Superallowed $\beta$-Decay Studies at TRIUMF-ISAC: New Precision Measurements at the Limits of Nuclear Stability

Gordon C. Ball

TITAN Workshop, TRIUMF June 11, 2005

- overview of superallowed Fermi $0^+ \rightarrow 0^+ \beta$-decay
  - present status of $V_{ud}$ and the CKM unitarity problem
- the search for ‘trivial explanations’ to resolve the problem
  - focus on nuclear structure dependent corrections
  - where are new measurements are needed
- New developments in superallowed $\beta$-decay studies at ISAC
  - high precision lifetime and branching ratio measurements with the $8\pi$ gamma-ray spectrometer and SCEPTAR
  - high precision mass measurements of highly-charged ions(TITAN)
- Need for improved $Q_{EC}$ measurements
- Summary
Probing for Physics beyond the Standard Model via the Cabibbo-Kobayashi-Maskawa (CKM) matrix

- The CKM matrix plays a central role in the Standard Model
  - it is a matrix that describes mixing of different quark families because of the weak interaction
    \[
    \begin{pmatrix}
    d' \\
    s' \\
    b'
    \end{pmatrix}
    = 
    \begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
    \end{pmatrix}
    \begin{pmatrix}
    d \\
    s \\
    b
    \end{pmatrix}
    \]

- The CKM matrix must satisfy unitary condition
  \[ V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1 \]

The first row of the CKM matrix provides the most demanding experimental test of the unitarity condition.
Current Status of Experimental Test of CKM Unitarity

- For CKM unitarity, length of bar $\equiv 1$
- Violation of unitarity at any level has profound consequences

Different from Unitarity condition at 98% confidence level

Contribution from nuclear physics

Note scale!
Present status of $V_{us}$

- Obtained from semileptonic decay of neutral and charged kaons
  - four independent determinations $K^+_e3$, $K^+_\mu3$, $K^o_e3$ and $K^o_\mu3$
  - need to measure the decay rate $\Gamma(K \rightarrow \pi l \nu + n \gamma)$ and the momentum dependence of two form factors $f_+(t)$ and $f_0(t)$
  - theoretical radiative and isospin-breaking corrections
  - present PDG value $|V_{us}| = 0.2196 (23)$

- new experiments in progress  E865, KLOE, NA48, KTeV, CMD2
  - $K^+ \rightarrow \pi^0 e^+ \nu_e (K^+_3e)$  ($E865$, Sher et al  PRL 91(2003)261802) results in $|V_{us}| = 0.2272 (23_{rate})$
  - removes unitarity problem but inconsistent with recent NA48 and KLOE data
Unitarity for $f_+(0) = 0.961$ and $0.981$
Nuclear Physics Contribution to the CKM Matrix

- \[ V_{ud}^2 = \frac{G_V^2}{G_F^2} \]

where \( G_F^2 \) is the Fermi coupling constant determined from muon decay and \( G_V^2 \) is related to the \( \beta \) decay between \( T=1, J^{\pi}=0^+ \) analogue states by:

\[ ft(1 + \delta_R)(1 - \delta_C) = \frac{K}{2G_V^2(1 + \Delta_V^R)} = \text{constant} \]

- Phase space factor and takes into account interaction of nuclear coulomb field and \( \beta \) particle
- Calculated corrections dependent on nuclear structure
- Radiative correction independent of nuclear structure

- Leading order terms in \( \delta_R \) and \( \Delta^V_R \) (radiative corrections) are on a firm footing (QED)
- \( \delta_C \) represents isospin-symmetry-breaking correction
  - viewed as greatest contribution to overall uncertainty
Experimental quantities needed for CKM Matrix Unitarity tests

• In order to extract $G^2$, the decay process must be limited to pure Fermi decay, achieved by considering only $0^+(A,Z) \rightarrow 0^+(A,Z-1)$ decays between isobaric analogue states

• The experimental contribution to $f t (1− \delta_c)(1+ \delta_R )$

  1) decay $Q$ value (or masses of initial and final state) to determine $f$

  2) Half life $t_{1/2}$

  3) $0^+ \rightarrow 0^+$ branching ratio

• Experimentally, need $t_{1/2}$, branching ratio, and masses measured to better than $± 0.1\%$

\[ 0^+ \rightarrow 0^+ \text{ branching ratio} = \text{fraction of decays to } 0^+ \text{ level} \]

\[ Experimental \ input \ to \ f t (1− \delta_c)(1+ \delta_R ) \]
Current status of precision \( F_t \) values

\[
F_t = 3072.7 \pm 0.8
\]

\[
\chi^2/\nu = 0.42
\]

Enforce Unitarity: \( \chi^2/\nu = 16.7 \)

J.C. Hardy and I.S. Towner, PRC 71, 055501 (2005)
Future directions for superallowed $\beta$-decay studies

- Present uncertainty in $V_{ud}$ is dominated by theoretical corrections (Towner and Hardy, Phys. Rev C66(2002)035501)
  - uncertainties in radiative corrections are small
  - focus is on isospin symmetry-breaking corrections ($\delta_C$)

Experimental Measurements

- Improved precision for nine well-known transitions
- Study of $T_Z = 0$, odd-odd nuclei with $A \geq 62$
  - all nuclei are near proton drip line resulting in large $Q$ values ($\sim 10$ MeV) and short half-lives ($\sim 50-100$ ms)
- Study of $T_Z = 1$ nuclei with $18 \leq A \leq 38$
  - all nuclei have large ($\sim 5-50\%$) branches to excited $1^+$ states

Improved theoretical calculation needed especially for $A \geq 62$
Isospin Symmetry Breaking Corrections 

Calculated $\delta c$ (%) 

Z of Daughter 

Isospin Symmetry Breaking Corrections 

Calculated $\delta c$ (%) 

Z of Daughter 

Isospin Symmetry Breaking Corrections 

Calculated $\delta c$ (%) 

Z of Daughter
High-precision Superallowed $\beta$-decay studies at ISAC

High precision lifetime measurements at GPS

High-precision branching ratio and lifetime measurements with the $8\pi$ and SCEPTAR

High-precision mass measurements with TITAN
74Rb Half-Life Measurements


Half-Life

previous: 64.9 ± 0.5 ms

ISAC:

- ~ 4000 74Rb ions s⁻¹
- isobaric contaminant 74Ga (t ½ = 8.12 m)
- t ½ uncertainty 0.05%

64.761 ± 0.031 ms
Summary of high-precision lifetime measurements for $^{26m}$Al

- $6346 \pm 5$ ms            Freeman et al (1969)
- $6346 \pm 5$ ms            Azuelos et al    (1974)
- $6339.5 \pm 4.5$ ms       Alburger el al   (1977)
- $6346.2 \pm 2.6$ ms       Koslowsky et al (1983)
- $6344.9 \pm 1.9$ ms       weighted average

Present objectives:
- a new measurement with a precision of 1.5 – 2.0 ms
- requires a beam intensity of $\sim 5 \times 10^4$ /s and a purity of >99.99%
β-decay studies with the reconfigured $8\pi$ gamma-ray spectrometer and SCEPTAR at ISAC-I

- 20 Compton-Suppressed HPGe detectors
- 20 plastic scintillators or
- 10 plastics and
- 5 Si(Li) detectors
- Tape transport
- Beam from ISAC

SCEPTAR
$8\pi$ Spectrometer with SCEPTAR and moving tape system
Online $^{62}$Ga β-γ Coincidence Spectra

- $\sim 1600^{62}$Ga/s for 3 days
- $\sim 80\%$ laser ionized
- $^{62}$Cu bkg reduced by a factor of $\sim 20$

MCS betas from SCEPTAR

$^{62}$Ga decays

- $\sim 2.1 \times 10^8$

$^{62}$Cu bkg reduced by a factor of $\sim 20$
$^{34}\text{Ar}$ Superallowed Beta Decay

\begin{align*}
^{34}\text{Ar} & \\
\text{ft} = 3046 \pm 17 \text{ s} & \\
0^+ & 844.5 \pm 3.4 \text{ ms} \\
\beta^+ & \\
1.30 \% & \\
0.86 \% & \\
\beta^+ & \\
2.49 \% & 0.91 \% \\
94.44 \pm 0.23 \% & \\
^{34}\text{Cl} & \\
\end{align*}
Test of Gamma-Ray Lifetime Method with Radioactive $^{26}\text{Na}$ Beam to $8\pi$ – August 2002

![Graph showing the decay of gamma-ray activity over time.](image)

- **Total $\gamma$-ray Activity**
- **Gate on $^{26}\text{Mg}$ 1809 keV photopeak**
- **Half-Life Statistical Precision: ±0.05%**
E985: Half-life and Branching-ratio Measurement of $^{18}$Ne Superallowed Fermi β decay (Spokesperson: M.B. Smith)

Mass excess ($Q_{EC}$) known to ± 1.5 keV ($^{18}$Ne) and ± 0.6 keV ($^{18}$F)

Excitation energy of $0^+$ state known to ± 0.08 keV
Half-life measurement with the $8\pi$ spectrometer

- 90 hours of beam at 10,000 – 30,000 $^{18}$Ne ions/s
- $t_{1/2} \sim 0.1\%$ precision
- first Fermi $\beta$ decay half-life measured with the $8\pi$ at ISAC

$T_{1/2} (^{18}\text{Ne}) = 1.668 \pm 0.005 \text{ s}$

$\chi^2/\nu = 0.87$

M.B. Smith, G.F. Grinyer et al., to be published
<table>
<thead>
<tr>
<th>Parent/daughter nuclei</th>
<th>property(^1)</th>
<th>Measured energy, (Q_{EC}) (keV)</th>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>(^{38}\text{Km}) (^{38}\text{Ar})</td>
<td>(Q_{EC}(gs))</td>
<td>5914.76 ± 0.60 [Ja78]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(E_x(p0^+))</td>
<td>130.4 ± 0.3 [En98]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Q_{EC}(sa))</td>
<td>6044.6 ± 1.5 [Bu79]</td>
<td>6044.38 ± 0.12 [Ha98]</td>
</tr>
<tr>
<td>(^{42}\text{Sc}) (^{42}\text{Ca})</td>
<td>(Q_{EC}(sa))</td>
<td>6423.71 ± 0.40 [Vo77]</td>
<td>6425.84 ± 0.17(^8)</td>
</tr>
<tr>
<td>(^{46}\text{V}) (^{46}\text{Ti})</td>
<td>(Q_{EC}(sa))</td>
<td>7053.3 ± 1.8 [Sq76]</td>
<td>7050.41 ± 0.60 [Vo77]</td>
</tr>
<tr>
<td>(^{50}\text{Mn}) (^{50}\text{Cr})</td>
<td>(Q_{EC}(sa))</td>
<td>7632.8 ± 2.8 [Ha74d]</td>
<td>7631.91 ± 0.40 [Vo77]</td>
</tr>
<tr>
<td>(^{54}\text{Co}) (^{54}\text{Fe})</td>
<td>(Q_{EC}(sa))</td>
<td>8241.2 ± 1.8 [Ho74]</td>
<td>8245.6 ± 3.0 [Ha74d]</td>
</tr>
<tr>
<td>(^{74}\text{Rb}) (^{74}\text{Kr})</td>
<td>(ME(p))</td>
<td>−51915.2 ± 4.0 [Ke04]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(ME(d))</td>
<td>−62332.0 ± 2.1 [Ke04]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Q_{EC}(sa))</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Current status of precision $Ft$ values

$Ft = 3072.7 \pm 0.8$

$\chi^2/\nu = 0.42$

Enforce Unitarity: $\chi^2/\nu = 16.7$

J.C. Hardy and I.S. Towner, PRC 71, 055501 (2005)
Future High Precision measurements for
Superallowed $\beta$-Decay Studies at ISAC

- $^{34}$Ar: $t_{1/2}$, BR
- $^{74}$Rb: BR, mass
- $^{62}$Ga: $t_{1/2}$, BR, mass
- $^{66}$As: $t_{1/2}$, BR, mass
- $^{70}$Br: $t_{1/2}$, BR, mass
- $^{38m}$K: BR, $0^+_2$
- $^{18}$Ne: $t_{1/2}$, BR, mass
- $^{26m}$Al: $t_{1/2}$, BR, mass
Summary

• New techniques are improving the precision of superallowed $\beta$-decay studies and providing for the extension to other cases such as the short lived heavier nuclei

• Higher precision mass measurements are needed not only to determine the $Q_{EC}$ values for $A \geq 62$, $T_Z = 0$ nuclei but also to improve and/or verify previous data for the nine “well known” cases

• Improved theoretical corrections for $\delta_C$ are needed especially for heavier nuclei.

• The theoretical uncertainty in $\Delta R$ common to neutron, pion and beta decay needs to be addressed.

• Several new high statistics measurements of $V_{us}$ are in progress but uncertainties of the vector form factor remain

• What will be the outcome, trivial or not?
\[8\pi\] Collaborators 2002 - 2004

<table>
<thead>
<tr>
<th><strong>TRIUMF</strong></th>
<th><strong>Guelph</strong></th>
<th><strong>Queens</strong></th>
<th><strong>Livermore</strong></th>
<th><strong>Texas A&amp;M</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>G.C. Ball</td>
<td>C.E. Svensson</td>
<td>J.R. Leslie</td>
<td>J. A. Becker</td>
<td>J.C. Hardy</td>
</tr>
<tr>
<td>J. Behr</td>
<td>P.E. Garrett</td>
<td>I.S. Towner</td>
<td>W.E. Ormand</td>
<td>V. Iacob</td>
</tr>
<tr>
<td>P. Bricault</td>
<td>A.A. Phillips</td>
<td>Simon Fraser</td>
<td>A. Schiller</td>
<td></td>
</tr>
<tr>
<td>M. Dombsky</td>
<td>M.A. Schumaker</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>G.C. Ball</strong></th>
<th><strong>C.E. Svensson</strong></th>
<th><strong>J.R. Leslie</strong></th>
<th><strong>Livermore</strong></th>
<th><strong>Texas A&amp;M</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>G. Hackman</td>
<td>G.F. Grinyer</td>
<td>M.E. Hayden</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J.A. Macdonald†</td>
<td>B. Hyland</td>
<td>T. Warner</td>
<td>E. Zganjar</td>
<td>R. Propri</td>
</tr>
<tr>
<td>C. Ravuri</td>
<td>P. Finlay</td>
<td>J. Ressler</td>
<td>A. Piechaczek</td>
<td></td>
</tr>
<tr>
<td>A. Andreyev</td>
<td>C. Andreoiu</td>
<td>British Columbia</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>M.B. Smith</strong></th>
<th><strong>J.J. Valiente-Dobon</strong></th>
<th><strong>M. Pearson</strong></th>
<th><strong>Michigan</strong></th>
<th><strong>D.M. Cullen</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>H.C. Scraggs</td>
<td>C. Mcmaster</td>
<td>M. Pearson</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Morton</td>
<td>J.A. Cameron</td>
<td>Berkeley</td>
<td>S. Nuss-Warren</td>
<td>Surrey</td>
</tr>
<tr>
<td>C. Pearson</td>
<td>J.C. Waddington</td>
<td>D. Ward</td>
<td>E. Tardiff</td>
<td>P. Regan</td>
</tr>
<tr>
<td>C. Osborne</td>
<td>B. Singh</td>
<td>Georgia Tech.</td>
<td>K. Krane</td>
<td>P.M. Walker</td>
</tr>
<tr>
<td>J. Daoud</td>
<td>B. Washbrook</td>
<td>J.L. Wood</td>
<td>Oregon</td>
<td>C. Wheldon</td>
</tr>
<tr>
<td>E. Cunningham</td>
<td>M. Lee</td>
<td>W.D. Kulp</td>
<td></td>
<td>S.F. Ashley</td>
</tr>
<tr>
<td>D.F. Hodgson</td>
<td>N. Novo</td>
<td>J. Allmond</td>
<td>P. Schmelzenbach</td>
<td>S.J. Williams</td>
</tr>
<tr>
<td>K. Cheung</td>
<td>Colorado</td>
<td>St. Mary’s</td>
<td></td>
<td>Vienna</td>
</tr>
<tr>
<td>B. Eshpeter</td>
<td>F. Sarazin</td>
<td>AERI, Japan</td>
<td>T. Shizuma</td>
<td>J. Schwarzenberg</td>
</tr>
<tr>
<td>K. Koopmans</td>
<td>Toronto</td>
<td></td>
<td></td>
<td>GSI</td>
</tr>
<tr>
<td>D. Van der Kamp</td>
<td>T.E. Drake</td>
<td></td>
<td></td>
<td>Y. Litvinov</td>
</tr>
</tbody>
</table>

**Professor/Scientist** | **Research Associate** | **Graduate Student** | **Undergraduate Student** | †deceased
The superallowed $\beta$-emitter $^{26m}$Al

**Present status**

$t^{1/2} = 6.3449 \pm 0.0019$ s

$BR \geq 99.97\%$

$Q_{EC} = 4232.42 \pm 0.35$ keV

$ft = 3035.8(17)$

**Theoretical corrections**

$\delta_C - \delta_{NS} = 0.261(24)\%$

$\delta_R^1 = 1.46(2)\%$
High-precision branching ratio measurement for $^{26\text{m}}\text{Al}$

Present limit $< 7 \times 10^{-5}$

Proposal to reduce the limit to $< 7 \times 10^{-6}$

- Requires a beam purity of $\sim 10^{-5}$

88%
Theoretical corrections in superallowed Fermi $\beta$ decay

- it is convenient to separate the radiative corrections into two terms
  \[ \delta_R = \delta^{1}_R + \delta_{\text{NS}} \]
- combining the radiative and Coulomb nuclear structure dependent corrections we obtain:
  \[ F_t = f_t (1 + \delta^{1}_R)(1 + \delta_{\text{NS}} - \delta_C) \]

<table>
<thead>
<tr>
<th>Parent</th>
<th>$\delta_{\text{NS}}(%)$</th>
<th>$\delta_{\text{C}1}(%)$</th>
<th>$\delta_{\text{C}2}(%)$</th>
<th>$\delta_C - \delta_{\text{NS}}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{C}$</td>
<td>$-0.360(35)$</td>
<td>$0.010(10)$</td>
<td>$0.170(15)$</td>
<td>$0.540(39)$</td>
</tr>
<tr>
<td>$^{14}\text{O}$</td>
<td>$-0.250(50)$</td>
<td>$0.050(20)$</td>
<td>$0.270(15)$</td>
<td>$0.570(56)$</td>
</tr>
<tr>
<td>$^{18}\text{Ne}$</td>
<td>$-0.290(35)$</td>
<td>$0.230(30)$</td>
<td>$0.390(10)$</td>
<td>$0.910(47)$</td>
</tr>
<tr>
<td>$^{22}\text{Mg}$</td>
<td>$-0.240(20)$</td>
<td>$0.010(10)$</td>
<td>$0.255(10)$</td>
<td>$0.505(24)$</td>
</tr>
<tr>
<td>$^{26}\text{Si}$</td>
<td>$-0.230(20)$</td>
<td>$0.040(10)$</td>
<td>$0.330(10)$</td>
<td>$0.600(24)$</td>
</tr>
<tr>
<td>$^{30}\text{S}$</td>
<td>$-0.190(15)$</td>
<td>$0.195(30)$</td>
<td>$0.740(20)$</td>
<td>$1.125(39)$</td>
</tr>
<tr>
<td>$^{34}\text{Ar}$</td>
<td>$-0.185(15)$</td>
<td>$0.030(10)$</td>
<td>$0.610(40)$</td>
<td>$0.825(44)$</td>
</tr>
<tr>
<td>$^{38}\text{Ca}$</td>
<td>$-0.180(15)$</td>
<td>$0.020(10)$</td>
<td>$0.710(50)$</td>
<td>$0.910(53)$</td>
</tr>
<tr>
<td>$^{42}\text{Ti}$</td>
<td>$-0.240(20)$</td>
<td>$0.220(100)$</td>
<td>$0.555(40)$</td>
<td>$1.015(110)$</td>
</tr>
<tr>
<td>$T_x = 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{26m}\text{Al}$</td>
<td>$0.009(20)$</td>
<td>$0.040(10)$</td>
<td>$0.230(10)$</td>
<td>$0.261(24)$</td>
</tr>
<tr>
<td>$^{34}\text{Cl}$</td>
<td>$-0.085(15)$</td>
<td>$0.105(20)$</td>
<td>$0.530(30)$</td>
<td>$0.720(39)$</td>
</tr>
<tr>
<td>$^{38m}\text{K}$</td>
<td>$-0.100(15)$</td>
<td>$0.100(20)$</td>
<td>$0.520(40)$</td>
<td>$0.720(47)$</td>
</tr>
<tr>
<td>$^{42}\text{Sc}$</td>
<td>$0.030(20)$</td>
<td>$0.060(30)$</td>
<td>$0.430(30)$</td>
<td>$0.460(47)$</td>
</tr>
<tr>
<td>$^{45}\text{V}$</td>
<td>$-0.040(7)$</td>
<td>$0.095(20)$</td>
<td>$0.330(25)$</td>
<td>$0.465(33)$</td>
</tr>
<tr>
<td>$^{50}\text{Mn}$</td>
<td>$-0.042(7)$</td>
<td>$0.055(20)$</td>
<td>$0.450(30)$</td>
<td>$0.547(37)$</td>
</tr>
<tr>
<td>$^{54}\text{Co}$</td>
<td>$-0.029(7)$</td>
<td>$0.040(15)$</td>
<td>$0.570(40)$</td>
<td>$0.639(43)$</td>
</tr>
<tr>
<td>$^{62}\text{Ga}$</td>
<td>$-0.040(20)$</td>
<td>$0.330(40)$</td>
<td>$1.05(15)$</td>
<td>$1.42(16)$</td>
</tr>
<tr>
<td>$^{66}\text{As}$</td>
<td>$-0.050(20)$</td>
<td>$0.250(40)$</td>
<td>$1.15(15)$</td>
<td>$1.45(16)$</td>
</tr>
<tr>
<td>$^{70}\text{Br}$</td>
<td>$-0.060(20)$</td>
<td>$0.350(40)$</td>
<td>$1.00(20)$</td>
<td>$1.41(21)$</td>
</tr>
<tr>
<td>$^{74}\text{Rb}$</td>
<td>$-0.065(20)$</td>
<td>$0.130(60)$</td>
<td>$1.30(40)$</td>
<td>$1.50(41)$</td>
</tr>
</tbody>
</table>