High-Precision Half-Life and Branching Ratio Measurements for the Superallowed $\beta^+$ Emitters at the TRIUMF-ISAC Facility

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Superallowed Fermi Beta Decays

- In general, $\beta$ decay $f_t$ values can be expressed as:

$$f_t = \frac{K}{G_A^2 |M_{fi}(GT)|^2 + G_V^2 |M_{fi}(F)|^2}$$

- For the special case of $0^+ \rightarrow 0^+$, we have a pure Fermi ($S_\beta = 0$) allowed ($L_\beta = 0$) transition. Transitions between *isobaric analogue states* are known as superallowed Fermi beta decays.
Testing Fundamental Properties of the Weak Interaction with Superallowed Decays

• The Fermi beta decay transition is the isospin ladder operator. For superallowed transitions between T=1 isobaric analogue states, the matrix element is simply:

\[ |M_{fi}(F)|^2 = (T - T_Z)(T + T_Z + 1) = 2 \]

• The superallowed ft values thus simplify:

\[ ft = \frac{K}{G_A^2 |M_{fi}(GT)|^2 + G_V^2 |M_{fi}(F)|^2} \Rightarrow \frac{K}{2G_V^2} \]

- = 0 for Pure Fermi decays
- = 2 for decays between T=1 IAS
- constants (Conserved Vector Current hypothesis)
A Selection of Beta Decay $ft$ Values

![Graph showing beta decay $ft$ values for various isotopes.](image)
Superallowed ft values

\[ ft \approx \frac{K}{2G^2_V} \]

\[ 2\% \]
Superallowed Fermi Beta Decay: Theoretical Corrections

\[ F_t = F_t \left(1 + \delta_R \right) \left(1 + \delta_{NS} - \delta_C \right) = \frac{K}{2G_v^2 \left(1 + \Delta_R \right)} = \text{constant} \]

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

\( \delta_R = \text{nucleus dependent radiative correction to order } Z^2 \alpha^3: \approx 1.4\% \)
  - depends on electron’s energy and \( Z \) of nucleus

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

\( \delta_C = \text{nucleus dependent isospin-symmetry-breaking (ISB) correction: } 0.2\% \text{ to } 1.5\% \)
  - strong nuclear structure dependence (radial overlap)
Corrected Superallowed $F_t$ Values

- The superallowed data confirm the CVC hypothesis at the level of $1.2 \times 10^{-4}$. 

\[
F_{t\text{WS}} = 3072.27(62)_{\text{stat}}^{(36)}_{\delta R} \text{ s}, \quad \chi^2/\nu = 0.52
\]
Search for Physics Beyond the Standard Model

- Can use the superallowed data to search for contributions from scalar couplings in the weak interaction.

**SM description**

\[ \mathcal{F} t = \text{constant} \]

With Scalar Interaction

\[ \mathcal{F} t (1 + b_F \gamma \langle W^{-1} \rangle) = \text{constant} \]

\[ W = \text{Total Positron Energy} \]
\[ b_F = \text{Fierz Interference Term} \]
\[ \gamma = \sqrt{1 - (\alpha Z)^2} \]

The \langle W^{-1} \rangle dependence means that it is the lowest-Z decays that are most sensitive to contributions from a scalar interaction.

Current limit from Hardy & Towner, Phys Rev. C, 91, 025501 (2015): \( b_F = -0.0028(26) \)

Limits dominated by the lightest superallowed decays \( ^{14}\text{O} \) and, in particular, \( ^{10}\text{C} \).
• Up to 100 $\mu$A, 500 MeV protons from TRIUMF’s main cyclotron are accelerated onto targets which produce high-intensity secondary radioactive ion beams by the ISOL technique
High-Precision Half-Life Measurements
\(^{10}\text{C},\ ^{14}\text{O},\ \text{and} \ ^{18}\text{Ne} \) decay schemes

- Characteristic \(\gamma\)-rays are emitted following the \(\beta\) decays of the light \((T_Z = -1)\) superallowed emitters
- Half-life measurements can be performed by both direct \(\beta\) counting and \(\gamma\)-ray photopeak counting

\[ Q = 3648 \text{ keV} \]

\[^{10}\text{C}, \ ^{14}\text{O}, \ \text{and} \ ^{18}\text{Ne} \] decay schemes
γ Counting — The $8\pi$ Spectrometer

- Spherical array of 20 BGO Compton suppressed HPGe detectors
- $\sim 1\%$ photopeak efficiency at 1.3 MeV
The $8\pi$ spectrometer can be used in combination with several auxiliary detectors, one of which is the ZDS.

- Fast plastic scintillator, $\sim20\%$ solid angle coverage
- Cycles: Beam is implanted onto a tape at the centre of the array. The decay activity is measured for many half-lives. The tape is then moved into disposal box which is shielded by a lead wall in order to remove any long lived contaminants out of view of the detector.
β Counting — 4π gas counter

- 4π continuous-flow proportional gas counter with tape transfer system
- Directly detects β particles with ~100% efficiency
- Cycles: Implant beam, move into gas counter and measure the decay activity for many half-lives. Move tape into tape disposal box to remove long-lived contaminants from the gas counter
The $^{10}$C half-life

- The adopted $^{10}$C half-life is evaluated using the 4 most precise measurements.
- The inconsistencies in the dataset result in a highly inflated uncertainty on the adopted world average half-life.

\[ T_{1/2} = 19.3052 \pm 0.0071 \text{ s} \]

The $^{10}\text{C}$ half-life

- More than 200 individual superallowed measurements of comparable precision are currently used to set the limit on $b_F$.
- If the half-life from either of the two peaks in the ideograph is adopted, the central value of $b_F$ is shifted by more than $0.5\sigma$.
- An accurate and precise determination of the $^{10}\text{C}$ half-life is thus critical to the limits set of $b_F$ set by the superallowed data.

$\begin{align*}
\text{bf} &= -0.0016 \pm 0.0026 \\
\text{bf} &= -0.0031 \pm 0.0026
\end{align*}$
γ Photopeak Counting

A total of 58 runs were taken, comprised of 562 cycles. The dead-time and pile-up corrected data are summed and a single fit to the data is performed.
\[ T_{1/2,\gamma}(^{10}\text{C}) = 19.2969 \pm 0.0052_{\text{sys}} \pm 0.0052_{\text{stat}} = 19.2969 \pm 0.0074 \text{ s} \]

Relative precision of 0.03%
**β Counting**

**A=10 Beam:**
- $^{10}$C: $T_{1/2} = 19.3$ s

**$^{10}$C$^{16}$O:** $T_{1/2} = 19.3$ s

**$^{13}$N:** $T_{1/2} = 598$ s

Contaminant, with $T_{1/2}$ consistent with that of $^{13}$N, was measured in the A=26 beam. Could be delivered as:
- $^{13}$N$_2$ (mass diff. to $^{10}$C$^{16}$O ~10 ppm)
- HC$^{13}$N (mass diff. ~70 ppm), etc…
β Counting — Systematics

• Extensive investigation of systematics was performed.
• No inflation of the statistical uncertainty (all $\chi^2/\nu < 1$)
• Vary the fixed parameters within their ±1σ limits. No statistically significant change in the half-life is observed.

$T_{1/2}(^{10}\text{C}) = 19.3009 \pm 0.0017$ s

The most precise (0.009%) superallowed $T_{1/2}$ reported to date!
Results — $^{10}$C Half-life

$T_{1/2} = 19.3015 \pm 0.0025$ s

Improvement in the uncertainty by a factor of 3!

- Updated $^{10}$C half-life

$\chi^2/\nu = 0.44$

$\{b_F = -0.0018(21)$ and $C_s/C_V = -b_F/2 = 0.0009(11)\}$

Grouping the previous $^{14}$O half-life measurements based on detection method (direct $\beta$ counting or detecting the 2313 keV $\gamma$-ray) yields half-lives that disagree at the 2\(\sigma\) level.
$^{14}$O Half-life Measurements

**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

**β** (ZDS)

$\chi^2/\nu = 2.27$
$T_{1/2} = 70.599(19)$ s

**γ**

$\chi^2/\nu = 1.14$
$T_{1/2} = 70.609(85)$ s

$\chi^2/\nu = 0.94$
$T_{1/2}^{14}$O $= 70.632 \pm 0.086$ s

Residuals $\chi^2/\nu = 1.28$
$T_{1/2}^{14}$O $= 70.609 \pm 0.020$ s
The half-life measurements for $^{14}$O now form a consistent data set.

A more precise measurement is still desired and can be performed at ISAC using the 4π gas counter.
Two Shell Model approaches to calculate $\delta_C$:

- Use radial wave functions derived from a Woods-Saxon (WS) potential,
- Use self-consistent Hartree-Fock (HF) eigenfunctions.

Can use experimentally determined $F_t$ values to constrain $\delta_C$.

Beam:
${}^{18}\text{Ne} \left( T_{1/2} = 1.664 \text{ s} \right)$
${}^{18}\text{F} \left( T_{1/2} = 110 \text{ min} \right)$

Cycle:
0.5–2 s implant
2.3–3.9 s cooling/tape move
40 s decay counting
\[ T_{1/2}^{({}^{18}\text{Ne})} = 1.66424^{+0.00054}_{-0.00048} \text{ s}, \chi^2/\nu = 0.74 \]

- Half-life measured to 0.03\%, world average improved by a factor of 2
- The half-life has now been determined to the level needed for the ft high-precision cases. An improvement in the branching ratio in needed order to include the \(^{18}\text{Ne}\) ft value among the high-precision cases.
High-Precision Branching Ratio Measurements
A ≥ 62 Superallowed Decays: Pandemonium

- For large Q-value β decays, there are generally many weak β branches to the large number of daughter states within the Q-value window.
- Each individual gamma-ray from high-lying states is very weak and may be undetectable.
- The sum of this intensity represents a significant fraction of the non-analogue intensity.
Overcoming the Pandemonium Effect

How to Overcome:

- 2+ states are $\beta$ 2nd-forbidden

- Theory can estimate relative gamma-ray BR

\[
I_2' = I_{\text{out}} - I_{\text{in}}
\]

\[
\overline{B}_{gs} = \frac{I_{gs}'}{I_{gs}' + I_2'}
\]

⇒ Estimate of unobserved intensities, $I_{gs}'$
Branching Ratio Measurements: The $8\pi$, PACES, and SCEPTAR

- **PACES** — 5 Si(Li) detectors used to measure conversion electrons
- **SCEPTAR** — 10 plastic scintillators used to tag the beta particles
\( ^{74}\text{Rb} \) Branching Ratio

- Previously known decay scheme included 7 levels and 10 transitions

• 23 excited states identified in $^{74}$Kr were identified.
• 58 new $\gamma$-ray and electron transitions were identified.
• Improvement in the branching ratio measurement by a factor of 3.
Branching Ratio Measurements with GRIFFIN

- 16 large-volume clover-type HPGe detectors
- 64 individual HPGe crystals

~ 300-500 times the $\gamma$-$\gamma$ coincidence efficiency of the $8\pi$ spectrometer
Preliminary $^{62}$Ga Branching Ratio

- GRIFFIN: $\sim3 \times 10^8$ decay
- $8\pi$: $\sim6 \times 10^8$ decays
- With half of the decays we have much higher statistics with the high-efficiency GRIFFIN array!

Gate set on 954 keV $\gamma$-ray.
Preliminary $^{62}\text{Ga}$ Angular Correlations

- $(J^n) \rightarrow 2^+ \rightarrow 0^+$ 1388-954 keV cascade in $^{62}\text{Ga}$ decay.
- No definite $J^n$ assignment, but can place limit on mixing ratios: $\delta < -0.1$
- Data favours $0^+$ assignment, but need 4x more data to make a definitive spin assignment.
Conclusions

- At TRIUMF–ISAC we perform high-precision half-life (GPS/8π), branching ratio (8π/GRIFIN) and Q-value (TITAN) measurements for superallowed Fermi β decays – all of the experimental inputs required for ft value determination.

- Simultaneous β and γ counting half-life measurements help address systematic uncertainties (\(^{10}\text{C},^{14}\text{O},^{18}\text{Ne}\)) and they are important because it is the lowest-Z superallowed decays that are most sensitive to contributions from scalar currents in the weak interaction.

- The \(^{10}\text{C}\) β measurement represents the most precise superallowed half-life measurement reported to date and the first to achieve a relative precision below 10^{-4}.

- Recent improvements of the \(^{10}\text{C}\) Ft value results in an improved limit on the Fierz interference term, with the newest limit being \(b_F = -0.0018(21)\).

- The pandemonium problem that has previously limited the experimental precision of \(A \geq 62\) Ft values has been overcome.

- With the new high-efficiency GRIFIN detector we have the ability to identify more weak transitions (pandemonium) and can resolve the spin assignment of the first excited 0\(^+\) state in \(^{62}\text{Ga}\).
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