

# ***Superallowed Nuclear $\beta$ Decay***

***The Precision Frontier of Low-Energy Nuclear Physics***

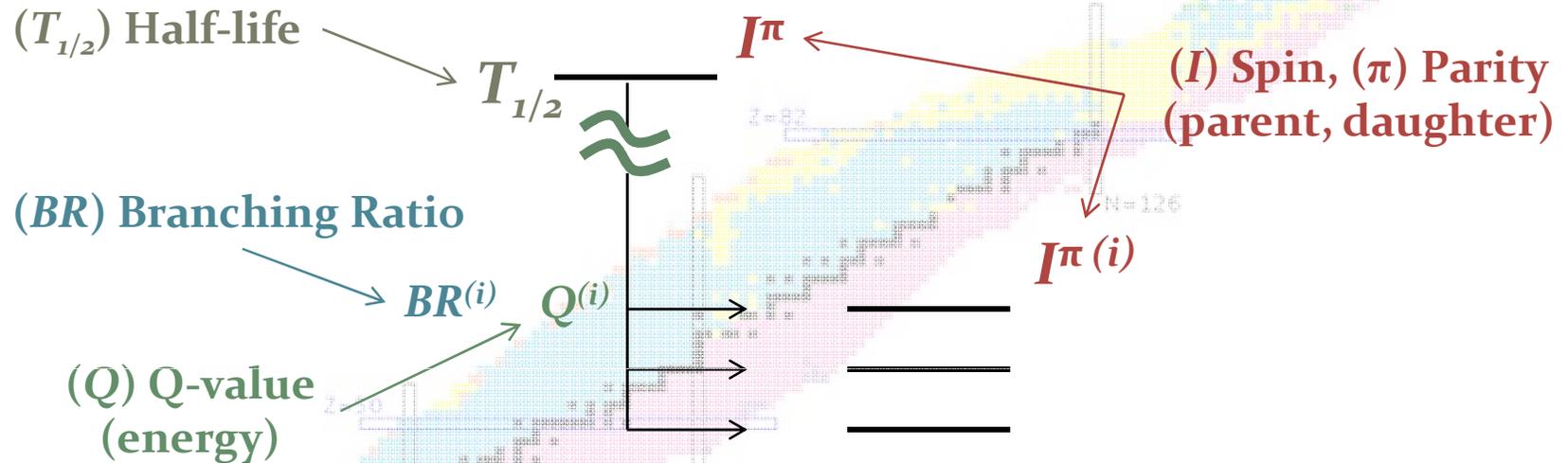
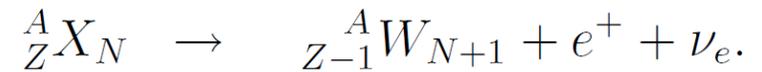
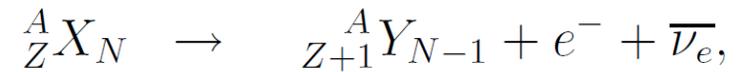
*Geoff Grinyer*

*Michigan State University  
National Superconducting Cyclotron Laboratory  
NNPSS-TSI June 23 2010*

# Outline

- Introduction and Review
  - Nuclear  $\beta$  decay
  - Isospin symmetry and isospin symmetry breaking
  - Conserved Vector Current hypothesis (CVC)
- Status of Superallowed Fermi  $\beta$  Decay
  - $V_{ud}$  and CKM unitarity
- Case Study  $^{62}\text{Ga}$ : “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 $\beta$ Decay



- Selection Rules:

$$\pi_P = \pi_D (-1)^L$$

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

- Allowed Decay

- L=0

- “Forbidden” Decay

- L=1, 2, 3, ...

- Fermi (Vector)

- S=0  $\beta \uparrow\downarrow \nu_e$

- Gamow-Teller (Axial-Vector)

- S=1  $\beta \uparrow\uparrow \nu_e$

# $\beta$ Decay Classification

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

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

- The  $ft$  value is a powerful way to characterize  $\beta$  decay

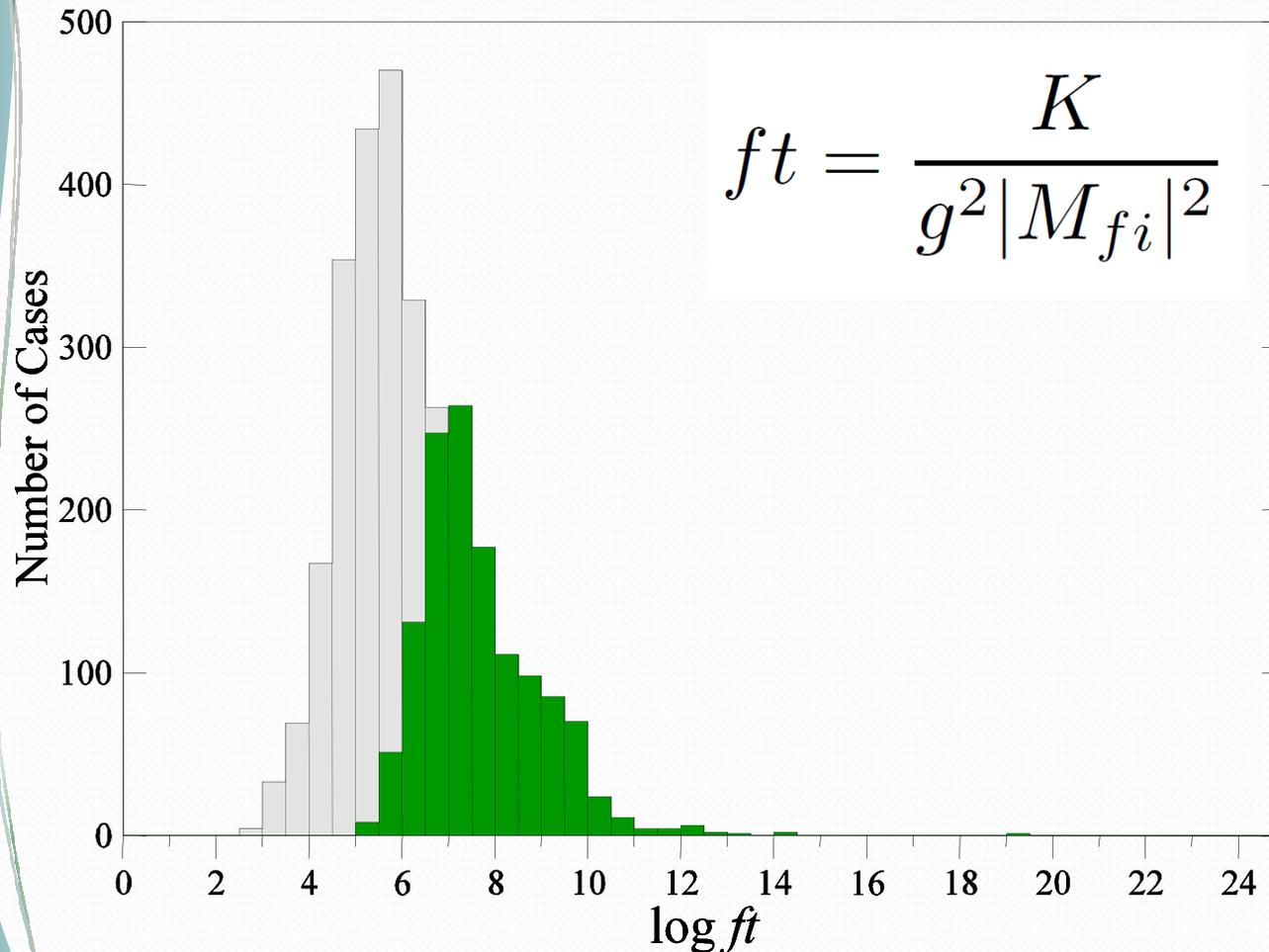
$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{g^2 |M_{fi}|^2}$$

Q-value  $\swarrow$  Half-life  $\swarrow$  Constants  $\swarrow$   
 Branching Ratio  $\nearrow$  Matrix Element  $\swarrow$   
 Coupling Strength  $\swarrow$

# $\beta$ 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  $\beta$  decay  $ft$  values



**Allowed:**

$1^+ \rightarrow 0^+, 2^- \rightarrow 2^-$   
(2497)

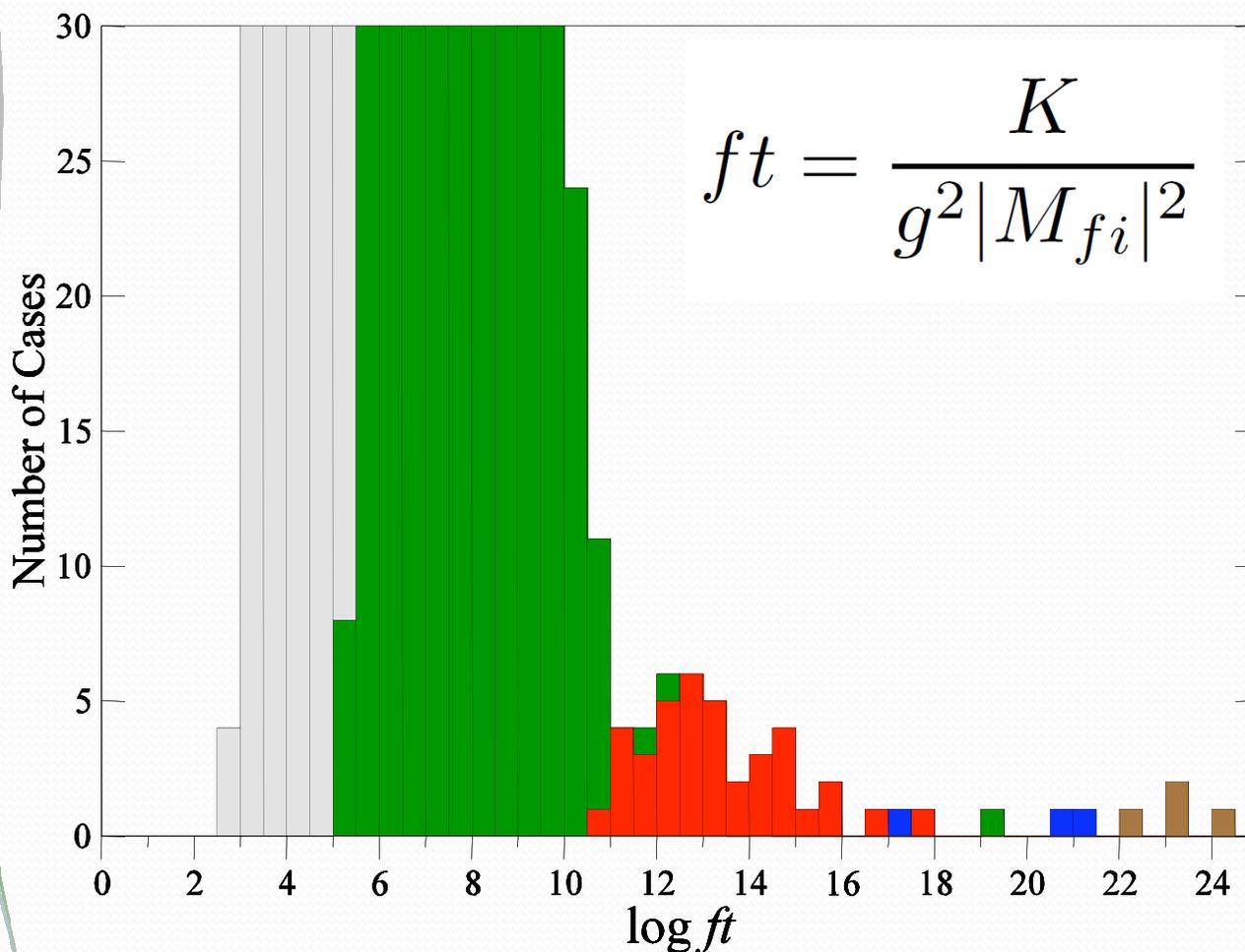
**1<sup>st</sup> Forbidden:**

$2^+ \rightarrow 0^+, 2^- \rightarrow 2^+$   
(1297)

# $\beta$ decay $ft$ values

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

- $\beta$  decay  $ft$  values span ~ 21 orders of magnitude



**Allowed:**

$1^+ \rightarrow 0^+, 2^- \rightarrow 2^-$   
(2497)

**1<sup>st</sup> Forbidden:**

$2^+ \rightarrow 0^+, 2^- \rightarrow 2^+$   
(1297)

**2<sup>nd</sup> Forbidden:**

$2^+ \rightarrow 0^+, 5^+ \rightarrow 2^+$   
(39)

**3<sup>rd</sup> & 4<sup>th</sup> Forbidden**

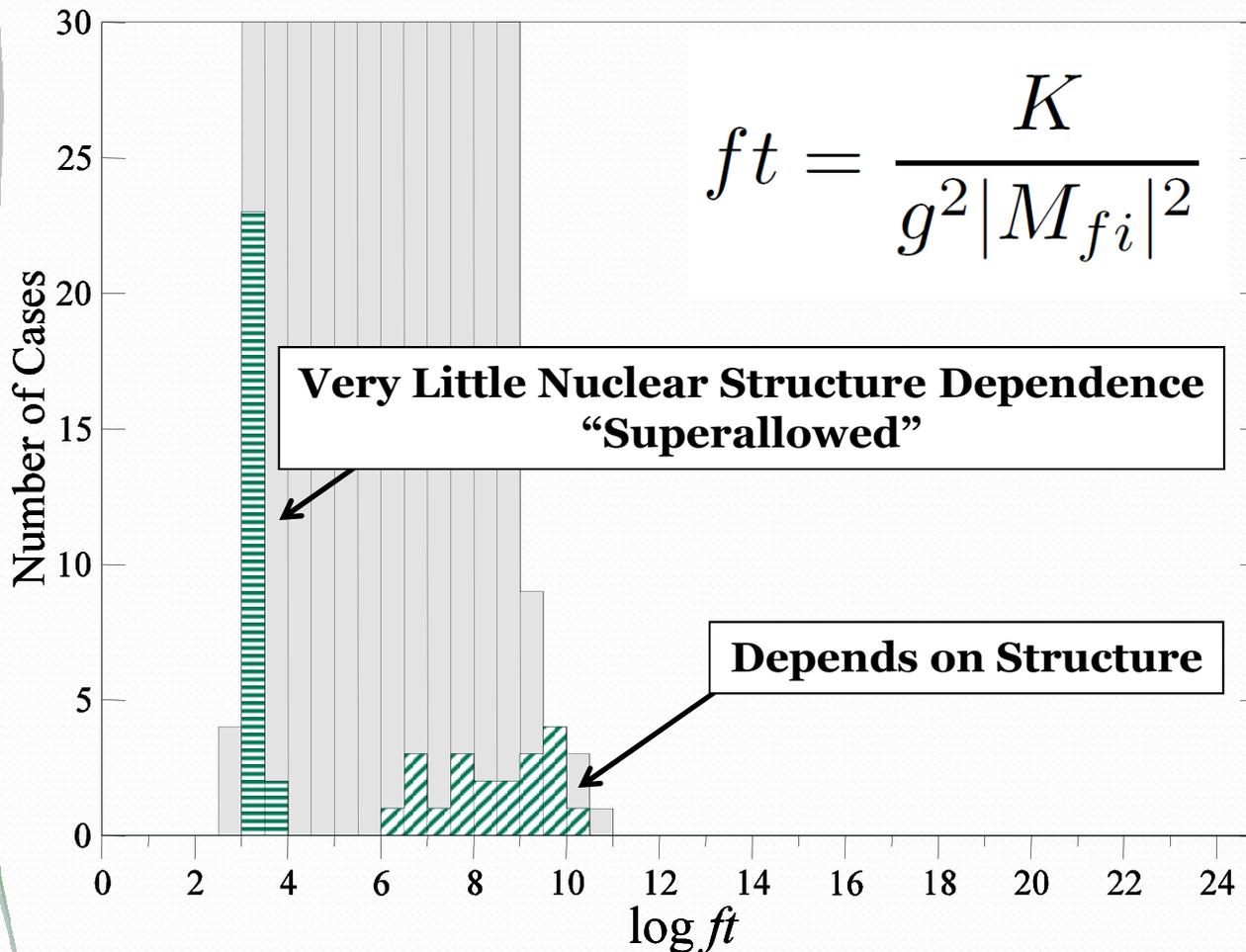
$4^- \rightarrow 0^+, 6^+ \rightarrow 2^+$   
(3), (4)

← 21 orders of magnitude! →

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

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

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



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

**Allowed (pure F):**  
 $0^+ \rightarrow 0^+$   
 (25 + 20)

# Nuclear Isospin

- 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

$$\textcircled{\mathbf{p}} \quad t_z(p) = -\frac{1}{2} \qquad \textcircled{\mathbf{n}} \quad t_z(n) = +\frac{1}{2}$$



1932 - Heisenberg

- Isospin projection and total isospin of a nucleus



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

- For  $0^+ \rightarrow 0^+ \beta$  decay ( $n \leftrightarrow p$ ) 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) 8

# CVC Hypothesis

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

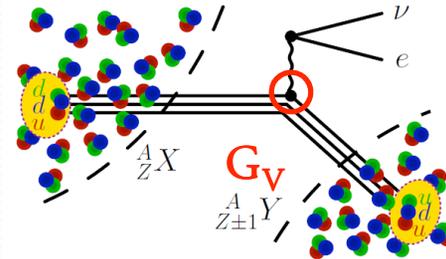
- Electric charge of the proton is not altered inside a nucleus
  - E&M is governed by a conserved vector current (CVC)

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



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

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



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

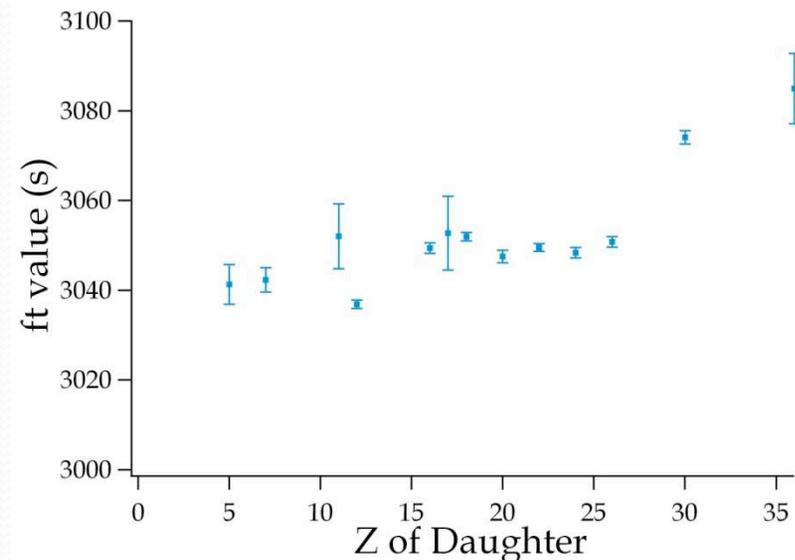
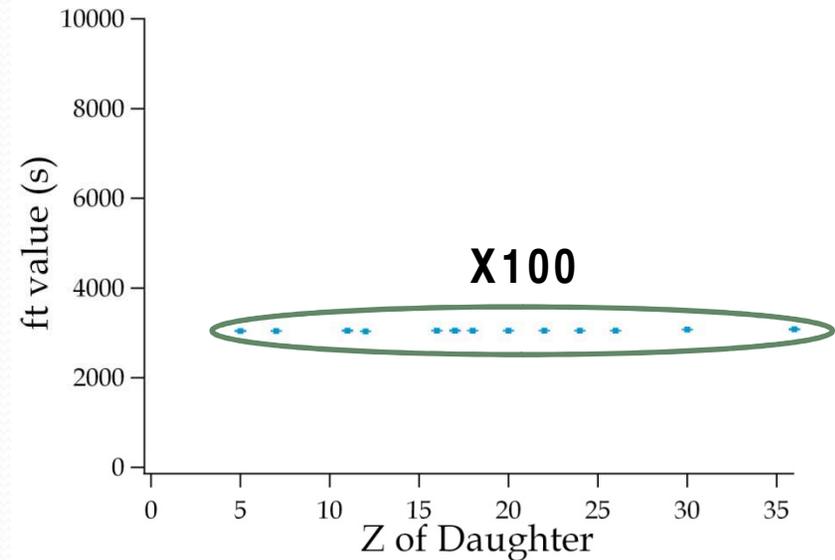
$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{2G_V^2} = \text{constant}$$

↑ Isospin symmetry      ↑ CVC

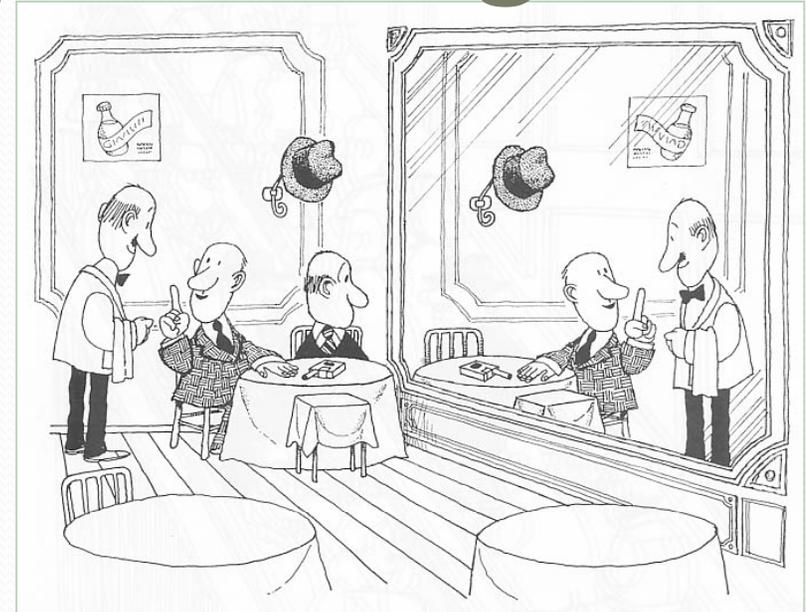
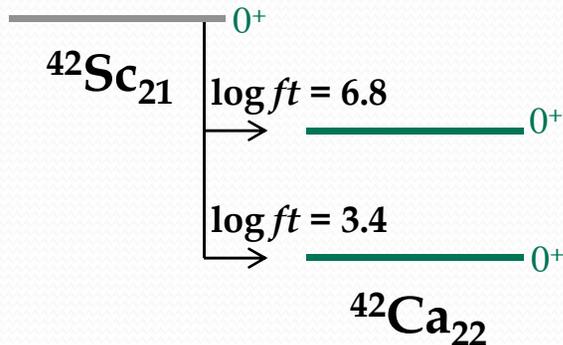
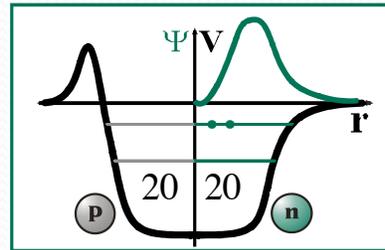
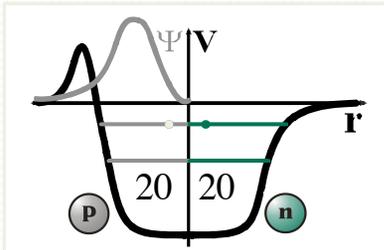
# Superaligned Survey (2009)

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  $\leq 0.4\%$
  - 8  $ft$  values known to  $\leq 0.05\%$
- All known  $ft$  values
  - Span  $ft = 10^3$  to  $10^{24}$  s
- All allowed  $ft$  values
  - Span  $ft = 10^3$  to  $10^{10}$
- Superaligned  $ft$  values
  - Span  $ft = 3040$  to  $3100$  s (2%)
  - Assumes isospin symmetry



# Isospin Symmetry Breaking

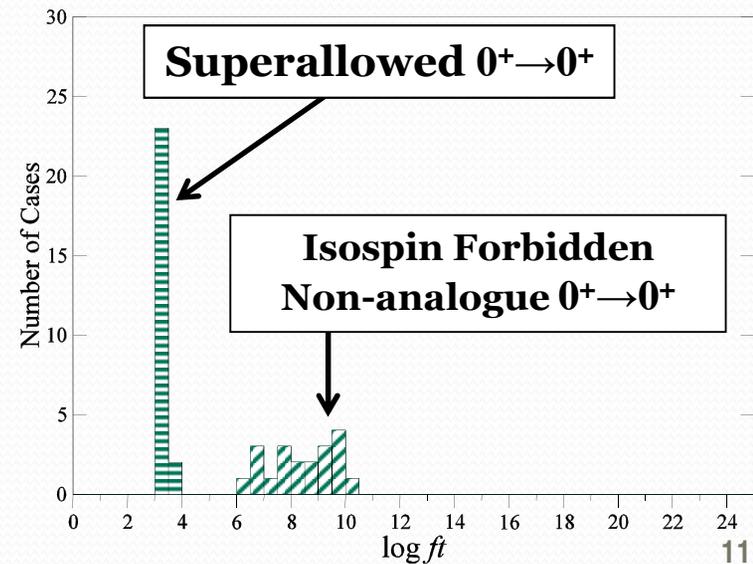


- If isospin symmetry were *exact*

- Only the S.A.F. decay would occur
- Non-analogue decays have been observed
  - Suppressed by factors of > 1000

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

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

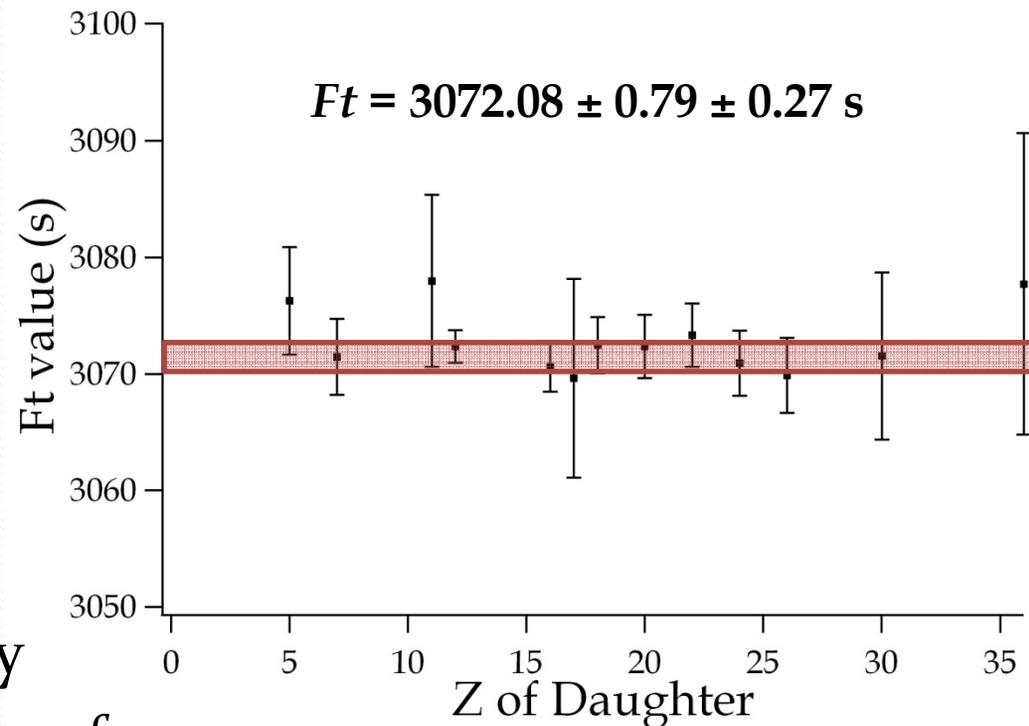


# World Status (2009)

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

- Apply  $\delta_C, \delta_R$  corrections
- World average  $Ft$ 
  - $Ft = 3072.08(79) \text{ s}$
  - $\chi^2/\nu = 0.28$
- CVC hypothesis
  - Validated ( $10^{-4}$  level)
- Systematic uncertainty
  - $\pm 0.27 \text{ s}$  from comparison of two sets of  $\delta_C$  calculations

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

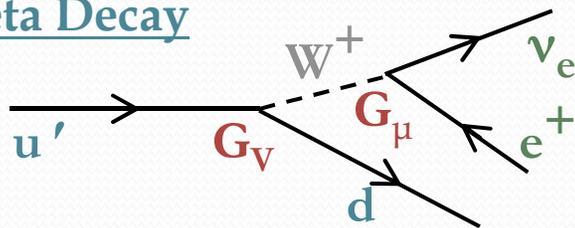


# Evaluation of $G_V$ and $V_{ud}$

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

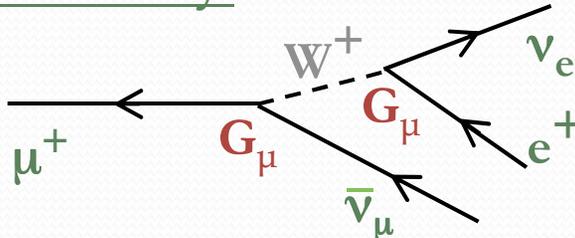


$$\mathcal{F}t = \frac{K}{2G_V^2} = \text{constant}$$

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

- Compare to the corresponding value  $G_\mu$  from  $\mu$  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  $^{14}\text{O}$ :  $3069(13) \text{ s}$  [0.4% !]
  - $G_V = 0.982G_\mu!$  Expected  $G_V = 1.0G_\mu$
- 1963 N.Cabibbo Phys. Rev. Lett. 10 531 (1963)
  - Weak eigenstates  $\neq$  mass eigenstates
  - Included “mixing” between 2 generations
  - Expressed as a unitary rotation
  - Cabibbo angle  $\theta_C = 11^\circ$  explains  $^{14}\text{O}$  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

Leptons	Quarks	$u$ up	$c$ charm	$t$ top
		$d$ down	$s$ strange	$b$ bottom
		$\nu_e$ e- Neutrino	$\nu_\mu$ $\mu$ - Neutrino	$\nu_\tau$ $\tau$ - Neutrino
	$e$ electron	$\mu$ muon	$\tau$ tau	
	I	II	III	
	The Generations of Matter			

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

$$\begin{aligned} V_{ud} &= \cos \theta_C & V_{us} &= \sin \theta_C \\ V_{cd} &= -\sin \theta_C & V_{cs} &= \cos \theta_C \end{aligned}$$

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



2008 Nobel Prize in Physics  
 1/4 Kobayashi & 1/4 Maskawa

# CKM Quark Mixing Matrix

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

- Three generation quark mixing matrix

Leptons	Quarks	$u$ up	$c$ charm	$t$ top
		$d$ down	$s$ strange	$b$ bottom
		$\nu_e$ e-Neutrino	$\nu_\mu$ $\mu$ -Neutrino	$\nu_\tau$ $\tau$ -Neutrino
	$e$ electron	$\mu$ muon	$\tau$ tau	
	I	II	III	
	The Generations of Matter			

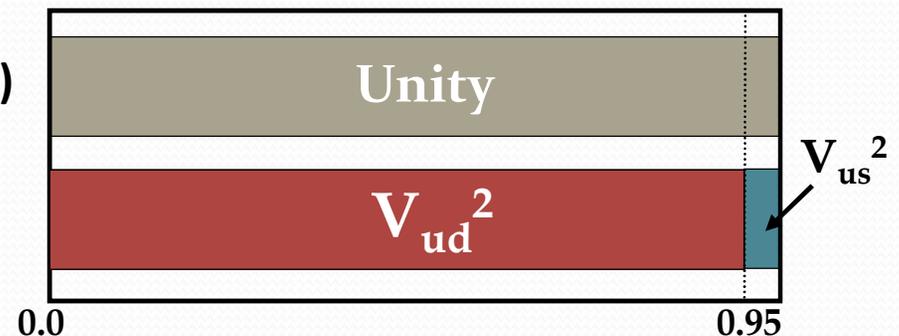
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{aligned} V_{ud} &= 0.97 & V_{us} &= 0.22 & V_{ub} &< 0.01 \\ V_{cd} &= 0.23 & V_{cs} &= 1.04 & V_{cb} &< 0.01 \\ V_{td} &< 0.01 & V_{ts} &= 0.04 & V_{tb} &> 0.74 \end{aligned}$$

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

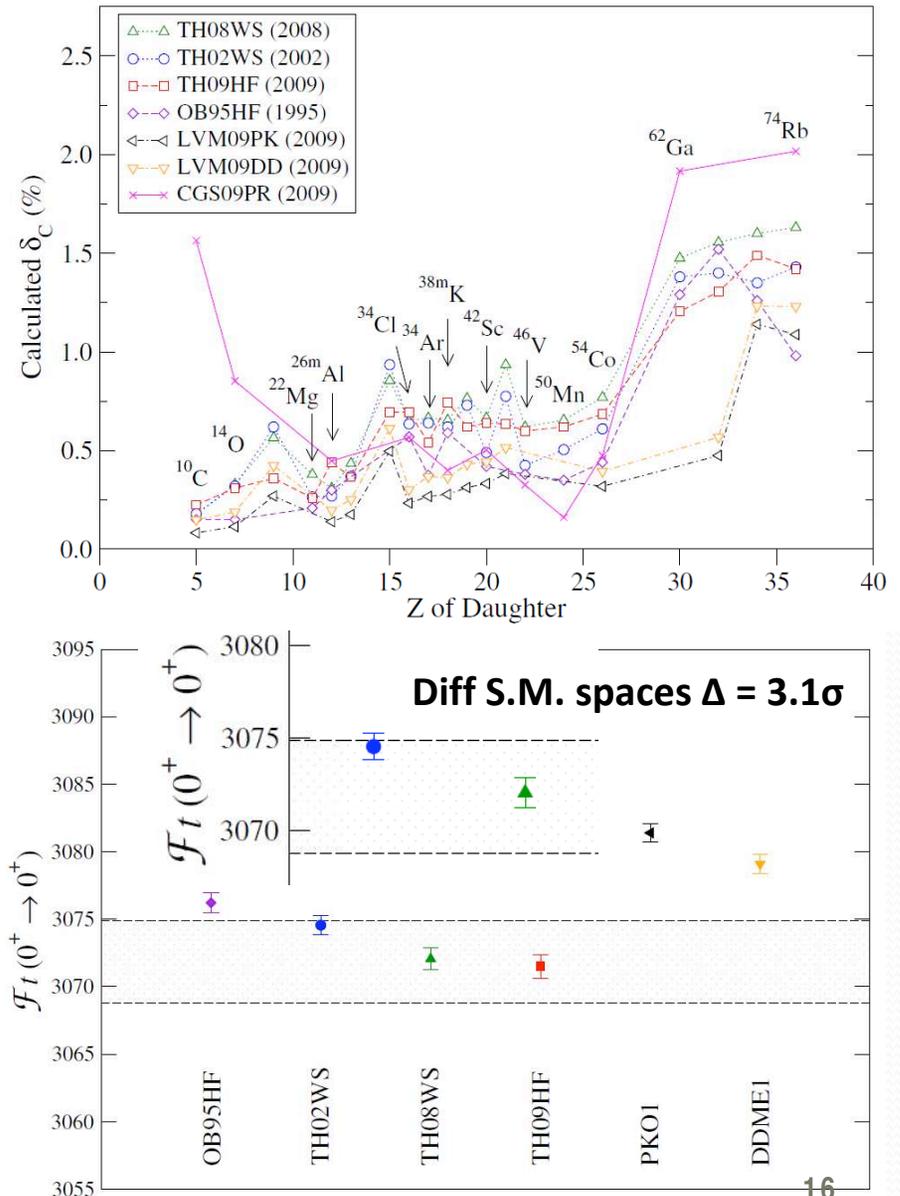
- Most precise experimental test of unitarity comes from the top row
  - Present Status\*:  $V_{ud} = 0.97425(22)$ ,  $V_{us} = 0.2246(12)$ ,  $V_{ub} = 0.0039(4)$

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



# Recent I.S.B. Calculations

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





***Experimental Results***  
***Superaligned Decay of  $^{62}\text{Ga}$***

# The case of $^{62}\text{Ga}$

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

- Status of the  $^{62}\text{Ga}$   $ft$  value in 2005...

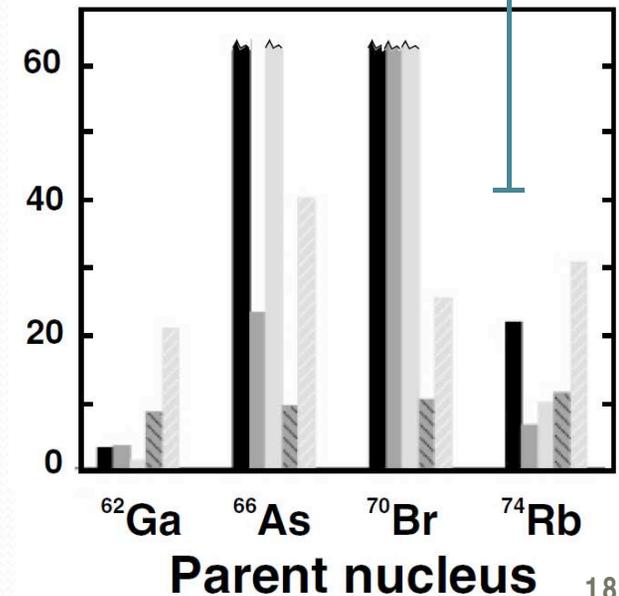
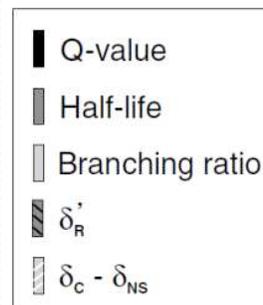
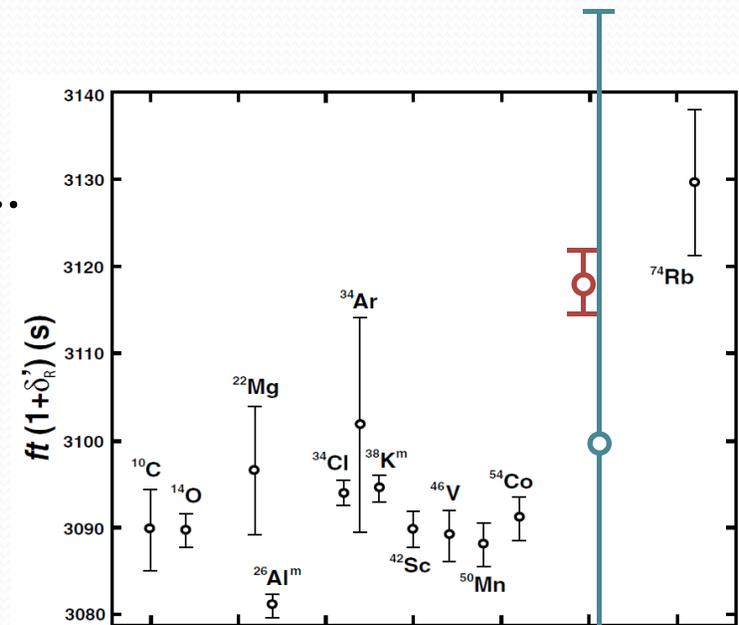
- $ft(1+\delta_R) = 3102(48) \text{ s}$

- Since: all 3 quantities measured

- Q-value (0.004%) Jyväskylä
  - $T_{1/2}$  (0.022%) TRIUMF
  - B.R. (0.001%) TRIUMF

- Present value

- $ft(1+\delta_R) = 3119(3) \text{ s}$
  - 16x improvement
  - Ft value now limited by  $\delta_C$



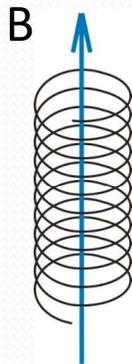
# Penning Trap Basics

Figures courtesy of A.Kwiatkowski NSCL

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

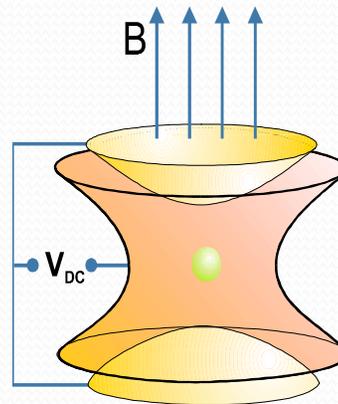
$$\mathbf{F} = q\mathbf{v} \times \mathbf{B} = \frac{mv^2}{r}$$

## Magnetic field

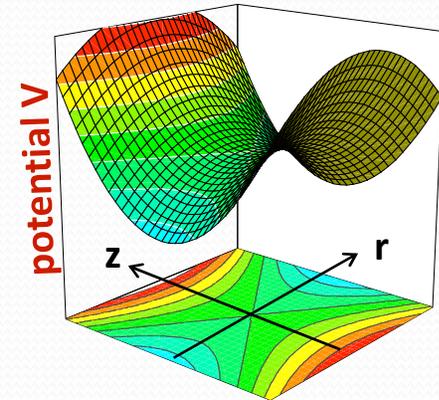


2D Radial confinement

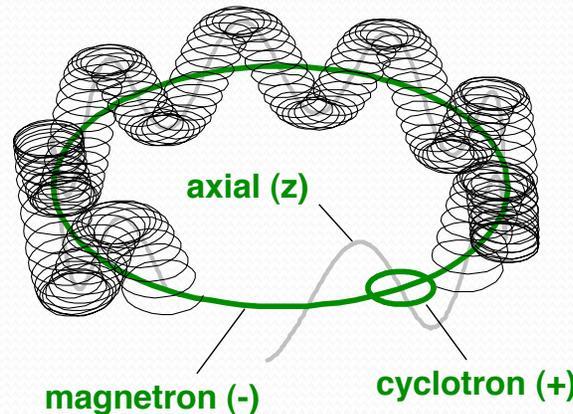
## Electric quadrupole field



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 $^{62}\text{Ga}$

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

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

$$r = \frac{\nu_{c,\text{ref}}}{\nu_c} \quad m = r(m_{\text{ref}} - m_e) + m_e$$

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



**JYFLTRAP**  
Univ. Jyväskylä, Finland

R.I.B production  
30 keV

Mass separation

Deflector

R.F.Q.  
Cooler/buncher

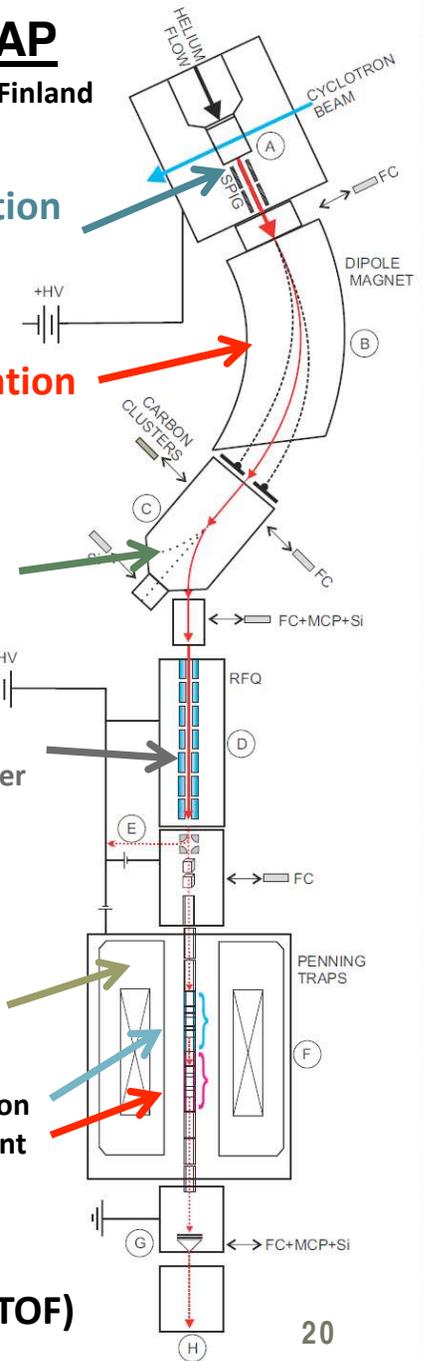
7T S.C. solenoid

**Penning Traps**

Trap 1 – Isobaric purification

Trap 2 – mass measurement

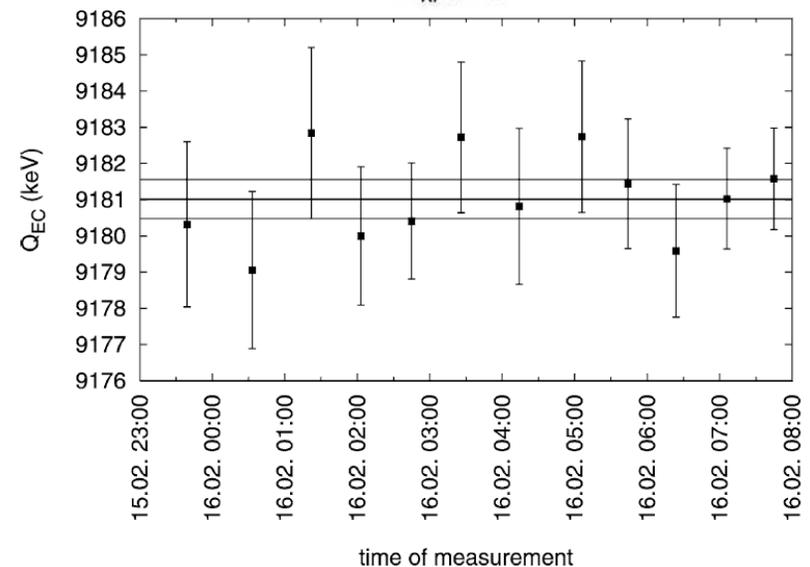
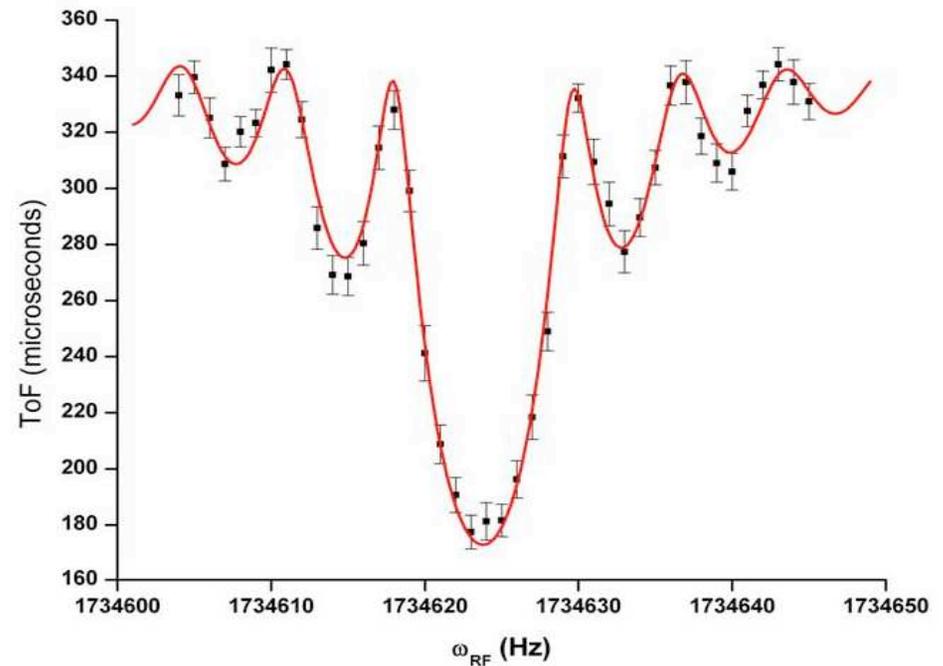
Detector Station (TOF)



# Mass of $^{62}\text{Ga}$

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

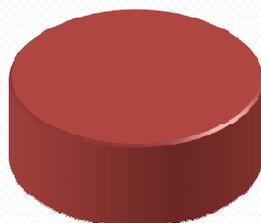
- Final result for  $^{62}\text{Ga}$ :
  - Q-value = 9181.07(38) keV
  - $f$  -value = 26401.6(83)
- Overall precision:
  - Q-value = 0.004%
  - $f$  -value = 0.03%
- Previous values
  - Q-value = 9171(26) keV ( $\downarrow$  70x)
  - $f$  -value = 26250(400) ( $\downarrow$  50x)



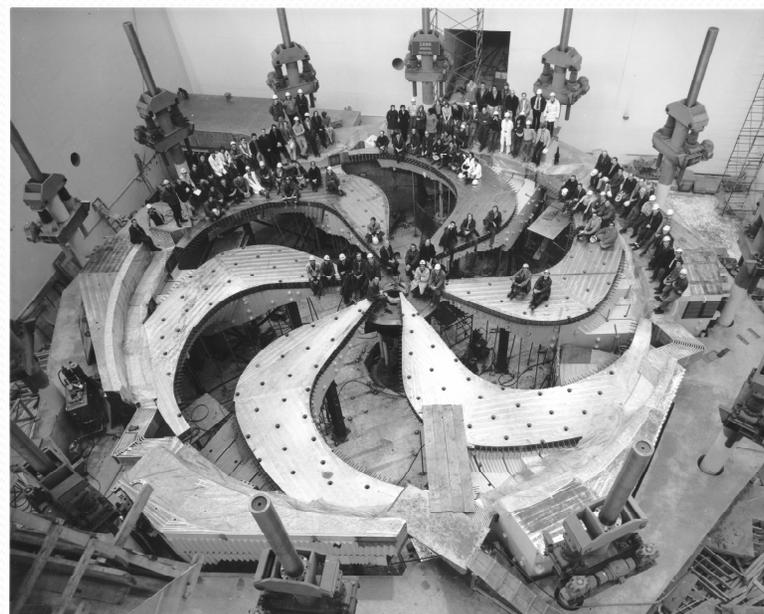
# $^{62}\text{Ga}$ $T_{1/2}$ and Branching Ratio

- Performed at TRIUMF-ISAC:

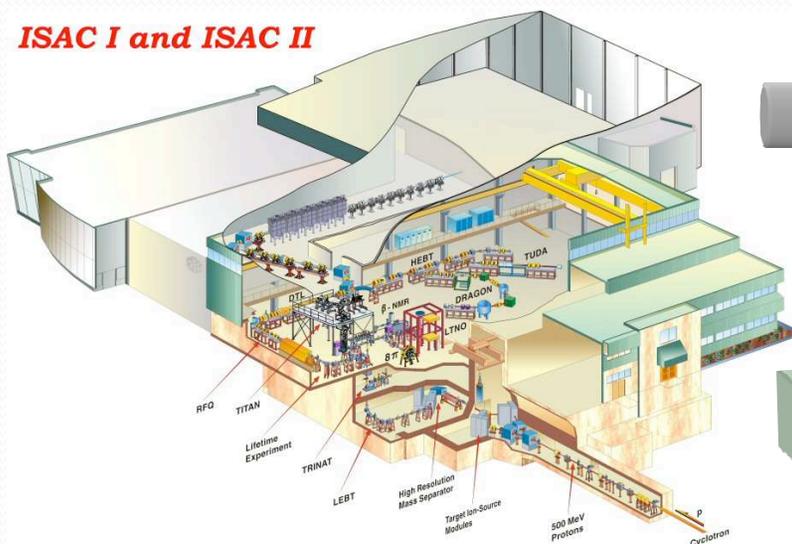
TRIUMF 500 MeV  
Cyclotron 100  $\mu\text{A}$



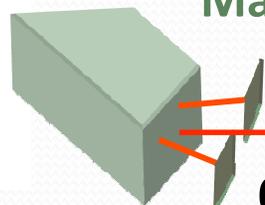
proton beam



*ISAC I and ISAC II*



Production Target  
Ion Source



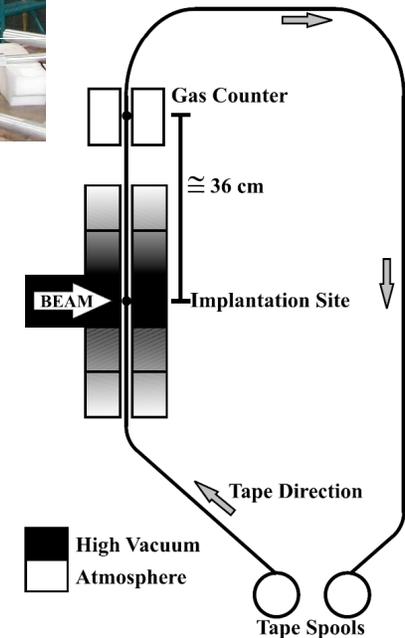
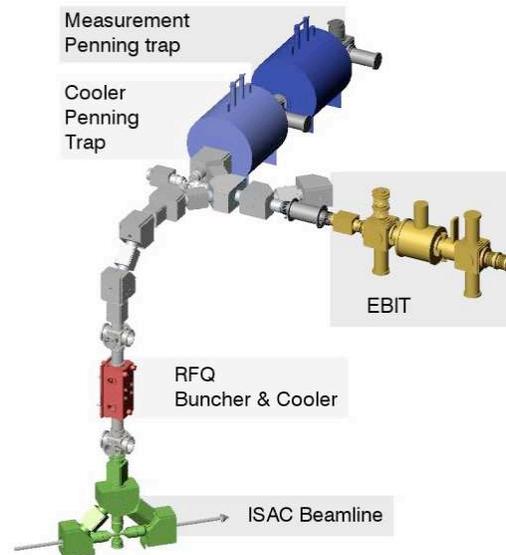
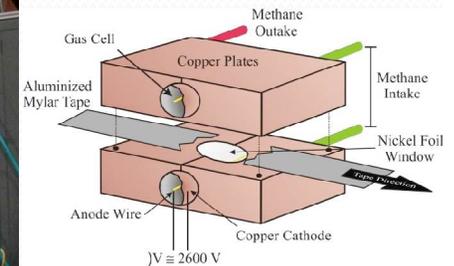
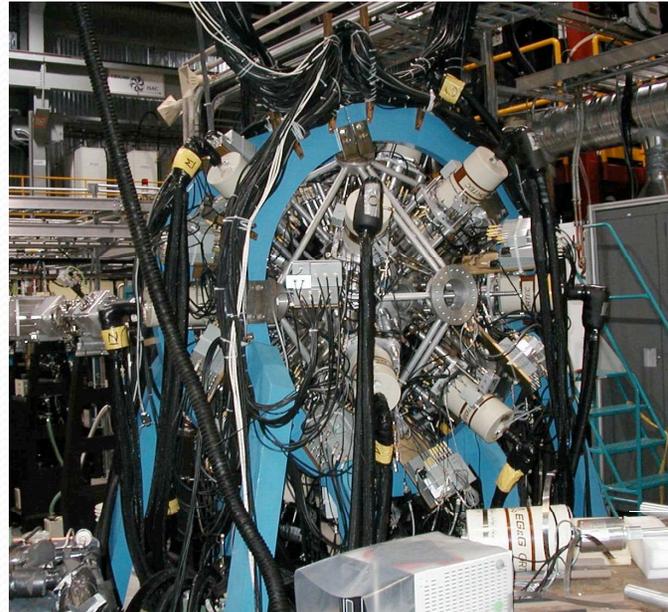
Mass Separator

60 keV ion beam

Experiments

# Experiments at TRIUMF

- $8\pi$   $\gamma$ -ray spectrometer
  - 20 HPGe detectors
  - $\beta$ 's,  $\beta$  delayed  $\gamma$ -rays
  - $\beta$  branching ratios
- Counter and fast tape
  - $\beta$  particle counting
  - Half-life measurements
- Penning Trap (TITAN)
  - High-precision masses



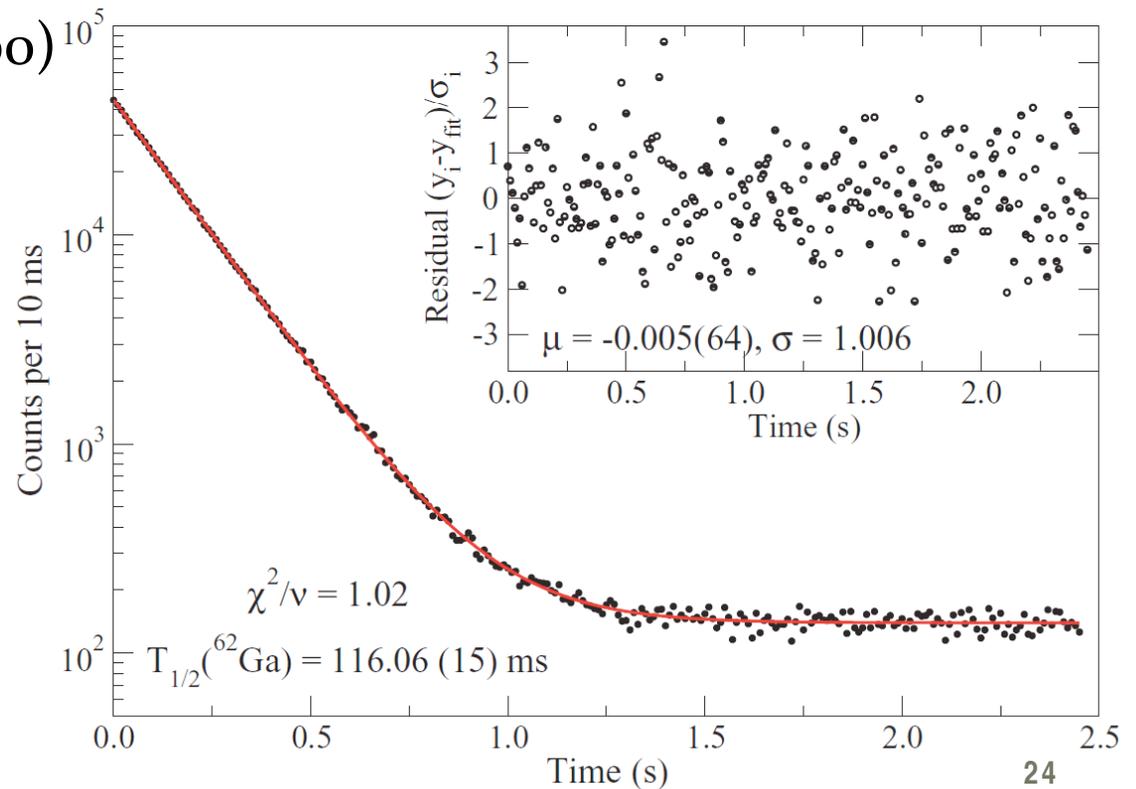
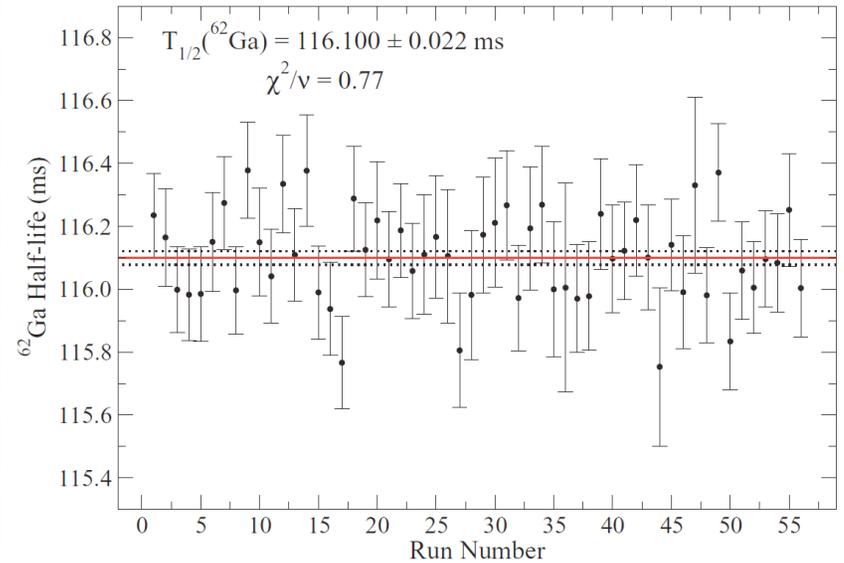
# Half-life of $^{62}\text{Ga}$

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

- $^{62}\text{Ga}$  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 =  $T_{1/2}$



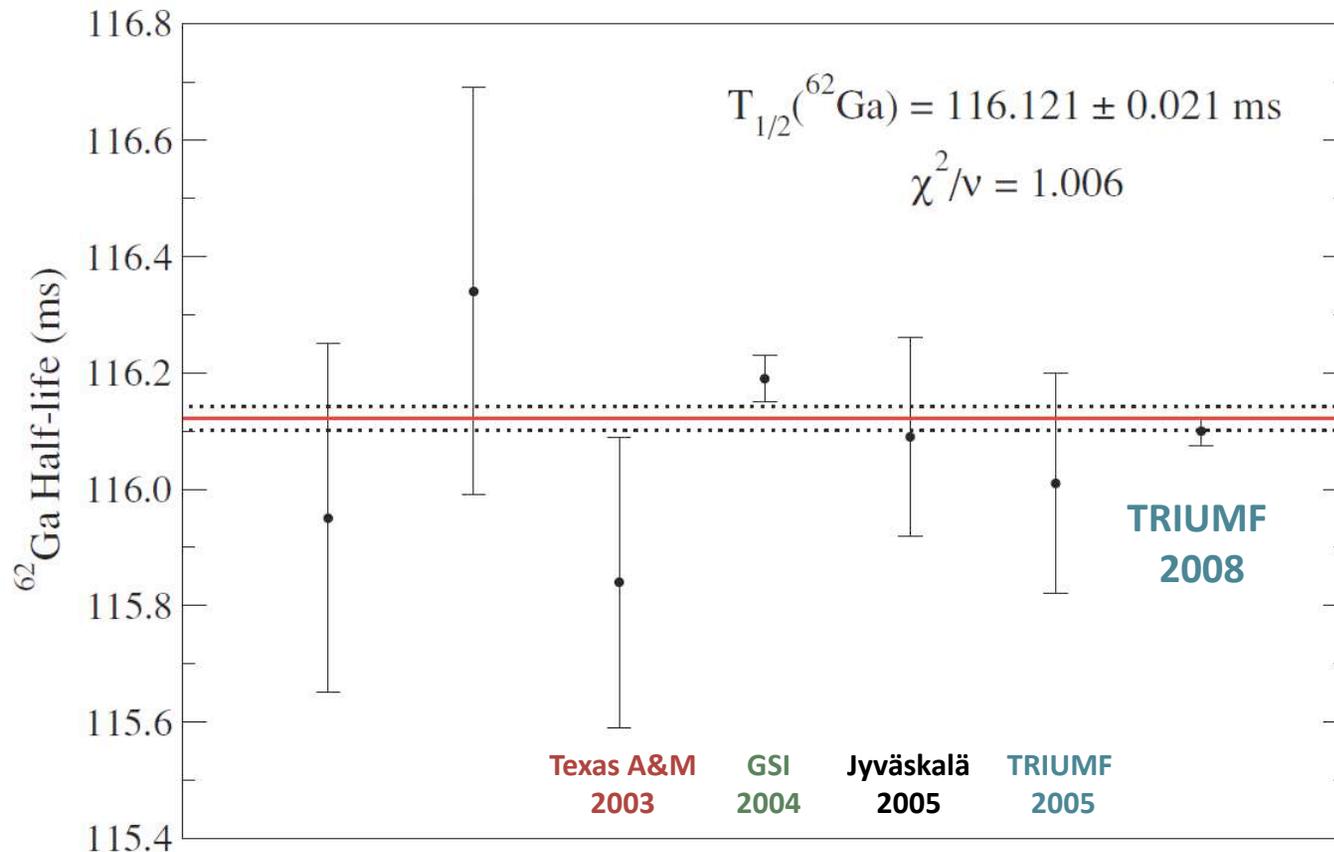
# Half-life of $^{62}\text{Ga}$

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

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

- $^{62}\text{Ga}$  Half-life

- Average TRIUMF result (2008):  $116.100 \pm 0.025$  s (0.02%)
- Previous world average (2005):  $116.175 \pm 0.038$  s (0.04%)



# New Result: Half-life of $^{26m}\text{Al}$

- $^{26m}\text{Al}$  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  $\beta^+$  emitter  $^{26m}\text{Al}^m$**

UNIVERSITY OF GUELPH

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

The CKM matrix plays a central role in the Standard Model by describing the mixing of the different quark generations.

$$|V\rangle = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} |u\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

This matrix represents a unitary transformation between the quark mass eigenstates and their weak-interaction eigenstates.

The first row of the CKM matrix provides the most demanding experimental test of the unitarity condition:

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

**Measuring  $V_{ud}$  via superallowed Fermi  $\beta$  decay  $f t$  and  $F t$  values**

Hadronic correction, estimated at order  $\sim 2\%$  (10% (model dependent))

Hadronic structure-dependent radiative corrections (2%–10%)

$$F t = f t \left( 1 + \delta_{NS} - \delta_{SU(2)} - (\delta_{SU(3)} + \delta_{SU(2)}) \right) \text{ constant}$$

Dependent on hadronic, hadronic, isospin symmetry-breaking (strong and electromagnetic) corrections (2%–10%)

The conserved vector current (CVC) hypothesis states that the vector coupling constant for the weak interaction is not renormalized in the nuclear medium. For all superallowed  $\beta$  values should be the same after applying small  $\sim 1\%$  theoretical corrections. We can then average the experimental  $F t$  values to determine a precise value for  $V_{ud}$ .

$$V_{ud}^2 = \frac{\sum_i (F t)_i}{2.3056 \times 10^4}$$

Using radiative corrections (model dependent)  $\sim 0.3\%$  (10% (model dependent))

The uncertainty in  $F t$  is dominated by the uncertainty in the theoretical corrections, including a contribution accounting for a systematic difference between two different calculations of  $\delta_{SU(3)}$  using Woods-Saxon and Hartree-Fock radial wave functions.

Since  $^{26m}\text{Al}$  has the smallest nuclear structure dependent correction of all superallowed transitions, a higher precision  $^{26m}\text{Al}$   $F t$  value will decrease the uncertainty for the other radiative corrections.

**Experiment and Data Analysis**

The experiment was performed at TRIUMF, Canada's National Laboratory for Particle and Particle Physics Research, where 40 nA of 200 MeV protons impinged upon a  $^{26}\text{Al}$  target and the resulting radioactive reaction products were created and sent through a mass separator.

A 30 kV static 20 beam was implanted under various static 22 mm wide Mylar tape for 6–34. Due to contamination from  $^{26}\text{Al}^m$  ( $T_{1/2} = 1.0728(25)$  s) the beam spot was allowed to cool for 20–25s, reducing the  $^{26}\text{Al}^m$  contamination to a negligible level before moving the  $^{26}\text{Al}$  sample to the centre of a 40 cm continuous flow gas proportional counter, where the beta decays were counted.

The  $\beta$  particles from the decay of the sample were registered independently using two microchannel-plate modules (MCPs) with 200-line (100  $\mu\text{m}$ ) wire width. The two tubes were varied on a run-by-run basis.

The decay data were analyzed using a maximum likelihood method. The total number of counts in the detector was determined by fitting the data to a single exponential decay curve. The half-life was determined by fitting the data to a single exponential decay curve.

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A final systematic uncertainty estimated by propagating the data fits by the statistical and experimental uncertainties using the method outlined in the text. The final value for the  $^{26m}\text{Al}^m$  half-life is:

$$T_{1/2}(^{26m}\text{Al}^m) = 6.3445$$

At 0.01%, this represents the measurement of any superallowed  $\beta$  to date.

**Compa**

AP- $F t$  value agrees with the value determined by the Woods-Saxon and Hartree-Fock calculations. Further studies are in progress.

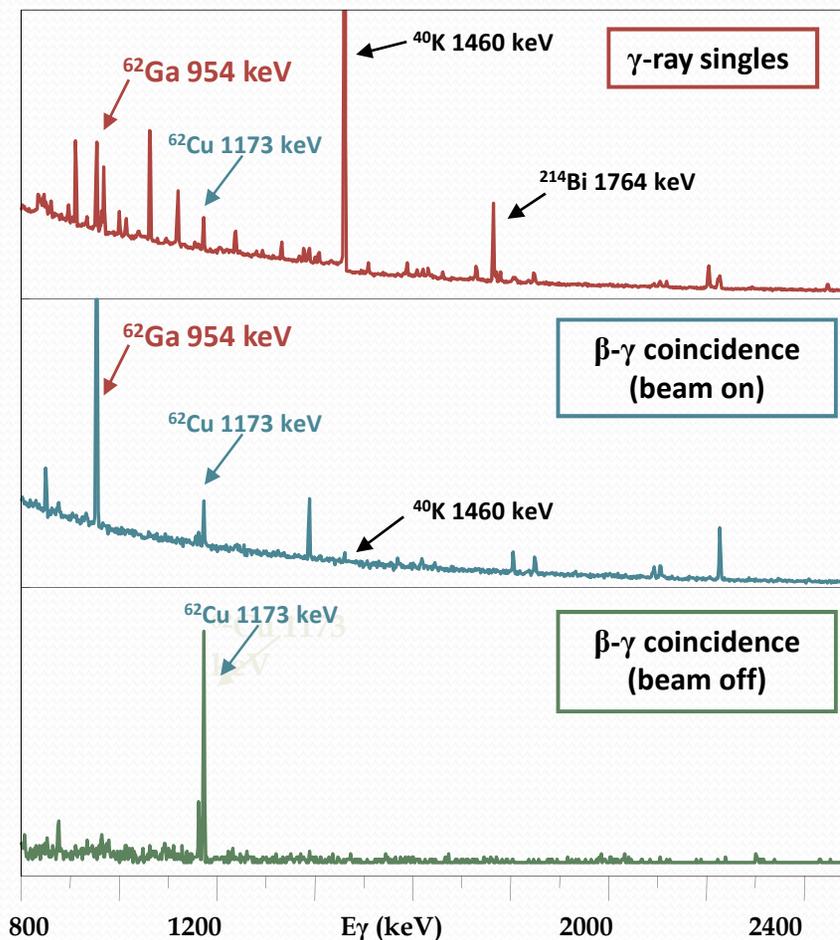
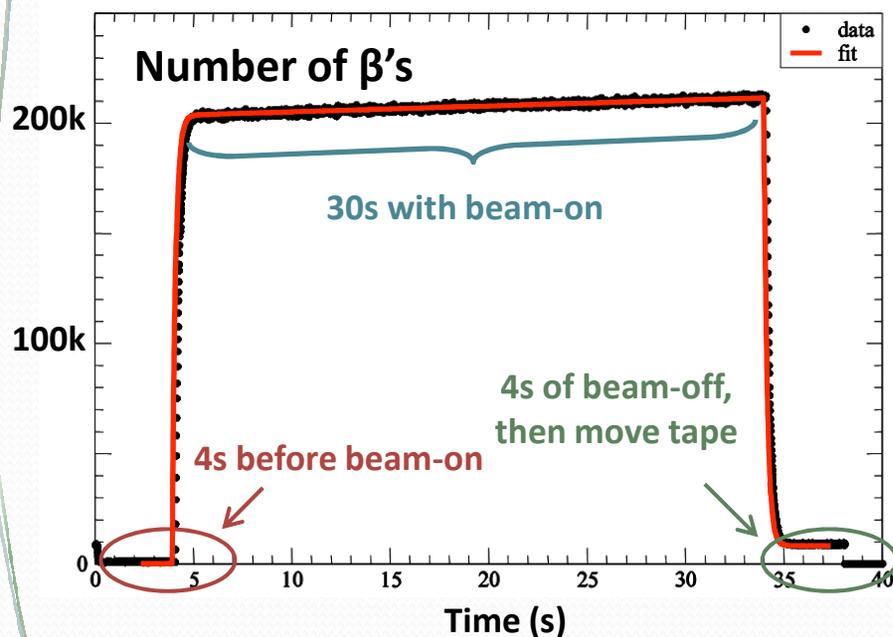
The high precision AP- $F t$   $\chi^2/\nu$  values for the other superallowed  $\beta$  decays of the first row are:  $^{10}\text{C}$  (1.02),  $^{14}\text{O}$  (1.01),  $^{18}\text{F}$  (1.01),  $^{22}\text{F}$  (1.01),  $^{26}\text{Mg}$  (1.01),  $^{30}\text{Si}$  (1.01),  $^{34}\text{S}$  (1.01),  $^{38}\text{S}$  (1.01),  $^{42}\text{Ca}$  (1.01),  $^{46}\text{Ca}$  (1.01),  $^{50}\text{Ti}$  (1.01),  $^{54}\text{Ti}$  (1.01),  $^{58}\text{Fe}$  (1.01),  $^{62}\text{Fe}$  (1.01),  $^{66}\text{Ni}$  (1.01),  $^{70}\text{Ni}$  (1.01),  $^{74}\text{Ni}$  (1.01),  $^{78}\text{Ni}$  (1.01),  $^{82}\text{Zn}$  (1.01),  $^{86}\text{Zn}$  (1.01),  $^{90}\text{Zn}$  (1.01),  $^{94}\text{Zn}$  (1.01),  $^{98}\text{Zn}$  (1.01),  $^{102}\text{Zn}$  (1.01),  $^{106}\text{Zn}$  (1.01),  $^{110}\text{Zn}$  (1.01),  $^{114}\text{Zn}$  (1.01),  $^{118}\text{Zn}$  (1.01),  $^{122}\text{Zn}$  (1.01),  $^{126}\text{Zn}$  (1.01),  $^{130}\text{Zn}$  (1.01),  $^{134}\text{Zn}$  (1.01),  $^{138}\text{Zn}$  (1.01),  $^{142}\text{Zn}$  (1.01),  $^{146}\text{Zn}$  (1.01),  $^{150}\text{Zn}$  (1.01),  $^{154}\text{Zn}$  (1.01),  $^{158}\text{Zn}$  (1.01),  $^{162}\text{Zn}$  (1.01),  $^{166}\text{Zn}$  (1.01),  $^{170}\text{Zn}$  (1.01),  $^{174}\text{Zn}$  (1.01),  $^{178}\text{Zn}$  (1.01),  $^{182}\text{Zn}$  (1.01),  $^{186}\text{Zn}$  (1.01),  $^{190}\text{Zn}$  (1.01),  $^{194}\text{Zn}$  (1.01),  $^{198}\text{Zn}$  (1.01),  $^{202}\text{Zn}$  (1.01),  $^{206}\text{Zn}$  (1.01),  $^{210}\text{Zn}$  (1.01),  $^{214}\text{Zn}$  (1.01),  $^{218}\text{Zn}$  (1.01),  $^{222}\text{Zn}$  (1.01),  $^{226}\text{Zn}$  (1.01),  $^{230}\text{Zn}$  (1.01),  $^{234}\text{Zn}$  (1.01),  $^{238}\text{Zn}$  (1.01),  $^{242}\text{Zn}$  (1.01),  $^{246}\text{Zn}$  (1.01),  $^{250}\text{Zn}$  (1.01),  $^{254}\text{Zn}$  (1.01),  $^{258}\text{Zn}$  (1.01),  $^{262}\text{Zn}$  (1.01),  $^{266}\text{Zn}$  (1.01),  $^{270}\text{Zn}$  (1.01),  $^{274}\text{Zn}$  (1.01),  $^{278}\text{Zn}$  (1.01),  $^{282}\text{Zn}$  (1.01),  $^{286}\text{Zn}$  (1.01),  $^{290}\text{Zn}$  (1.01),  $^{294}\text{Zn}$  (1.01),  $^{298}\text{Zn}$  (1.01),  $^{302}\text{Zn}$  (1.01),  $^{306}\text{Zn}$  (1.01),  $^{310}\text{Zn}$  (1.01),  $^{314}\text{Zn}$  (1.01),  $^{318}\text{Zn}$  (1.01),  $^{322}\text{Zn}$  (1.01),  $^{326}\text{Zn}$  (1.01),  $^{330}\text{Zn}$  (1.01),  $^{334}\text{Zn}$  (1.01),  $^{338}\text{Zn}$  (1.01),  $^{342}\text{Zn}$  (1.01),  $^{346}\text{Zn}$  (1.01),  $^{350}\text{Zn}$  (1.01),  $^{354}\text{Zn}$  (1.01),  $^{358}\text{Zn}$  (1.01),  $^{362}\text{Zn}$  (1.01),  $^{366}\text{Zn}$  (1.01),  $^{370}\text{Zn}$  (1.01),  $^{374}\text{Zn}$  (1.01),  $^{378}\text{Zn}$  (1.01),  $^{382}\text{Zn}$  (1.01),  $^{386}\text{Zn}$  (1.01),  $^{390}\text{Zn}$  (1.01),  $^{394}\text{Zn}$  (1.01),  $^{398}\text{Zn}$  (1.01),  $^{402}\text{Zn}$  (1.01),  $^{406}\text{Zn}$  (1.01),  $^{410}\text{Zn}$  (1.01),  $^{414}\text{Zn}$  (1.01),  $^{418}\text{Zn}$  (1.01),  $^{422}\text{Zn}$  (1.01),  $^{426}\text{Zn}$  (1.01),  $^{430}\text{Zn}$  (1.01),  $^{434}\text{Zn}$  (1.01),  $^{438}\text{Zn}$  (1.01),  $^{442}\text{Zn}$  (1.01),  $^{446}\text{Zn}$  (1.01),  $^{450}\text{Zn}$  (1.01),  $^{454}\text{Zn}$  (1.01),  $^{458}\text{Zn}$  (1.01),  $^{462}\text{Zn}$  (1.01),  $^{466}\text{Zn}$  (1.01),  $^{470}\text{Zn}$  (1.01),  $^{474}\text{Zn}$  (1.01),  $^{478}\text{Zn}$  (1.01),  $^{482}\text{Zn}$  (1.01),  $^{486}\text{Zn}$  (1.01),  $^{490}\text{Zn}$  (1.01),  $^{494}\text{Zn}$  (1.01),  $^{498}\text{Zn}$  (1.01),  $^{502}\text{Zn}$  (1.01),  $^{506}\text{Zn}$  (1.01),  $^{510}\text{Zn}$  (1.01),  $^{514}\text{Zn}$  (1.01),  $^{518}\text{Zn}$  (1.01),  $^{522}\text{Zn}$  (1.01),  $^{526}\text{Zn}$  (1.01),  $^{530}\text{Zn}$  (1.01),  $^{534}\text{Zn}$  (1.01),  $^{538}\text{Zn}$  (1.01),  $^{542}\text{Zn}$  (1.01),  $^{546}\text{Zn}$  (1.01),  $^{550}\text{Zn}$  (1.01),  $^{554}\text{Zn}$  (1.01),  $^{558}\text{Zn}$  (1.01),  $^{562}\text{Zn}$  (1.01),  $^{566}\text{Zn}$  (1.01),  $^{570}\text{Zn}$  (1.01),  $^{574}\text{Zn}$  (1.01),  $^{578}\text{Zn}$  (1.01),  $^{582}\text{Zn}$  (1.01),  $^{586}\text{Zn}$  (1.01),  $^{590}\text{Zn}$  (1.01),  $^{594}\text{Zn}$  (1.01),  $^{598}\text{Zn}$  (1.01),  $^{602}\text{Zn}$  (1.01),  $^{606}\text{Zn}$  (1.01),  $^{610}\text{Zn}$  (1.01),  $^{614}\text{Zn}$  (1.01),  $^{618}\text{Zn}$  (1.01),  $^{622}\text{Zn}$  (1.01),  $^{626}\text{Zn}$  (1.01),  $^{630}\text{Zn}$  (1.01),  $^{634}\text{Zn}$  (1.01),  $^{638}\text{Zn}$  (1.01),  $^{642}\text{Zn}$  (1.01),  $^{646}\text{Zn}$  (1.01),  $^{650}\text{Zn}$  (1.01),  $^{654}\text{Zn}$  (1.01),  $^{658}\text{Zn}$  (1.01),  $^{662}\text{Zn}$  (1.01),  $^{666}\text{Zn}$  (1.01),  $^{670}\text{Zn}$  (1.01),  $^{674}\text{Zn}$  (1.01),  $^{678}\text{Zn}$  (1.01),  $^{682}\text{Zn}$  (1.01),  $^{686}\text{Zn}$  (1.01),  $^{690}\text{Zn}$  (1.01),  $^{694}\text{Zn}$  (1.01),  $^{698}\text{Zn}$  (1.01),  $^{702}\text{Zn}$  (1.01),  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$^{1398}\text{Zn}$  (1.01),  $^{1402}\text{Zn}$  (1.01),  $^{1406}\text{Zn}$  (1.01),  $^{1410}\text{Zn}$  (1.01),  $^{1414}\text{Zn}$  (1.01),  $^{1418}\text{Zn}$  (1.01),  $^{1422}\text{Zn}$  (1.01),  $^{1426}\text{Zn}$  (1.01),  $^{1430}\text{Zn}$  (1.01),  $^{1434}\text{Zn}$  (1.01),  $^{1438}\text{Zn}$  (1.01),  $^{1442}\text{Zn}$  (1.01),  $^{1446}\text{Zn}$  (1.01),  $^{1450}\text{Zn}$  (1.01),  $^{1454}\text{Zn}$  (1.01),  $^{1458}\text{Zn}$  (1.01),  $^{1462}\text{Zn}$  (1.01),  $^{1466}\text{Zn}$  (1.01),  $^{1470}\text{Zn}$  (1.01),  $^{1474}\text{Zn}$  (1.01),  $^{1478}\text{Zn}$  (1.01),  $^{1482}\text{Zn}$  (1.01),  $^{1486}\text{Zn}$  (1.01),  $^{1490}\text{Zn}$  (1.01),  $^{1494}\text{Zn}$  (1.01),  $^{1498}\text{Zn}$  (1.01),  $^{1502}\text{Zn}$  (1.01),  $^{1506}\text{Zn}$  (1.01),  $^{1510}\text{Zn}$  (1.01),  $^{1514}\text{Zn}$  (1.01),  $^{1518}\text{Zn}$  (1.01),  $^{1522}\text{Zn}$  (1.01),  $^{1526}\text{Zn}$  (1.01),  $^{1530}\text{Zn}$  (1.01),  $^{1534}\text{Zn}$  (1.01),  $^{1538}\text{Zn}$  (1.01),  $^{1542}\text{Zn}$  (1.01),  $^{1546}\text{Zn}$  (1.01),  $^{1550}\text{Zn}$  (1.01),  $^{1554}\text{Zn}$  (1.01),  $^{1558}\text{Zn}$  (1.01),  $^{1562}\text{Zn}$  (1.01),  $^{1566}\text{Zn}$  (1.01),  $^{1570}\text{Zn}$  (1.01),  $^{1574}\text{Zn}$  (1.01),  $^{1578}\text{Zn}$  (1.01),  $^{1582}\text{Zn}$  (1.01),  $^{1586}\text{Zn}$  (1.01),  $^{1590}\text{Zn}$  (1.01),  $^{1594}\text{Zn}$  (1.01),  $^{1598}\text{Zn}$  (1.01),  $^{1602}\text{Zn}$  (1.01),  $^{1606}\text{Zn}$  (1.01),  $^{1610}\text{Zn}$  (1.01),  $^{1614}\text{Zn}$  (1.01),  $^{1618}\text{Zn}$  (1.01),  $^{1622}\text{Zn}$  (1.01),  $^{1626}\text{Zn}$  (1.01),  $^{1630}\text{Zn}$  (1.01),  $^{1634}\text{Zn}$  (1.01),  $^{1638}\text{Zn}$  (1.01),  $^{1642}\text{Zn}$  (1.01),  $^{1646}\text{Zn}$  (1.01),  $^{1650}\text{Zn}$  (1.01),  $^{1654}\text{Zn}$  (1.01),  $^{1658}\text{Zn}$  (1.01),  $^{1662}\text{Zn}$  (1.01),  $^{1666}\text{Zn}$  (1.01),  $^{1670}\text{Zn}$  (1.01),  $^{1674}\text{Zn}$  (1.01),  $^{1678}\text{Zn}$  (1.01),  $^{1682}\text{Zn}$  (1.01),  $^{1686}\text{Zn}$  (1.01),  $^{1690}\text{Zn}$  (1.01),  $^{1694}\text{Zn}$  (1.01),  $^{1698}\text{Zn}$  (1.01),  $^{1702}\text{Zn}$  (1.01),  $^{1706}\text{Zn}$  (1.01),  $^{1710}\text{Zn}$  (1.01),  $^{1714}\text{Zn}$  (1.01),  $^{1718}\text{Zn}$  (1.01),  $^{1722}\text{Zn}$  (1.01),  $^{1726}\text{Zn}$  (1.01),  $^{1730}\text{Zn}$  (1.01),  $^{1734}\text{Zn}$  (1.01),  $^{1738}\text{Zn}$  (1.01),  $^{1742}\text{Zn}$  (1.01),  $^{1746}\text{Zn}$  (1.01),  $^{1750}\text{Zn}$  (1.01),  $^{1754}\text{Zn}$  (1.01),  $^{1758}\text{Zn}$  (1.01),  $^{1762}\text{Zn}$  (1.01),  $^{1766}\text{Zn}$  (1.01),  $^{1770}\text{Zn}$  (1.01),  $^{1774}\text{Zn}$  (1.01),  $^{1778}\text{Zn}$  (1.01),  $^{1782}\text{Zn}$  (1.01),  $^{1786}\text{Zn}$  (1.01),  $^{1790}\text{Zn}$  (1.01),  $^{1794}\text{Zn}$  (1.01),  $^{1798}\text{Zn}$  (1.01),  $^{1802}\text{Zn}$  (1.01),  $^{1806}\text{Zn}$  (1.01),  $^{1810}\text{Zn}$  (1.01),  $^{1814}\text{Zn}$  (1.01),  $^{1818}\text{Zn}$  (1.01),  $^{1822}\text{Zn}$  (1.01),  $^{1826}\text{Zn}$  (1.01),  $^{1830}\text{Zn}$  (1.01),  $^{1834}\text{Zn}$  (1.01),  $^{1838}\text{Zn}$  (1.01),  $^{1842}\text{Zn}$  (1.01),  $^{1846}\text{Zn}$  (1.01),  $^{1850}\text{Zn}$  (1.01),  $^{1854}\text{Zn}$  (1.01),  $^{1858}\text{Zn}$  (1.01),  $^{1862}\text{Zn}$  (1.01),  $^{1866}\text{Zn}$  (1.01),  $^{1870}\text{Zn}$  (1.01),  $^{1874}\text{Zn}$  (1.01),  $^{1878}\text{Zn}$  (1.01),  $^{1882}\text{Zn}$  (1.01),  $^{1886}\text{Zn}$  (1.01),  $^{1890}\text{Zn}$  (1.01),  $^{1894}\text{Zn}$  (1.01),  $^{1898}\text{Zn}$  (1.01),  $^{1902}\text{Zn}$  (1.01),  $^{1906}\text{Zn}$  (1.01),  $^{1910}\text{Zn}$  (1.01),  $^{1914}\text{Zn}$  (1.01),  $^{1918}\text{Zn}$  (1.01),  $^{1922}\text{Zn}$  (1.01),  $^{1926}\text{Zn}$  (1.01),  $^{1930}\text{Zn}$  (1.01),  $^{1934}\text{Zn}$  (1.01),  $^{1938}\text{Zn}$  (1.01),  $^{1942}\text{Zn}$  (1.01),  $^{1946}\text{Zn}$  (1.01),  $^{1950}\text{Zn}$  (1.01),  $^{1954}\text{Zn}$  (1.01),  $^{1958}\text{Zn}$  (1.01),  $^{1962}\text{Zn}$  (1.01),  $^{1966}\text{Zn}$  (1.01),  $^{1970}\text{Zn}$  (1.01),  $^{1974}\text{Zn}$  (1.01),  $^{1978}\text{Zn}$  (1.01),  $^{1982}\text{Zn}$  (1.01),  $^{1986}\text{Zn}$  (1.01),  $^{1990}\text{Zn}$  (1.01),  $^{1994}\text{$



# $^{62}\text{Ga}$ 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
  - $8\pi$  spectrometer
  - Inner array of  $\beta$  counters
  - $N_{\beta} = 6.3 \times 10^8$



# $^{62}\text{Ga}$ Branching Ratio

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

- Observed + Pandemonium (Shell-model calculation):

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

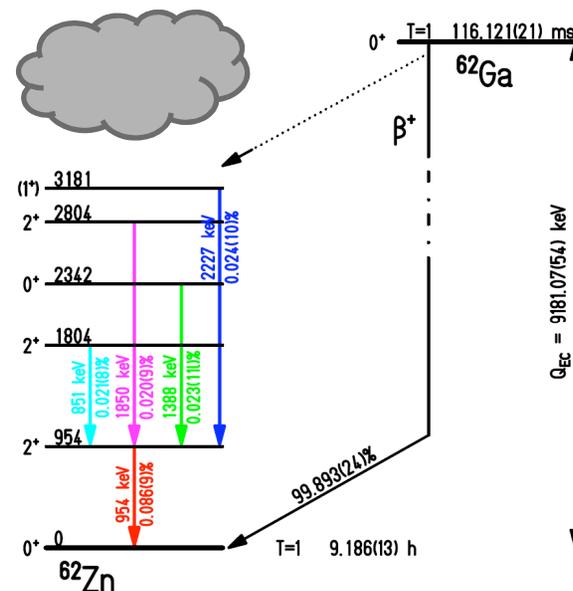
2% precision (pointing to 0.134(3))  
6% precision (pointing to 0.008(8))

- Ground-state branching ratio

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

$$= \mathbf{99.858(8)\%}$$

0.008% precision !!



- As a general rule

- Works only if S.A.F. decay is to ground state and B.R. > 95%

$$\sum_{j=0}^n BR(j) = \mathbf{5.0(1)\%}$$

2% precision (pointing to 5.0(1))

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

0.1% precision (pointing to 95.0(1))

# Experimental Impact for $^{62}\text{Ga}$

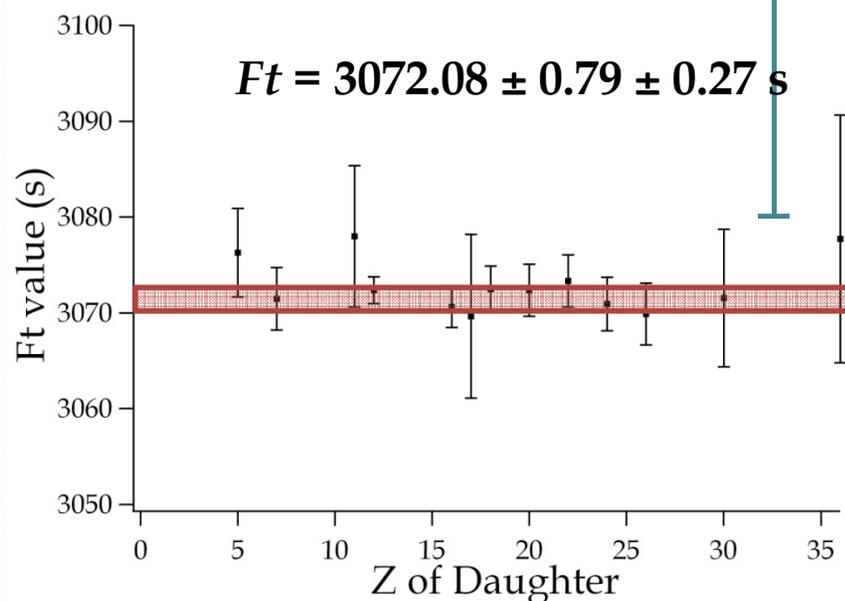
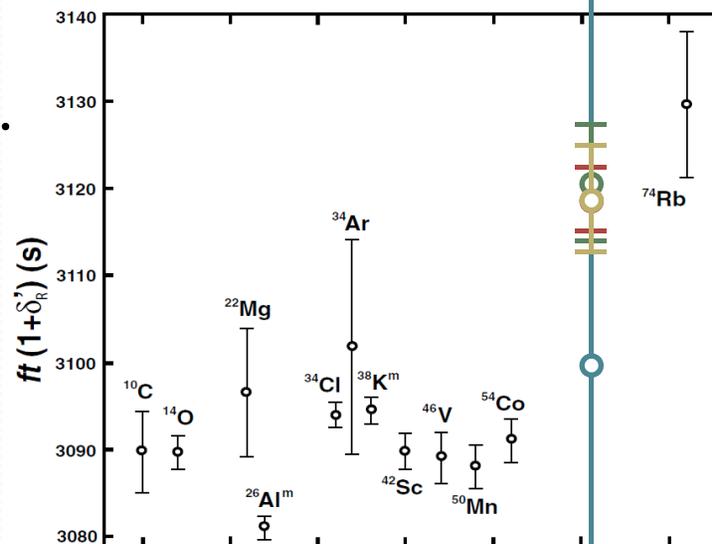
- Status of the  $^{62}\text{Ga}$   $ft$  value in 2005...

- $ft(1+\delta_R) = 3102(48) \text{ s}$
- $+Q\text{-value} = 3121(6) \text{ s}$
- $+T_{1/2} = 3119(5) \text{ s}$
- $+B.R. = 3119(3) \text{ s}$
- 16x improvement!

- Corrected  $Ft$  value for  $^{62}\text{Ga}$

- $Ft(2005) = 3058(47) \text{ s}$
- $Ft(2010) = 3072(7) \text{ s}$

Uncertainty dominated by theory  
(experimental contribution negligible)



# Can $ft$ to Constrain Theory

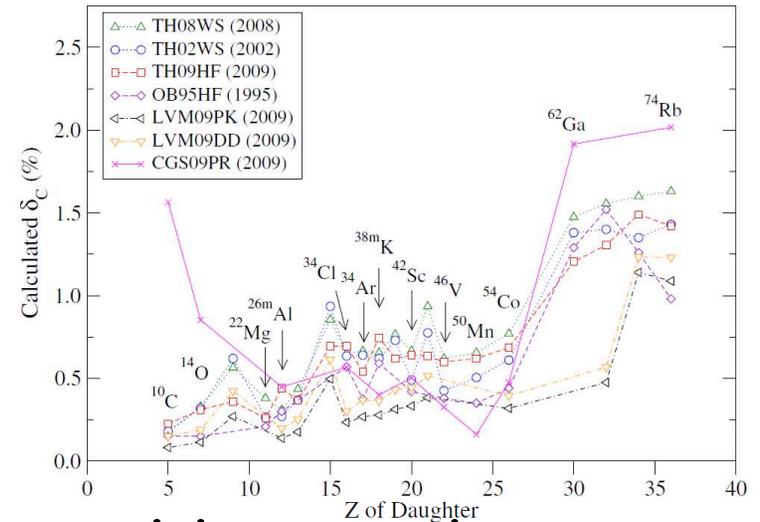
- $^{62}\text{Ga}$   $Ft$  value limited by theory

Theoretical (TH08WS)  $\delta_C = 1.5(2) \%$

Theoretical (TH02WS)  $\delta_C = 1.4(2) \%$

Theoretical (TH09HF)  $\delta_C = 1.2(7) \%$

Theoretical (OB95HF)  $\delta_C = 1.3(2) \%$



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

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

“experimental” theoretical correction  $\rightarrow$   $(1 - \delta_C)$   $\leftarrow$  World average of 12 others  
 $\leftarrow$  Rad. Correction ( $^{62}\text{Ga}$ )  
 $\leftarrow$  Experimental  $ft$  ( $^{62}\text{Ga}$ )

- Using  $ft = 3074.1(15) \text{ s}$ ,  $\delta_R = 1.46(9) \%$ ,  $Ft = 3072.1(8) \text{ s}$

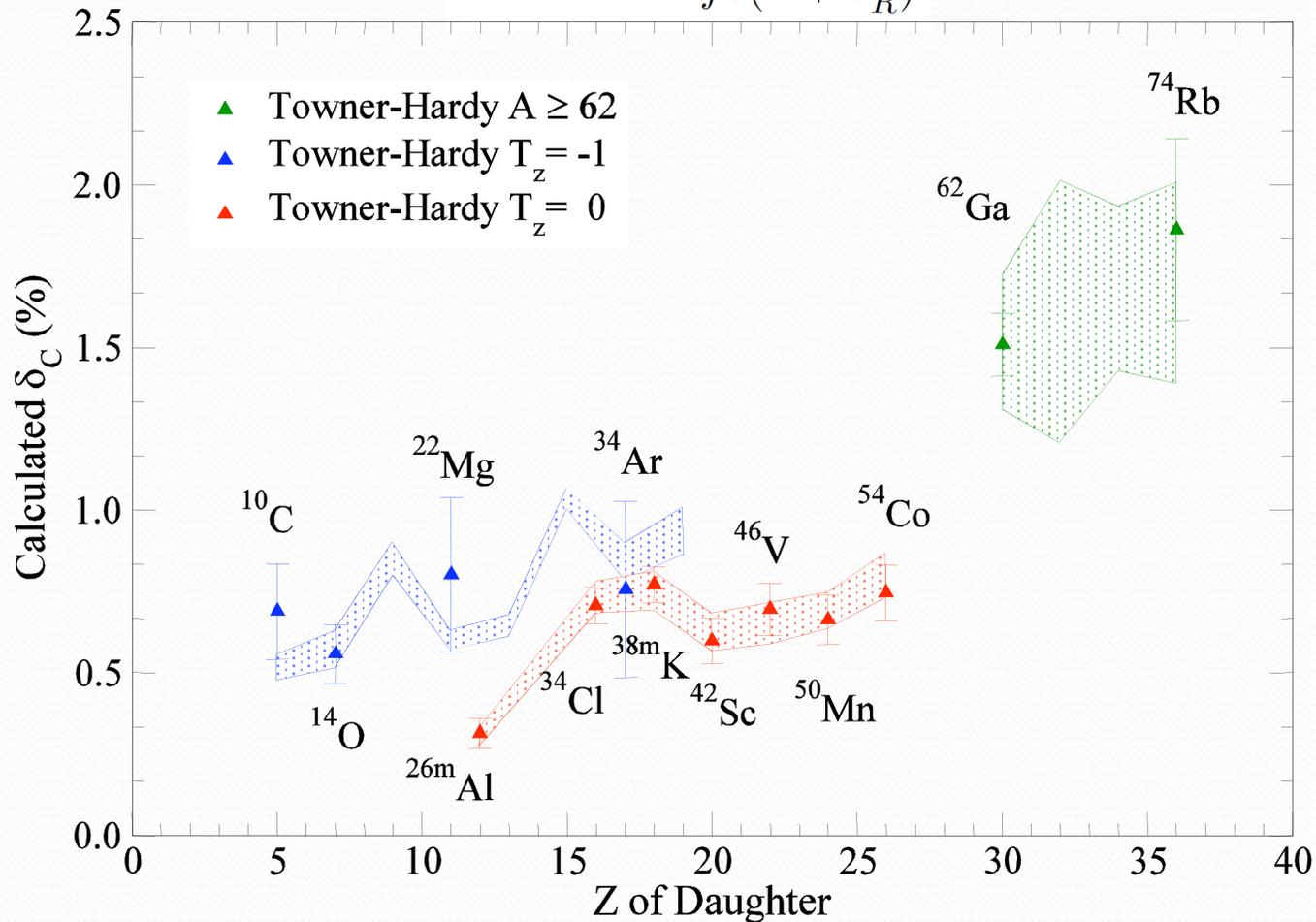
Experimental  $\delta_C = 1.45(10) \%$

**Not an ABSOLUTE test!**

# “Experimental” Corrections

- Using the THo8WS calculations,  $Ft = 3072.1(8)s$

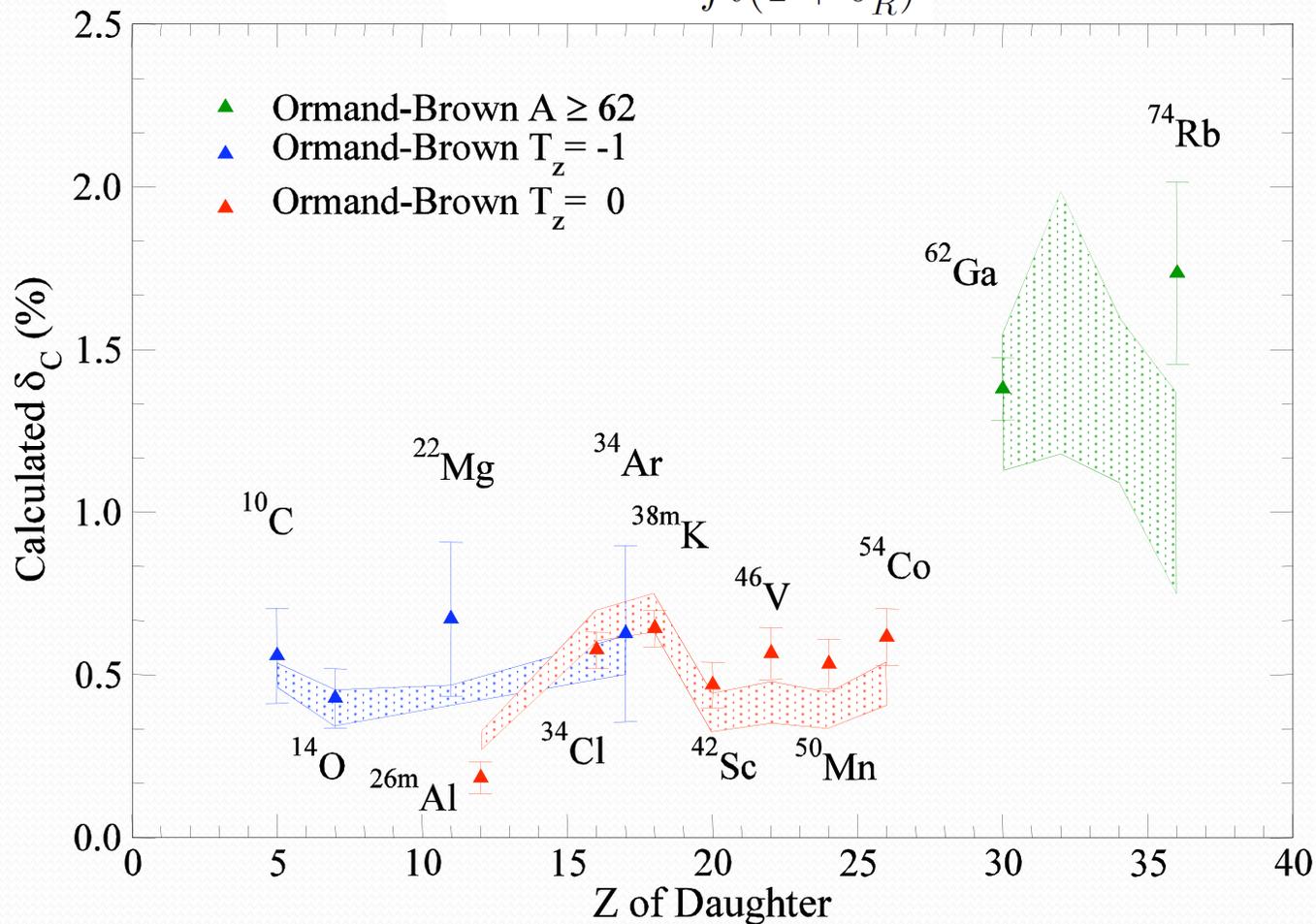
$$(1 - \delta_C) = \frac{(\overline{Ft})^*}{ft(1 + \delta'_R)}$$



# “Experimental” Corrections

- Using the OB95HF calculations,  $Ft = 3076.2 \text{ s}$

$$(1 - \delta_C) = \frac{(\overline{Ft})^*}{ft(1 + \delta'_R)}$$



# Alternative Approaches

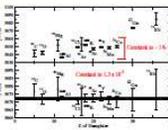
- Spectroscopic factors from low-energy transfer reactions
  - See poster by Kyle Leach (University of Guelph)

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

**Experimental Guidance of ISB Corrections via Direct Nuclear Reactions**  
 K.G. Leach<sup>1</sup>, P.E. Garrett<sup>2</sup>, G.C. Ball<sup>3</sup>, J.C. Bangay<sup>4</sup>, L. Bianco<sup>5</sup>, G.A. Demand<sup>6</sup>, T. Faesslermann<sup>7</sup>, P. Finlay<sup>8</sup>, K.L. Green<sup>9</sup>, R. Hartertberger<sup>1</sup>, R. Krücken<sup>1</sup>, A.A. Phillips<sup>1</sup>, E.T. Rand<sup>1</sup>, C.S. Sumthararatchi<sup>1</sup>, C.E. Svensson<sup>1</sup>, I.S. Towner<sup>1</sup>, S. Triambak<sup>1</sup>, H.-F. Wirth<sup>1</sup>, and J. Wong<sup>1</sup>  
<sup>1</sup>University of Guelph, Canada - <sup>2</sup>TRIUMF, Vancouver, Canada - <sup>3</sup>TU München, Germany - <sup>4</sup>LMU München, Germany - <sup>5</sup>Queen's University, Canada

**Motivation**

Through precision measurements of  $f_1$  values, studies of superallowed  $0^+ \rightarrow 0^+$  nuclear  $\beta$  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  $f_1$  values are thus expected to be nucleus independent.



$f_1 = f_1(1 + \delta_R)(1 - \delta_C) = \frac{K}{2M_p(1 + \Delta_M)} = \text{constant}$

The figure above shows the experimental  $f_1$  values, as well as the corrected  $f_1$  values for the 13 most precisely measured superallowed nuclei.

**Isospin Symmetry Breaking**

The ISB correction can be represented as a sum of two terms [1]. The first term,  $\delta_C$ , accounts for the first-order effects of isospin mixing between parent and daughter nuclear states. The second term,  $\delta_R$ , corrects for imperfect spatial overlap between the initial and final state wavefunctions, which can be important to include in the ground state of the  $\beta$  decaying nucleus. An examination of experimental data for  $f_1$  values in  $^{68}\text{Zn}$  and  $^{68}\text{Ga}$  is shown in Figure 1.

Where  $\delta_C$  is the spectroscopic factor for pickup of a neutron in the final state  $\alpha$  from an  $i$  particle state of spin  $T_i$  or  $T_i + 1$ , and  $\delta_R$  is the spectroscopic factor for pickup of a neutron in the final state  $\alpha$  from an  $i$  particle state of spin  $T_i$  or  $T_i + 1$ .

- Recent revisions to the CVC hypothesis in the  $^{68}\text{Zn}$   $\beta$  decay model space [1]
- Accurate calculation of the spectroscopic factor for pickup of a larger number of particles or holes are needed to provide a more precise and accurate  $f_1$  value in order to provide a stringent test of CVC in the upper  $\beta$  shell

**Neutron Particle-Hole Ground State Configurations**

Current Towner and Hardy $^{68}\text{Zn}$ Calculation Model Space [2]	$^{68}\text{Zn}$ Experimentally Accessible
$1g_{7/2}$	$1g_{7/2}$
$2p_{1/2}$	$2p_{1/2}$
$1f_{7/2}$	$1f_{7/2}$
$2p_{3/2}$	$2p_{3/2}$
$1f_{5/2}$	$1f_{5/2}$
$1f_{7/2}$	$1f_{7/2}$

<sup>68</sup>Ni Closed-Shell Core

**$^{68}\text{Zn}(d, n)^{68}\text{Zn}$  Experiment**



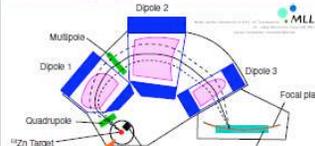
Observing the states populated in the single neutron pickup reaction  $^{68}\text{Zn}(d, n)^{68}\text{Zn}$  will help determine the relative strengths of each particle-hole configuration. This experiment directly probes neutron hole states in  $^{68}\text{Zn}$ .

**Experimental Details**

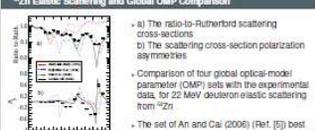
- MP tandem Van de Graaff and Stern-Gerlach polarization source provided a 22 MeV deuteron beam with 60-64% polarization
- Beam was incident on 126  $\mu\text{g}/\text{cm}^2$  of  $^{68}\text{Zn}$  with a 13  $\mu\text{g}/\text{cm}^2$  carbon backing



**MLL-LMU OSD Magnetic Spectrograph**



**$^{68}\text{Zn}$  Elastic Scattering and Global OMP Comparison**

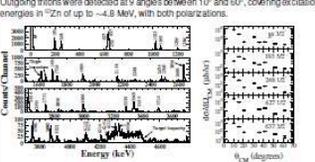


- a) The ratio to-Rutherford scattering cross-sections
- b) The scattering cross-section polarization asymmetries

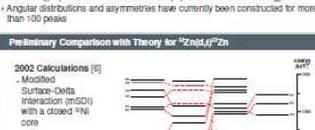
Comparison of four global optical-model parameter (OMP) sets with the experimental data, for 22 MeV deuteron-elastic scattering from  $^{68}\text{Zn}$

- The set of An and Cai (2006) (Ref. [5]) best reproduce the observed elastic scattering data

**$^{68}\text{Zn}(d, n)^{68}\text{Zn}$  Experimental Data**



Outgoing neutrons were detected at 9 angles between  $10^\circ$  and  $60^\circ$ , covering excitation energies in  $^{68}\text{Zn}$  of up to  $\sim 4$  MeV, with both polarizations.



- $^{68}\text{Zn}$  energy spectrum above for 22 MeV  $^{68}\text{Zn}$  polarized deuterons at  $\theta_{lab} = 30^\circ$
- Angular distributions and asymmetries have currently been constructed for more than 100 peaks

**Preliminary Comparison with Theory for  $^{68}\text{Zn}(d, n)^{68}\text{Zn}$**

**2002 Calculations [8]**

- Modified Surface-Orbit Interaction (mSOI) with a closed  $^{68}\text{Ni}$  core

**2006 Calculations [1]**

- mSOI and OMP1 with a  $^{68}\text{Ni}$  core, opening up to one  $f_{7/2}$  hole



**Summary**

- Experimental  $f_1$  values are needed to help guide superallowed ISB calculation model space truncations
- The need for guidance is most evident in the  $^{68}\text{Ga}$   $\beta$  decay daughter nucleus  $^{68}\text{Zn}$ , since the experimental  $f_1$  value of  $^{68}\text{Ga}$  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

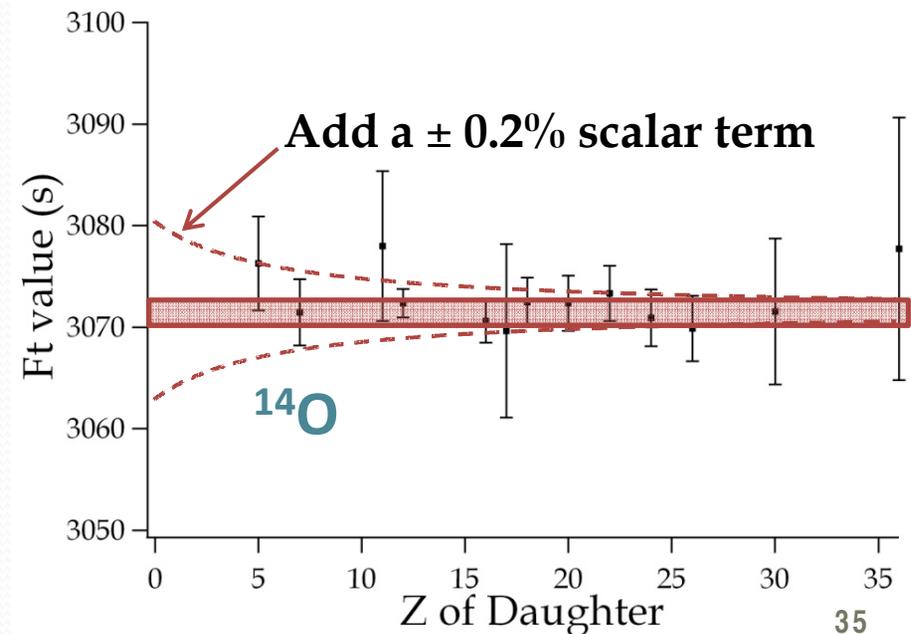
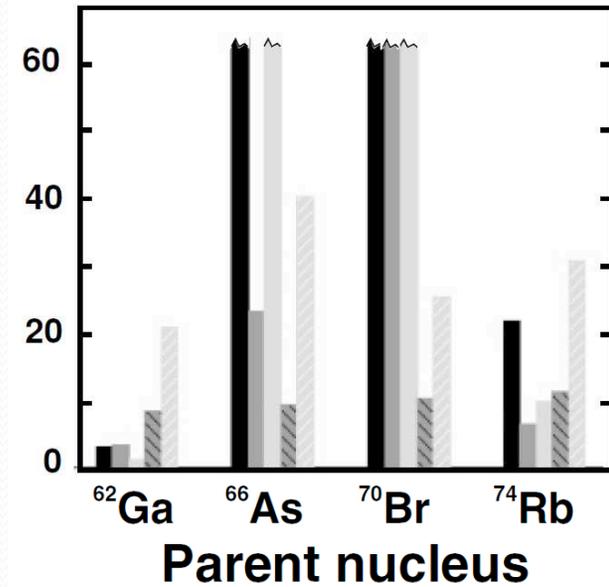
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- [1] I.S. Towner and J.C. Hardy, Phys. Rev. C 77, 025501 (2008)
- [2] J.C. Hardy and I.S. Towner, Phys. Rev. C 79, 055502 (2009)
- [3] I.S. Towner, Private Communication (2009)
- [4] H.-F. Wirth et al., MLL-LMU Jahresbericht, 71 (2000)
- [5] Xianxi An and Chongxi 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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# On The Horizon

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



# 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  $\delta_C$  values unsatisfactory
- New facilities with state-of-the-art experiment and theory
  - Leading to an improved understanding of these effects

