Superallowed Fermi β Decay

Two decades of fundamental research at ISAC

Gwen Grinyer

On behalf of everyone at ISAC and 20 amazing years!

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Nuclear β decay

- **Powerful technique to study nuclear structure**

β⁻ $\quad {}^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^- + \overline{\nu_e},$

neutron ⟶ proton

β⁺ $\quad {}^{A}_{Z}X_N \rightarrow {}^{A}_{Z-1}W_{N+1} + e^+ + \nu_e.$

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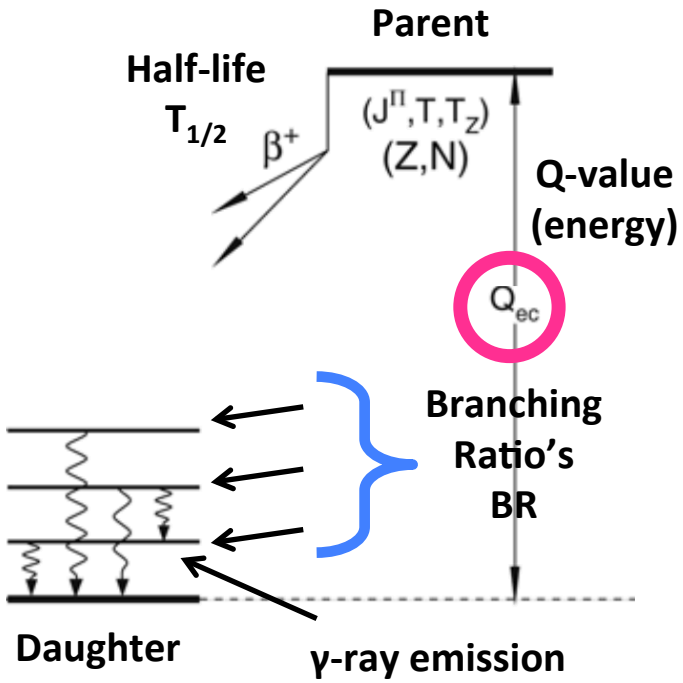

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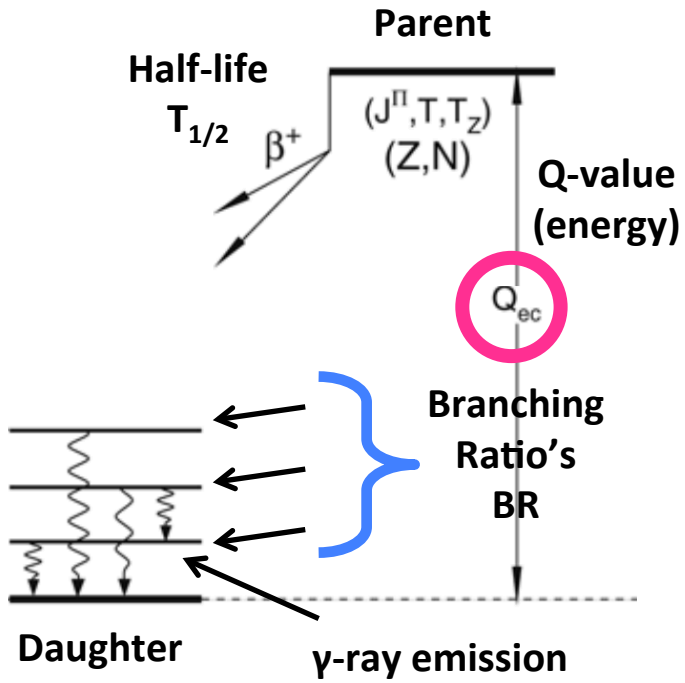
$\vec{J}_P = \vec{J}_D + \vec{L} + \vec{S}$ Momentum

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



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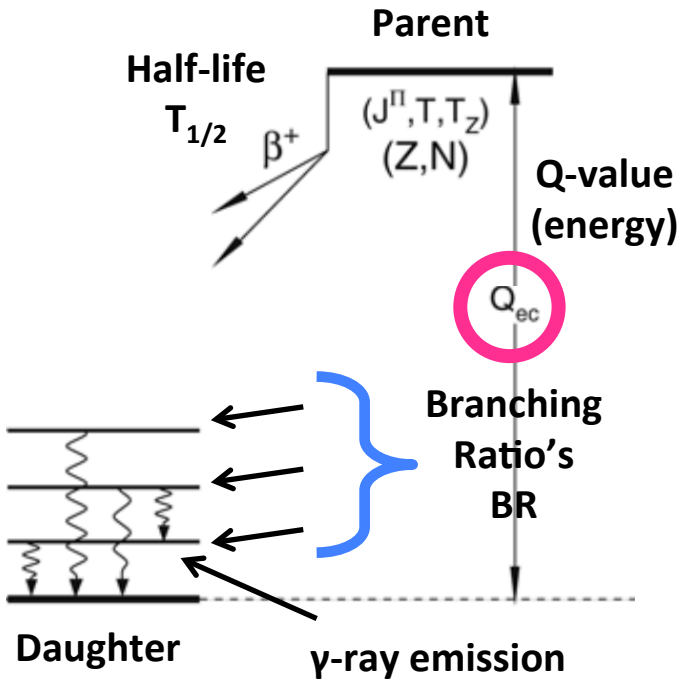
Momentum $\qquad$ Parity

- **Allowed decays (L=0, Δπ=no)**
  - **Forbidden decays (L=1,2,3,…)**
- **Fermi decays (S=0)**
  - **Gamow-Teller decays (S=1)**



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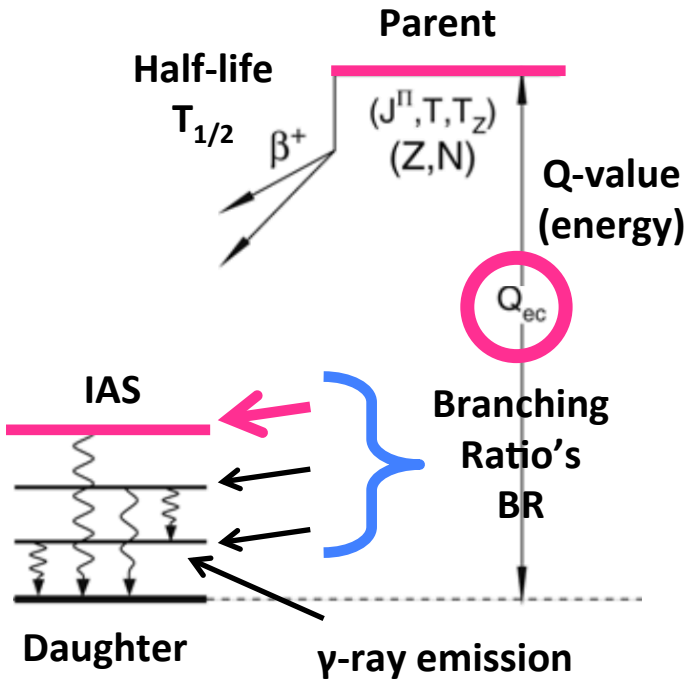
- **Super allowed Fermi decays (L=0, Δπ=no)**
  - **Allowed and *pure* Fermi decay (no GT)**
  - **Decays between *isobaric analog states (IAS)***
  - **States have identical wave functions**
  - **Isospin symmetry (neutrons = protons)**



Half-lives and *ft* values

B.Singh *et al.* **Nucl. Data Sheets 84, 487 (1998)**

Case	J^{π} (P→D)	Classification	$T_{1/2}$	Fraction
$^{18}N \rightarrow {}^{18}C$	$1^- \rightarrow 1^-$	Allowed (GT&F)	624 ms	64%
$^{6}He \rightarrow {}^{6}Li$	$0^+ \rightarrow 1^+$	Allowed (GT only)	807 ms	
$^{10}C \rightarrow {}^{10}B$	$0^+ \rightarrow 0^+$	Allowed (F only)	19 s	1%
$^{38}Cl \rightarrow {}^{38}Ar$	$2^- \rightarrow 2^+$	1st Forbidden	37 min	33%
$^{36}Cl \rightarrow {}^{36}Ar$	$2^+ \rightarrow 0^+$	2nd Forbidden	3×10^5 years	1%
$^{40}K \rightarrow {}^{40}Ca$	$4^- \rightarrow 0^+$	3rd Forbidden	1×10^9 years	0.1%
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- **The *ft* value is a convenient way to characterize nuclear β decay**

Half-life

Q-value

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

Constants

Branching Ratio

Matrix element

Strength

The *ft* values for Superallowed Fermi Decay

- **Two major simplifications to the *ft* values for superallowed decays**

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R.P.Feynman and M.Gell-Man PR 109, 193 (1958)

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  - **We assume the strength is universal (Conserved Vector Current hypothesis)**

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Fermi strength is *nucleus independent*

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

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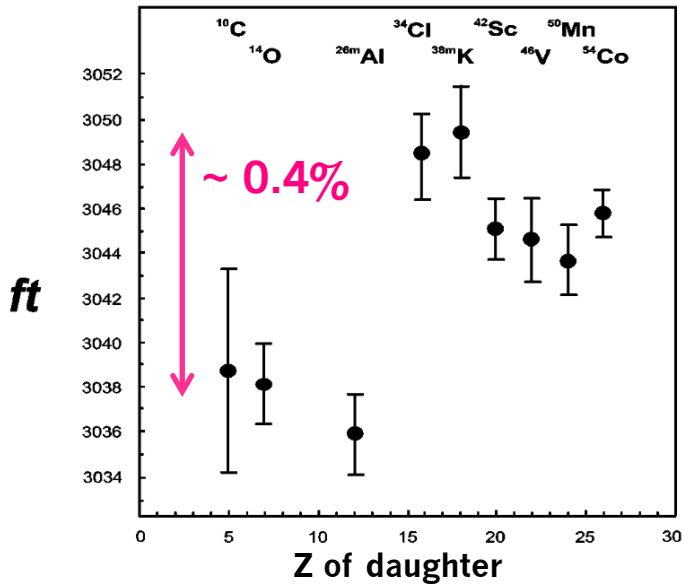
- **If isospin symmetry were perfect and if CVC were valid…**
  - **The *ft* value of any superallowed decay would be nucleus independent!**

Superallowed *ft* values (status in 2002)

I.S. Towner and J.C.Hardy PRC 66, 035501 (2002)

- **World survey of superallowed decays**
  - **> 220 independent measurements**
- **Superallowed *ft* values**
  - **Range from 3038 s to 3050 s (0.4%)**
  - **Higher-order effects (theory)**



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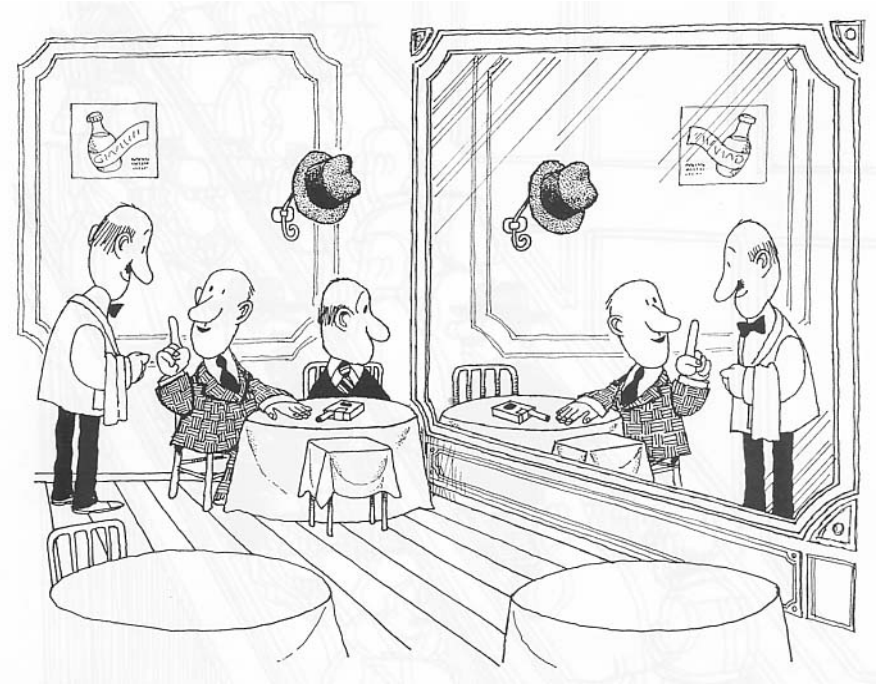

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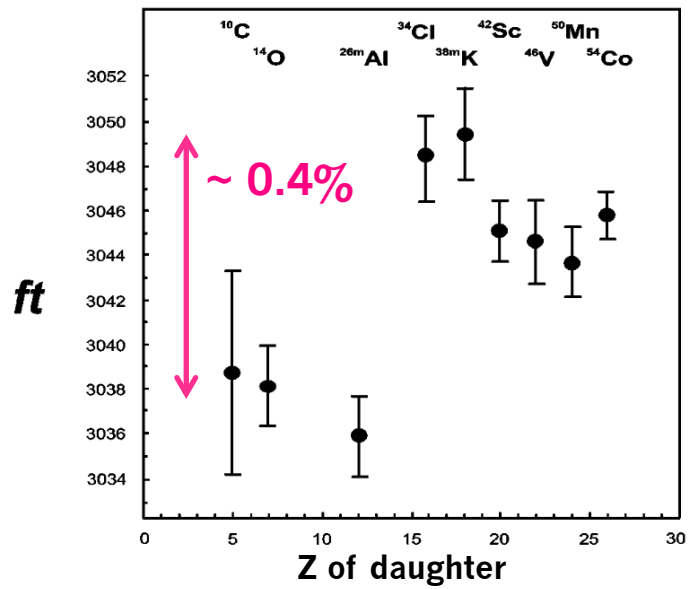
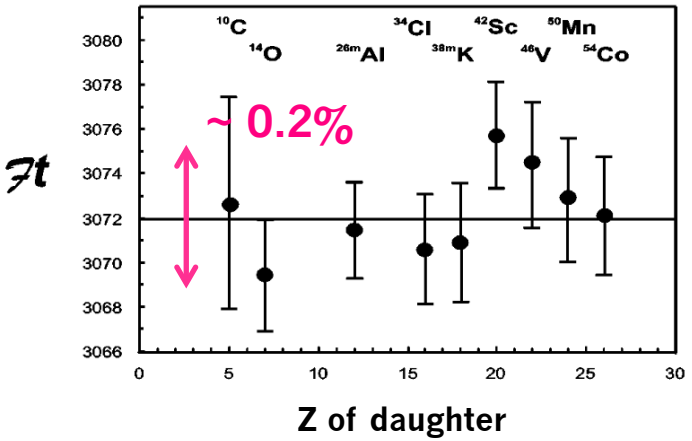
  - ***Constraint on theory* and "new physics"**





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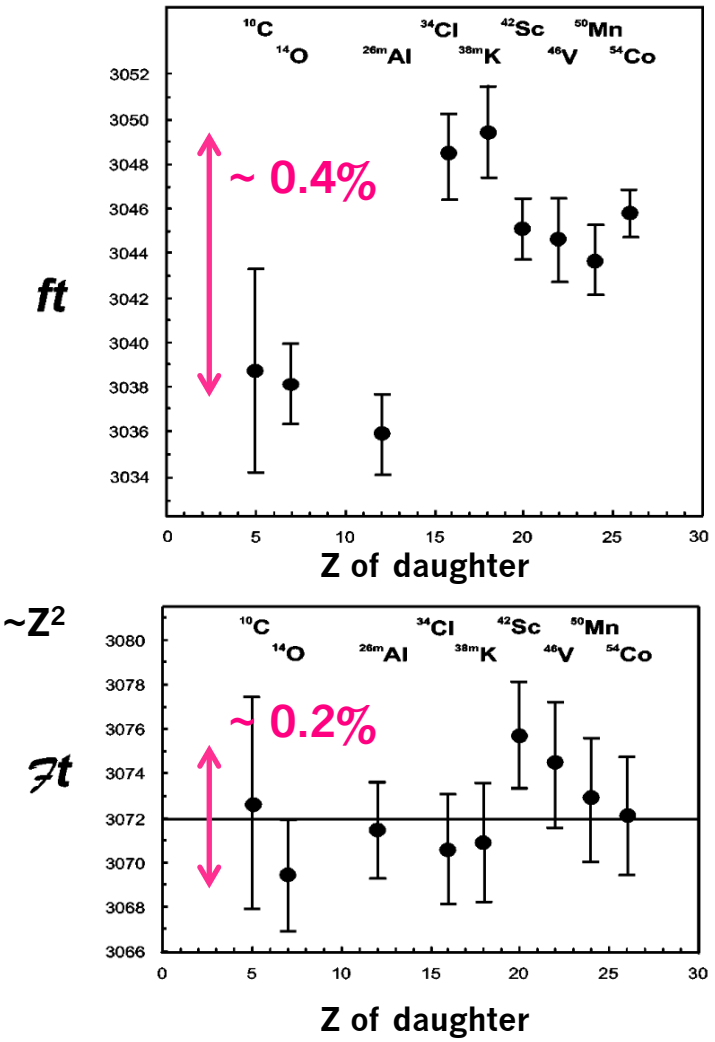
$$|M_F|^2 = 2(1 - \delta_C)$$

Coulomb
Increases with ~Z^2

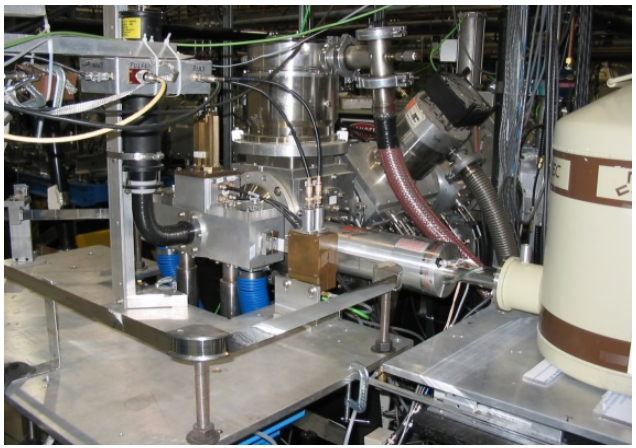
- Corrected Ft values
  - Validation of the CVC hypothesis
  - *Constraint on theory* and "new physics"
- ISAC – extend to heavier nuclei (S823)



Half-life of ^{74}Rb at GPS (Fall 1999)

- **4π gas counter and fast tape system**
  - **Collect data in cycles:** *beam on, off, move, count*

G.C.Ball *et al.* **PRL 86, 1454 (2001)**



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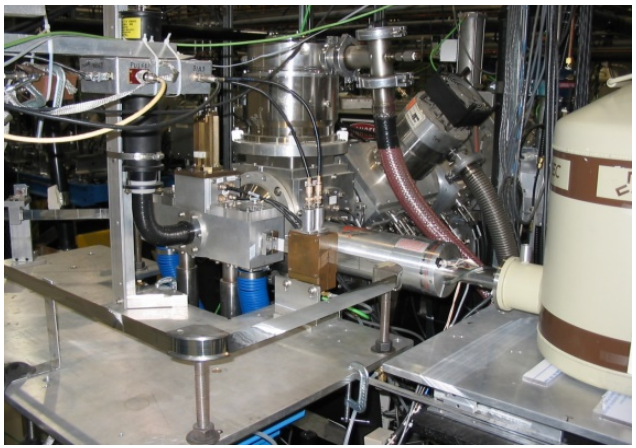

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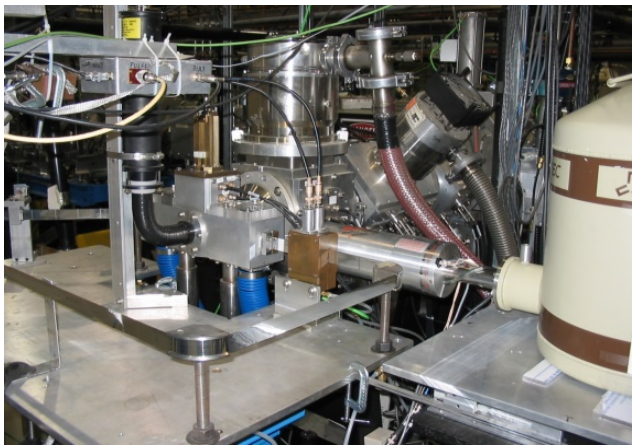

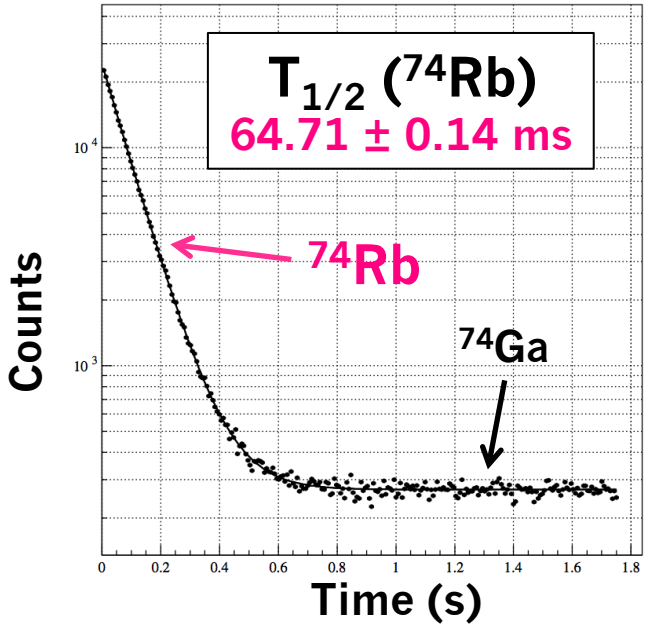

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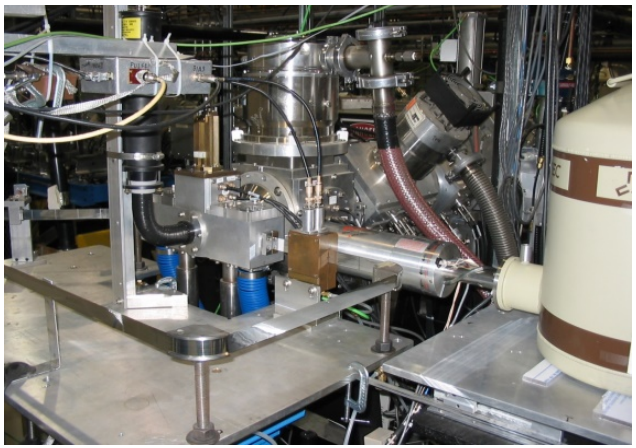

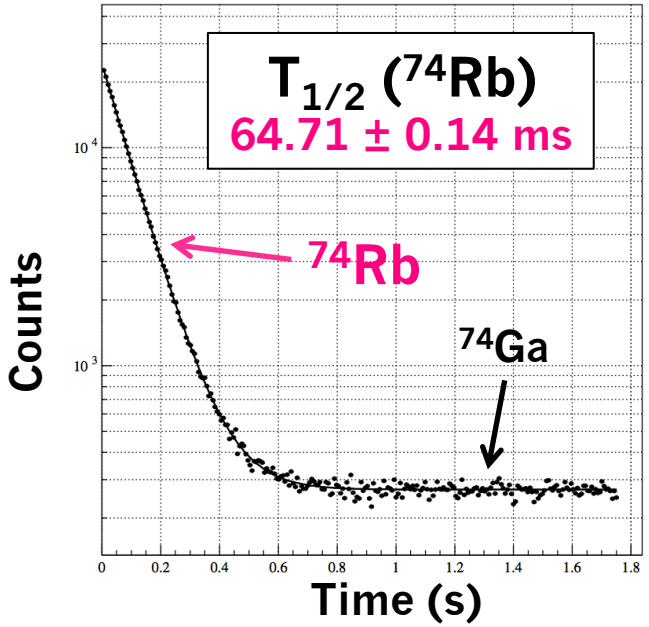

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  - **First ever Letter from ISAC!**
  - **Probably the first ever scientific publication!**

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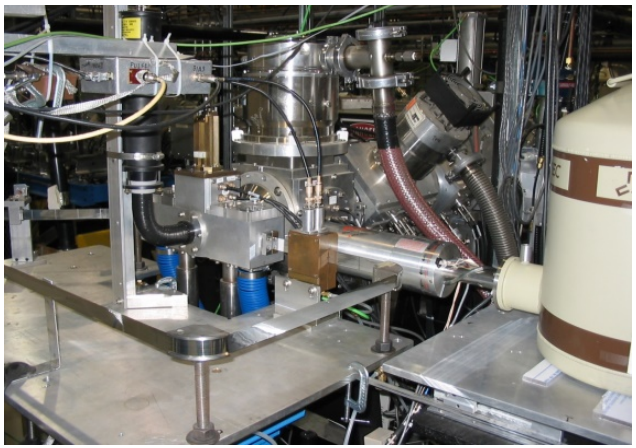

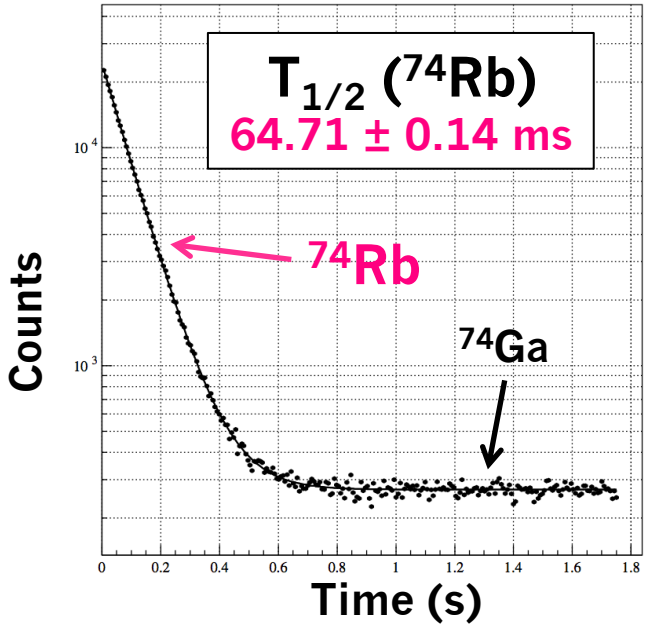

Branching ratio ^{74}Rb at GPS (Spring 2001)

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  - **Fast tape, HPGe, scintillators and Si(Li)**
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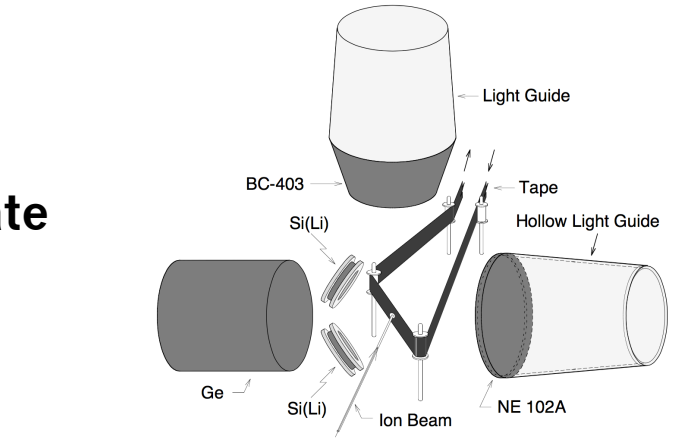

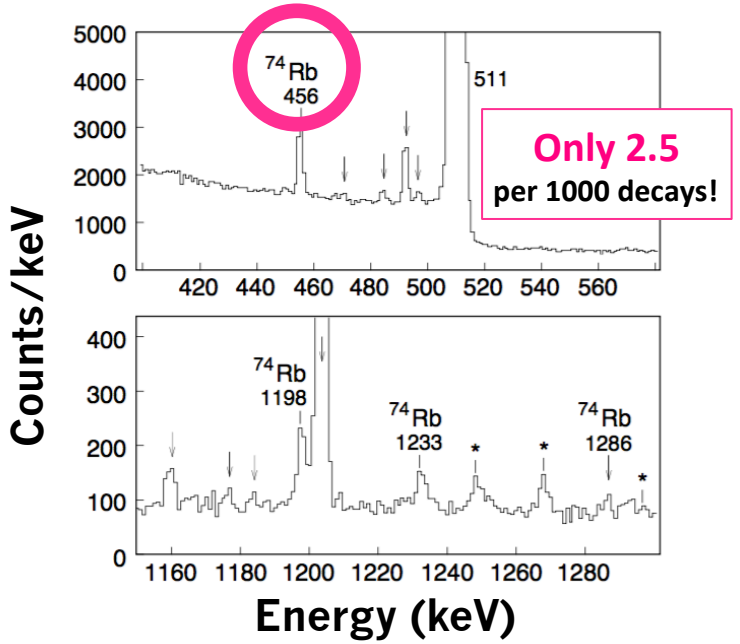

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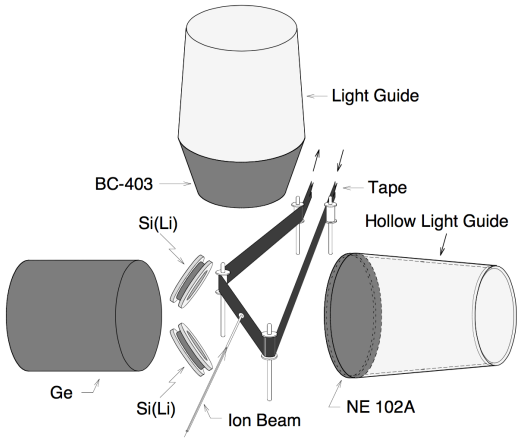

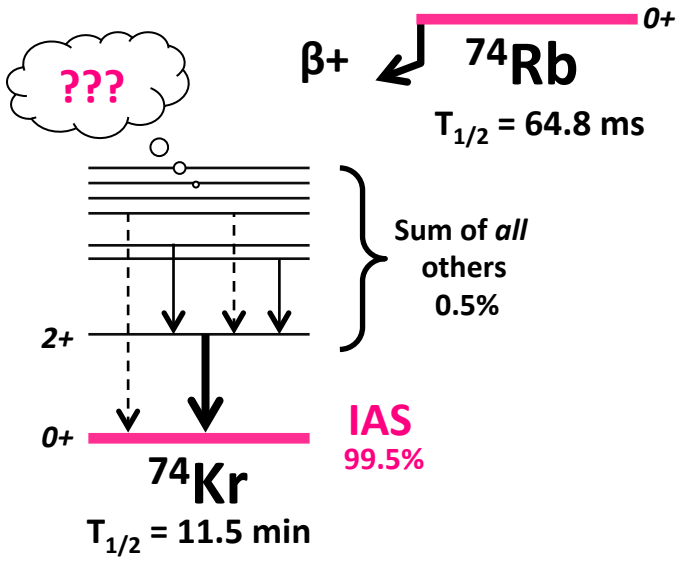

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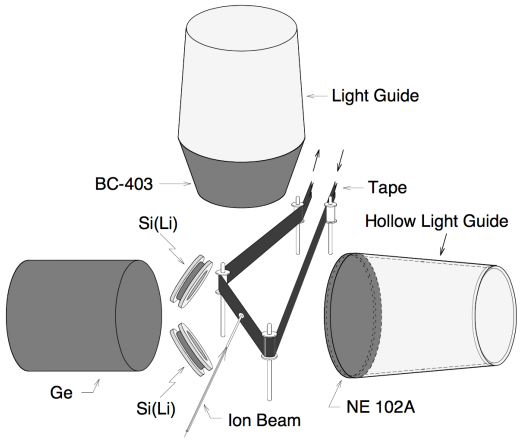
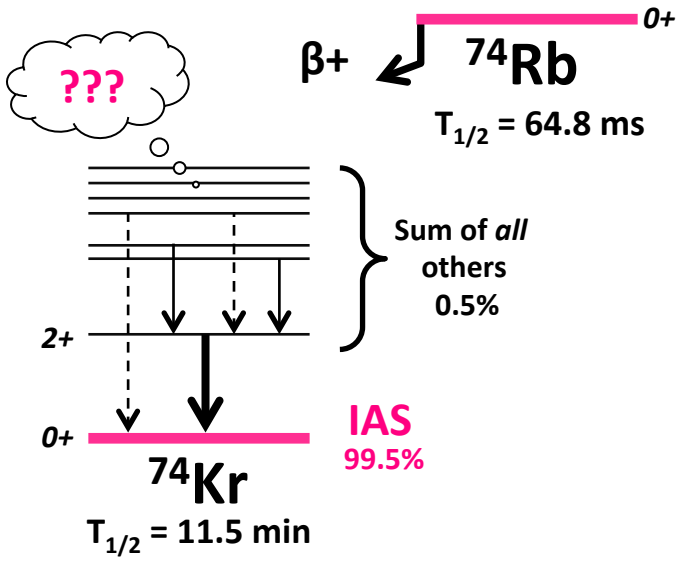


$$BR^{*}(^{74}Rb) = 0.5 \pm 0.1\ \%$$

Sum of *all* others



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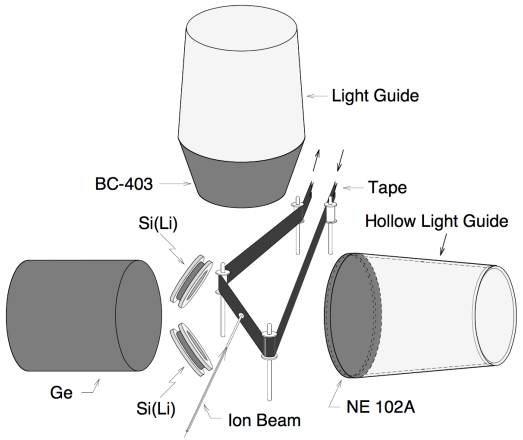

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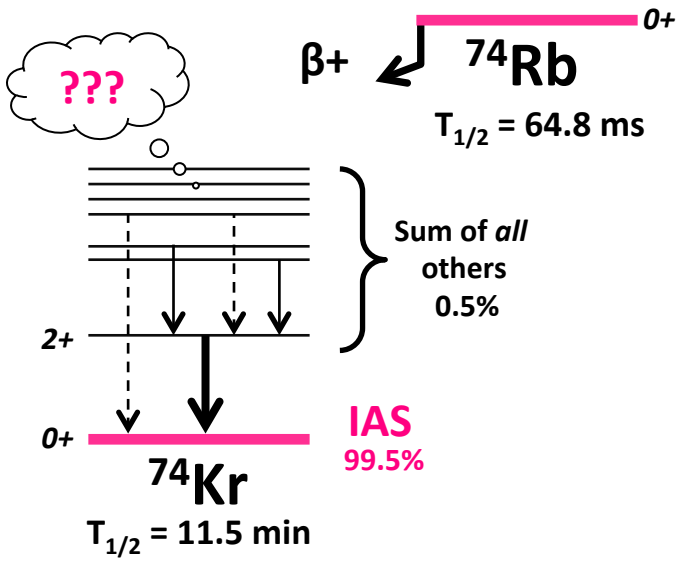
$$100\% - BR^{*}(^{74}Rb) = 99.5 \pm 0.1\ \%$$ Superallowed

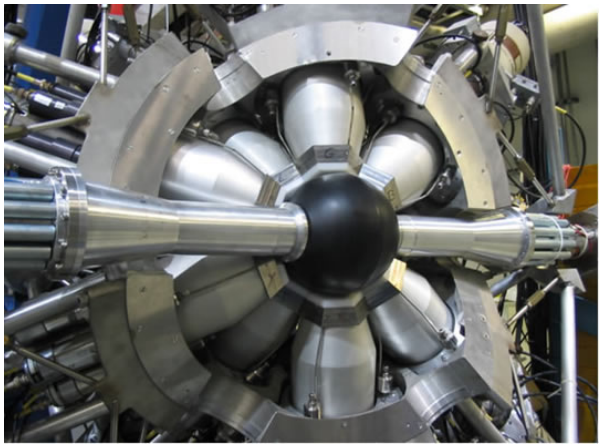


- **Precision: ± 0.1%**
- **First measurement ever of the ^{74}Rb BR!**

Branching ratios at the 8π and GRIFFIN

- **Can improve further with higher efficiency!**
  - **Higher statistical yield and weak transitions**
  - **Reduces statistical *and* model uncertainties!**

R.Dunlop *et al.* PRC 88, 045501 (2013)



8π spectrometer
(2002 – 2013)

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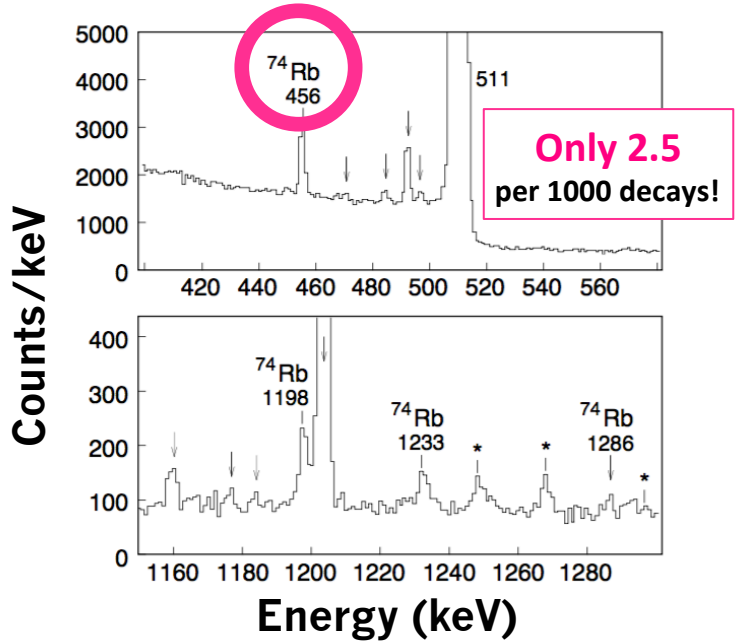
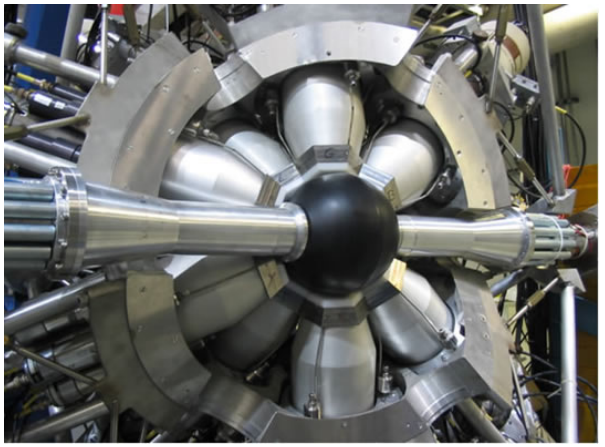
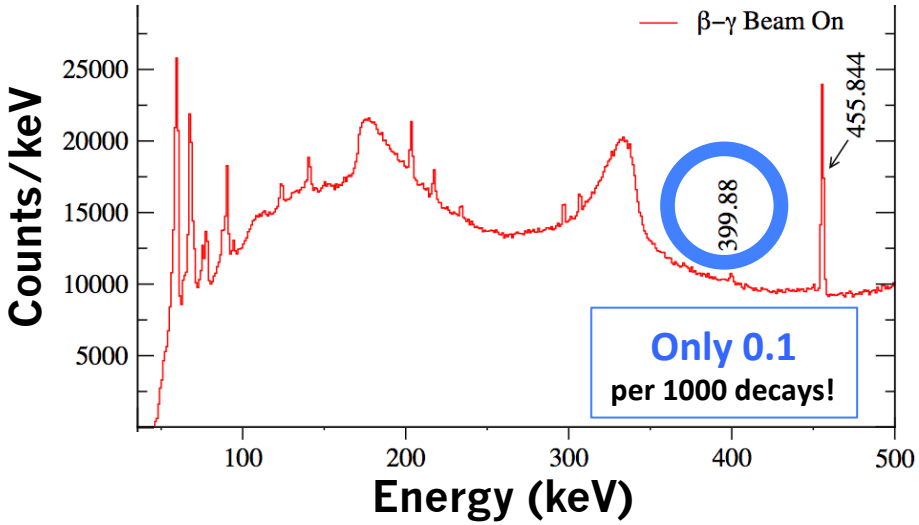
- **Example: ^{74}Rb with the 8π spectrometer**
  - **Total of 8.2x10^{8} detected ^{74}Rb decays!**
  - **Observed 58 γ-ray transitions (10 previously)**



R.Dunlop *et al.* PRC 88, 045501 (2013)



8π spectrometer
(2002 – 2013)



Branching ratios at the 8π and GRIFFIN

- **Can improve further with higher efficiency!**
  - **Higher statistical yield and weak transitions**
  - **Reduces statistical *and* model uncertainties!**

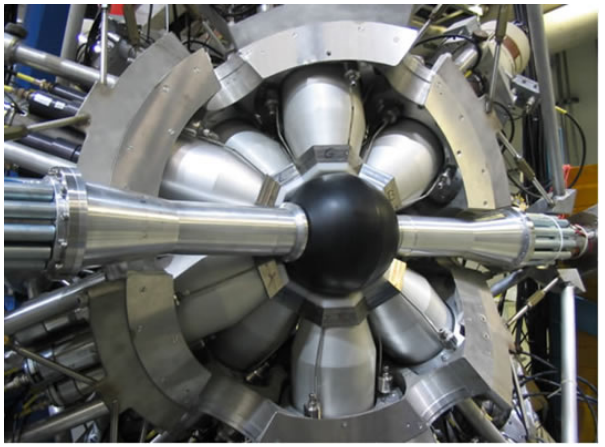
- **Example: ^{74}Rb with the 8π spectrometer**
  - **Total of 8.2x10^{8} detected ^{74}Rb decays!**
  - **Observed 58 γ-ray transitions (10 previously)**

- **Branching ratio of ^{74}Rb**

BR (^{74}Rb) = 99.545 ± 0.031 %

- **Precision: ± 0.03%**
- **Factor of 3 improvement!**

R.Dunlop *et al.* PRC 88, 045501 (2013)



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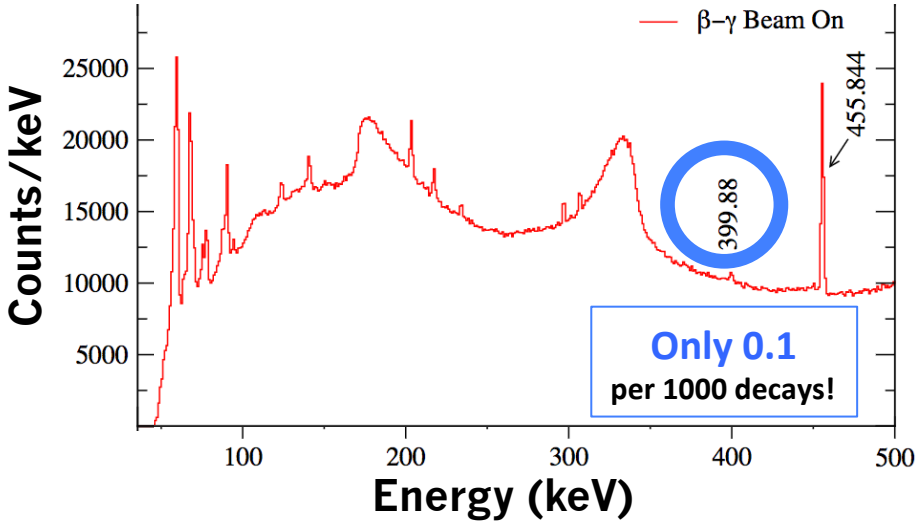

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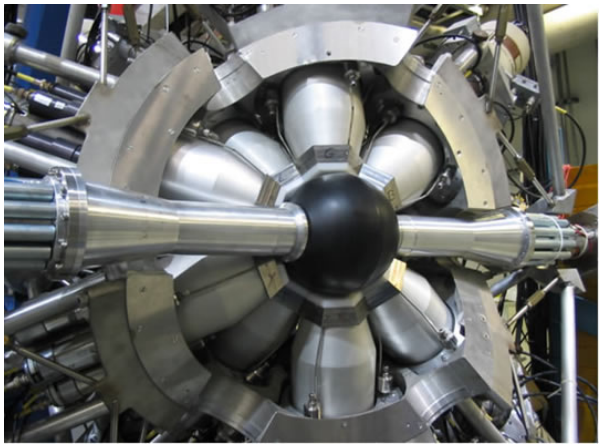
- **Next: GRIFFIN (10x more efficiency)**
  - **Experiment on ^{62}Ga next week (S1518)!**

R.Dunlop *et al.* PRC 88, 045501 (2013)



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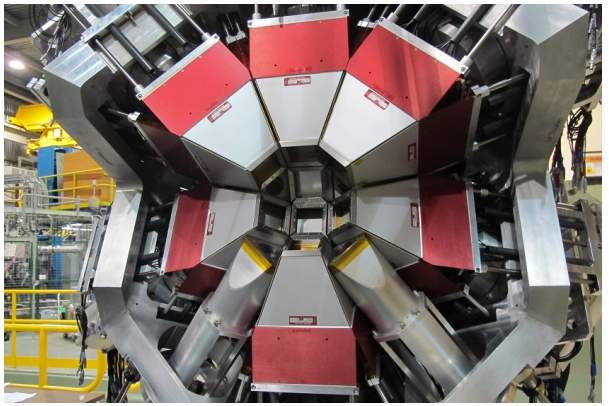
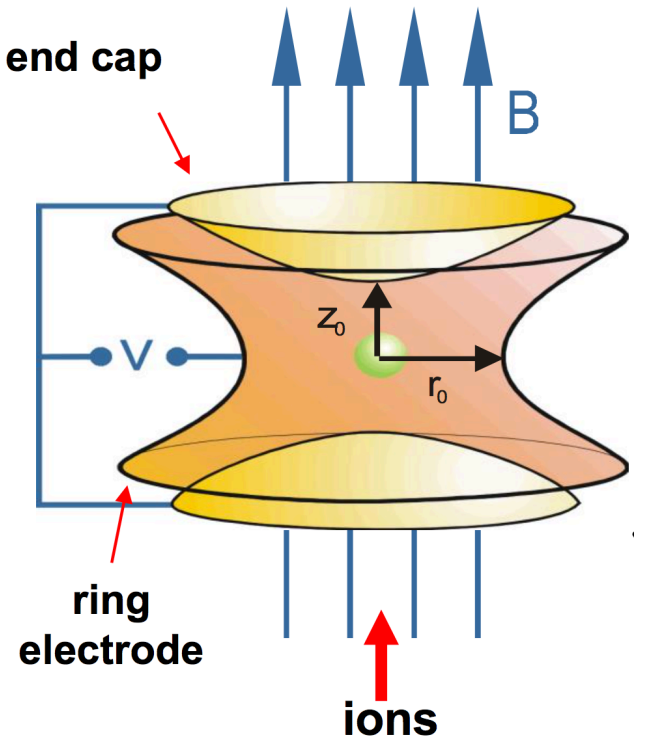


GRIFFIN
(2015 – present)

Q-value (mass) of ^{74}Rb at TITAN

- **Penning trap mass spectrometry**
  - **Trap charged ions in a magnetic field B**
  - **Deduce mass from cyclotron frequency ν_c**

S.Ettenauer *et al.* PRL 107, 272501 (2011)



$$2\pi\nu_c = (q/m) \cdot B$$

Q-value (mass) of ^{74}Rb at TITAN

- **Penning trap mass spectrometry**
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  - **Deduce mass from cyclotron frequency ν_c**

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  - **B – use a stronger magnetic field**
  - **T – increase excitation time**
  - **N – more statistics**
  - **q – use highly charged ions**

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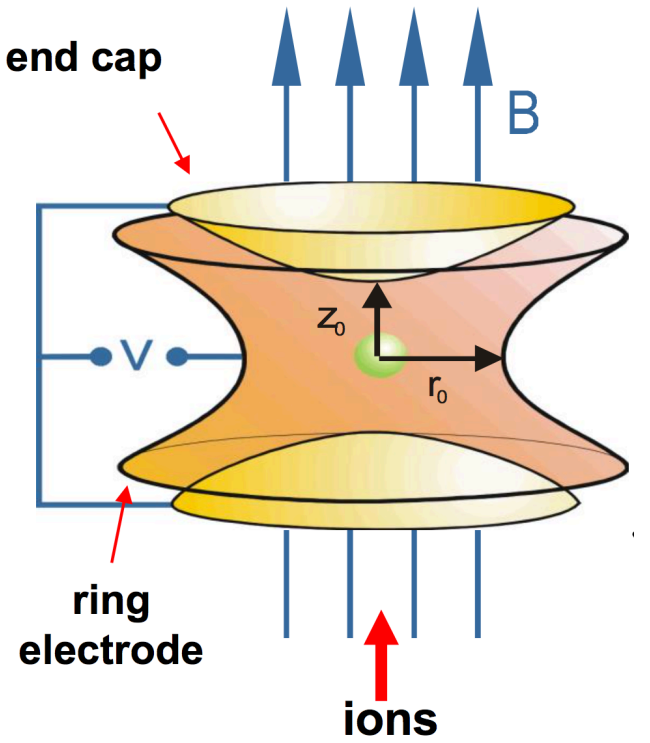

$$2\pi\nu_c = (q/m) \cdot B$$

$$\frac{\delta m}{m} \approx \frac{m}{q\,B\,T_{RF}\sqrt{N}}$$

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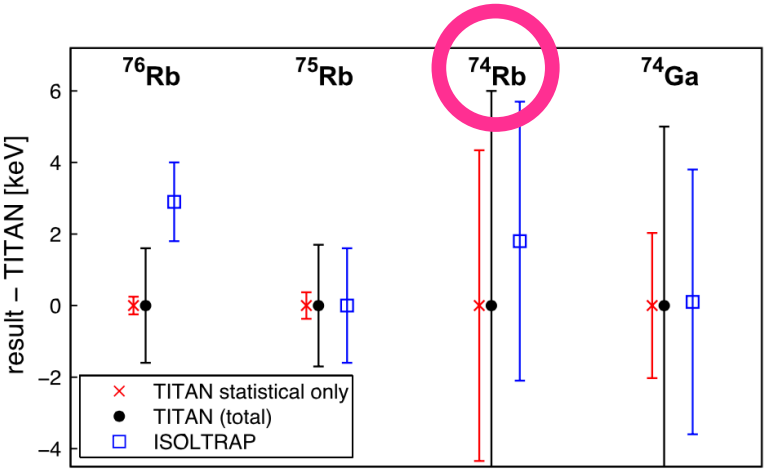
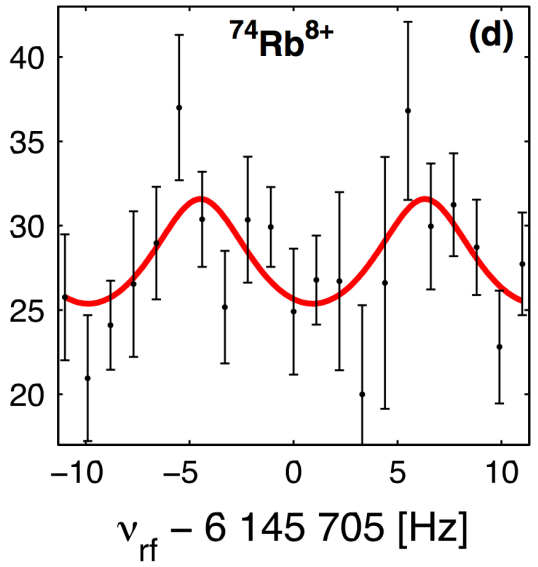
- **Penning trap mass spectrometry**
  - Trap charged ions in a magnetic field B
  - Deduce mass from cyclotron frequency ν_C
- **How to improve the precision (δm/m)**
  - B – use a stronger magnetic field
  - T – increase excitation time
  - N – more statistics
  - q – use highly charged ions
- **Mass excess of ^{74}Rb at TITAN**

ME (^{74}Rb) = –51916.5 ± 6.0 keV

  - Precision: ± 0.01% (8^+ charge state)
  - Good agreement with ISOLTRAP
  - First ever charge-bred rare-isotope mass!

S.Ettenauer *et al.* PRL 107, 272501 (2011)





Superallowed *ft* values (status in 2002)

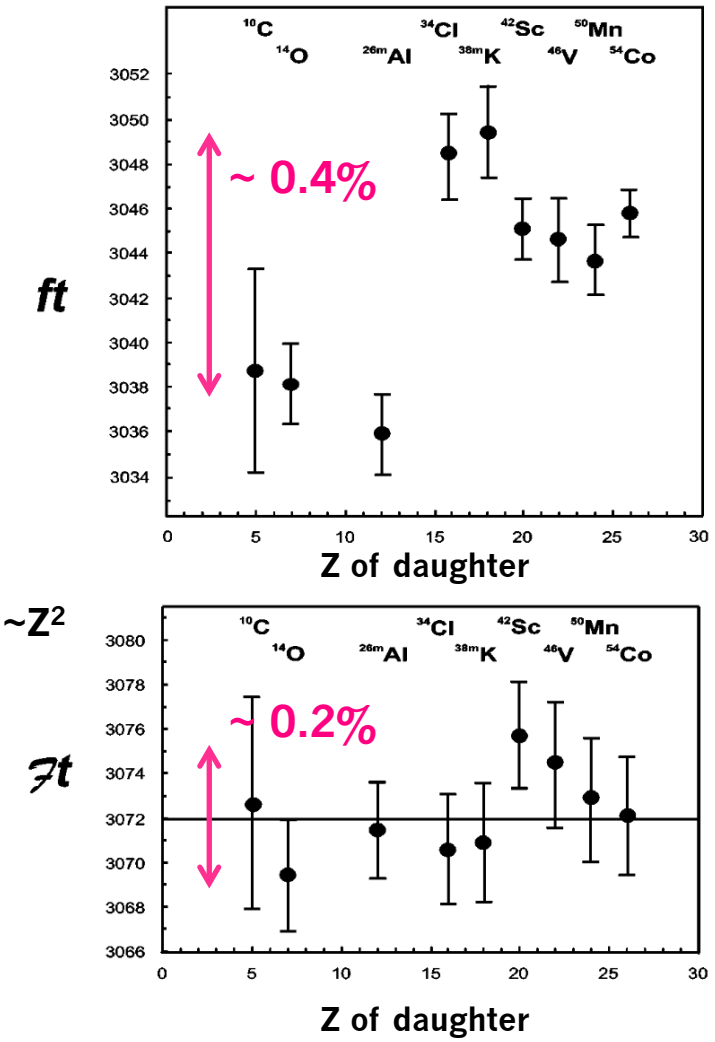
I.S. Towner and J.C.Hardy PRC 66, 035501 (2002)

- **World survey of superallowed decays**
  - **> 220 independent measurements**
- **Superallowed *ft* values**
  - **Range from 3038 s to 3050 s (0.4%)**
  - **Higher-order effects (theory)**
- **Isospin symmetry is not exact**
  - **Broken by *charge dependent* forces**

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

Coulomb
Increases with ~Z²

- **Corrected Ft values**
  - **Validation of the CVC hypothesis**
  - ***Constraint on theory* and "new physics"**
- **ISAC – extend to heavier nuclei (S823)**



Superallowed *ft* values (status today)

J.C.Hardy and I.S. Towner PRC 91, 025501 (2015)

- World survey of superallowed decays
  - > 220 independent measurements
- Superallowed *ft* values
  - Range from 3038 s to 3100 s (2%)
  - Higher-order effects (theory)
- Isospin symmetry is not exact
  - Broken by *charge dependent* forces

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

Coulomb
Increases with ~Z^2

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  - *Constraint on theory* and "new physics"
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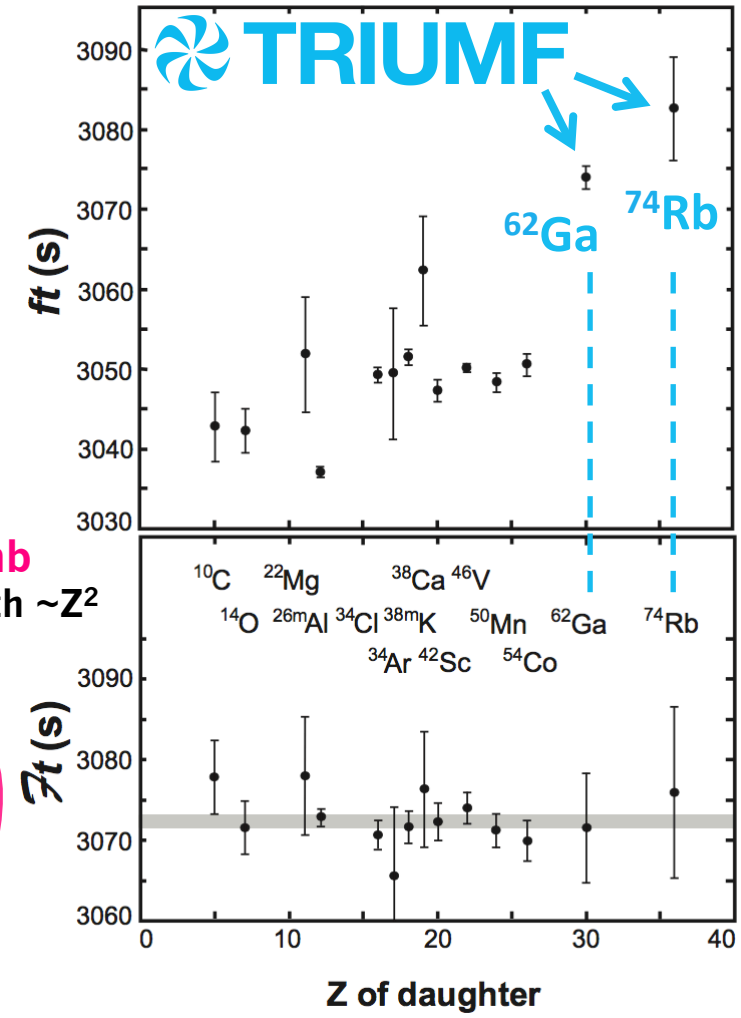
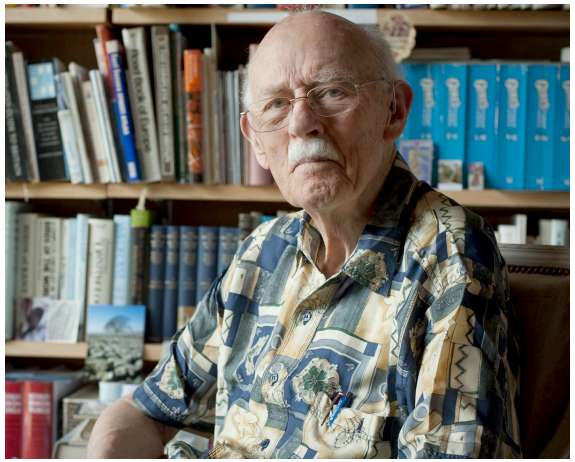


Wilkinson's Technique

- **Method developed by Denys Wilkinson**
  - **Pioneer in superallowed Fermi β decays**
  - **Long time TRIUMF visitor and colleague**

G.F.Grinyer *et al.* NIMA 622, 236 (2010)



Denys Wilkinson
(1922 – 2016)

". . . a breaker of stones on an old road to a not yet clearly marked destination."

Thornton Wilder – The Eighth Day

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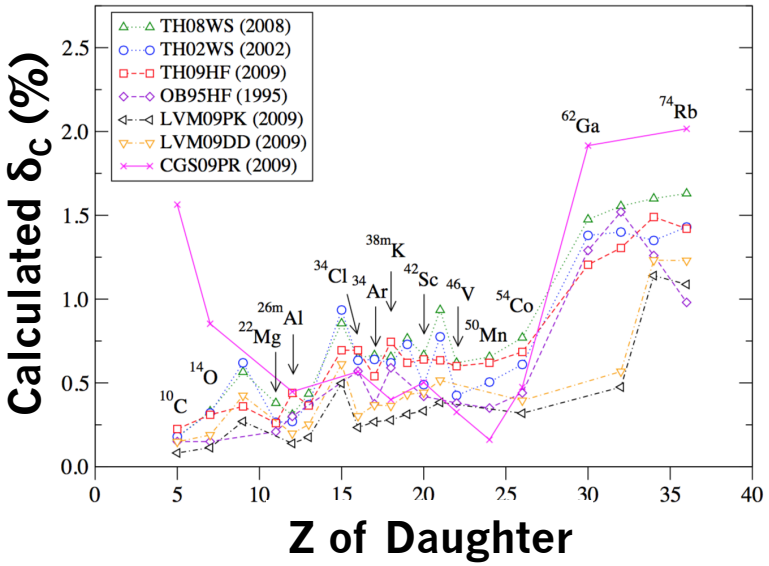

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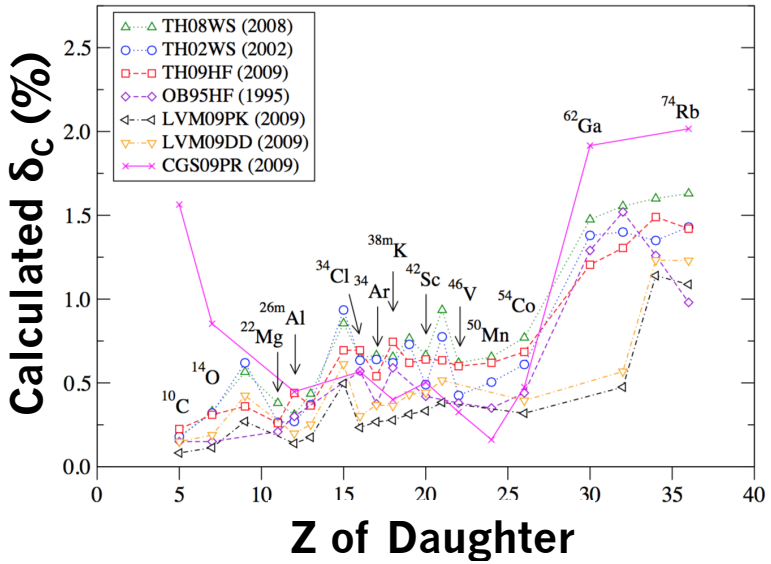

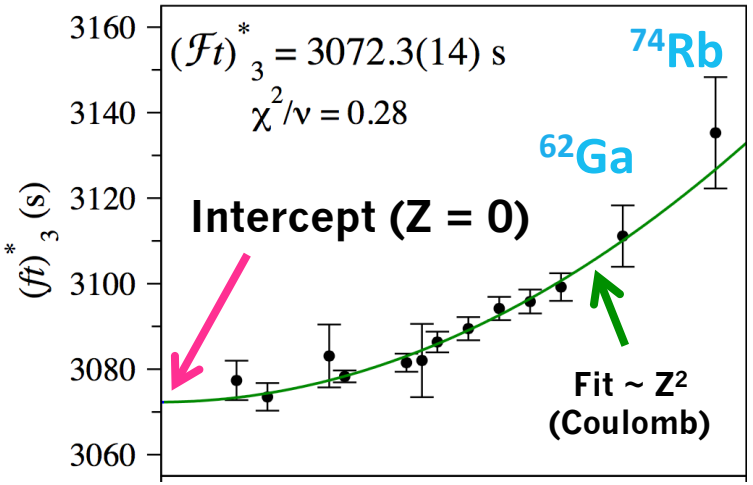

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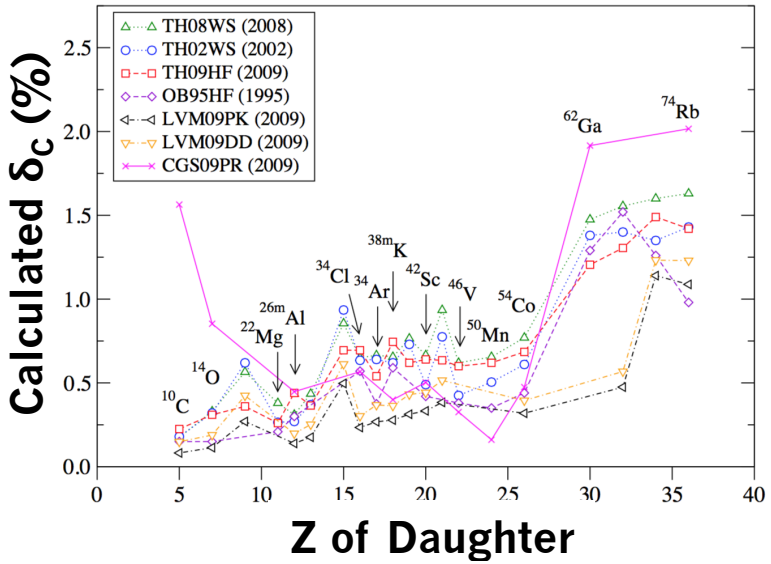
- **Wilkinson: Don't need a model for δ_C**
  - **Extrapolate *ft* values to Z = 0**
- **With ^{62}Ga and ^{74}Rb now known…**

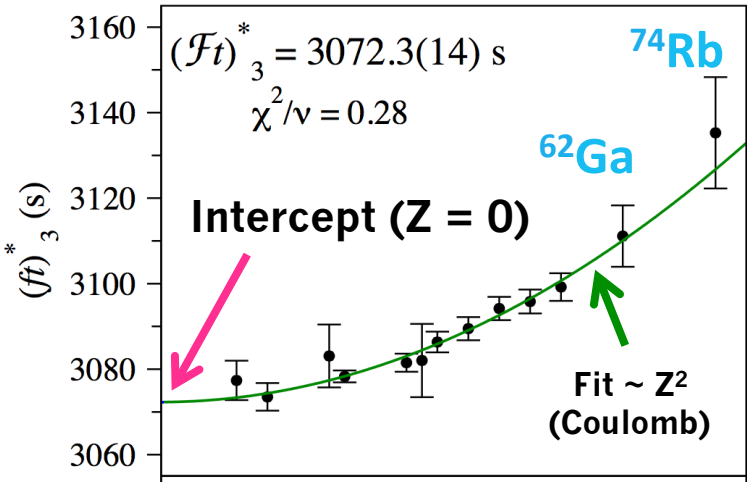
Ft (TH) = 3072.1 ± 0.8 s World average 2009

Ft (W) = 3071.5 ± 1.4 s Wilkinson 2009

  - **Agrees with sophisticated theories!**
  - **This was never the case in the past!**

G.F.Grinyer *et al.* NIMA 622, 236 (2010)





Wilkinson's Technique

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18th April 2009

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Perhaps, with your Eq. (20) and the convergence of the complementary approaches to the $\delta_{NS,C}$ - problem, we should now call it a day --- but that sentiment may just be a consequence of my antiquity.

It was a pleasure to meet you last September at TRIUMF. I shall be back again this year (1st August - 27th September) for my annual Summer migration and it would be nice if our paths were to cross again.

With kind wishes

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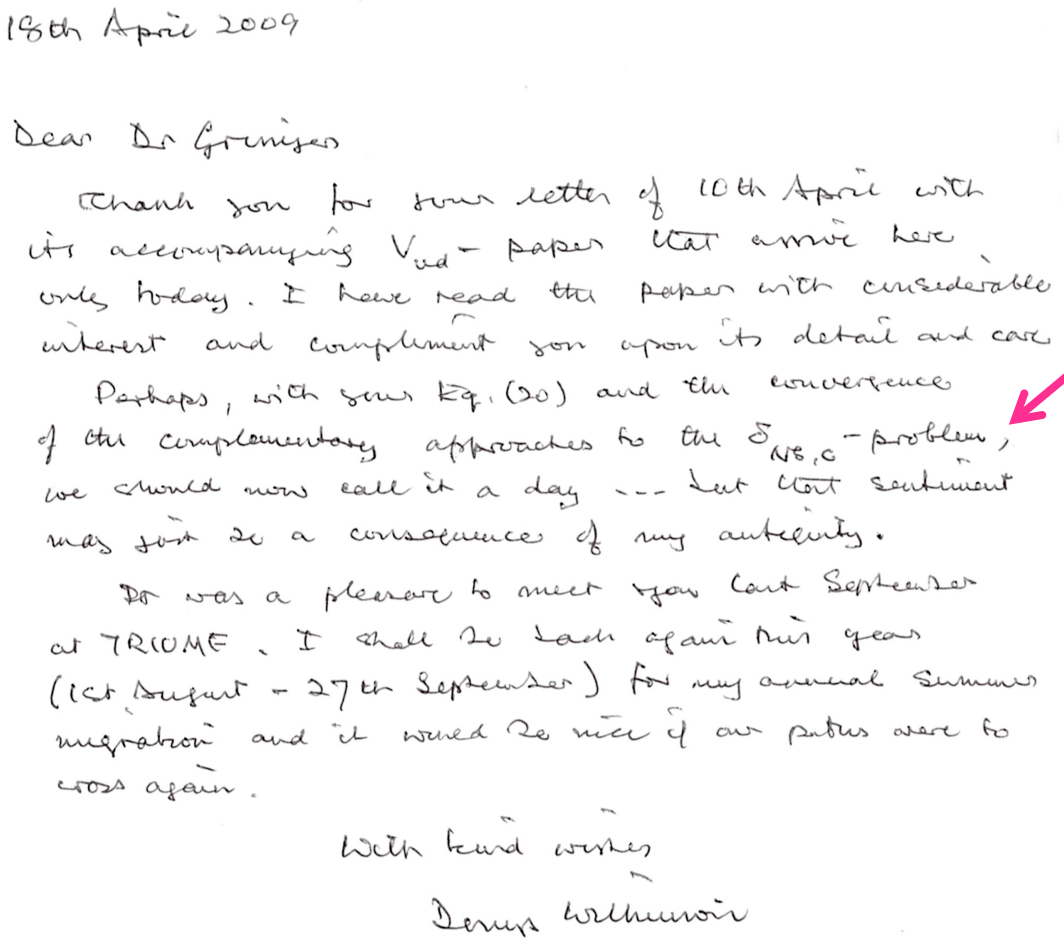

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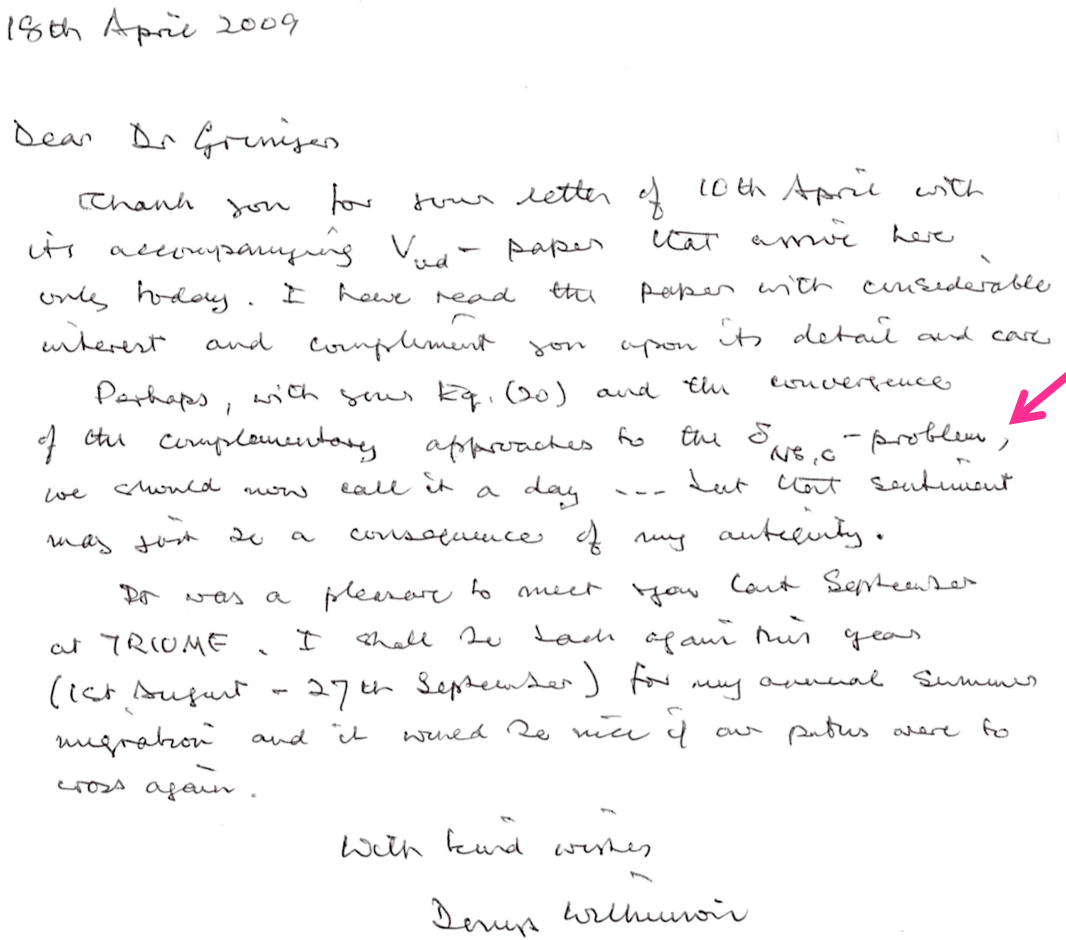

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Superallowed Decays: 20 years at ISAC

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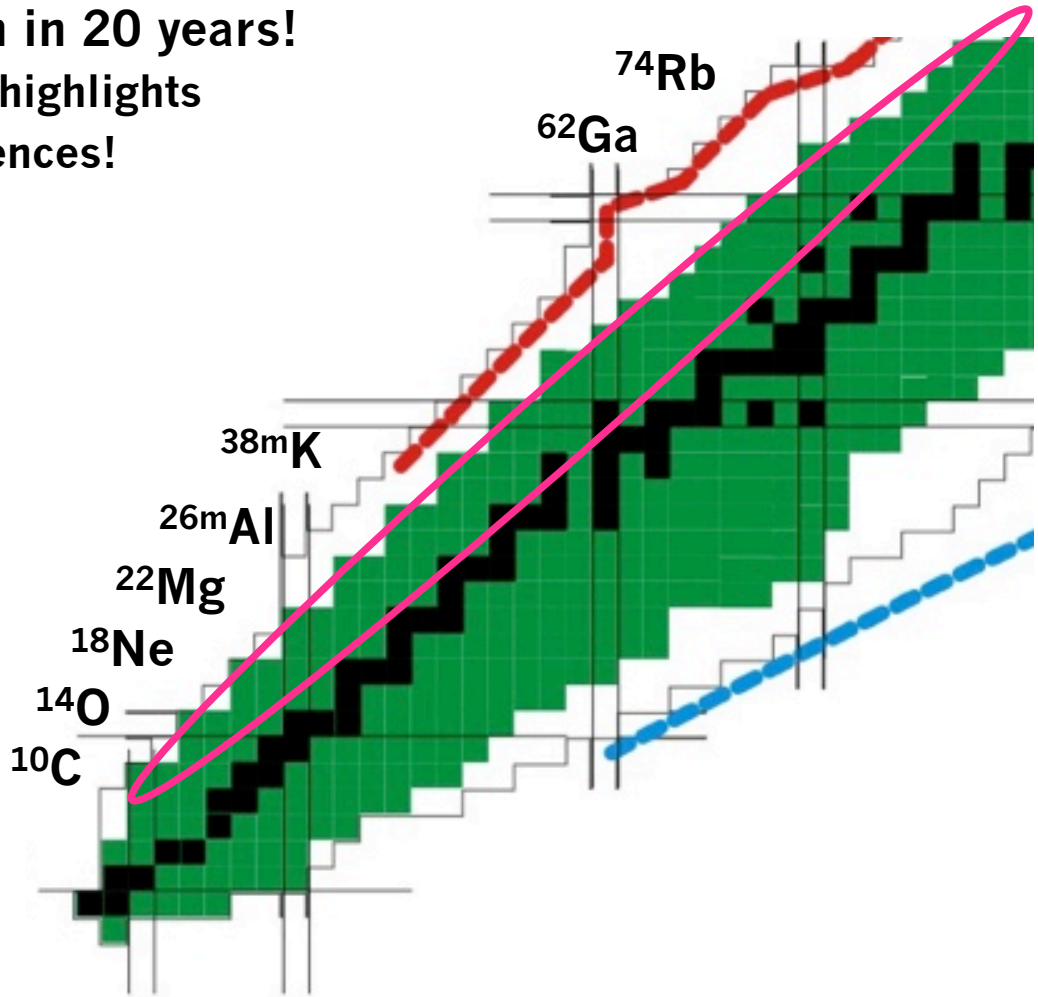
  - **I only had time for a few quick highlights**
  - **Fully biased by my own experiences!**



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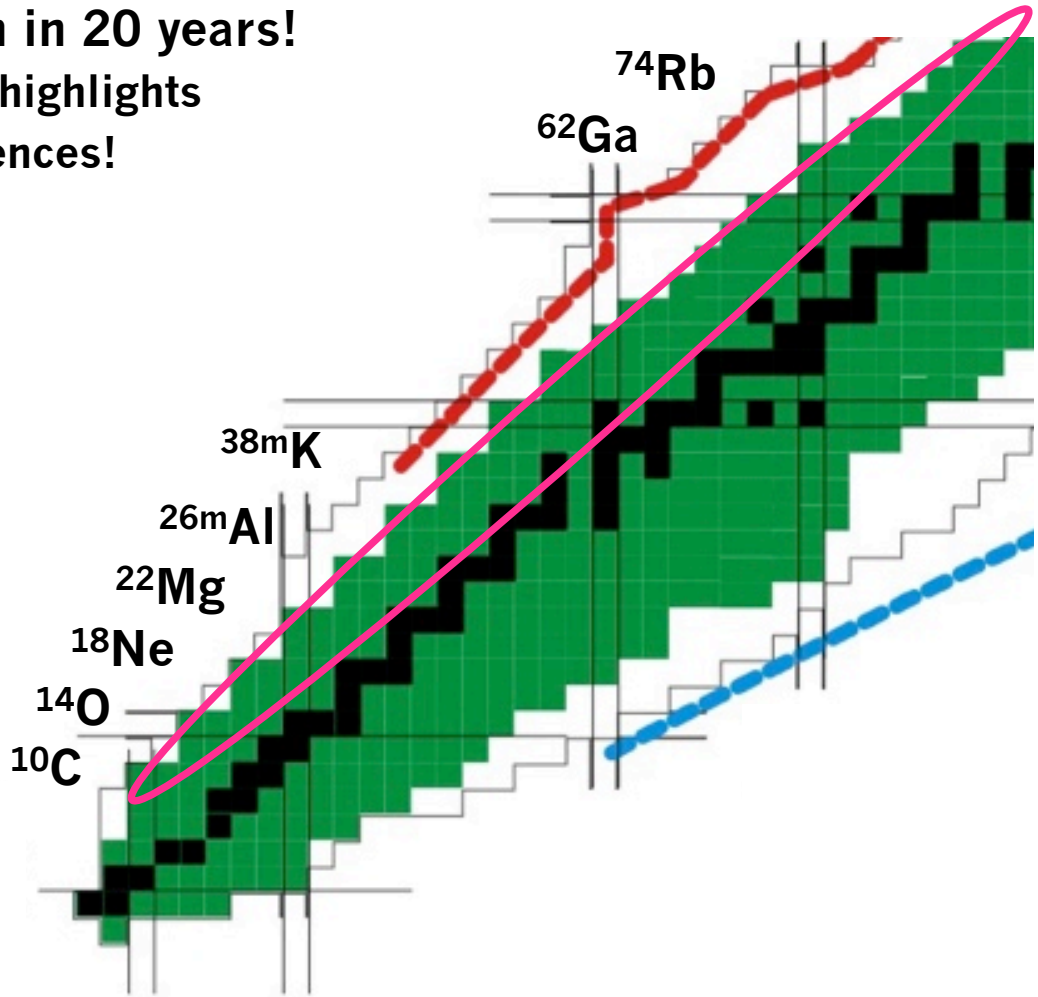

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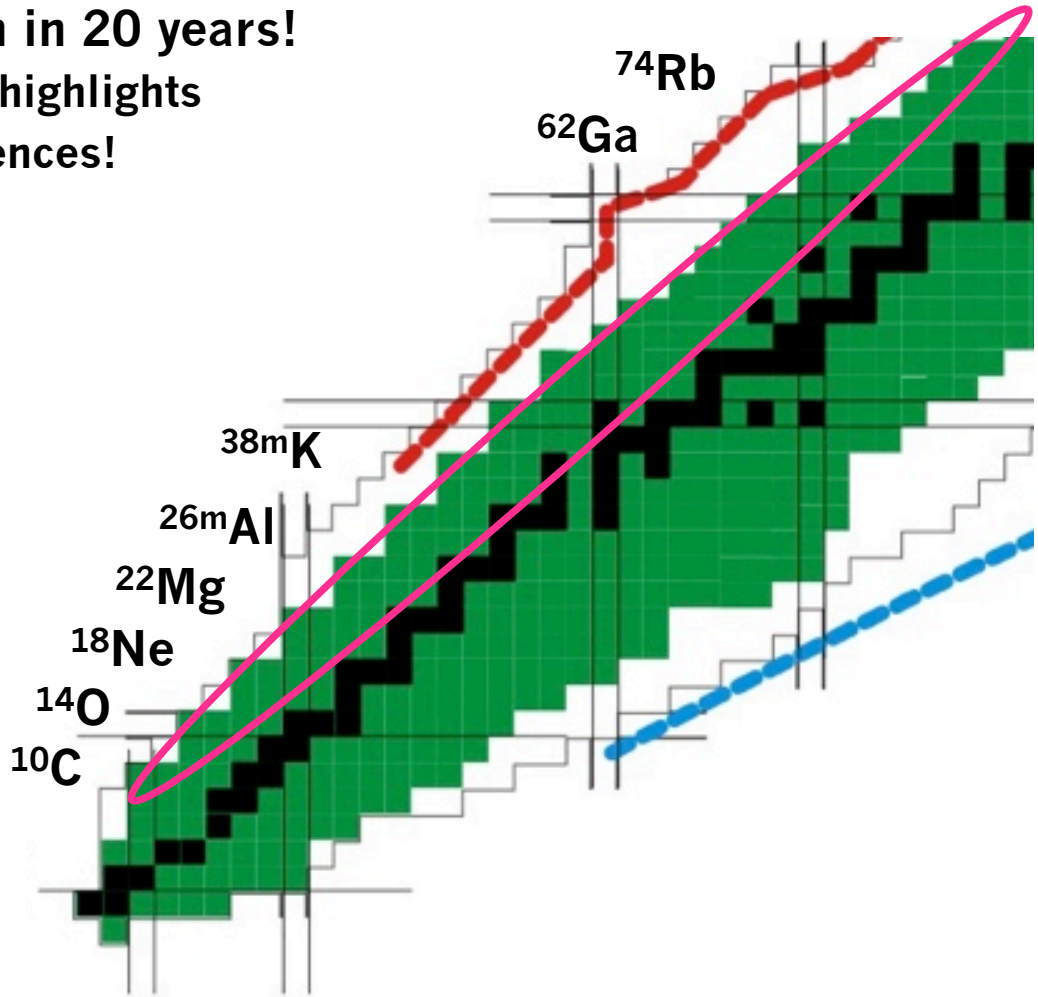
- **Science *crosses* disciplines**
  - **GPS, 8π and GRIFFIN**
  - **TITAN**
  - **Laser spectroscopy**
  - **Beam development/operations**
  - **Theory group**



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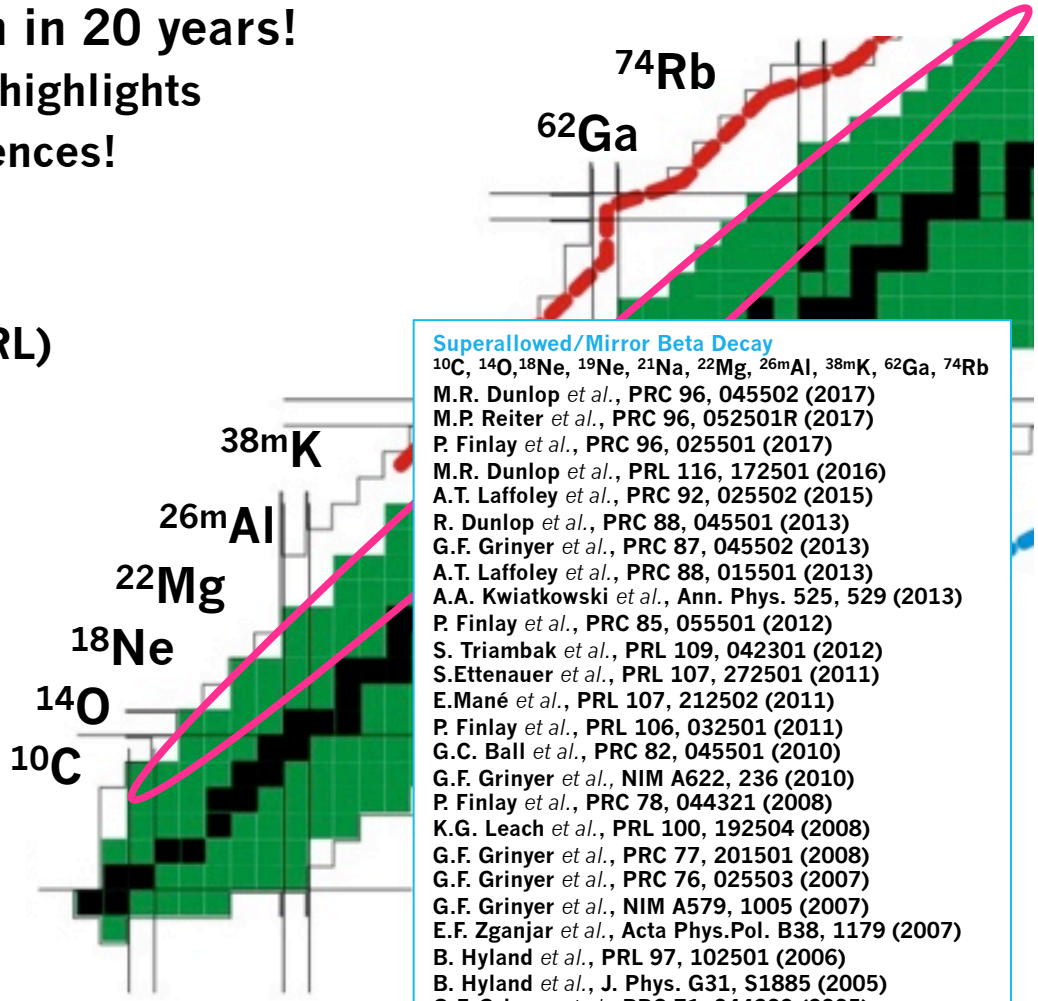

Superallowed/Mirror Beta Decay
^{10}C, ^{14}O,^{18}Ne, ^{19}Ne, ^{21}Na, ^{22}Mg, ^{26m}Al, ^{38m}K, ^{62}Ga, ^{74}Rb

M.R. Dunlop *et al.*, PRC 96, 045502 (2017)
M.P. Reiter *et al.*, PRC 96, 052501R (2017)
P. Finlay *et al.*, PRC 96, 025501 (2017)
M.R. Dunlop *et al.*, PRL 116, 172501 (2016)
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R. Dunlop *et al.*, PRC 88, 045501 (2013)
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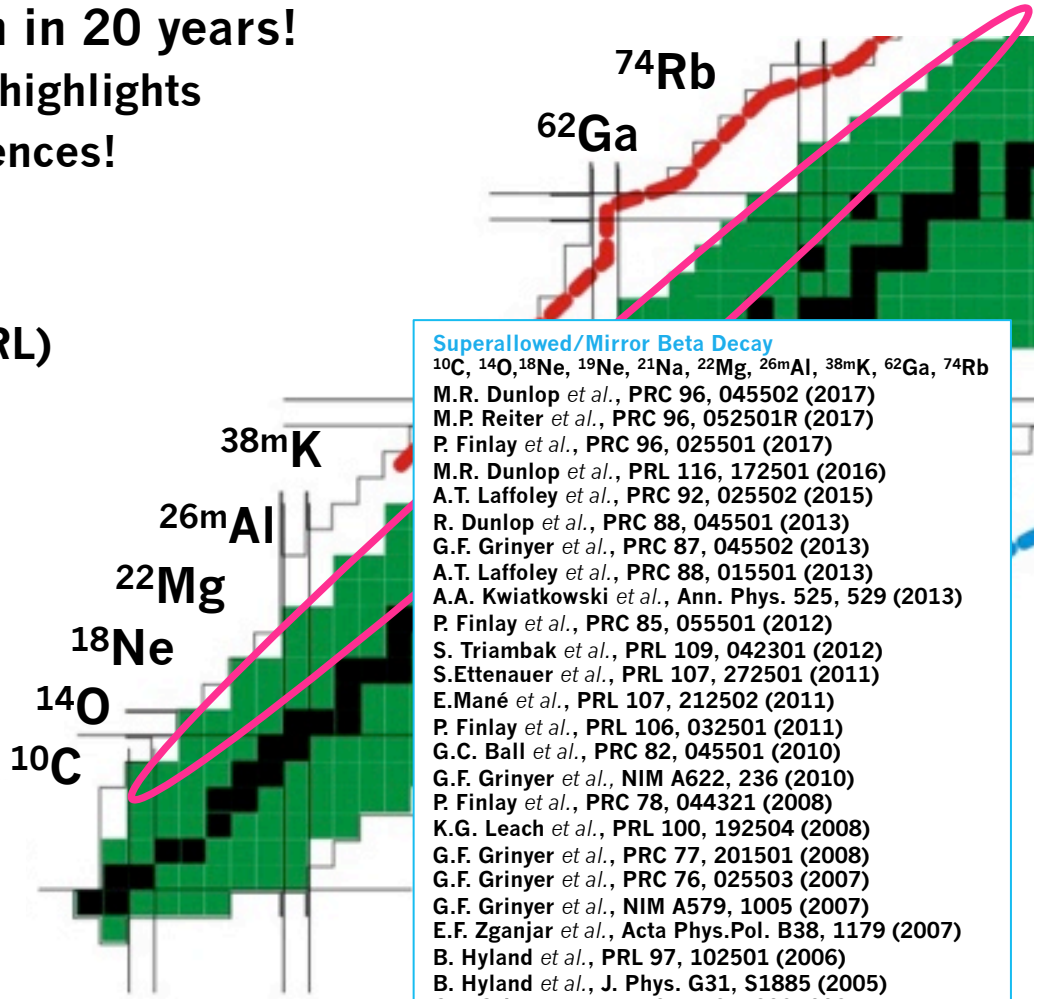

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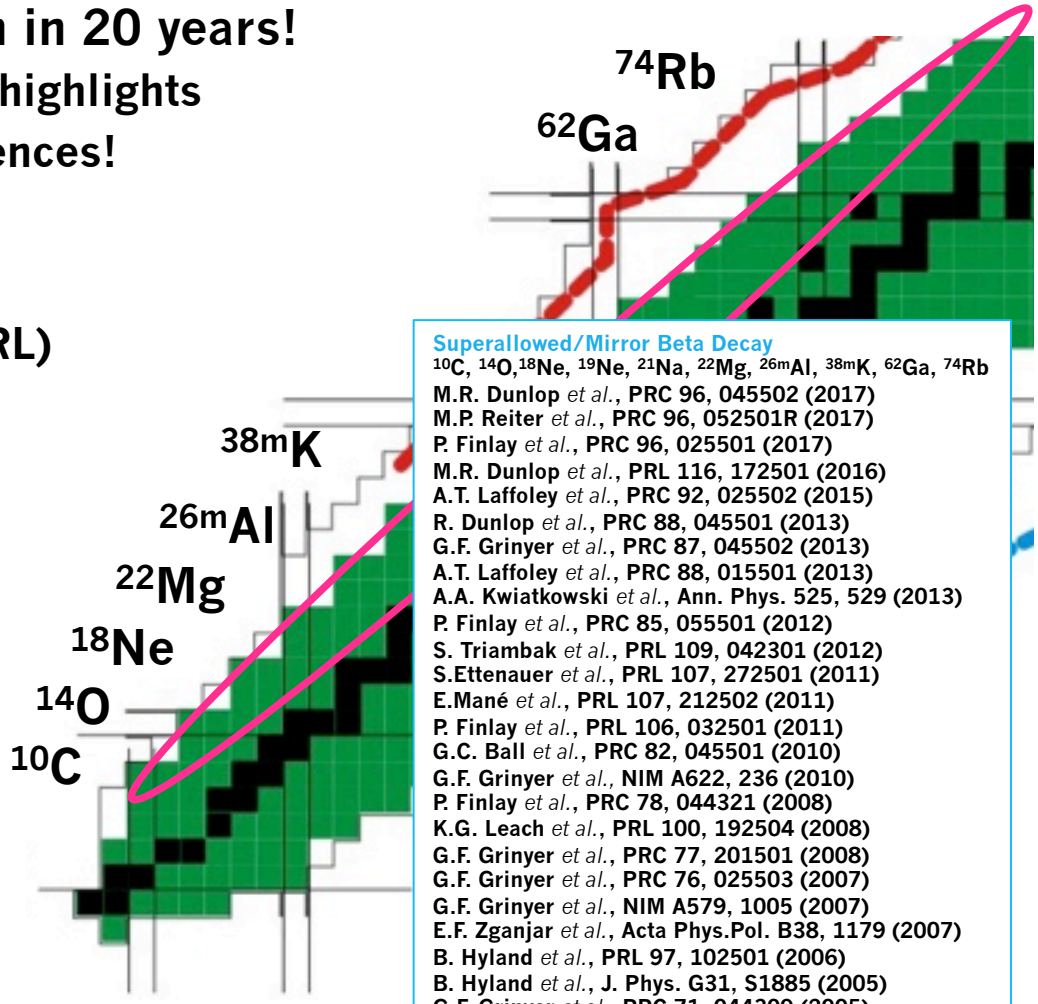
- **And lots of fond *memories***
  - **Amazing results and even more amazing people!**



Superallowed/Mirror Beta Decay
^{10}C, ^{14}O,^{18}Ne, ^{19}Ne, ^{21}Na, ^{22}Mg, ^{26m}Al, ^{38m}K, ^{62}Ga, ^{74}Rb

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Stay Tuned for More!

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