrections

→ Nuclear Shell Model
→ Relativistic Hartree-Fock
→ Random Phase Approximation
→ Energy Density Functional
Difference between Woods-Saxon and Hartree-Fock Radial Overlap Corrections
Up to 100 μA, 500 MeV proton beams from the TRIUMF main cyclotron produce high-intensity secondary beams of many of the superallowed emitters by the ISOL technique.
Superallowed Fermi $\beta$ Decay Studies at ISAC

- Halflives (GPS)
- Branching ratios ($8\pi$)
- Masses (TITAN)

Charge Radii (laser spectroscopy)

Near Future (GRIFFIN)

Halflives (ZDS)
Superallowed $\beta$ Decay Studies at ISAC

$T_{1/2}$, G.F. Grinyer, PRC 77, 201501 (2008)
BR, P. Finlay PRC 78, 044321 (2008)

$T_{1/2}$, G.C. Ball et al, PRL 106, 032501 (2011)
BR, P. Finlay et al, PRC 85, 055501 (2012)

$T_{1/2}$, G.F. Grinyer et al, PRC 76, 025503 (2007)
PRC 87, 045502 (2013)

Q: S. Ettenauer et al., PRL 107, 272501 (2011)
CR: E. Mané et al, PRL 107, 212502 (2011)

$T_{1/2}$ by $\beta$ and $\gamma$ counting
M. Dunlop et al.
Simultaneous independent direct $\beta$ and $\gamma$-ray counting experiments using the $8\pi$ spectrometer and the Zero-Degree Scintillator.

**$\gamma$ Counting:**
- Decay Selective
- Slow & Inefficient

**$\beta$ Counting:**
- Fast & Efficient
- Not Decay Selective

Previous measurements reveal a systematic discrepancy between detection method.
\[ T_{1/2}(\gamma) = 70.598 \pm 0.017 \text{ s} \]

\[ T_{1/2}(\beta) = 70.648 \pm 0.019 \text{ s} \]
$^{14}$O Half-Life Measurement at ISAC

Beam

$^{12}$C-$^{14}$O: $T_{1/2} = 70.620$ s

$^{26}$Al$^{m}$: $T_{1/2} = 6.3465$ s

$^{26}$Na: $T_{1/2} = 1.072$ s

$\gamma$ Counting

$\beta$ Counting
\[ \frac{\chi^2}{v} = 2.27 \]
\[ T_{1/2} = 70.599(19) \text{ s} \]

\[ \frac{\chi^2}{v} = 1.14 \]
\[ T_{1/2} = 70.609(85) \text{ s} \]

\[ \frac{\chi^2}{v} = 0.94 \]
\[ T_{1/2}^{(14)} \text{O} = 70.632 \pm 0.086 \text{ s} \]
Initial experiment shows consistency between $\beta$ and $\gamma$ half-life measurements for $^{14}$O.

A follow-up experiment is scheduled for July, 2014 to push to 0.01% precision.

$ft$ measurements for light superallowed Fermi $\beta$ emitters are required to constrain scalar currents in the weak interaction.

\[ T = 1 \quad ^{18}\text{Ne} \]

\[ T_{1/2} = 1.6654(11) \text{ s} \]
\[ Q = 4443.6 \text{ keV} \]

\[ \beta^+ \quad ^{18}\text{F} \]
\[ 1^+ \quad 0 \quad 92.11\% \]
\[ T_{1/2} = 109.73(2) \text{ min} \]
\[ Q = 1655.5 \text{ keV} \]

\[ T = 0 \quad ^{18}\text{F} \]
\[ 1^+ \quad 0 \quad 92.11\% \]

\[ \beta^+ \quad ^{18}\text{O} \quad 0^+ \]
\[ \text{stable} \]

\[ 0^+ \quad ^{18}\text{Ne} \]

\[ \beta^+ \quad ^{18}\text{F} \]
\[ 1^+ \quad 1701 \quad 0.19\% \]
\[ 0^- \quad 1081 \quad 0.0002\% \]

\[ T = 1 \]

\[ 0^+ \quad 1042 \quad 7.70\% \]
4π Gas Counter and Thick Tape Transport

- 4π continuous-flow gas-proportional counter and tape transport system
- Methane (CH₄) gas
- ~100% efficient β counter
- Very low background rates
$^{18}\text{Ne Sample Data} \quad \text{Gas Counter}$

$T_{1/2}(^{18}\text{Ne}) = 1.66413 \pm 0.00062 \text{ s}$

$\chi^2/\nu = 1.03$
Status of $^{18}\text{Ne}$ Half-life

Half-life precision improved by a factor of 3, to 0.025%
$^{74}$Rb Superallowed Decay ($T_{1/2} \sim 65$ ms)

**Halflife:** Measured with the GPS $4\pi$ gas proportional counter at ISAC.

\[ T_{1/2} = 64.761(31) \text{ ms} \]


**Mass:** First demonstration of a high charge state mass measurement for a short-lived isotope with the TITAN Penning trap.


**Charge Radius:** Measured via collinear laser spectroscopy:

\[ <r_{\text{ch}}^2>^{1/2} = 4.19(1) \text{ fm} \]

Reduces uncertainty in theoretical $\delta_{C2}$ by $\sim 20\%$

*E. Mané et al., Phys. Rev. Lett. 107, 212502 (2011).*

**Branching Ratio:** Measured with the $8\pi$ Spectrometer to $\pm 0.03\%$

\[ \text{BR} = 99.545 \ (31) \% \]

Superallowed $\beta$ Branching Ratios for $A \geq 62$ and the Pandemonium Effect

For large $Q$-value $\beta$ decays, there are generally many weak $\beta$ branches to the large number of daughter states within the $Q$-value window.

In the subsequent $\gamma$ decay, many individual $\gamma$-rays may be too weak to identify.

The sum of these unobserved $\gamma$ intensities will, however, generally be sufficient to prevent precision determination of $\beta$ decay branching ratios through $\gamma$-ray spectroscopy.
Simultaneous collection of $\gamma$-singles, $\gamma\gamma$ coincidences, $\beta$ tagging, conversion electrons, and lifetime measurements
Counting $^{74}\text{Rb} \beta$ Decays with SCEPTAR

# of $\beta$'s: $8.241(3) \times 10^8$
Identifying $\gamma$-rays from $^{74}\text{Rb}$ Decay

Raw $\gamma$-spectrum contains lines from room background and in-beam contaminants.

$\beta$-$\gamma$ coincidence, Bremsstrahlung suppression reduce background.

Spectrum during beam-off allows one to identify long-lived contaminants.
\(\gamma-\gamma\) Coincidences following ppm \(\beta\)-decay branches of \(^{74}\)Rb

All \(\beta - \gamma\) Coincidences

Gated on 456 keV \(\gamma\)-ray
Internal Conversion Decay of the $0^{+}_2$ State of $^{74}\text{Kr}$

$\beta - \gamma -$ electron Coincidence Spectrum
57 γ-ray transitions identified following $^{74}$Rb decay

Ground-state γ-feeding of $I_{gs} = 3950(70)$ ppm identified.
Controlling Pandemonium via $2^+$ “Collector” States

$I_{gs} = 3950(70)$ ppm

Direct $\beta$ feeding of $2^+$ states is negligible

$I'_{2+} = 1225(57)$ ppm

$B_{gs} = \frac{I'_{gs}}{(I'_{gs} + I'_{2+})}$

Expt + Shell Model:

$B_{gs} = 0.33(11)$

$I'_{gs} = 600(300)$ ppm

Superallowed Branching Ratio:

$99.545 \pm 0.031 \%$

R. Dunlop PRC 88, 045501 (2013)
$^{74}$Rb Superallowed Decay

$\bar{t} = 3072.35(75)$ s

$\chi^2/\nu = 0.31$

$\bar{t} = 3071.59(87)$ s

$\chi^2/\nu = 0.85$
$^{74}$Rb Superallowed Error Budget

**Before 2010**

**Current Results**
The Future …

Gamma Ray Infrastructure For Fundamental Investigations of Nuclei

A new high-efficiency decay spectroscopy facility for ISAC-I
16 large-volume clover-type HPGe γ-ray detector

17 times the efficiency of the 8π at $E_\gamma = 1\ \text{MeV}$

Efficiency improvement increases with γ-ray energy

$\sim 300x$ the γ-γ efficiency of the 8π
$^{74}$Rb Superallowed Decay with GRIFFIN

Gate on 456 keV
(a) 8pi Spectrometer

(b) GRIFFIN

Energy (keV)

Counts/keV
Angular Correlation Measurements with GRIFIFN (S1518: $^{62}$Ga superallowed decay)

Using GRIFIFN we can determine the spin-parity of the 2342 keV state.
World Superallowed Fermi $\beta$ Decay Data

$F_t = 3072.35(75)$ s

$\chi^2/\nu = 0.31$
World Superallowed Fermi β Decay Data

CVC hypothesis confirmed to ± 0.013%

Set limits on maximally parity violating weak scalar currents:

$$\frac{C_S}{C_V} = 0.0011 \pm 0.0013$$

$V_{ud}$ determined from the superallowed data is, by far, the most precisely determined element of the CKM quark-mixing matrix:

$$|V_{ud}| = 0.97425 \pm 0.00022$$

and together with $V_{us}$ (and $V_{ub}$) provides the most demanding experimental test of the unitarity of the CKM matrix:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.00008 \pm 0.00056$$

Model-dependence of the strongly nuclear structure dependent isospin symmetry breaking corrections in superallowed Fermi β decays remains a key focus of research for both the theoretical and experimental communities.
Superallowed $\beta$ Decay Studies at ISAC

- $T_{1/2}$, G.F. Grinyer, PRC 77, 201501 (2008)
- BR, K.G. Leach et al., PRL 100, 192504 (2008)
- $T_{1/2}$, G.C. Ball et al, PRC 82, 045501 (2010)
- $T_{1/2}$, G.F. Grinyer et al, PRC 76, 025503 (2007)
- PRC 87, 045502 (2013)
- Q: S. Ettenauer et al., PRL 107, 272501 (2011)

$T_{1/2}$ by $\beta$ and $\gamma$ counting M. Dunlop et al.