Superallowed Nuclear β Decay

The Precision Frontier of Low-Energy Nuclear Physics

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Outline

- Introduction and Review
  - Nuclear β decay
  - Isospin symmetry and isospin symmetry breaking
  - Conserved Vector Current hypothesis (CVC)

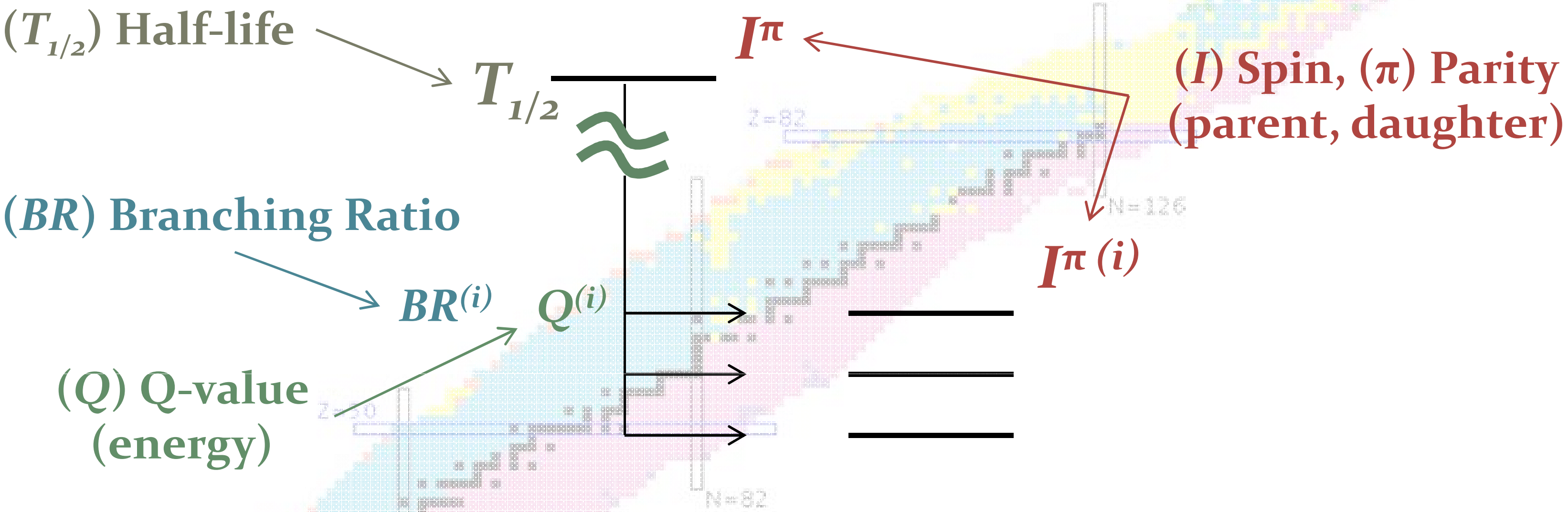
- Status of Superallowed Fermi β Decay
  - V_{ud} and CKM unitarity

- Case Study ^{62}Ga: "How to measure the *ft* value"
  - State-of-the-art facilities and experimental techniques
  - Comparison to theoretical isospin symmetry breaking corrections

- Summary and Conclusions

Nuclear β Decay

$$
\begin{aligned}
{}^{A}_{Z}X_{N} &\rightarrow {}^{\;\;A}_{Z+1}Y_{N-1} + e^{-} + \overline{\nu_e}, \\
{}^{A}_{Z}X_{N} &\rightarrow {}^{\;\;A}_{Z-1}W_{N+1} + e^{+} + \nu_e.
\end{aligned}
$$



($T_{1/2}$) Half-life

$T_{1/2}$

I^{π}

(I) Spin, (π) Parity (parent, daughter)

(BR) Branching Ratio

$BR^{(i)}$ $Q^{(i)}$

$I^{\pi\,(i)}$

(Q) Q-value (energy)

- Selection Rules: $\boxed{\pi_P = \pi_D\,(-1)^L}$ $\boxed{\vec{I}_P = \vec{I}_D + \vec{L} + \vec{S}}$
  - Allowed Decay
    - L=0
  - “Forbidden” Decay
    - L=1, 2, 3, …
  - Fermi (Vector)
    - S=0 β ↑↓ υ_e
  - Gamow-Teller (Axial-Vector)
    - S=1 β ↑↑ υ_e

β Decay Classification

B. Singh, J.L. Rodriguez, S.S.M.Wong, and J.K.Tuli, Nuclear Data Sheets 84, 487 (1998)

Case	I^π (P→D)	Classification	$T_{1/2}$	Fraction
^{18}N→^{18}C	$1^-\rightarrow1^-$	Allowed (GT&F)	624 ms	64%
^{6}He→^{6}Li	$0^+\rightarrow1^+$	Allowed (GT only)	807 ms	
^{10}C→^{10}B	$0^+\rightarrow0^+$	Allowed (F only)	19 s	1%
^{38}Cl→^{38}Ar	$2^-\rightarrow2^+$	1st Forbidden	37 min	33%
^{36}Cl→^{36}Ar	$2^+\rightarrow0^+$	2nd Forbidden	3 10^{5} years	1%
^{40}K→^{40}Ca	$4^-\rightarrow0^+$	3rd Forbidden	1 10^{9} years	0.1%
^{50}V→^{50}Cr	$6^+\rightarrow2^+$	4th Forbidden	1 10^{17} years	0.1%

- The *ft* value is a powerful way to characterize β decay

Q-value

Half-life

Constants

$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{g^2|M_{fi}|^2}$$

Matrix Element

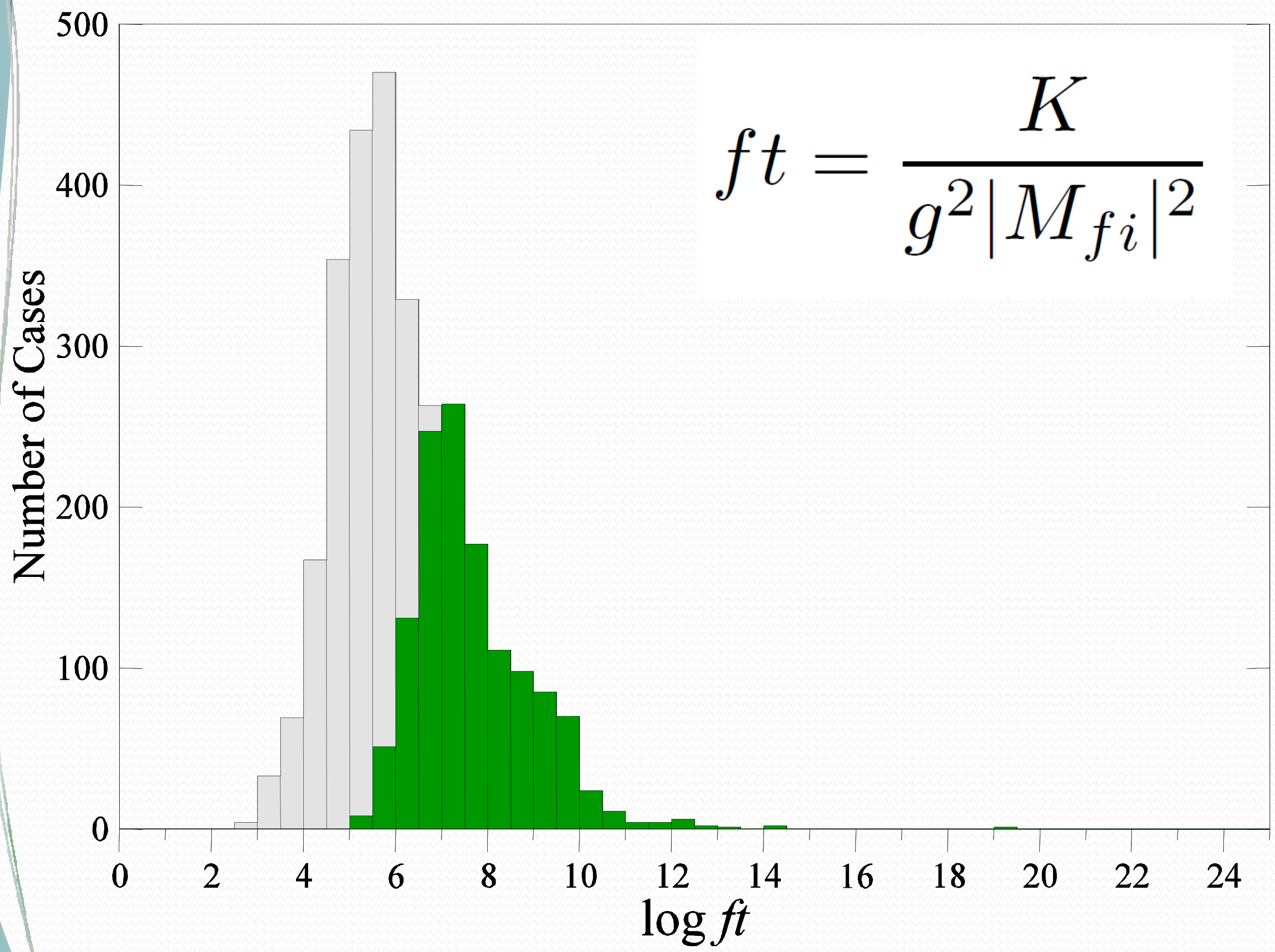
Branching Ratio

Coupling Strength

β decay *ft* values

B. Singh, J.L. Rodriguez, S.S.M.Wong, and J.K.Tuli, Nuclear Data Sheets 84, 487 (1998)

- Survey of 3840 β decay *ft* values



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

Allowed:

$1^+ \rightarrow 0^+$, $2^- \rightarrow 2^-$

(2497)

1^{st} Forbidden:

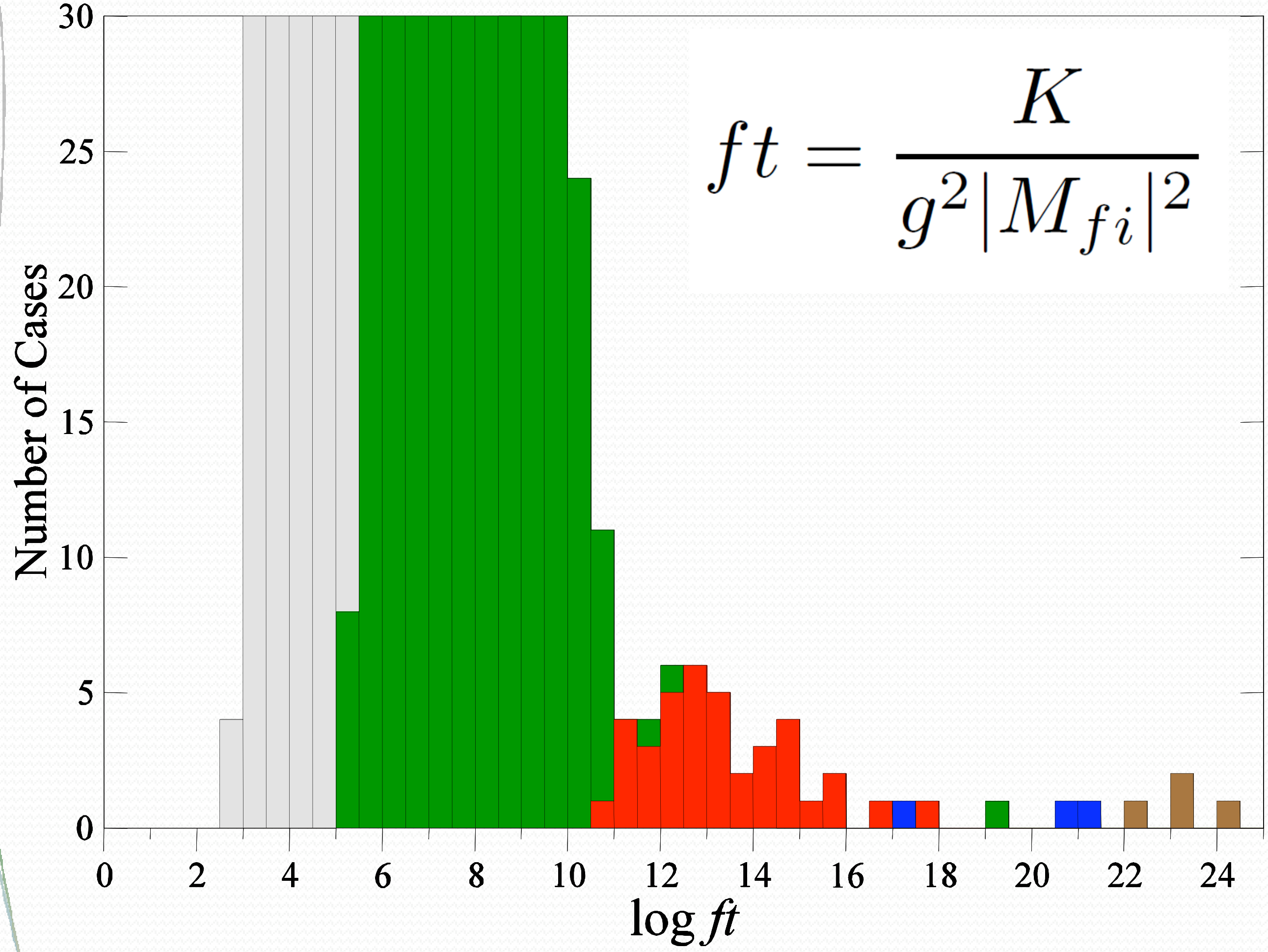
$2^+ \rightarrow 0^+$, $2^- \rightarrow 2^+$

(1297)

β decay *ft* values

B. Singh, J.L. Rodriguez, S.S.M.Wong, and J.K.Tuli, Nuclear Data Sheets 84, 487 (1998)

- β decay *ft* values span ~ 21 *orders of magnitude*



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

Allowed:
$1^+ \to 0^+$, $2^- \to 2^-$
(2497)

1st Forbidden:
$2^+ \to 0^+$, $2^- \to 2^+$
(1297)

2nd Forbidden:
$2^+ \to 0^+$, $5^+ \to 2^+$
(39)

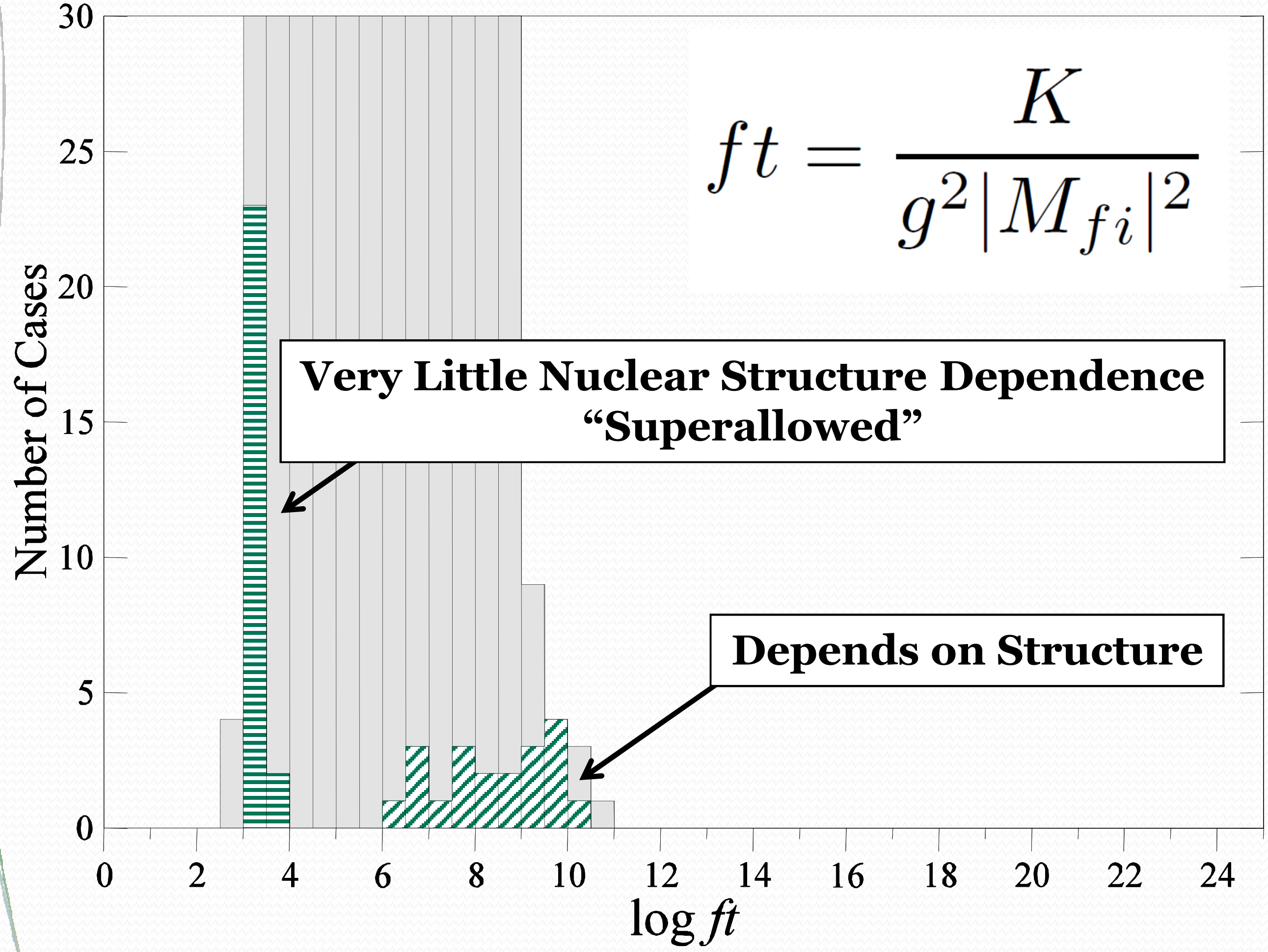
3rd & 4th Forbidden
$4^- \to 0^+$, $6^+ \to 2^+$
(3), (4)

← 21 orders of magnitude! →

$0^+ \rightarrow 0^+$ Pure Fermi Decay

- $0^+ \rightarrow 0^+$ is *pure* Fermi decay (no GT)

$$\vec{I}_P = \vec{I}_D + \vec{L} + \vec{S}$$



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

Allowed:

$1^+ \rightarrow 0^+$, $2^- \rightarrow 2^-$

(2497)

Allowed (*pure* F):

$0^+ \rightarrow 0^+$

(25 + 20)

Nuclear Isospin

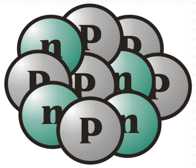
1932 - Heisenberg

- In 1932, months after the discovery of the neutron Heisenberg proposes the concept of “nucleons”
    - n’s and p’s are “spin” projections of nucleons

$$t_z(p) = -\frac{1}{2}$$

$$t_z(n) = +\frac{1}{2}$$

- Isospin projection and total isospin of a nucleus



$$T_z = \frac{1}{2}(N - Z) \qquad \mathbf{T} = |T_z|, |T_z| + 1, \cdots, \frac{N+Z}{2}$$

- For $0^+ \rightarrow 0^+$ β decay (n ↔ p) between *isobaric analogue states* (same ***T***, different T_z) the M.E. is an isospin ladder operator

$$|M_F|^2 = (T \mp T_z)(T \pm T_z + 1)$$

For *T* = 1 decays

$$|M_F|^2 = 2$$

EXACT!

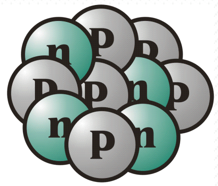
(to the extent that isospin is a valid symmetry)

CVC Hypothesis

R.P. Feynman and M. Gell-Mann Phys. Rev. 109 193 (1958)

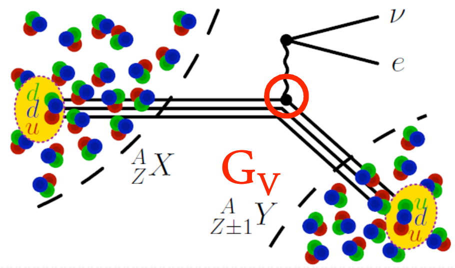
- Electric charge of the proton is not altered inside a nucleus
  - E&M is governed by a conserved vector current (CVC)

$$\boxed{e = 1.602\,176\,487 \times 10^{-19}\ \mathrm{C}}$$



- Hypothesize that a CVC also exists for weak interaction
  - Does the weak interaction have a universal coupling strength?

$$\boxed{G_V = 1.13621 \times 10^{-5}\ \mathrm{GeV}^{-2}}$$



- Consequence of CVC:
  - The *ft* values for ALL superallowed Fermi decays are identical!

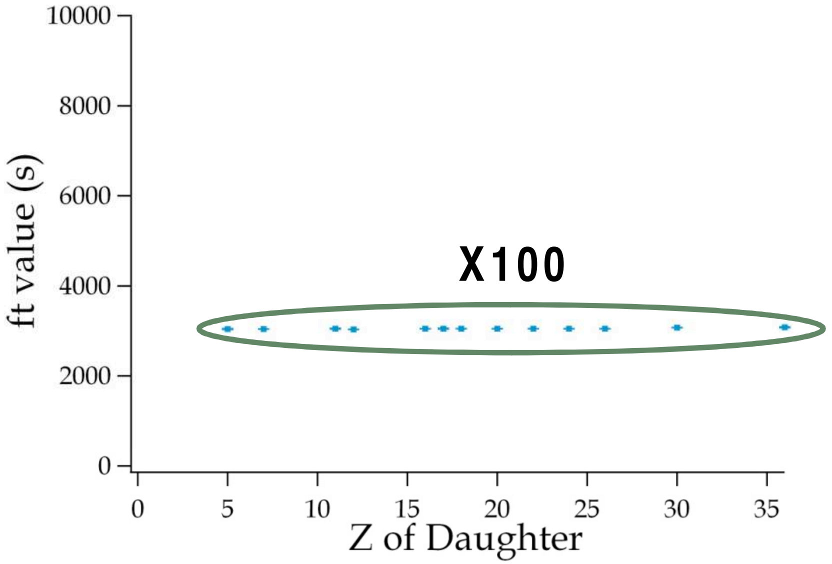
$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{2{G_V}^2} = \text{constant}$$

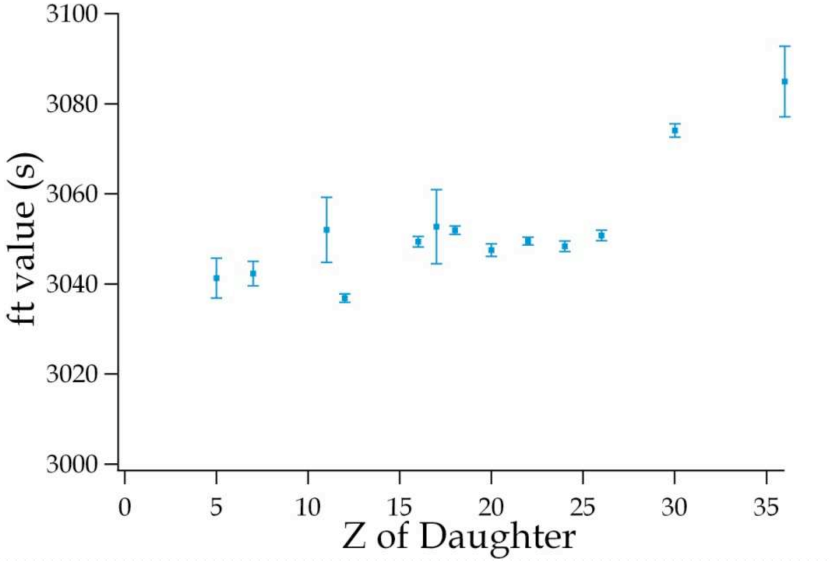
Isospin symmetry **CVC**

Superallowed Survey (2009)

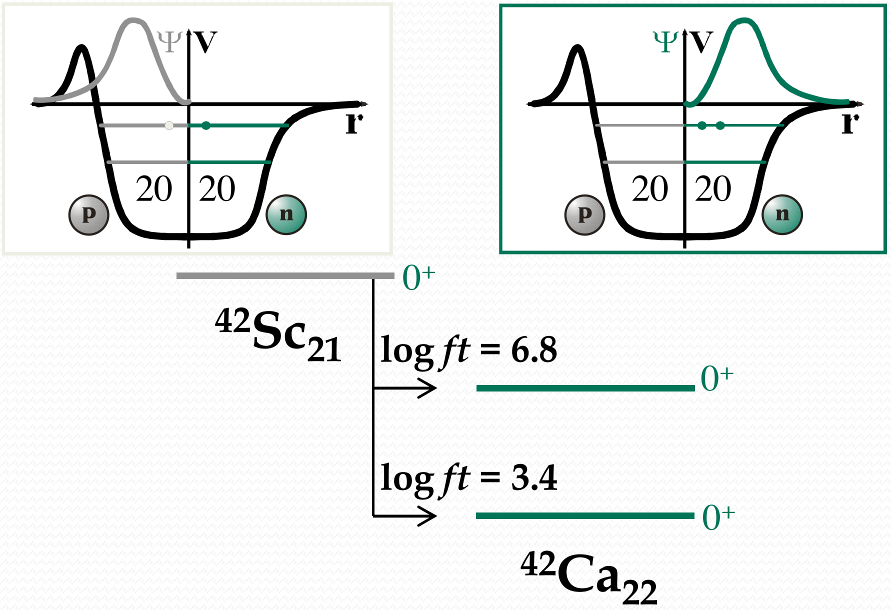
J.C. Hardy and I.S. Towner Phys. Rev. C 79 055502 (2009)

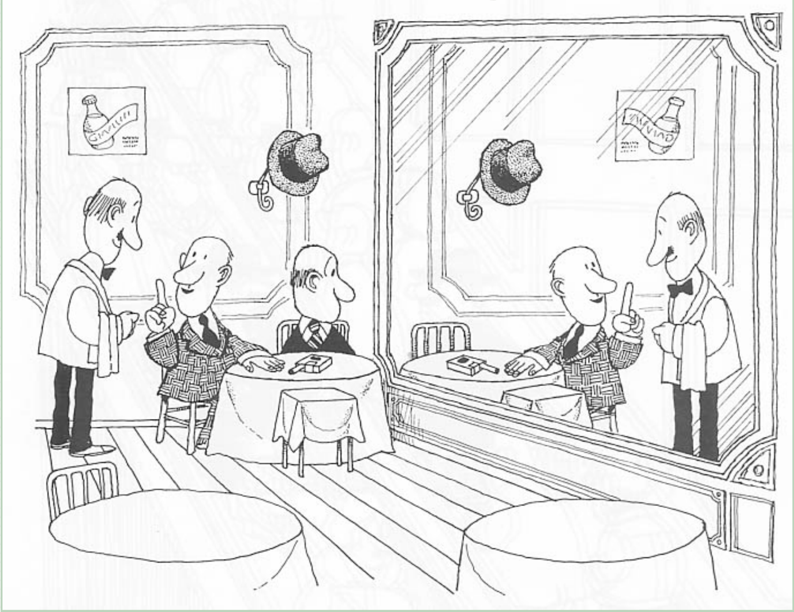
- Survey of world data
  - 130 independent measurements
  - 13 *ft* values known to ≤ 0.4%
  - 8 *ft* values known to ≤ 0.05%
- All known *ft* values
  - Span *ft* = 10^3 to 10^{24} s
- All allowed *ft* values
  - Span *ft* = 10^3 to 10^{10}
- Superallowed *ft* values
  - Span *ft* = 3040 to 3100 s (2%)
  - Assumes isospin symmetry





Isospin Symmetry Breaking

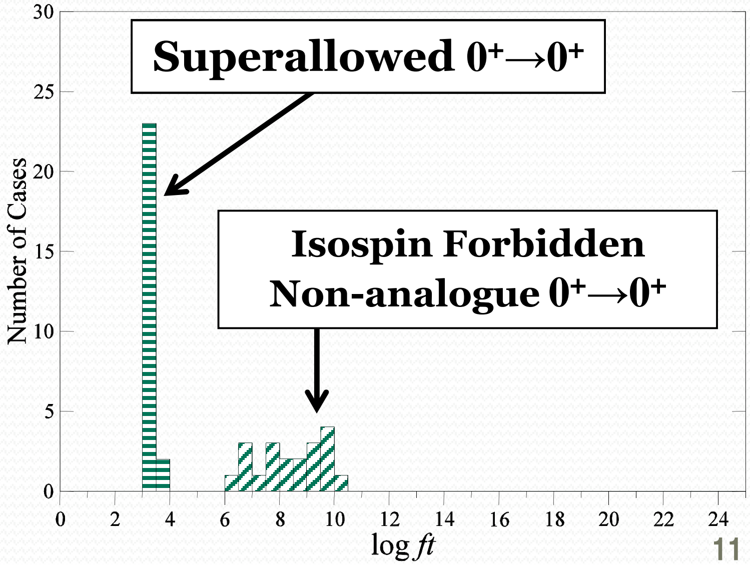




- If isospin symmetry were *exact*
  - *Only* the S.A.F. decay would occur
  - Non-analogue decays have been observed
    - Suppressed by factors of > 1000

$$|M_F^{ias}|^2 = 2(1-\delta_C)$$

$$|M_F^{nas}|^2 = 2\delta_C$$



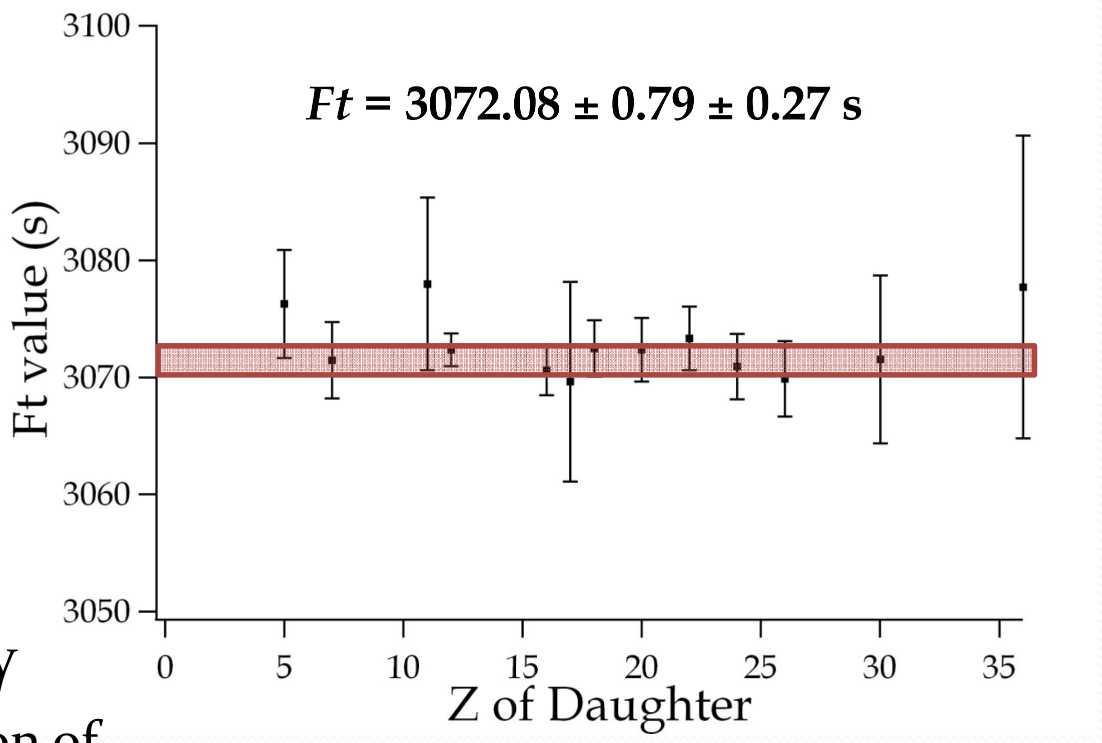
World Status (2009)

J.C. Hardy and I.S. Towner Phys. Rev. C 79 055502 (2009)

- Apply δ_C,δ_R corrections

$$\mathcal{F}t = ft(1+\delta_R)(1-\delta_C)$$

- World average *Ft*
  - $\mathcal{F}t$ = 3072.08(79) s
  - $\chi^2/\upsilon = 0.28$
- CVC hypothesis
  - Validated (10^{-4} level)
- Systematic uncertainty
  - ± 0.27 s from comparison of two sets of δ_C calculations

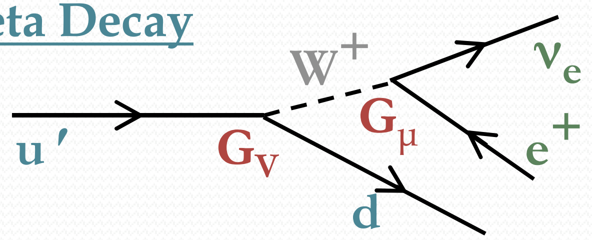


Evaluation of G_V and V_{ud}

I.S. Towner and J.C. Hardy Rep. Prog. Phys. 73 046301 (2010)

- With CVC satisfied from 13 superallowed decays, derive G_V

Beta Decay

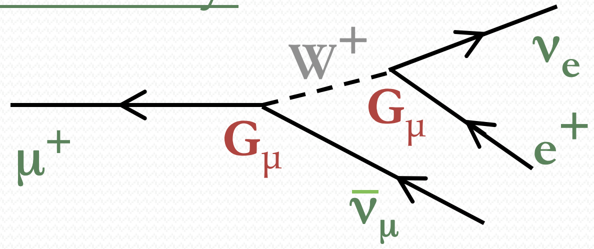


$$\mathcal{F}t = \frac{K}{2{G_V}^2} = \text{constant}$$

$G_V = 1.13621 \times 10^{-5}\ \text{GeV}^{-2}$

- Compare to the corresponding value G_μ from μ decay

Muon Decay

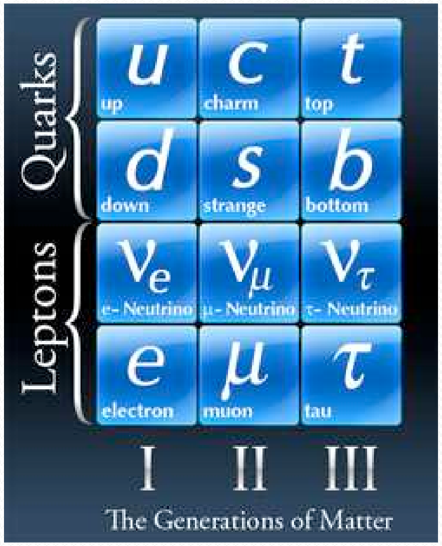


$G_\mu = 1.16637 \times 10^{-5}\ \text{GeV}^{-2}$

$V_{ud} = G_V/G_\mu = 0.97425(22)$

Quark Mixing

- 1958 **R.P. Feynman and M. Gell-Mann Phys. Rev. 109 193 (1958)**
  - CVC Hypothesis
- 1960 **R.K. Bardin et al. Phys. Rev. Lett. 5 323 (1960)**
  - *ft* value for ^{14}O: 3069(13) s [0.4% !]
  - $G_V = 0.982 G_\mu$! Expected $G_V = 1.0 G_\mu$
- 1963 **N.Cabibbo Phys. Rev. Lett. 10 531 (1963)**
  - Weak eigenstates ≠ mass eigenstates
  - Included "mixing" between 2 generations
  - Expressed as a unitary rotation
  - Cabibbo angle $\theta_C = 11°$ explains ^{14}O decay
- 1973 **M.Kobayashi and T.Maskawa Prog. Theor. Phys. 49 652 (1973)**
  - Require a third quark generation to explain CP violation
  - Cabibbo's 2x2 matrix is expanded to 3x3



$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$V_{ud} = \cos\theta_C$ $V_{us} = \sin\theta_C$

$V_{cd} = -\sin\theta_C$ $V_{cs} = \cos\theta_C$

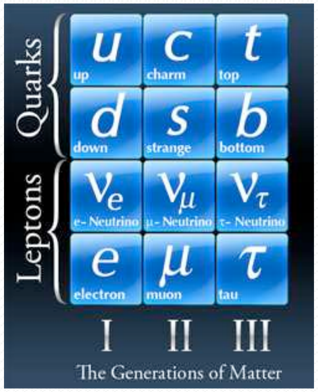
$$|V_{ud}|^2 + |V_{us}|^2 = 1$$

CKM Quark Mixing Matrix

2008 Nobel Prize in Physics
¼ Kobayashi & ¼ Maskawa

I.S. Towner and J.C. Hardy Rep. Prog. Phys. 73 046301 (2010)

- Three generation quark mixing matrix



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

$V_{ud} = 0.97$ $V_{us} = 0.22$ $V_{ub} < 0.01$

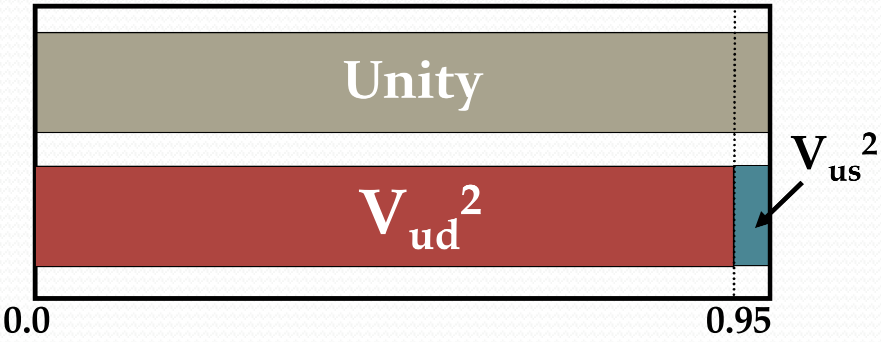
$V_{cd} = 0.23$ $V_{cs} = 1.04$ $V_{cb} < 0.01$

$V_{td} < 0.01$ $V_{ts} = 0.04$ $V_{tb} > 0.74$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$ Unitarity Condition

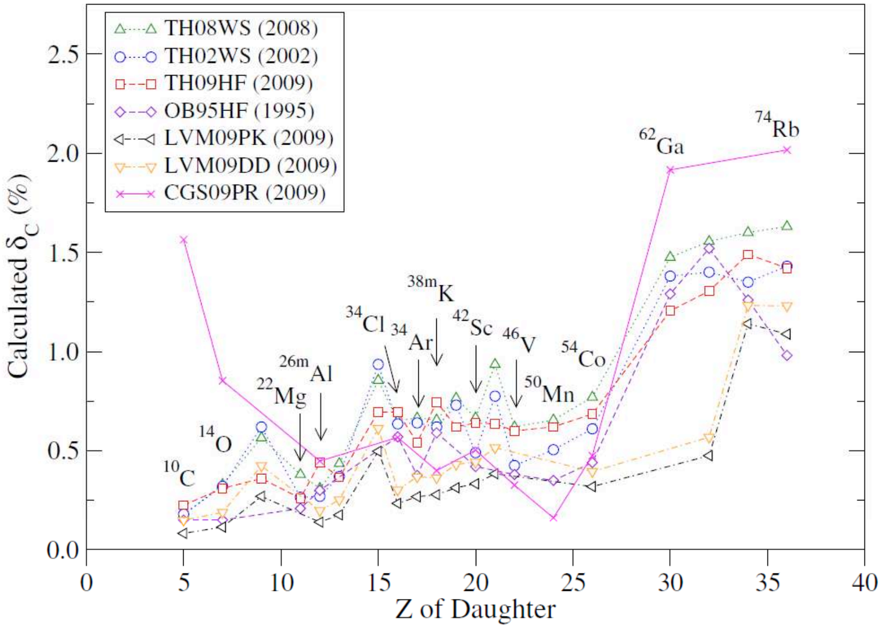
- Most precise experimental test of unitarity comes from the top row
  - Present Status*: $V_{ud} = 0.97425(22)$, $V_{us} = 0.2246(12)$, $V_{ub} = 0.0039(4)$

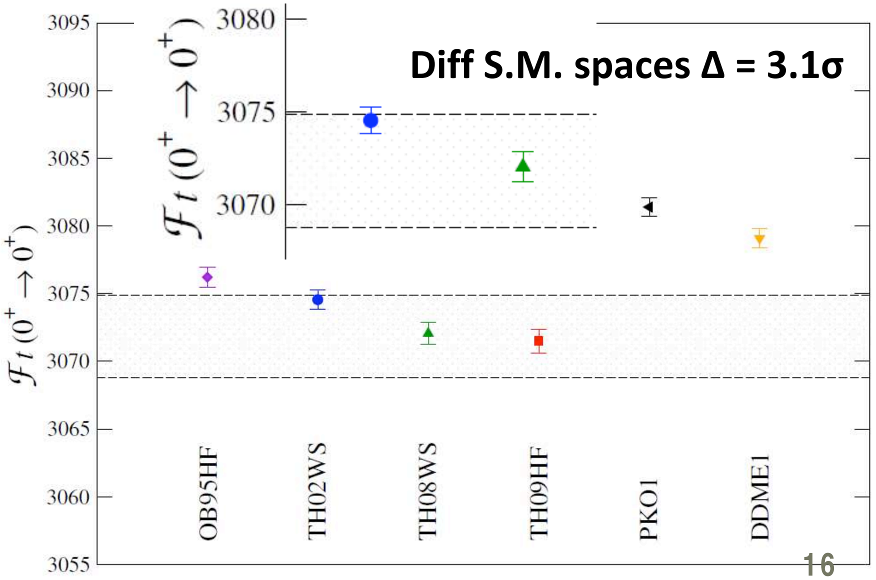
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(6)$$



Recent I.S.B. Calculations

- Several “sets” of δ_C values
  - Different approaches
    - Shell Models
    - Relativistic HF + RPA
    - Collective
    - Results differ by factors of 2
- Impact on V_{ud} and CKM:
  - All use same *ft*, δ_R values
- Strategy:
  - Constrain via experiment
  - Nuclei that exhibit largest theoretical differences





Diff S.M. spaces Δ = 3.1σ

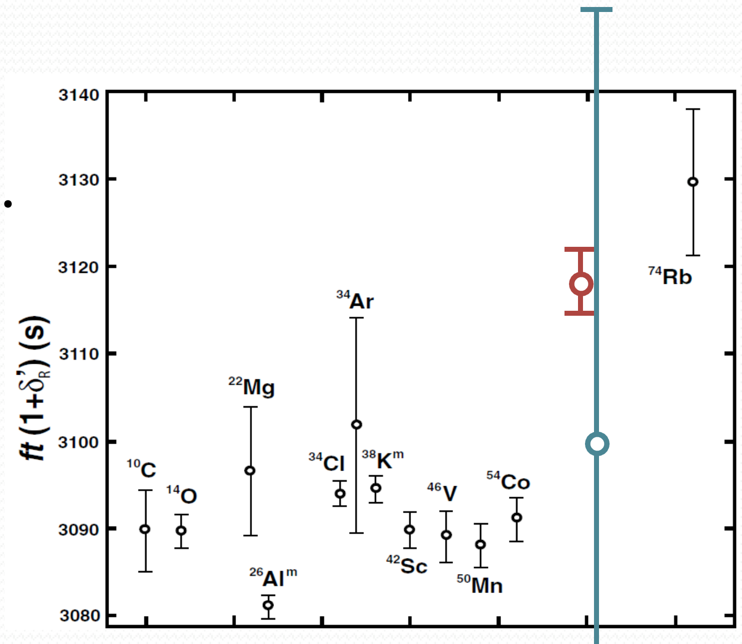
Experimental Results

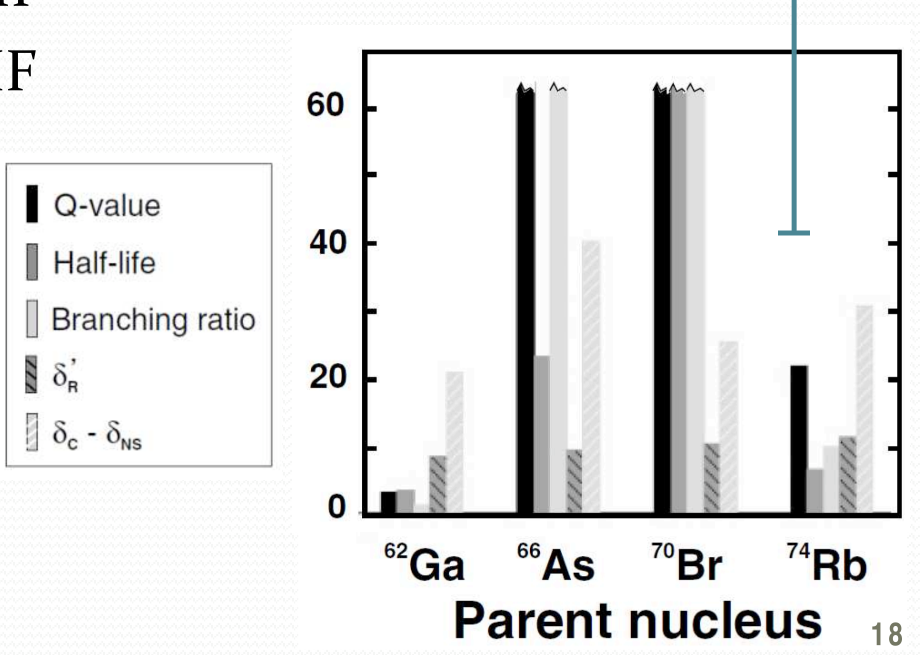
Superallowed Decay of ^{62}Ga

The case of ^{62}Ga

J.C. Hardy and I.S.Towner EPJA. 25 695 (2005)

- Status of the ^{62}Ga ft value in 2005…
  - $ft(1+\delta_R) = 3102(48)$ s
- Since: all 3 quantities measured
  - Q-value (0.004%) Jyväskalä
  - $T_{1/2}$ (0.022%) TRIUMF
  - B.R. (0.001%) TRIUMF
- Present value
  - $ft(1+\delta_R) = 3119(3)$ s
  - 16x improvement
  - Ft value now limited by δ_C





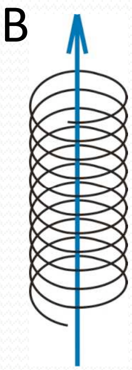
Penning Trap Basics

Figures courtesy of A.Kwiatkowski NSCL

- Ions with charge *q* mass *m* in a mag. field *B*
  - Circular motion with radius *r* and velocity *v*

$$\mathbf{F} = qv \times \mathbf{B} = \frac{mv^2}{r}$$

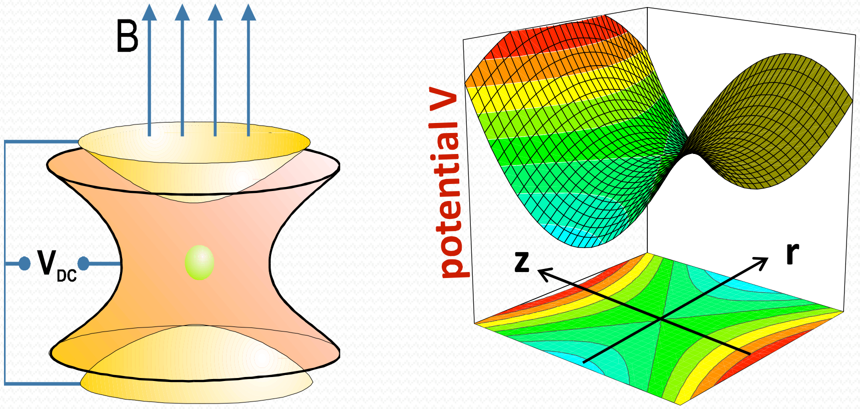
Magnetic field



2D Radial confinement

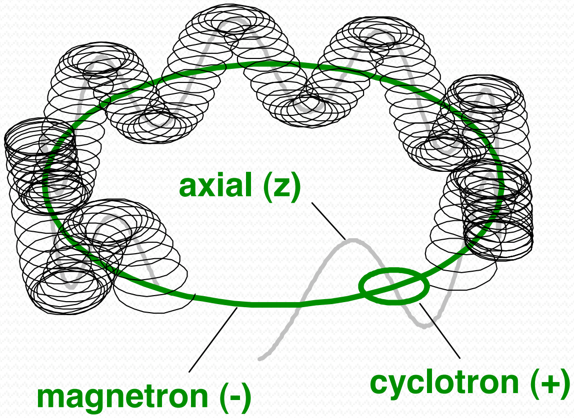
+

Electric quadrupole field



1D Axial confinement

3D confinement



3 Independent motions

Axial (z), Magnetron (-), reduced cyclotron (+)

$$2\pi\nu_c = \frac{v}{r} = \frac{qB}{m}$$

Mass of ^{62}Ga

JYFLTRAP

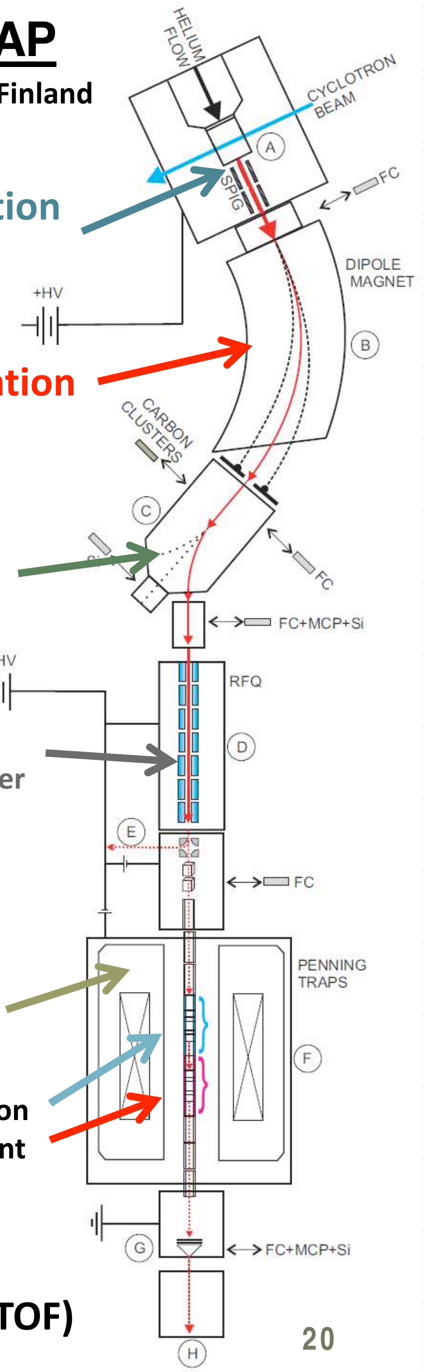
Univ. Jyväskalä, Finland

T.Eronen et al. Phys. Lett. B 636 191 (2006)

- Beams of ^{62}Ga produced at IGISOL
  - Trap ^{62}Ga and scan *rf* frequency
  - Release ^{62}Ga from the trap
  - Measure time-of-flight (Trap/Detector)
    - Shortest TOF = resonance υ_c frequency
  - ^{62}Ga frequency relative to ^{62}Zn, ^{62}Cu, ^{62}Ni

$$r = \frac{\nu_{\mathrm{c,ref}}}{\nu_{\mathrm{c}}} \qquad m = r\left(m_{\mathrm{ref}} - m_e\right) + m_e$$

$$Q_{\mathrm{EC}} = m_{\mathrm{mother}} - m_{\mathrm{daughter}} = (r-1)(m_{\mathrm{ref}} - m_e)$$



R.I.B production
30 keV

Mass separation

Deflector

R.F.Q.
Cooler/buncher

7T S.C. solenoid

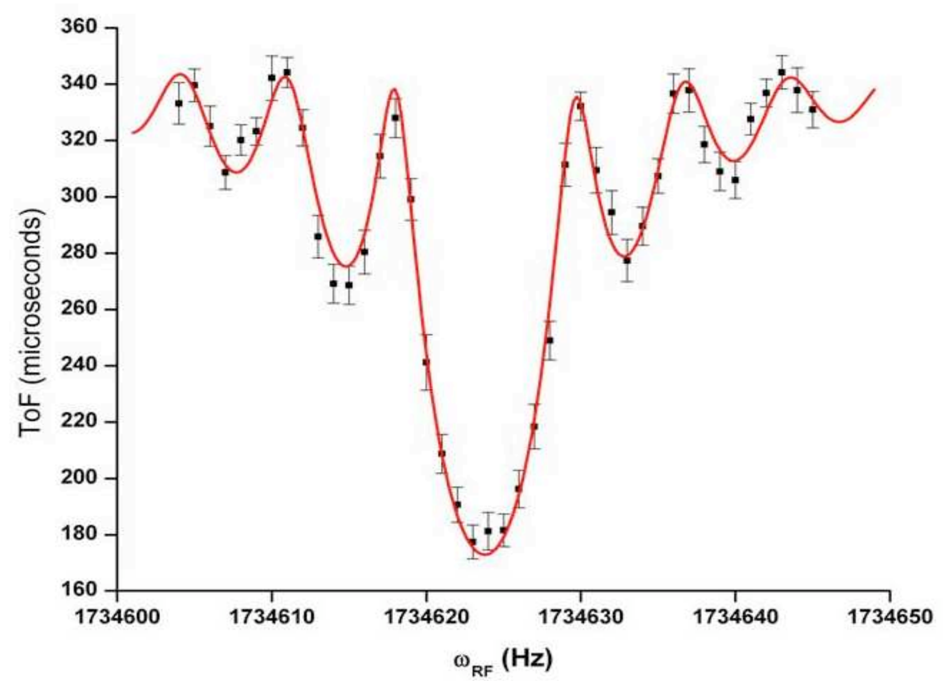
Penning Traps
Trap 1 – Isobaric purification
Trap 2 – mass measurement

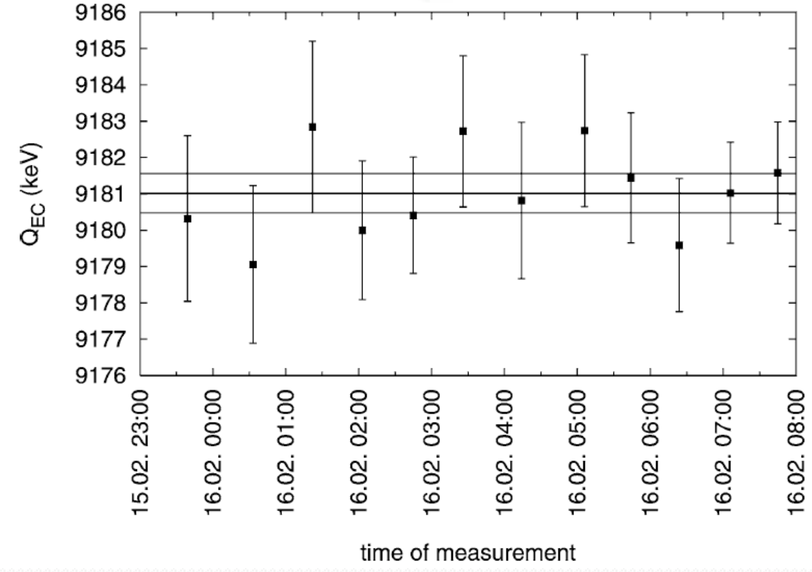
Detector Station (TOF)

Mass of ^{62}Ga

T.Eronen et al. Phys. Lett. B 636 191 (2006)

- Final result for ^{62}Ga:
  - Q-value = 9181.07(38) keV
  - *f* -value = 26401.6(83)
- Overall precision:
  - Q-value = 0.004%
  - *f* -value = 0.03%
- Previous values
  - Q-value = 9171(26) keV (↓ 70x)
  - *f* -value = 26250(400) (↓ 50x)





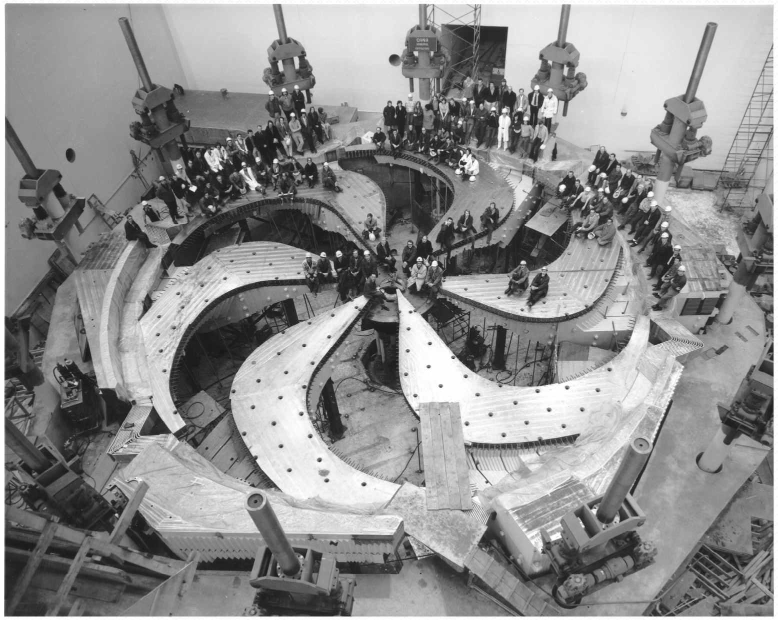
^{62}Ga $T_{1/2}$ and Branching Ratio

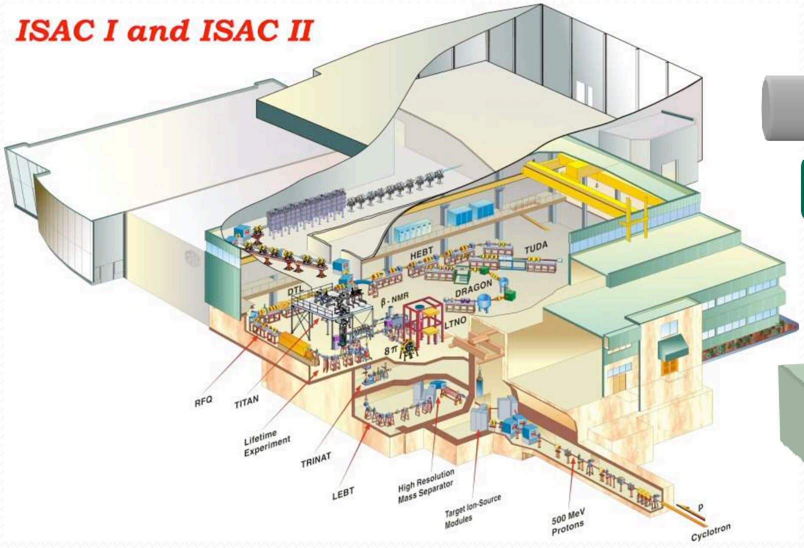
- Performed at TRIUMF-ISAC:

TRIUMF 500 MeV

Cyclotron 100 μA

proton beam





Production Target

Ion Source

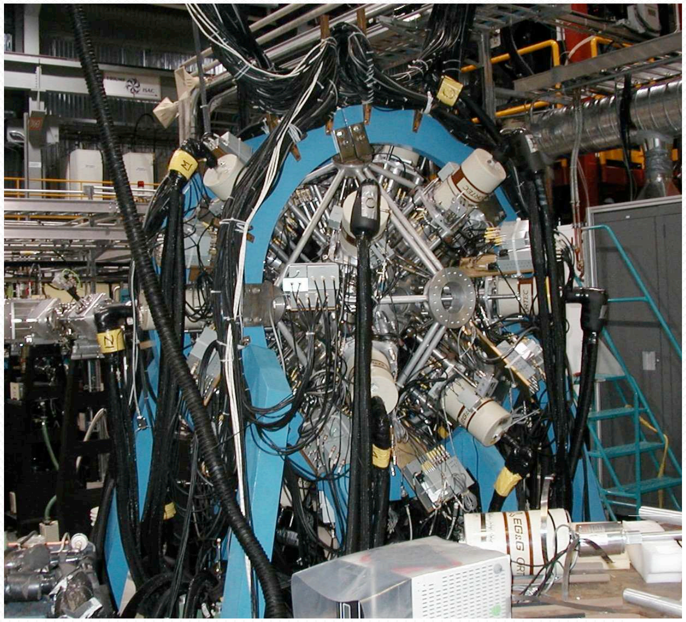
Mass Separator

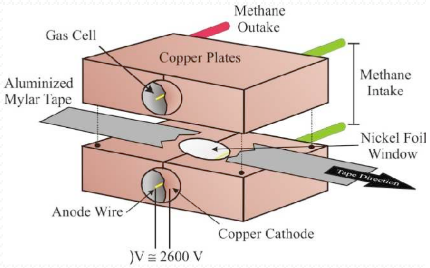
Experiments

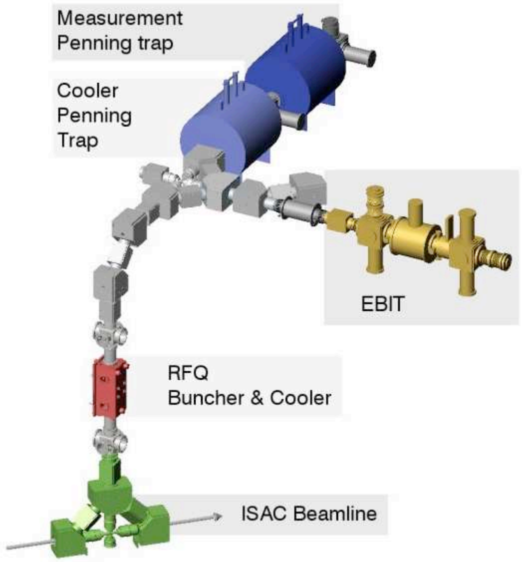
60 keV ion beam

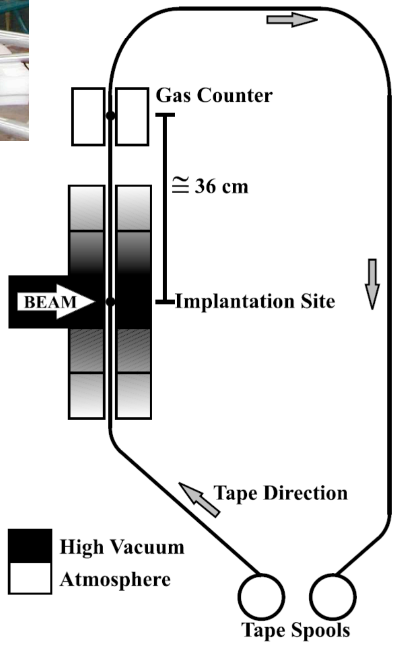
Experiments at TRIUMF

- 8π γ-ray spectrometer
  - 20 HPGe detectors
  - β's, β delayed γ-rays
  - β branching ratios
- Counter and fast tape
  - β particle counting
  - Half-life measurements
- Penning Trap (TITAN)
  - High-precision masses





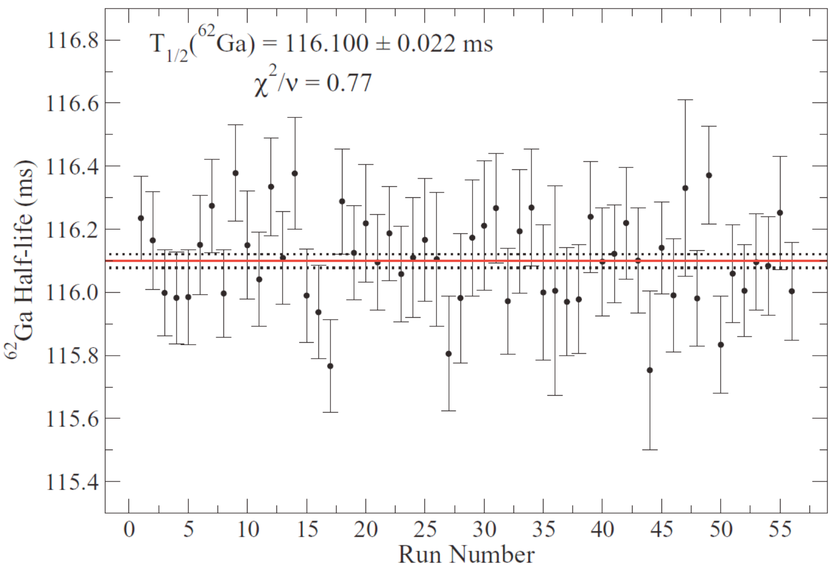


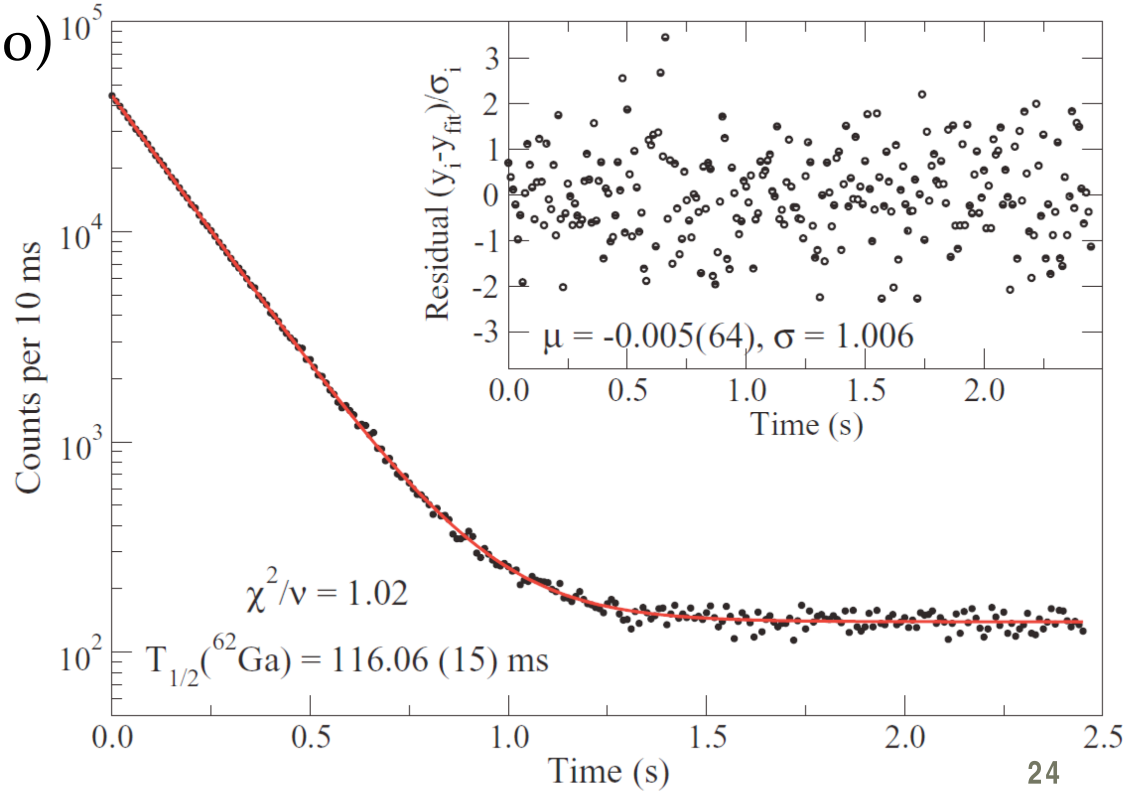


Half-life of ^{62}Ga

G.F. Grinyer et al. Phys. Rev. C 77 015501 (2008)

- ^{62}Ga beam of 8000 ions/s
  - Beam on 0.5 s, move tape
  - Count decay 2.5 s
  - Repeat 1200 times/hour
  - Run 65 hours (80,000)
- Half-life
  - Deduced from $Ae^{-\lambda t}$
  - 80,000 fits!
  - Sum & fit = 56 fits
  - Average = $T_{1/2}$



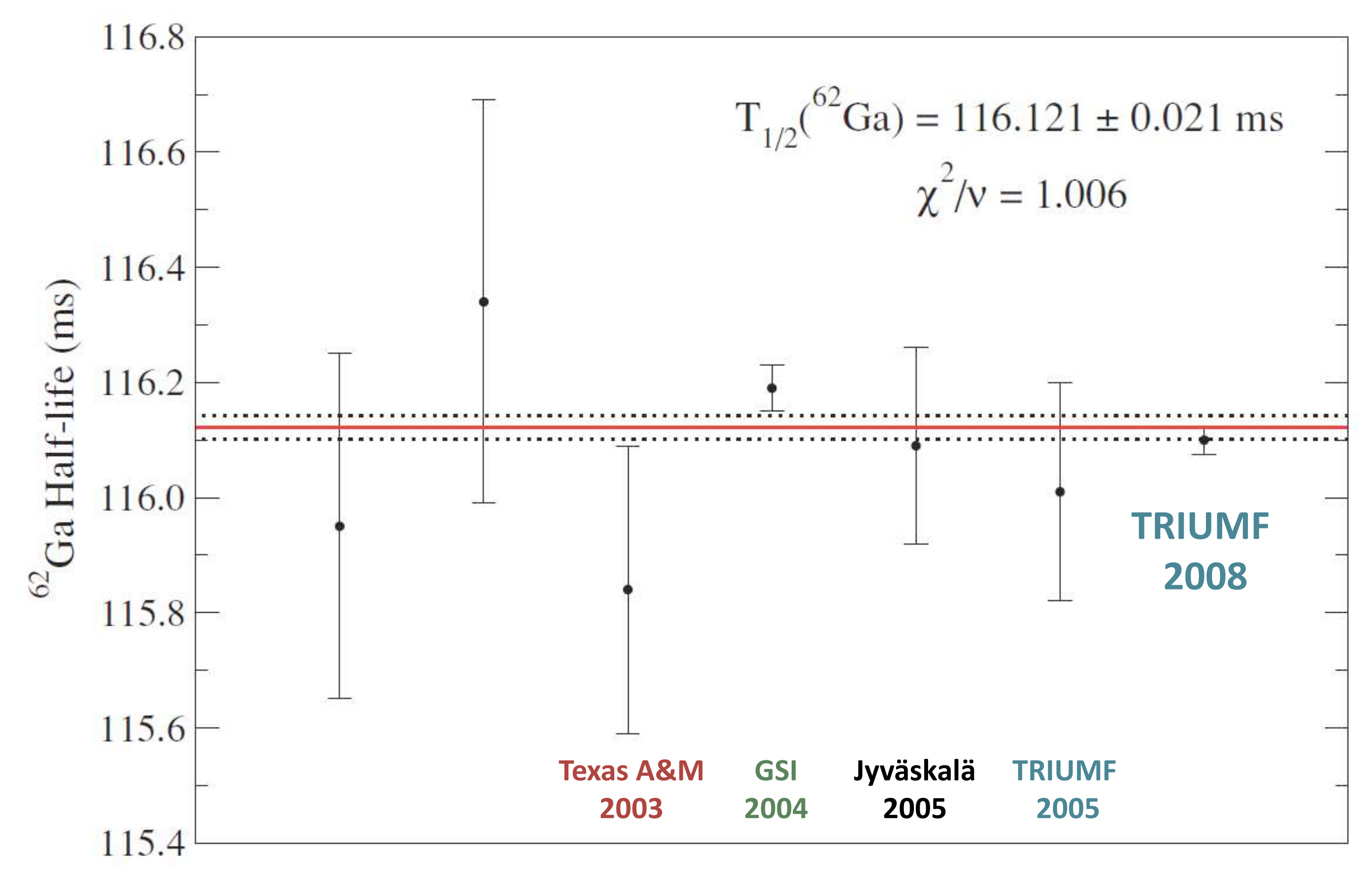


Half-life of ^{62}Ga

G.F. Grinyer et al. Phys. Rev. C 77 015501 (2008)

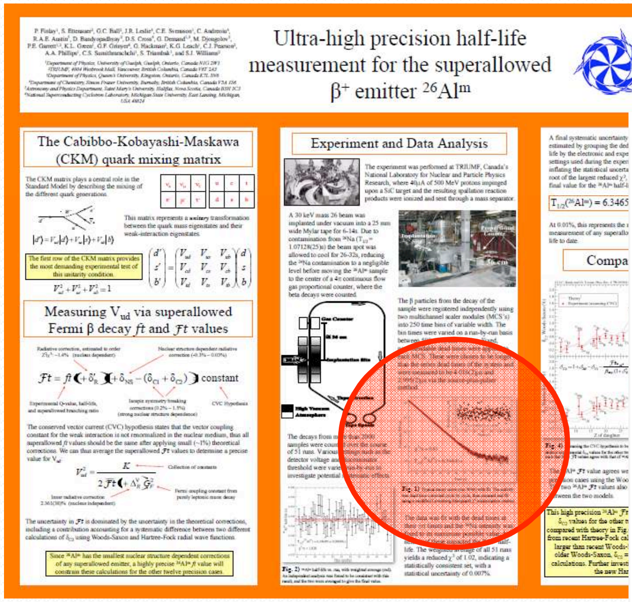
Most precise $T_{1/2}$ measurement for any superallowed decay!

- ^{62}Ga Half-life
  - Average TRIUMF result (2008): 116.100 ± 0.025 s (0.02%)
  - Previous world average (2005): 116.175 ± 0.038 s (0.04%)



New Result: Half-life of ^{26m}Al

- ^{26m}Al half-life
  - New result at TRIUMF: Half-life measured to 0.01%!
  - See Poster by Paul Finlay (University of Guelph)



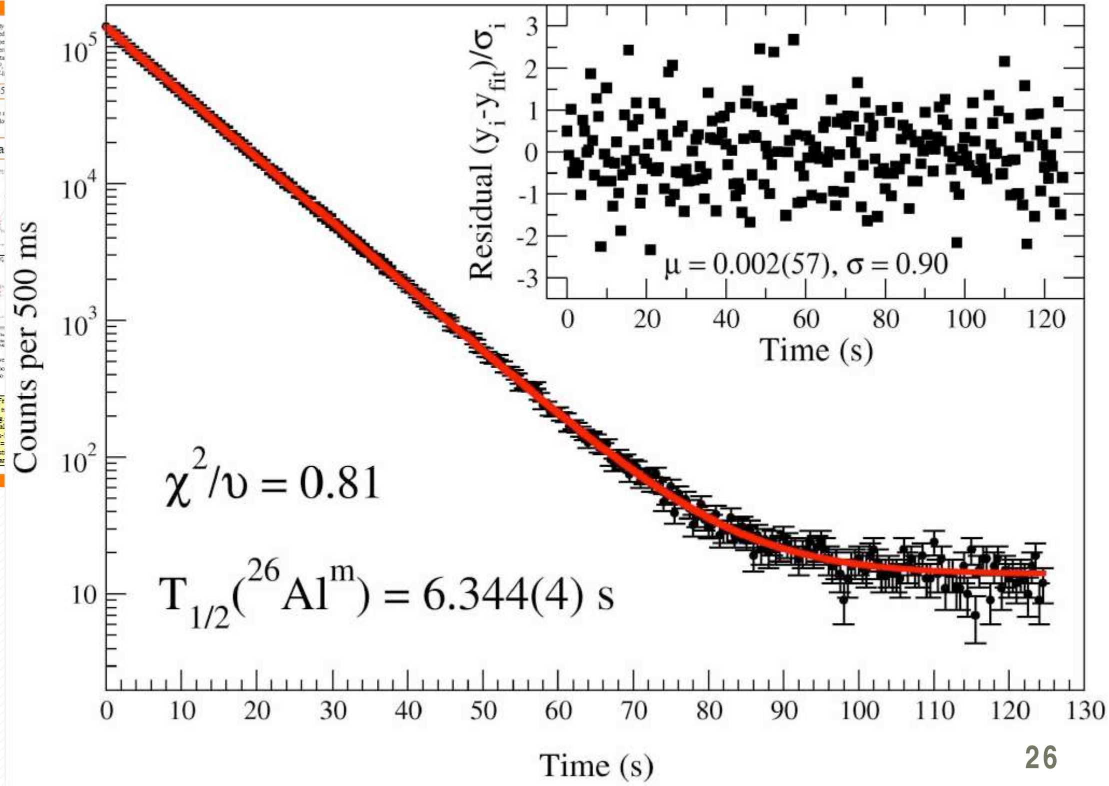
Ultra-high precision half-life measurement for the superallowed β^+ emitter ^{26}Al^m

UNIVERSITY of GUELPH

The Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix

Measuring V_{ud} via superallowed Fermi β decay ft and $\mathcal{F}t$ values

Experiment and Data Analysis



^{62}Ga Branching Ratio

P.Finlay et al. Phys. Rev. C 78 025502 (2008), B.Hyland et al. Phys. Rev. Lett. 97 102501 (2006)

- To measure a B.R. to states in the β decay daughter we need
  - Total number of β decays (count β particles)
  - What fraction feeds each state (count γ rays)

$$BR(j) = \frac{N_\gamma(j)}{N_\beta}$$

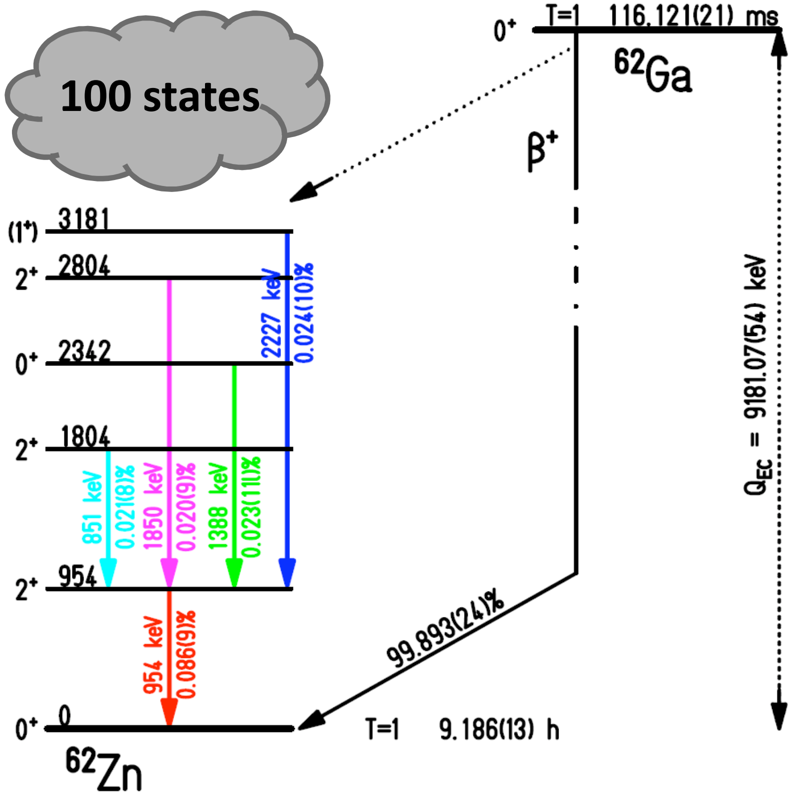
  - Ground state – no γ rays

$$BR(\text{g.s.}) = 1 - \sum_{j=0}^{n} BR(j)$$

- Obstacles for high-precision
  - Efficiency and “Pandemonium”

$$N_\gamma(j) = \frac{N_\gamma^{exp}(j)}{\boxed{\epsilon(j)}}$$

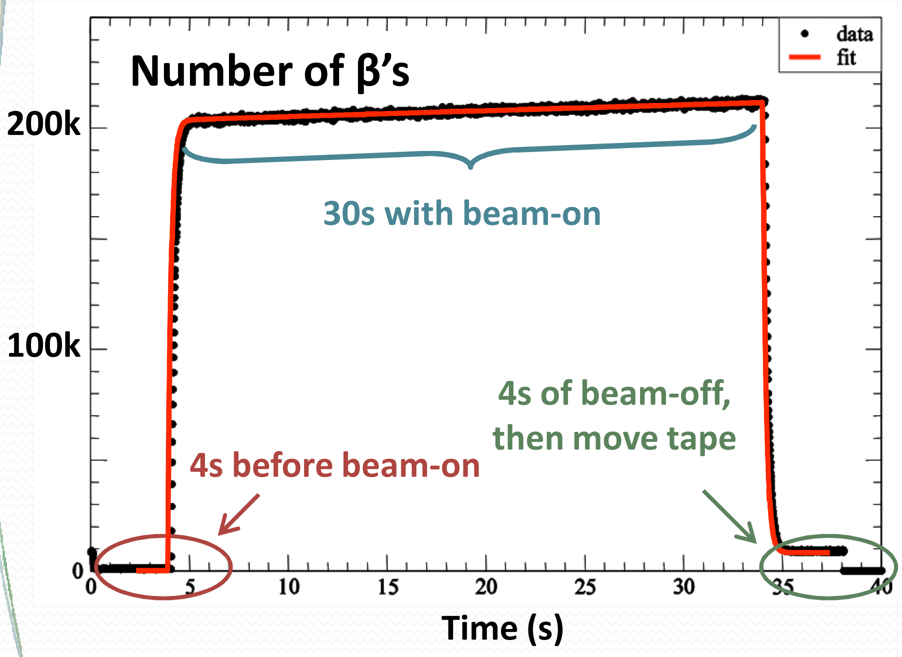
Uncertainty > 1%

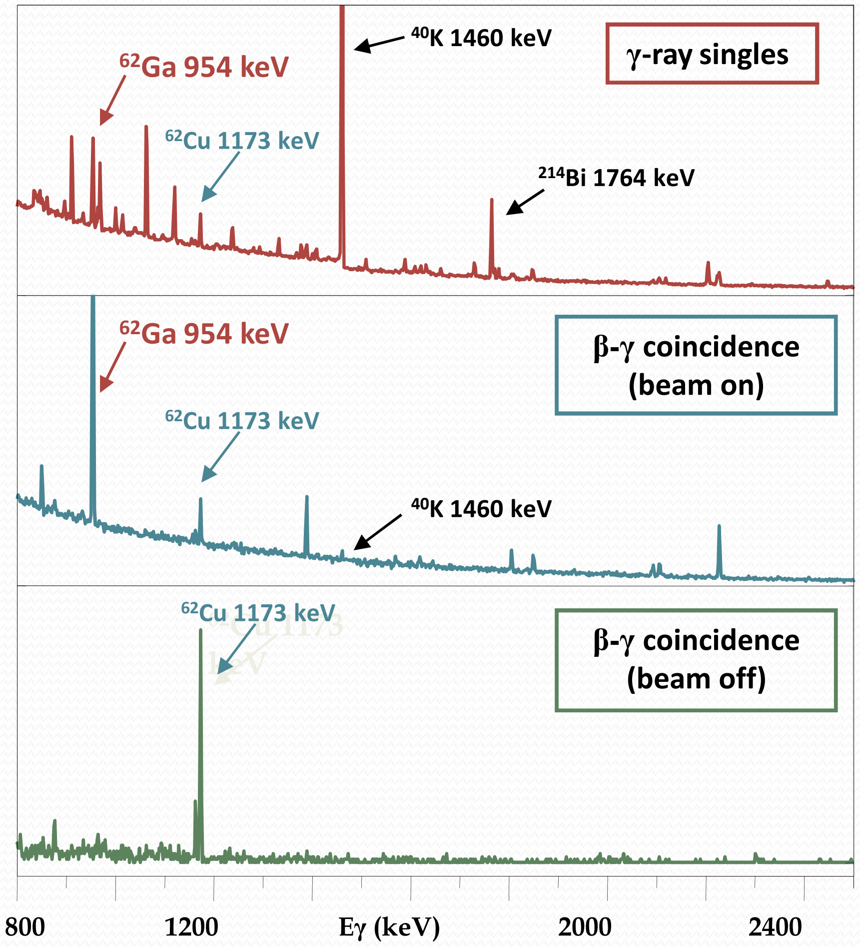


^{62}Ga Branching Ratio

P.Finlay et al. Phys. Rev. C 78 025502 (2008), B.Hyland et al. Phys. Rev. Lett. 97 102501 (2006)

- Experiment at TRIUMF
  - 8π spectrometer
  - Inner array of β counters
  - $N_\beta = 6.3 \quad 10^8$





^{62}Ga Branching Ratio

P.Finlay et al. Phys. Rev. C 78 025502 (2008)

- Observed + Pandemonium (Shell-model calculation):

2% precision

$$\sum_{j=0}^{n} BR(j) = 0.134(3) + 0.008(8) = 0.142(8)\ \%$$

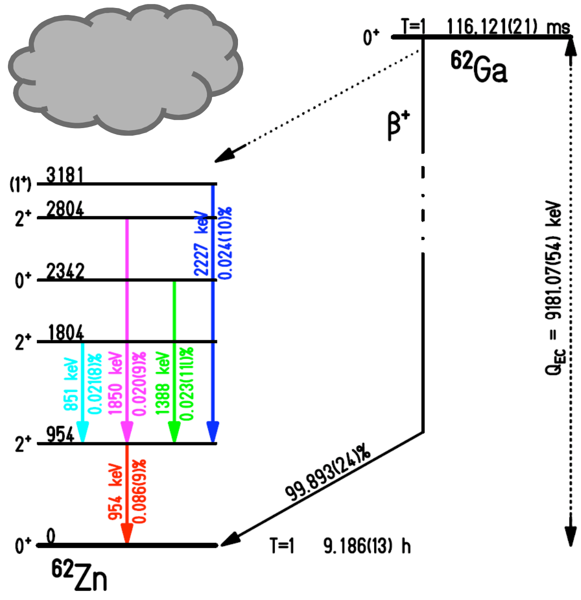
6% precision

- Ground-state branching ratio

$$BR(\mathrm{g.s.}) = 1 - \sum_{j=0}^{n} BR(j) = 100 - 0.142(8)\ \%$$

$$= 99.858(8)\%$$

0.008% precision !!



- <u>As a general rule</u>
  - Works only if S.A.F. decay is to ground state and B.R. > 95%

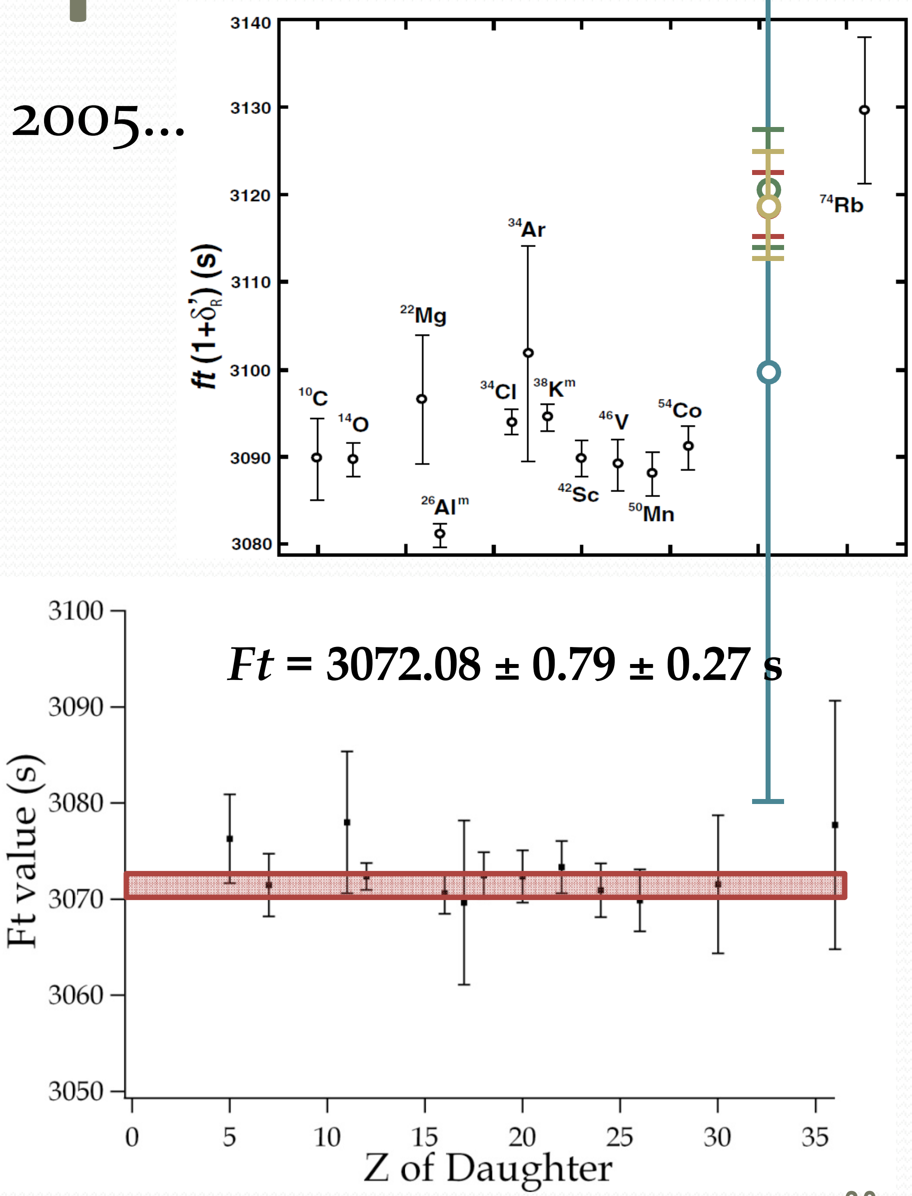
$$\sum_{j=0}^{n} BR(j) = 5.0(1)\ \% \qquad BR(\mathrm{g.s.}) = 1 - \sum_{j=0}^{n} BR(j) = 95.0(1)\%$$

2% precision

0.1% precision

Experimental Impact for ^{62}Ga

- Status of the ^{62}Ga *ft* value in 2005…
  - $ft(1+\delta_R)$ = 3102(48) s
  - +Q-value = 3121(6) s
  - $+T_{1/2}$ = 3119(5) s
  - +B.R. = 3119(3) s
  - 16x improvement!



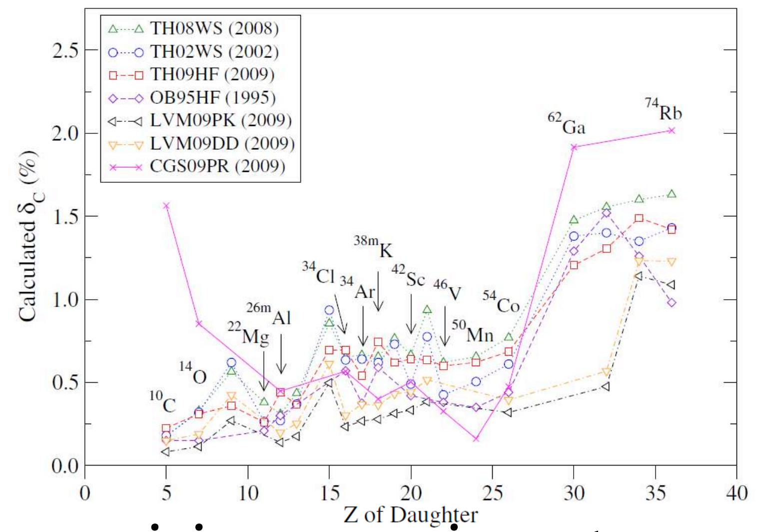
- Corrected *Ft* value for ^{62}Ga
  - Ft (2005) = 3058(47) s
  - Ft (2010) = 3072(7) s

Uncertainty dominated by theory (experimental contribution negligible)

Can *ft* to Constrain Theory

- ^{62}Ga *Ft* value limited by theory

Theoretical (TH08WS) δ_C = 1.5(2) %
Theoretical (TH02WS) δ_C = 1.4(2) %
Theoretical (TH09HF) δ_C = 1.2(7) %
Theoretical (OB95HF) δ_C = 1.3(2) %



- Constrain calculations using high-precision experiment
  - Assuming CVC we compute an “experimental” δ_C for ^{62}Ga

$$(1-\delta_C) = \frac{(\overline{\mathcal{F}t})^{*}}{ft(1+\delta'_R)}$$

World average of 12 others

Rad. Correction (^{62}Ga)

“experimental” theoretical correction

Experimental *ft* (^{62}Ga)

  - Using *ft* = 3074.1(15) s, δ_R = 1.46(9) %, ***Ft*** = 3072.1(8) s

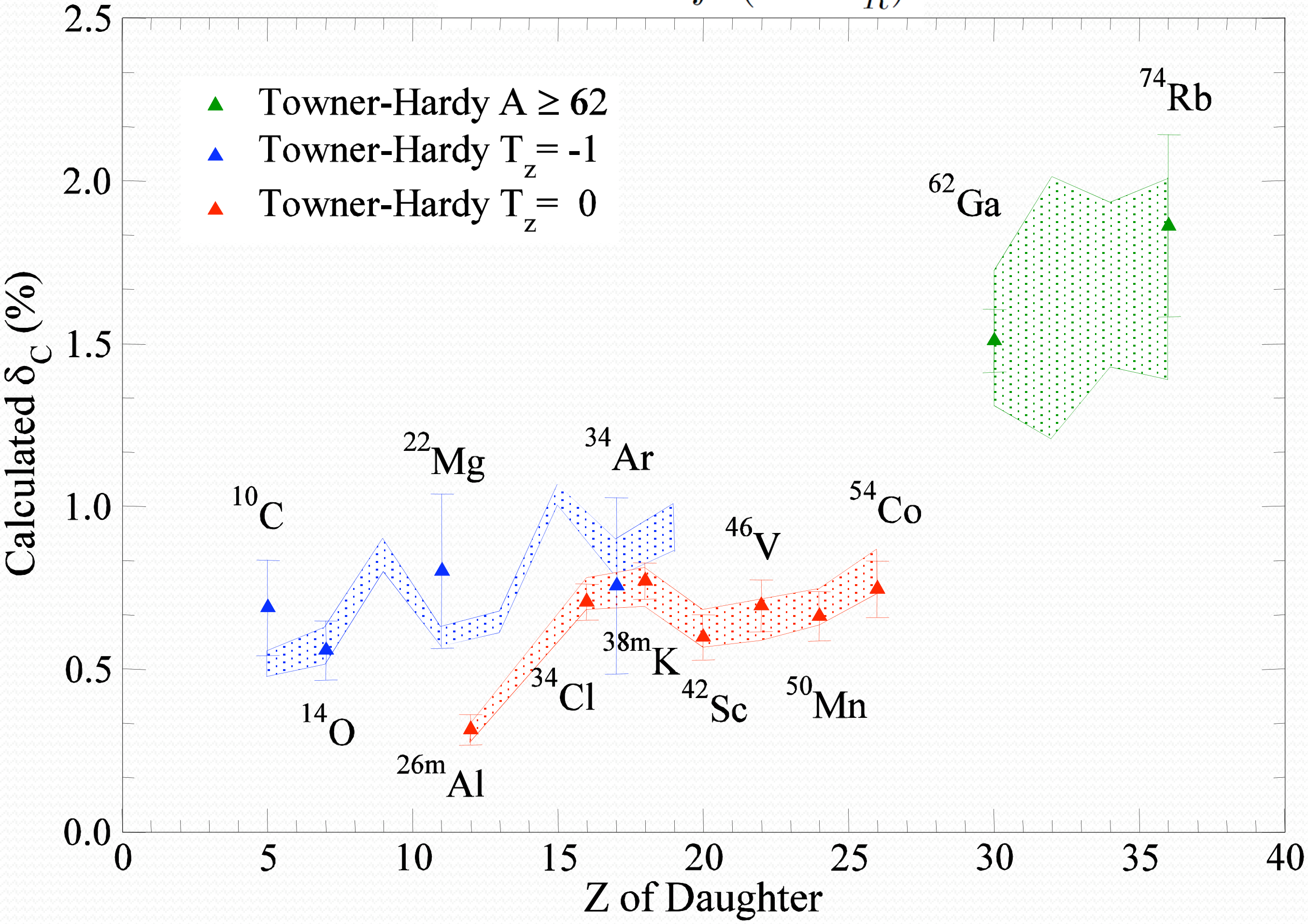
Experimental δ_C = 1.45(10) %

Not an ABSOLUTE test!

“Experimental” Corrections

- Using the TH08WS calculations, *Ft* = 3072.1(8)s

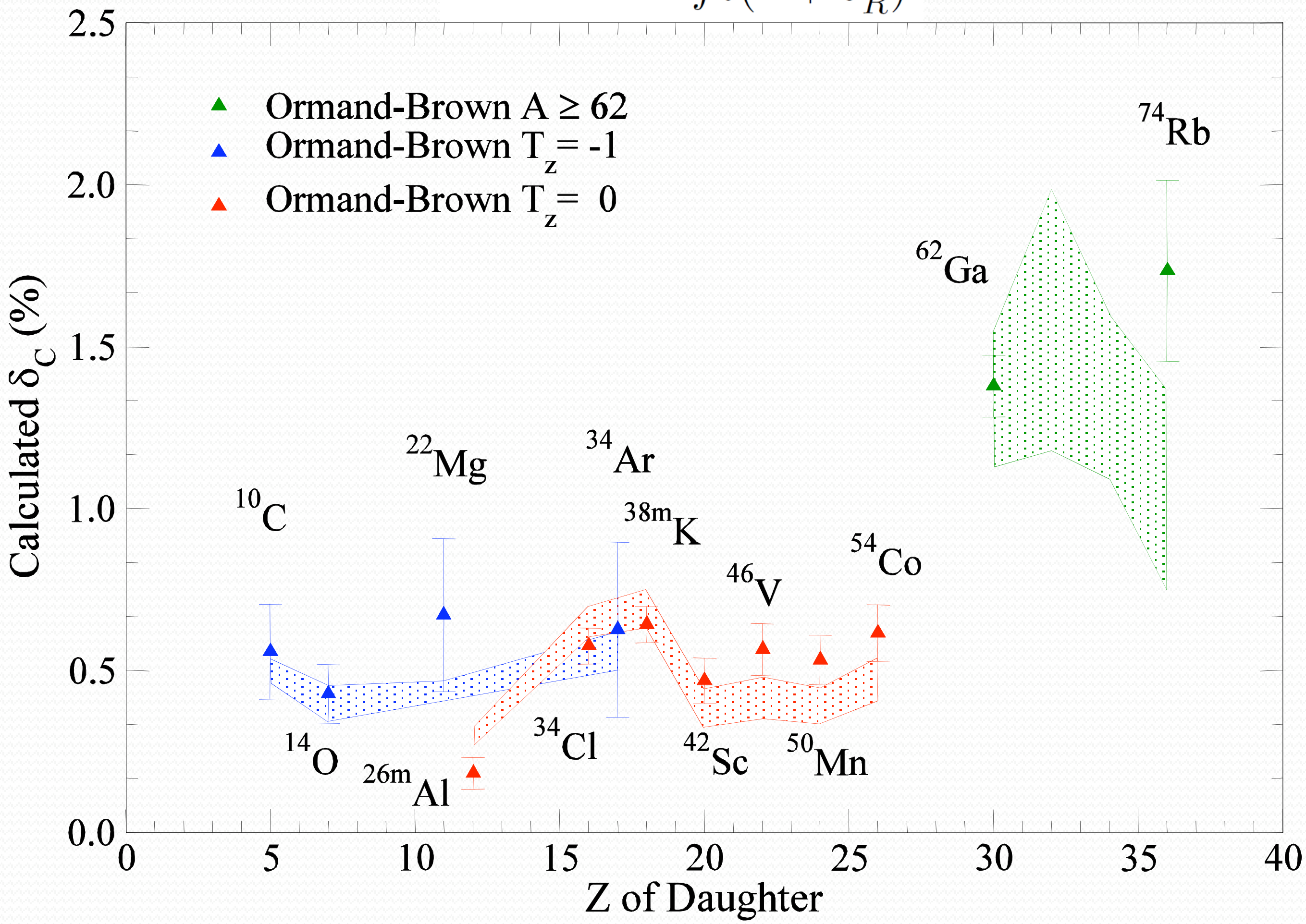
$$(1-\delta_C) = \frac{(\overline{\mathcal{F}t})^{\ *}}{ft(1+\delta'_R)}$$



“Experimental” Corrections

- Using the OB95HF calculations, *Ft* = 3076.2 s

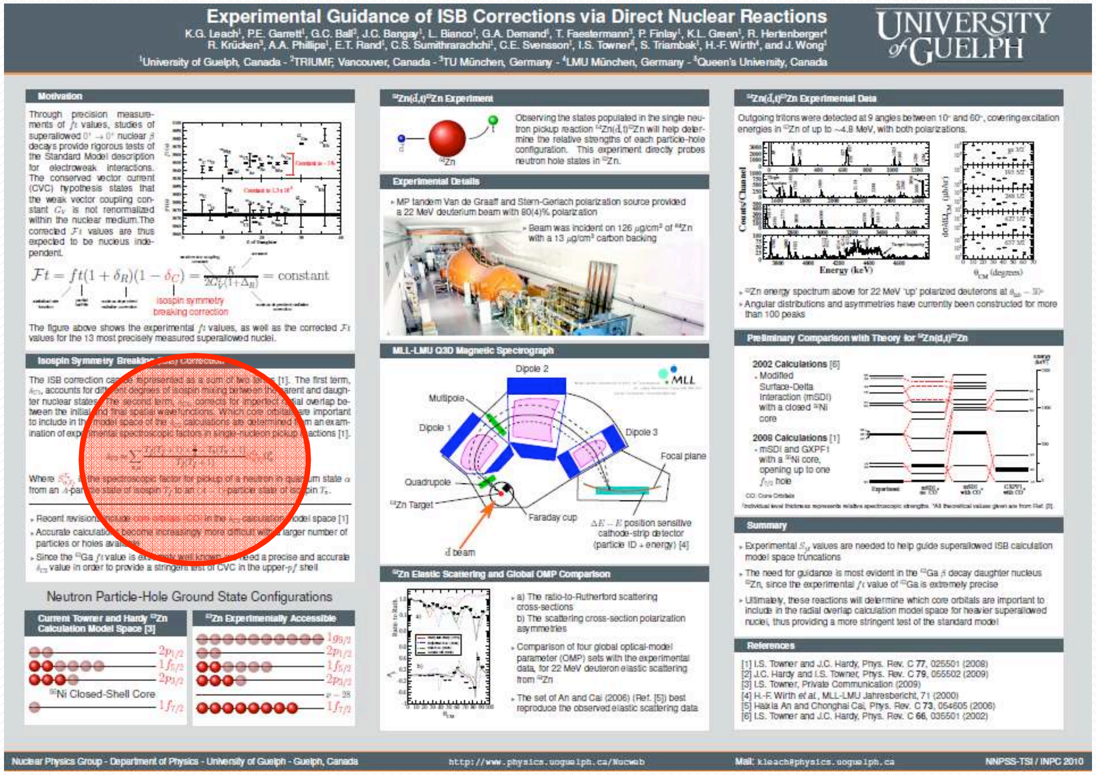
$$(1-\delta_C) = \frac{(\overline{\mathcal{F}t})^{\,*}}{ft(1+\delta'_R)}$$



Alternative Approaches

- Spectroscopic factors from low-energy transfer reactions
  - See poster by Kyle Leach (University of Guelph)

$$\delta_{C2} \approx \sum_{\pi,\alpha} \frac{T_f(T_f+1) + \frac{3}{4} - T_\pi(T_\pi+1)}{T_f(T_f+1)} S^{T_\pi}_{\alpha,T_f} \Omega^{\pi}_{\alpha}$$



Experimental Guidance of ISB Corrections via Direct Nuclear Reactions

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R. Krücken[3], A.A. Phillips[1], E.T. Rand[1], C.S. Sumithrarachchi[1], C.E. Svensson[1], I.S. Towner[5], S. Triambak[1], H.-F. Wirth[4], and J. Wong[1]
[1]University of Guelph, Canada - [2]TRIUMF, Vancouver, Canada - [3]TU München, Germany - [4]LMU München, Germany - [5]Queen's University, Canada

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Motivation

Through precision measurements of ft values, studies of superallowed $0^+ \to 0^+$ nuclear β decays provide rigorous tests of the Standard Model description for electroweak interactions. The conserved vector current (CVC) hypothesis states that the weak vector coupling constant G_V is not renormalized within the nuclear medium. The corrected $\mathcal{F}t$ values are thus expected to be nucleus independent.

$$\mathcal{F}t = ft(1+\delta_R)(1-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R)} = \text{constant}$$

isospin symmetry breaking correction

The figure above shows the experimental ft values, as well as the corrected $\mathcal{F}t$ values for the 13 most precisely measured superallowed nuclei.

Isospin Symmetry Breaking (ISB) Correction

The ISB correction can be represented as a sum of two terms [1]. The first term, δ_{C1}, accounts for different degrees of isospin mixing between the parent and daughter nuclear states. The second term, δ_{C2}, corrects for imperfect radial overlap between the initial and final spatial wavefunctions. Which core orbitals are important to include in the model space of the δ_{C2} calculations are determined from an examination of experimental spectroscopic factors in single-nucleon pickup reactions [1].

$$\delta_{C2} \approx \sum_{\pi,\alpha} \frac{T_f(T_f+1) + \frac{3}{4} - T_\pi(T_\pi+1)}{T_f(T_f+1)} S^{T_\pi}_{\alpha,T_f} \Omega^{\pi}_{\alpha}$$

Where $S^{T_\pi}_{\alpha,T_f}$ is the spectroscopic factor for pickup of a neutron in quantum state α from an A-particle state of isospin T_f to an $(A-1)$-particle state of isospin T_π.

- Recent revisions include core orbitals (CO) in the δ_{C2} calculation model space [1]
- Accurate calculations become increasingly more difficult with a larger number of particles or holes available
- Since the ^{62}Ga ft value is extremely well known, we need a precise and accurate δ_{C2} value in order to provide a stringent test of CVC in the upper-pf shell

Neutron Particle-Hole Ground State Configurations

Current Towner and Hardy ^{62}Zn Calculation Model Space [3]

^{62}Zn Experimentally Accessible

^{64}Zn($\vec{d}$,t)^{63}Zn Experiment

Observing the states populated in the single neutron pickup reaction ^{64}Zn($\vec{d}$,t)^{63}Zn will help determine the relative strengths of each particle-hole configuration. This experiment directly probes neutron hole states in ^{63}Zn.

Experimental Details

- MP tandem Van de Graaff and Stern-Gerlach polarization source provided a 22 MeV deuterium beam with 80(4)% polarization
- Beam was incident on 126 μg/cm^2 of ^{64}Zn with a 13 μg/cm^2 carbon backing

MLL-LMU Q3D Magnetic Spectrograph

$\Delta E - E$ position sensitive cathode-strip detector (particle ID + energy) [4]

^{64}Zn Elastic Scattering and Global OMP Comparison

- a) The ratio-to-Rutherford scattering cross-sections
  b) The scattering cross-section polarization asymmetries
- Comparison of four global optical-model parameter (OMP) sets with the experimental data, for 22 MeV deuteron elastic scattering from ^{64}Zn
- The set of An and Cai (2006) (Ref. [5]) best reproduce the observed elastic scattering data

^{64}Zn($\vec{d}$,t)^{63}Zn Experimental Data

Outgoing tritons were detected at 9 angles between 10° and 60°, covering excitation energies in ^{63}Zn of up to ~4.8 MeV, with both polarizations.

- ^{63}Zn energy spectrum above for 22 MeV 'up' polarized deuterons at $\theta_{lab} = 30°$
- Angular distributions and asymmetries have currently been constructed for more than 100 peaks

Preliminary Comparison with Theory for ^{64}Zn(d,t)^{63}Zn

2002 Calculations [6]
- Modified Surface-Delta Interaction (mSDI) with a closed ^{56}Ni core

2008 Calculations [1]
- mSDI and GXPF1 with a ^{56}Ni core, opening up to one $f_{7/2}$ hole

CO: Core Orbitals

Individual level thickness represents relative spectroscopic strengths. All theoretical values given are from Ref. [3].

Summary

- Experimental S_{lj} values are needed to help guide superallowed ISB calculation model space truncations
- The need for guidance is most evident in the ^{62}Ga β decay daughter nucleus ^{62}Zn, since the experimental ft value of ^{62}Ga is extremely precise
- Ultimately, these reactions will determine which core orbitals are important to include in the radial overlap calculation model space for heavier superallowed nuclei, thus providing a more stringent test of the standard model

References

[1] I.S. Towner and J.C. Hardy, Phys. Rev. C **77**, 025501 (2008)
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[3] I.S. Towner, Private Communication (2009)
[4] H.-F. Wirth *et al.*, MLL-LMU Jahresbericht, 71 (2000)
[5] Haixia An and Chonghai Cai, Phys. Rev. C **73**, 054605 (2006)
[6] I.S. Towner and J.C. Hardy, Phys. Rev. C **66**, 035501 (2002)

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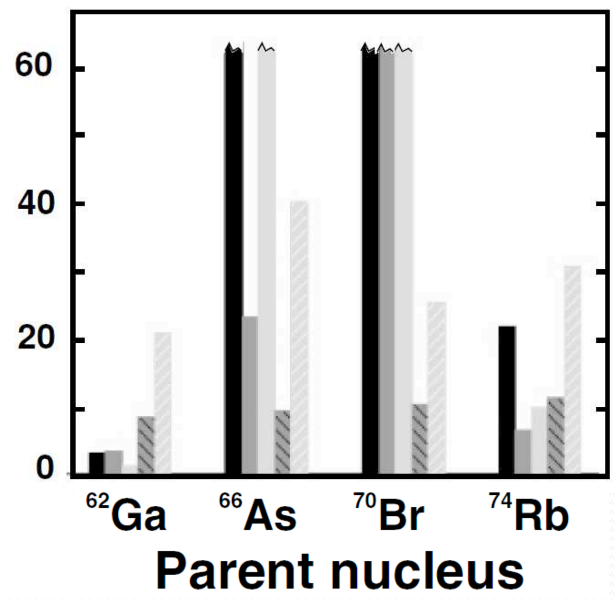
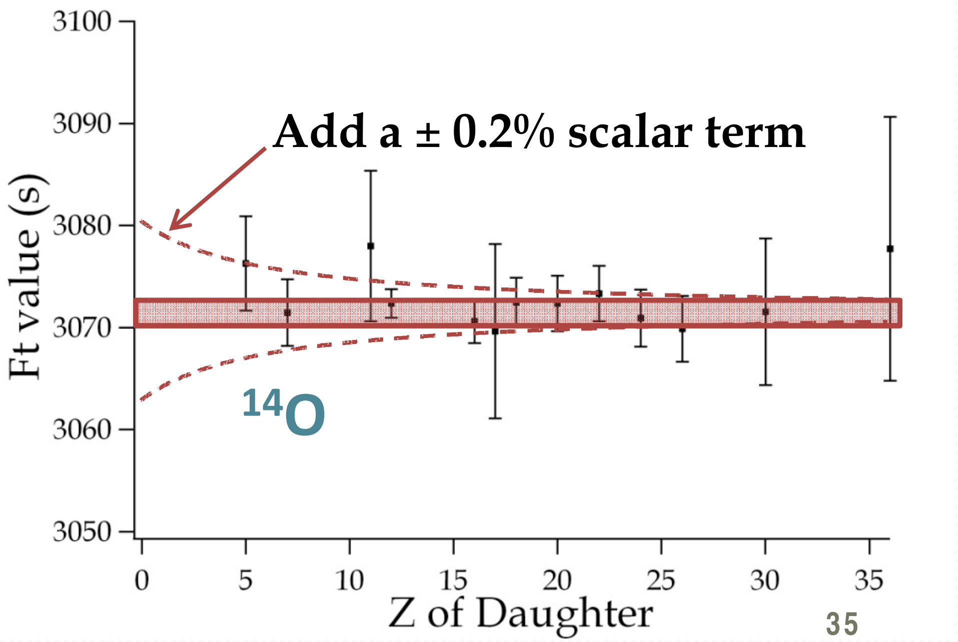
NNPSS-TSI / INPC 2010

On The Horizon

- Other heavy cases: ^{66}As, ^{70}Br, ^{74}Rb
  - All similar in principle to ^{62}Ga
  - Beam production is a challenge
- Light decays ^{10}C, ^{14}O
  - Search for scalers in β decay
  - *ab initio* calculations of δ_C
- Alternative techniques
  - T=1/2, T=2 decay
  - Transfer reactions




Add a ± 0.2% scalar term

^{14}O

Summary

- Most precise way to extract V_{ud} (by 6x) is through *ft* values of S.A.F. decay
  - Unlikely to change in the next 10 yrs
- Uncertainty dominated by theory
  - I.S.B corrections are an essential ingredient for CVC and V_{ud}
  - Range of δ_C values unsatisfactory
- New facilities with state-of-the-art experiment and theory
  - Leading to an improved understanding of these effects