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

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Superallowed Fermi Beta Decays

- In general, β decay ft values can be expressed as:

Phase Space (Q-value)

Constants

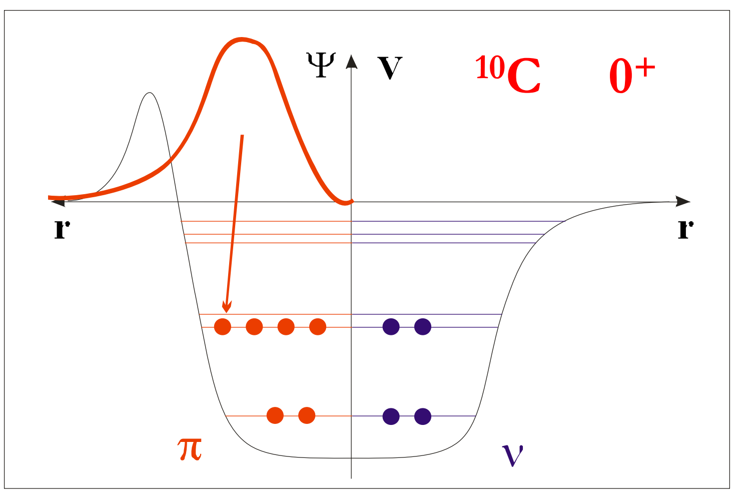
Matrix Element

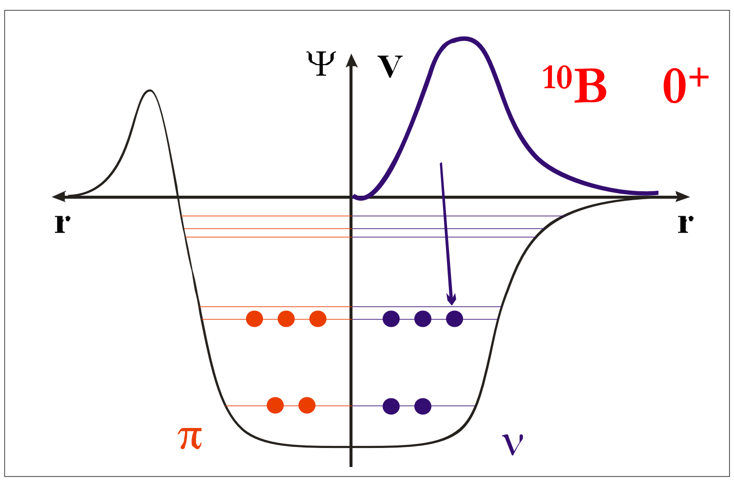
$$ft = \frac{K}{G_A^2|M_{fi}(GT)|^2 + G_V^2|M_{fi}(F)|^2}$$

$T_{1/2}$, BR

Weak Coupling Strength

- For the special case of $0^+ \longrightarrow 0^+$, we have a pure Fermi ($S_\beta = 0$) allowed ($L_\beta = 0$) transition. Transitions between *isobaric analogue states* are known as superallowed Fermi beta decays.





Testing Fundamental Properties of the Weak Interaction with Superallowed Decays

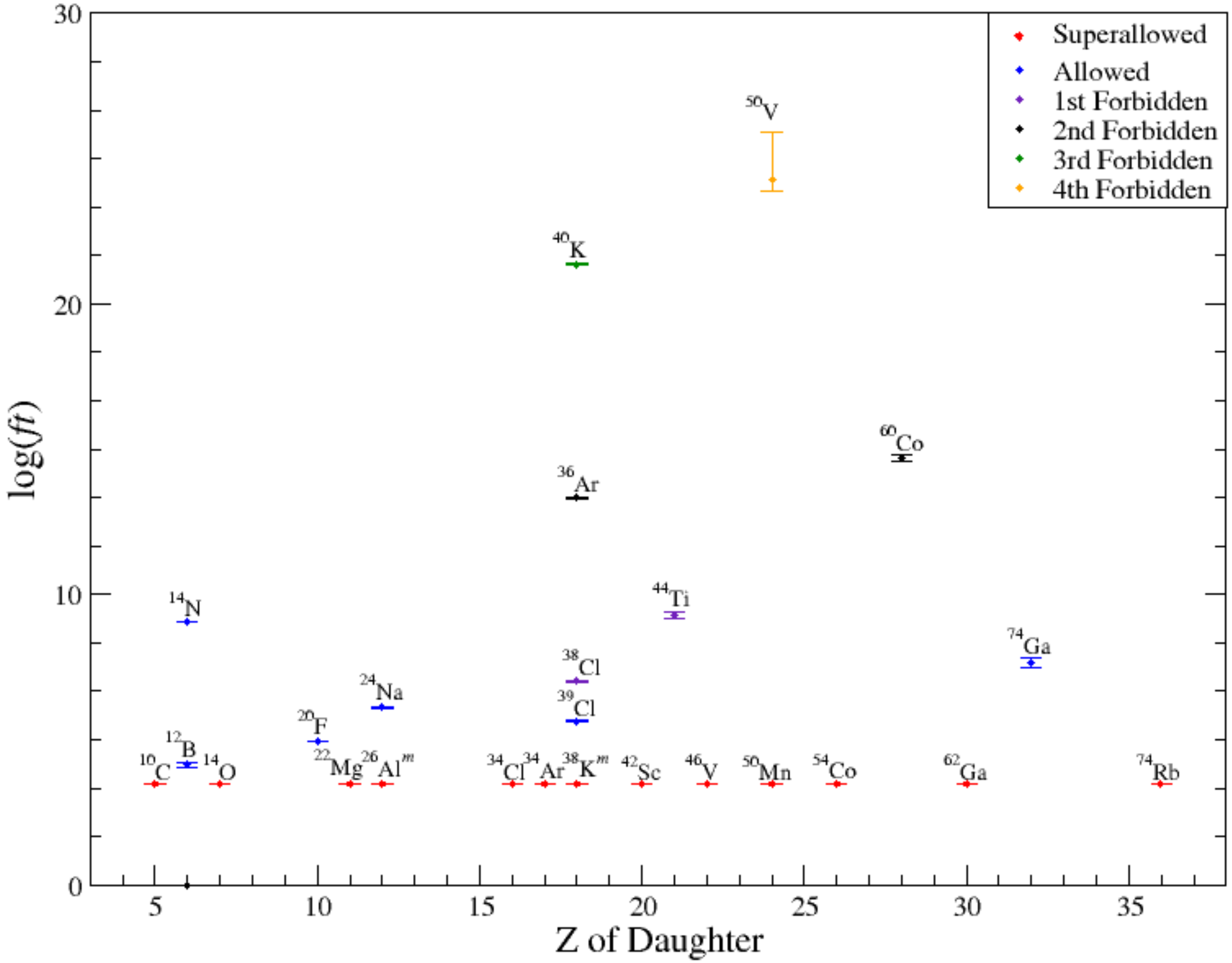
- The Fermi beta decay transition is the isospin ladder operator. For superallowed transitions between T=1 isobaric analogue states, the matrix element is simply:

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

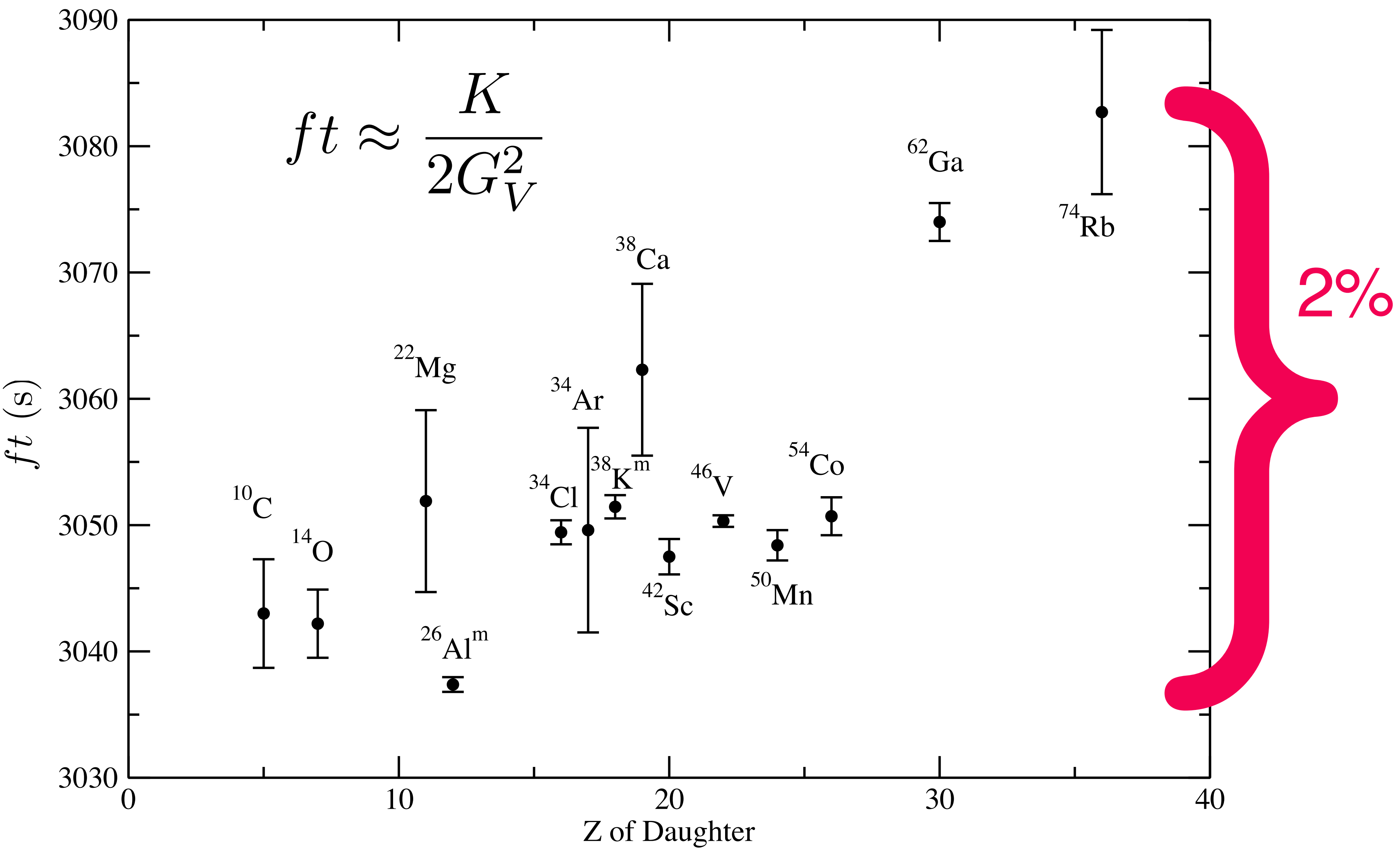
- The superallowed ft values thus simplify:

$$ft = \frac{K}{G_A^2 \underbrace{|M_{fi}(GT)|^2}_{\text{= 0 for Pure Fermi decays}} + G_V^2 \underbrace{|M_{fi}(F)|^2}_{\text{= 2 for decays between T=1 IAS}}} \Rightarrow \underbrace{\frac{K}{2G_V^2}}_{\text{constants (Conserved Vector Current hypothesis)}}$$

A Selection of Beta Decay ft Values



Superallowed ft values



Superallowed Fermi Beta Decay: Theoretical Corrections

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

"Corrected" $\mathcal{F}t$ value

Experiment
- Half-life
- Q-value
- Branching Ratio

Calculated corrections (≈1%)
(nucleus dependent)

Inner radiative correction (≈2.4%)
(nucleus independent)

CVC Hypothesis

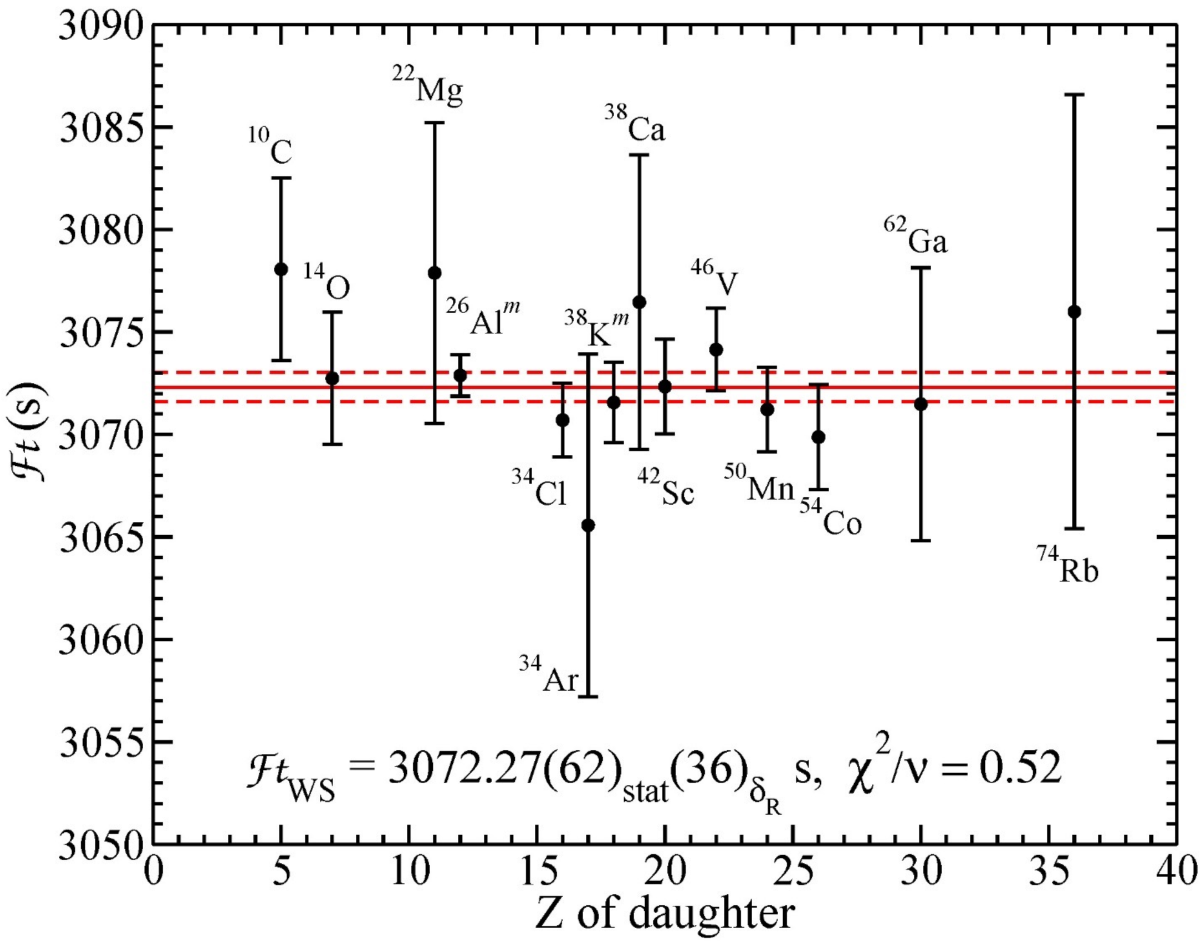
Δ_R = nucleus independent inner radiative correction: 2.361(38)%

δ_R = nucleus dependent radiative correction to order $Z^2\alpha^3$: ≈1.4%
- depends on electron's energy and *Z* of nucleus

δ_{NS} = nuclear structure dependent radiative correction: -0.3% to 0.03%

δ_C = nucleus dependent isospin-symmetry-breaking (ISB) correction: 0.2% to 1.5%
- strong nuclear structure dependence (radial overlap)

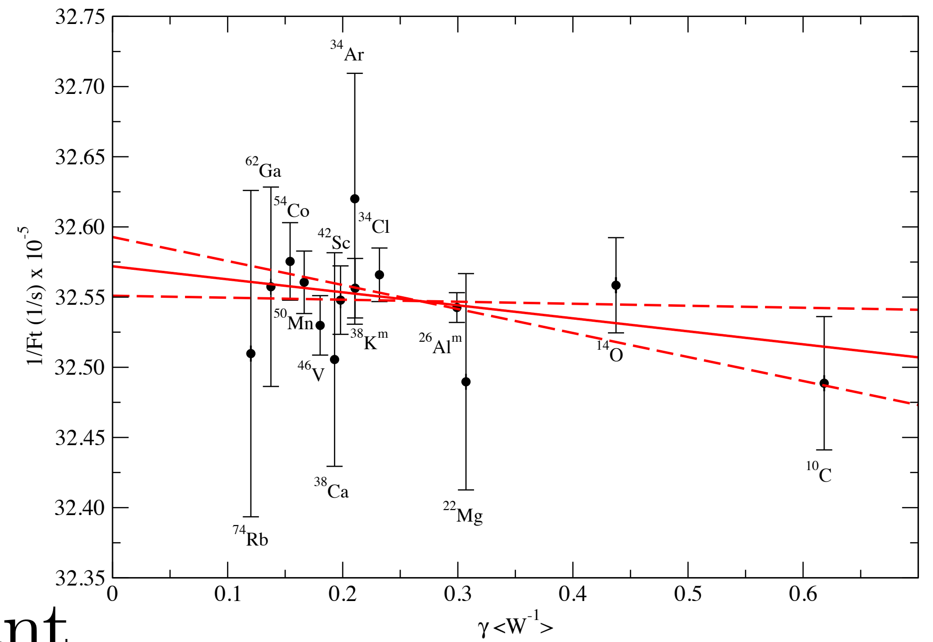
Corrected Superallowed Ft Values



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

Search for Physics Beyond the Standard Model

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



SM description

$$\mathcal{F}t = \text{constant}$$

With Scalar Interaction

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

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

$$W = \text{Total Positron Energy}$$

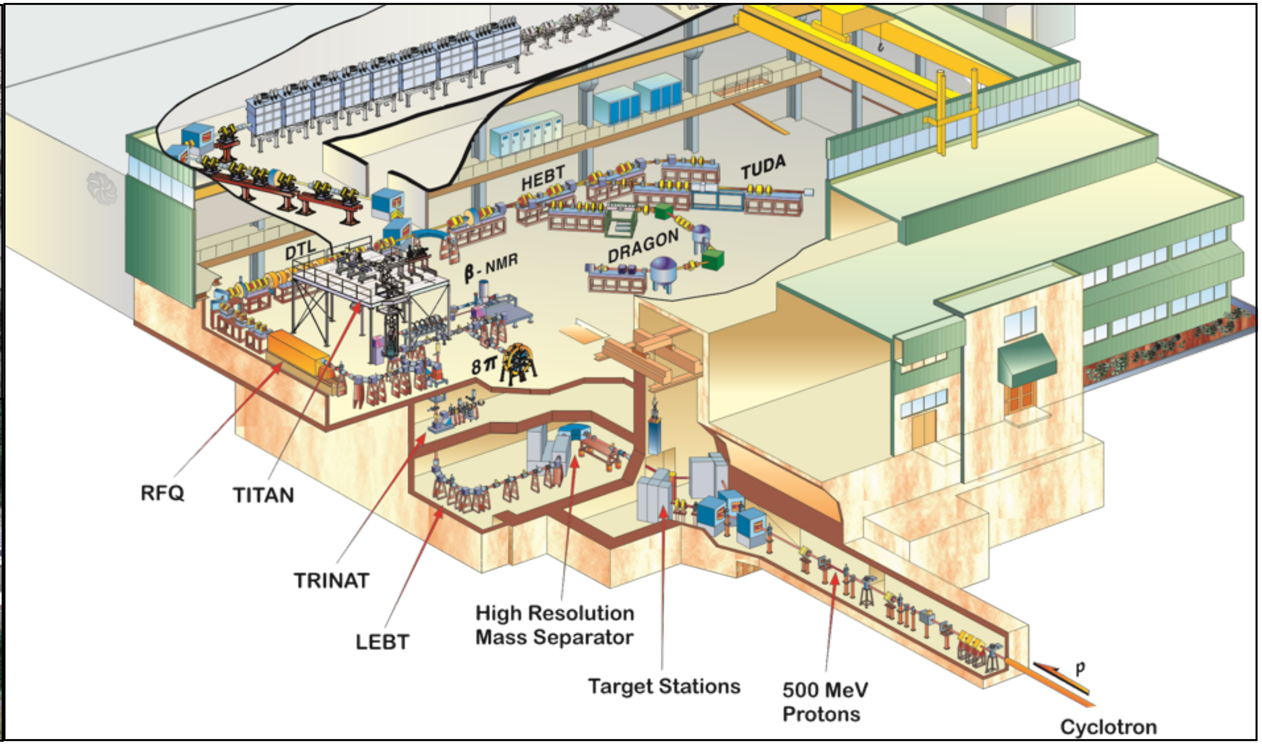
$$b_F = \text{Fierz Interference Term}$$

$$\gamma = \sqrt{1 - (\alpha Z)^2}$$

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

Limits dominated by the lightest superallowed decays ^{14}O and, in particular, ^{10}C

TRIUMF-ISAC



- Up to 100 μA, 500 MeV protons from TRIUMF's main cyclotron are accelerated onto targets which produce high-intensity secondary radioactive ion beams by the ISOL technique

$T_{1/2}$, G.C. Ball *et al.*, PRL **86**, 1454 (2001)
BR, A. Piechaczek *et al.*, PRC **67**, 051305 (2003)
<u>BR, R. Dunlop *et al.*, PRC 88, 045501 (2013)</u>
Q, S. Ettenauer *et al.*, PRL **107**, 272501 (2011)
CR, E. Mané *et al.*, PRL **107**, 212502 (2011)

$T_{1/2}$, G.F. Grinyer *et al.*, PRC **77**, 201501 (2008)
BR, B.H. Hyland *et al.*, PRL **97**, 102501 (2006)
BR, P. Finlay *et al.*, PRC **78**, 044321 (2008)
<u>BR, A. MacLean *et al.*, Analysis Ongoing</u>

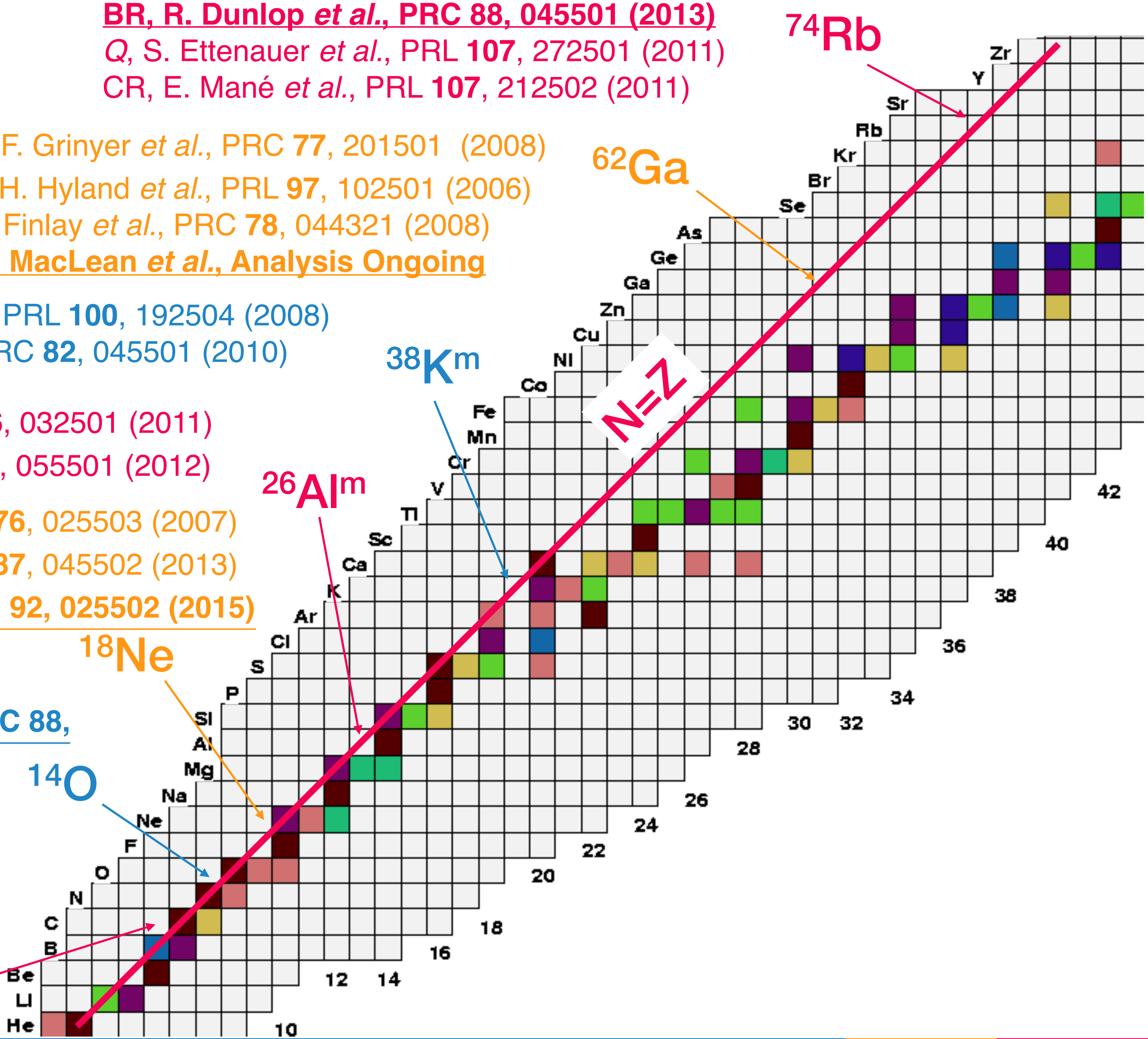
BR, K.G. Leach *et al.*, PRL **100**, 192504 (2008)
$T_{1/2}$, G.C. Ball *et al.*, PRC **82**, 045501 (2010)

$T_{1/2}$, P. Finlay *et al.*, PRL **106**, 032501 (2011)
BR, P. Finlay *et al.*, PRC **85**, 055501 (2012)

$T_{1/2}$, G.F. Grinyer *et al.*, PRC **76**, 025503 (2007)
$T_{1/2}$, G.F. Grinyer *et al.*, PRC **87**, 045502 (2013)
<u>$T_{1/2}$, A.T. Laffoley *et al.*, PRC 92, 025502 (2015)</u>

<u>$T_{1/2}$, A.T. Laffoley *et al.*, PRC 88, 015501 (2013)</u>

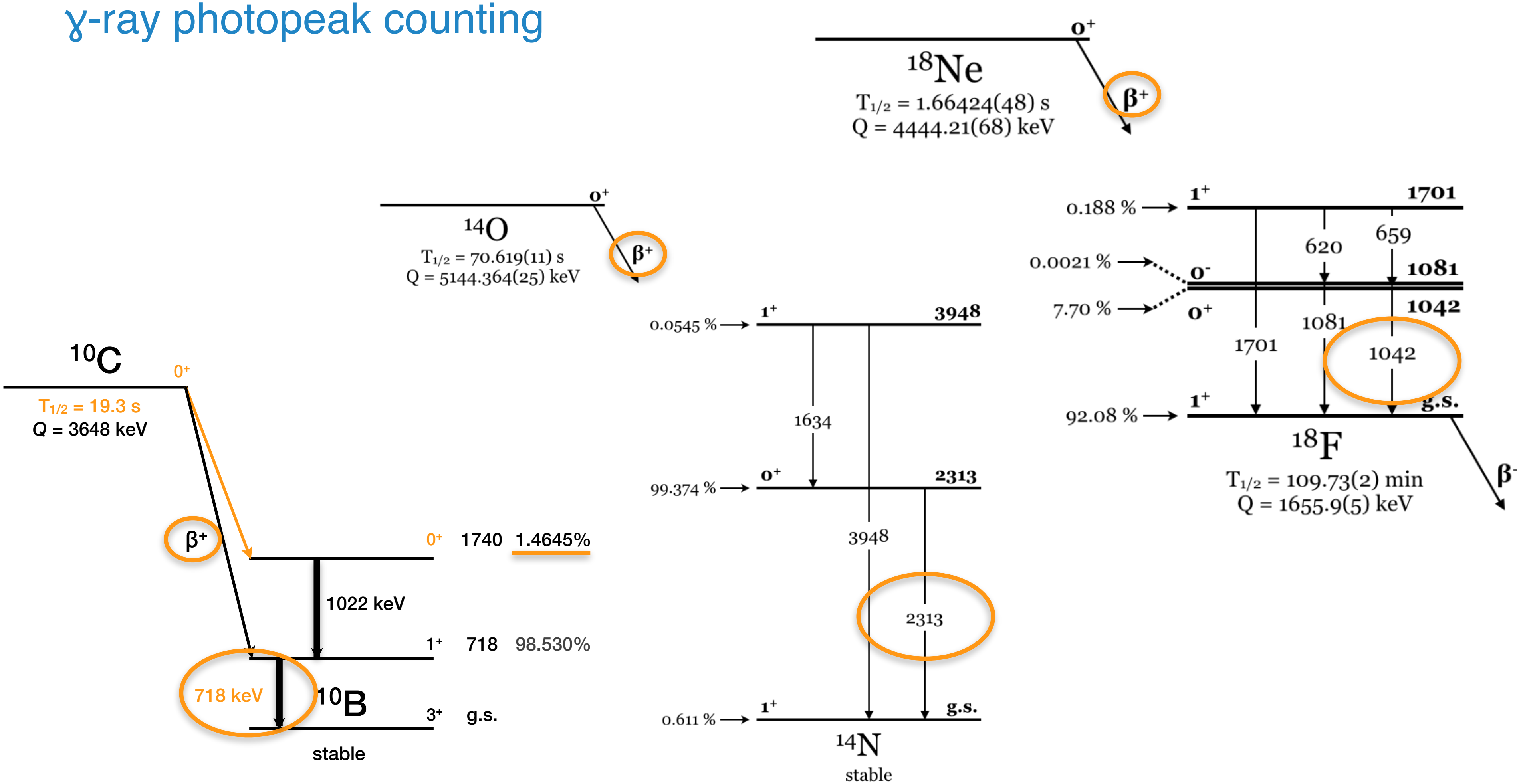
<u>$T_{1/2}$, M. R. Dunlop *et al.*, PRL 116, 172501 (2016)</u>



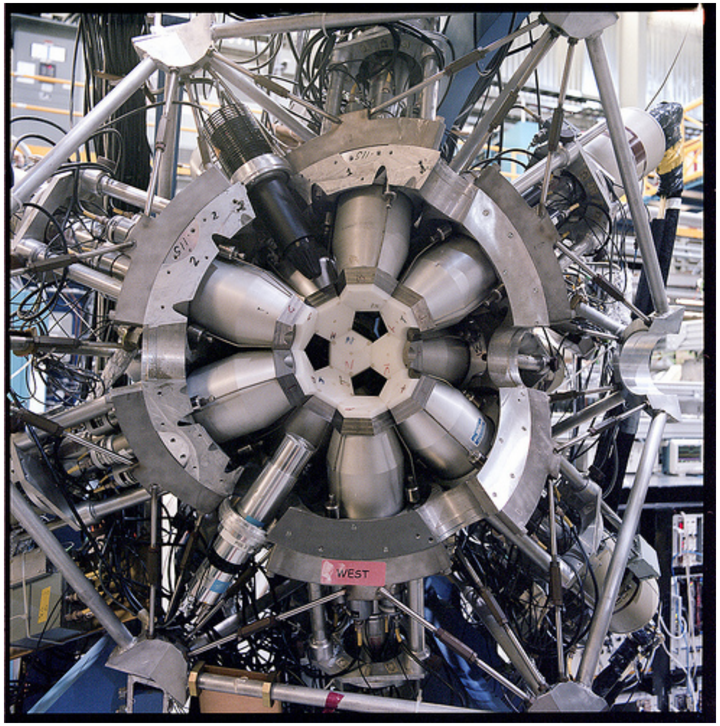
High-Precision Half-Life Measurements

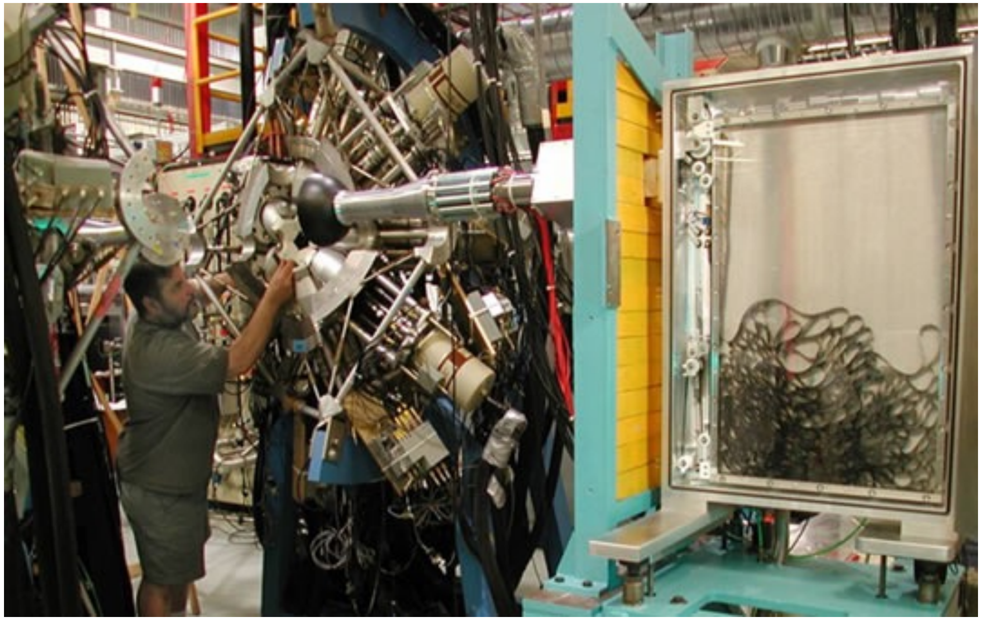
^{10}C, ^{14}O, and ^{18}Ne decay schemes

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



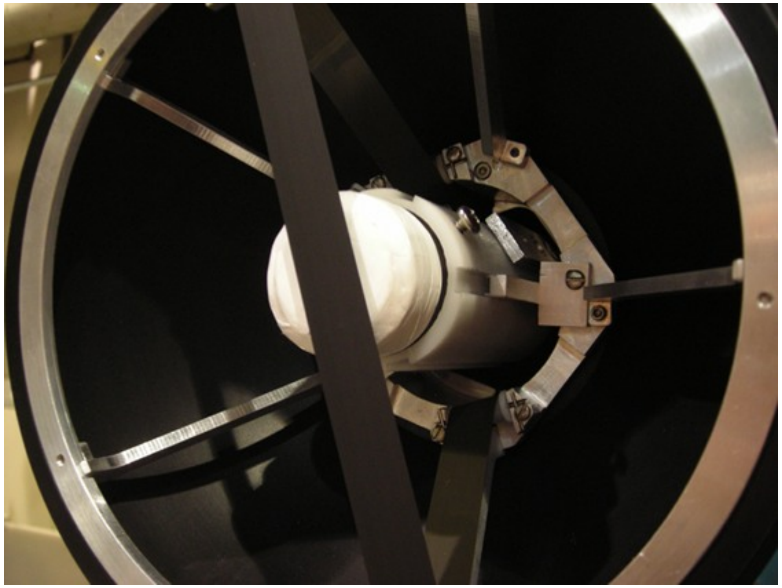
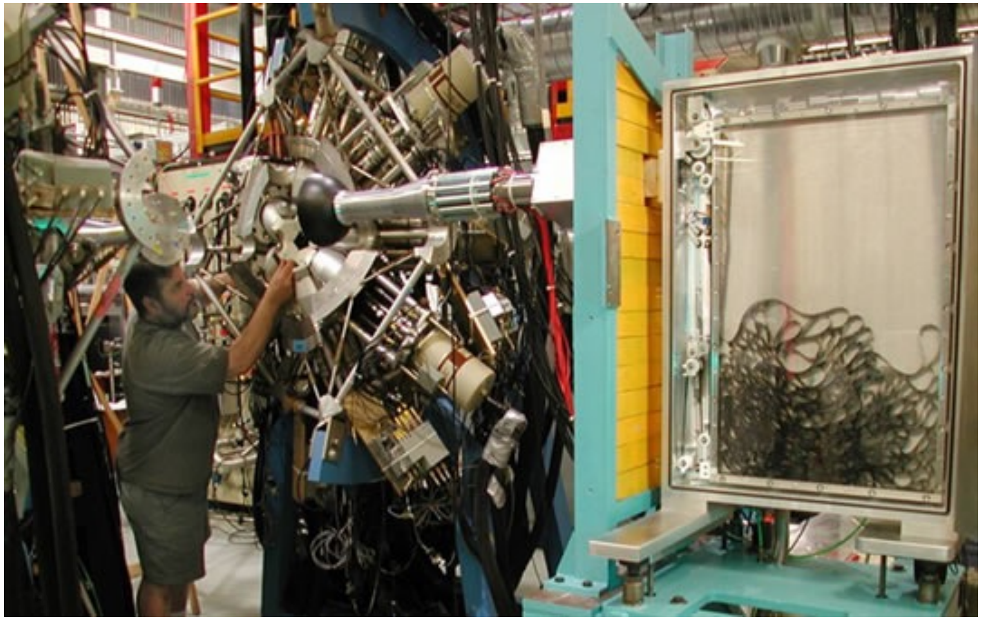
γ Counting — The 8π Spectrometer





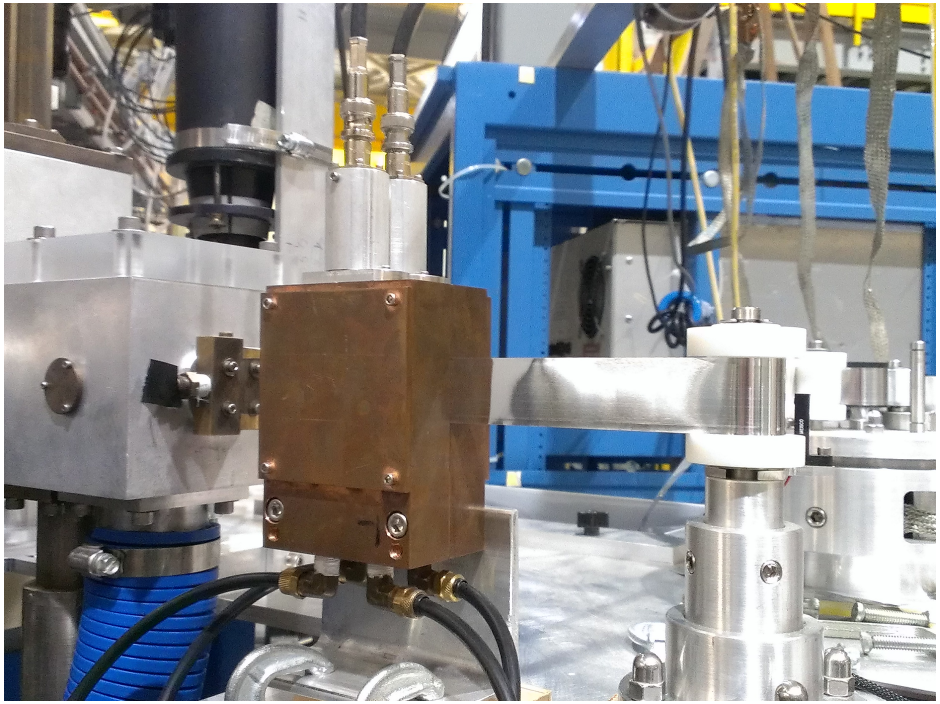
- Spherical array of 20 BGO Compton suppressed HPGe detectors
- ~1% photopeak efficiency at 1.3 MeV

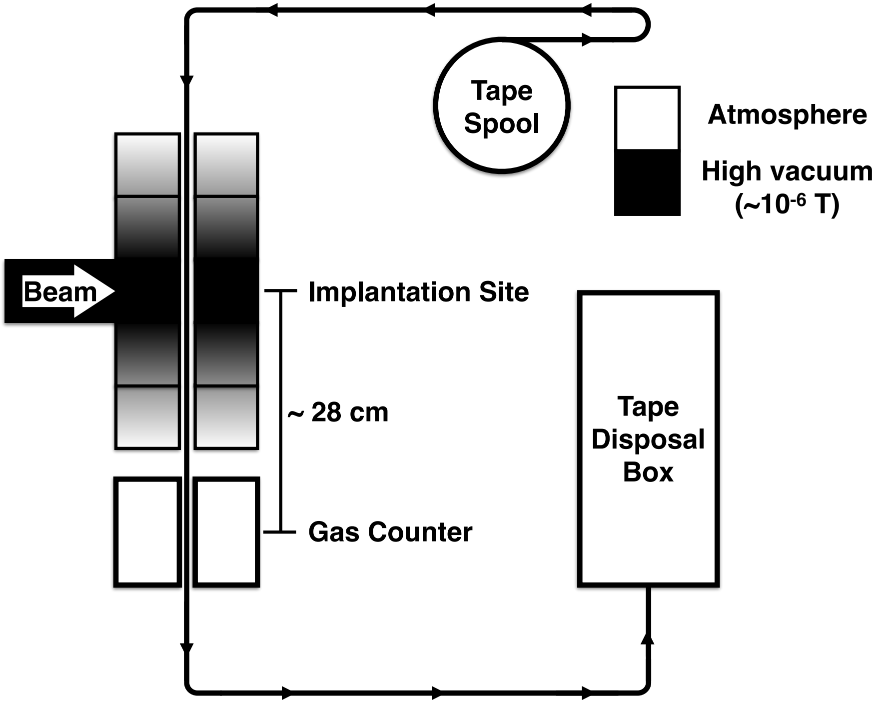
β Counting — Zero Degree Scintillator (ZDS)

- The 8π spectrometer can be used in combination with several auxiliary detectors, one of which is the ZDS
- Fast plastic scintillator, ~20% solid angle coverage
- Cycles: Beam is implanted onto a tape at the centre of the array. The decay activity is measured for many half-lives. The tape is then moved into disposal box which is shielded by a lead wall in order to remove any long lived contaminants out of view of the detector

β Counting — 4π gas counter

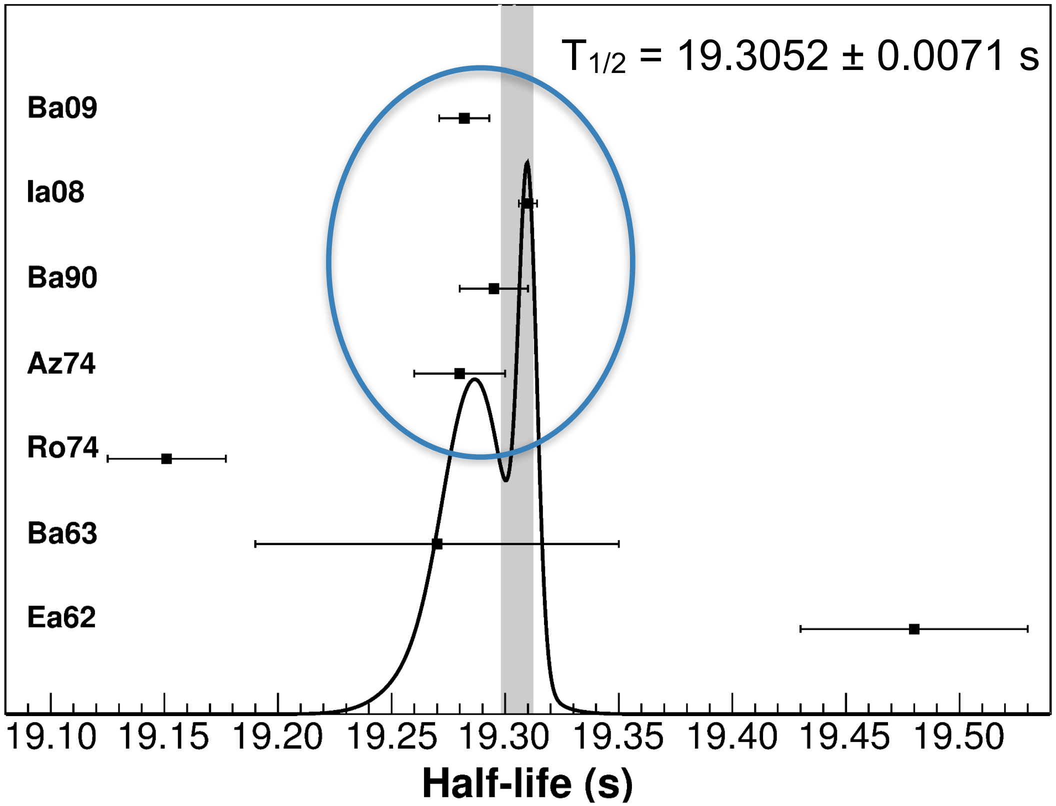




- 4π continuous-flow proportional gas counter with tape transfer system
- Directly detects β particles with ~100% efficiency
- Cycles: Implant beam, move into gas counter and measure the decay activity for many half-lives. Move tape into tape disposal box to remove long-lived contaminants from the gas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

The ^{10}C half-life

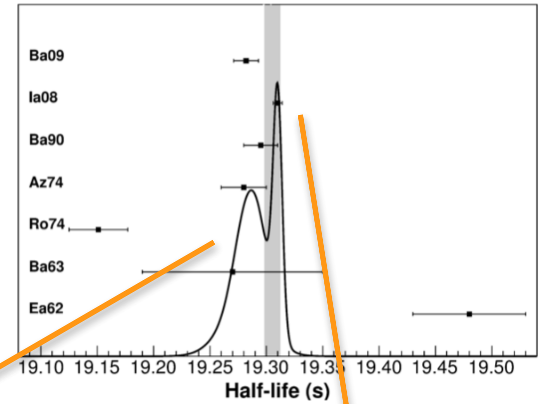
- The adopted ^{10}C half-life is evaluated using the 4 most precise measurements.
- The inconsistencies in the dataset result in a highly inflated uncertainty on the adopted world average half-life.

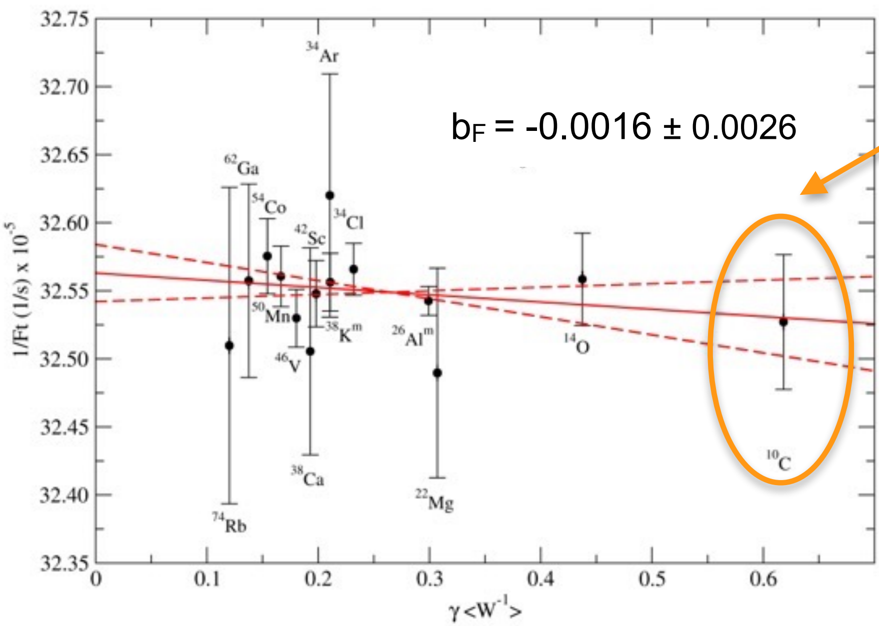


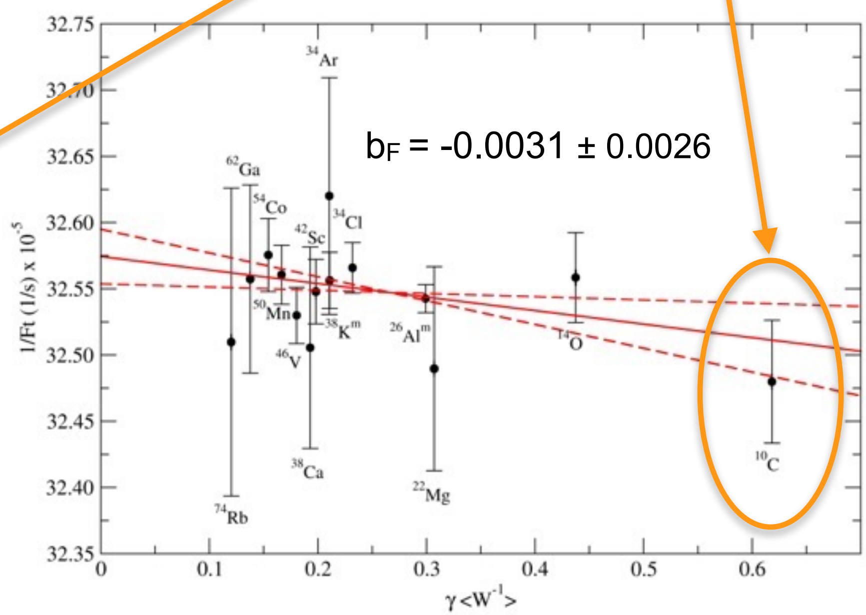
J. C. Hardy and I. S. Towner, Phys. Rev. C **91**, 025501 (2015)

The ^{10}C half-life

- More than 200 individual superallowed measurements of comparable precision are currently used to set the limit on b_F.
- If the half-life from either of the two peaks in the ideograph is adopted, the central value of b_F is shifted by more than 0.5σ.

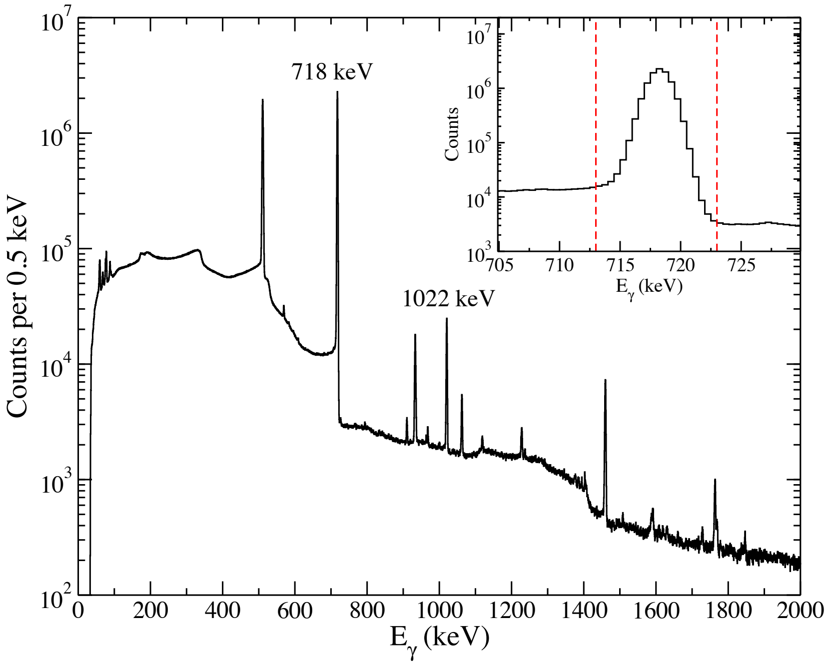






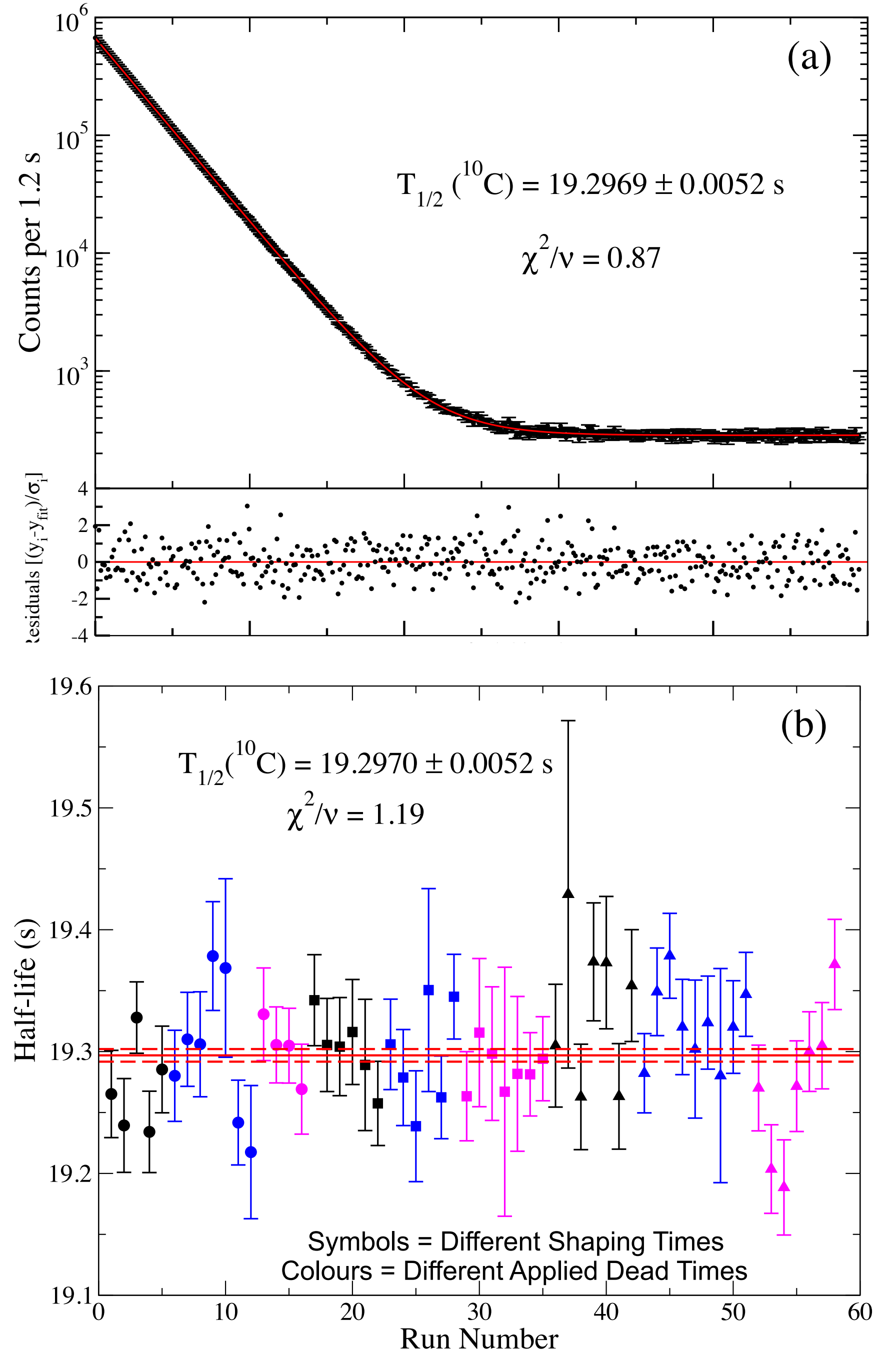
- An accurate and precise determination of the ^{10}C half-life is thus critical to the limits set of b_F set by the superallowed data.

γ Photopeak Counting

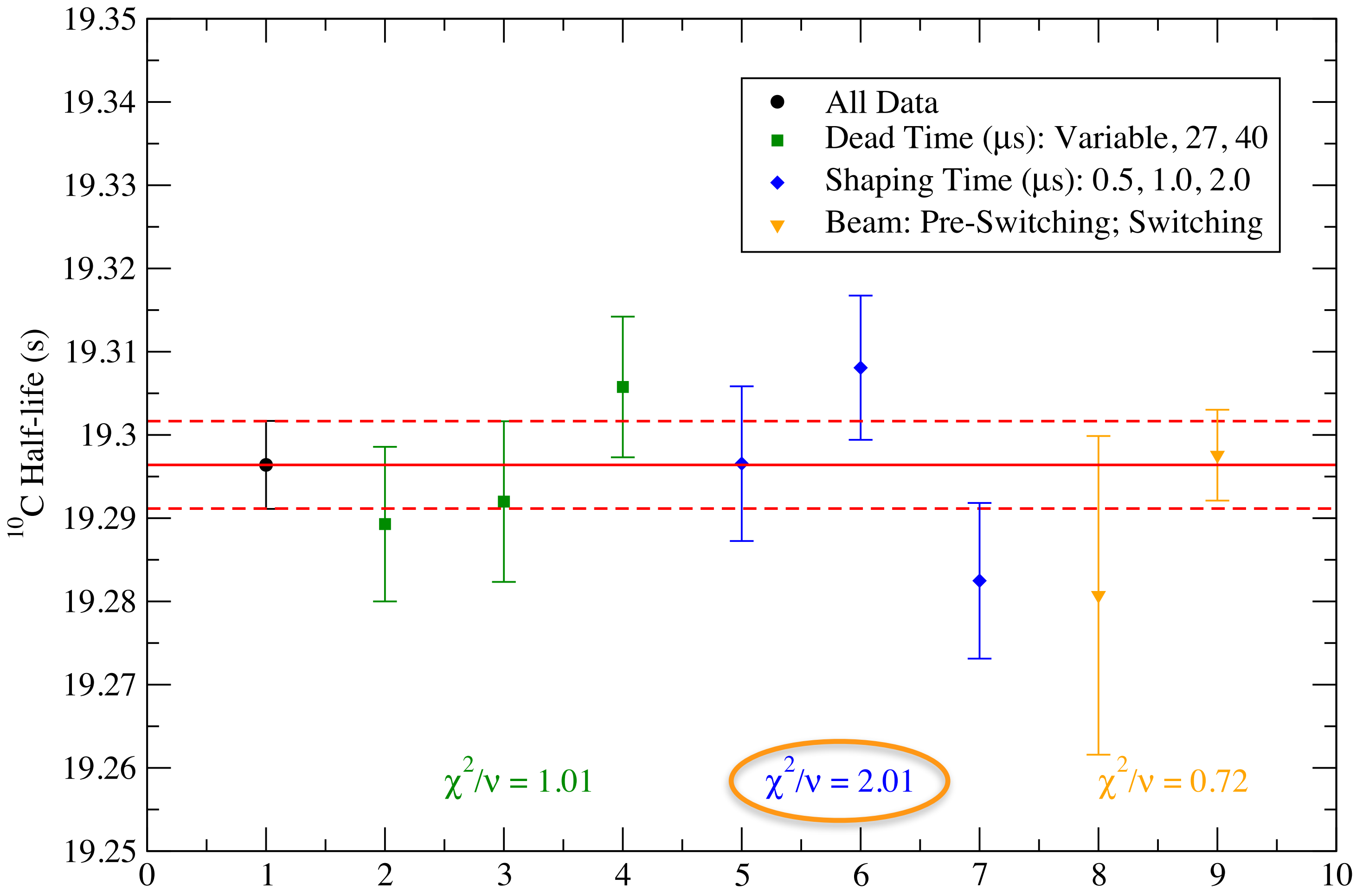


A total of 58 runs were taken, comprised of 562 cycles.

The dead-time and pile-up corrected data are summed and a single fit to the data is performed.



γ Photopeak Counting — Systematics



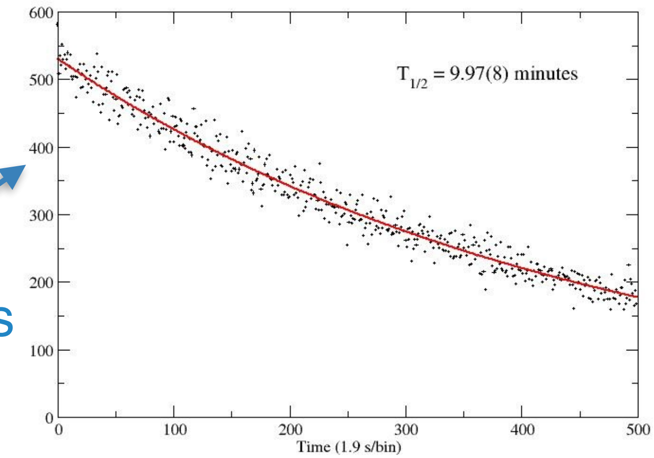
$T_{1/2,\gamma}(^{10}C) = 19.2969 \pm 0.0052_{sys} \pm 0.0052_{stat} = \underline{19.2969 \pm 0.0074\ s}$

Relative precision of 0.03%

β Counting

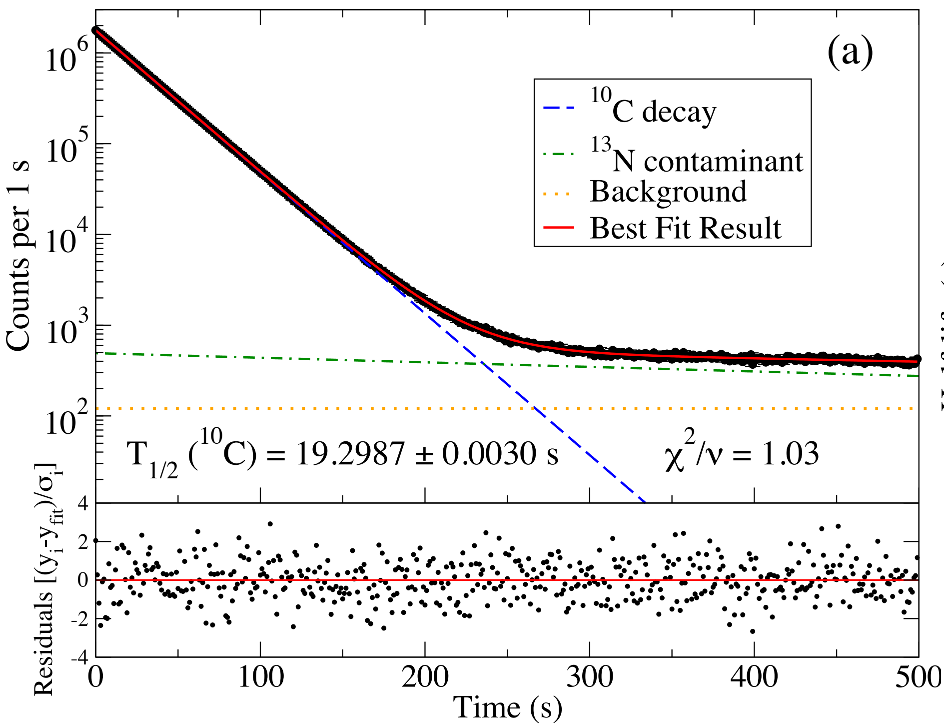
A=10 Beam:
^{10}C: $T_{1/2} = 19.3$ s

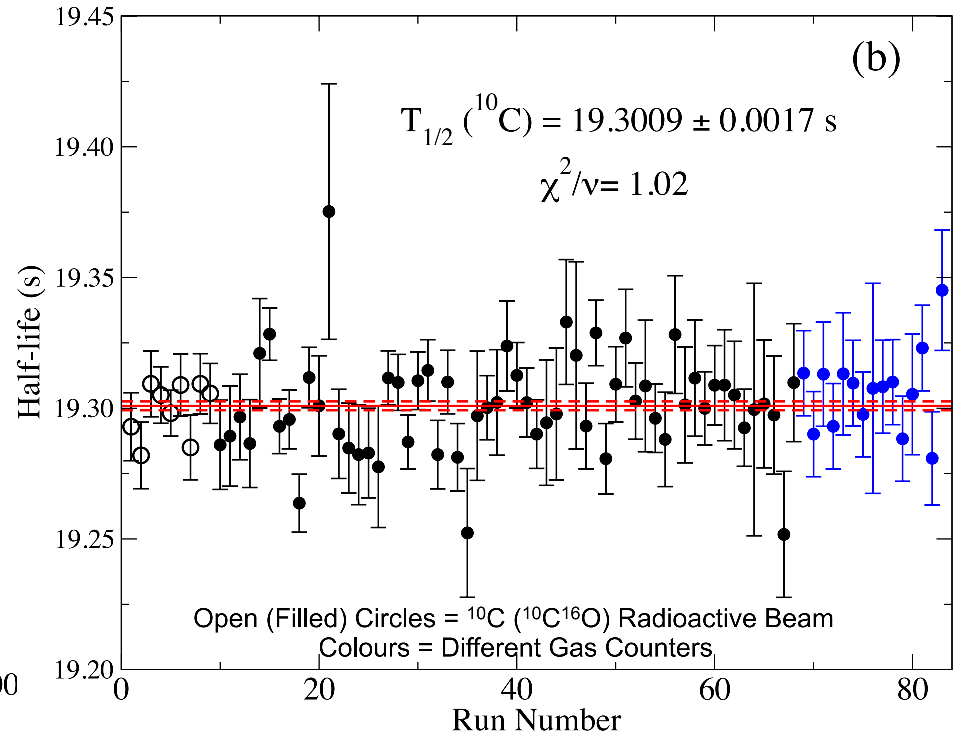
A=26 Beam:
$^{10}C^{16}O$: $T_{1/2} = 19.3$ s
^{13}N: $T_{1/2} = 598$ s



Contaminant, with $T_{1/2}$ consistent with that of ^{13}N, was measured in the A=26 beam. Could be delivered as:

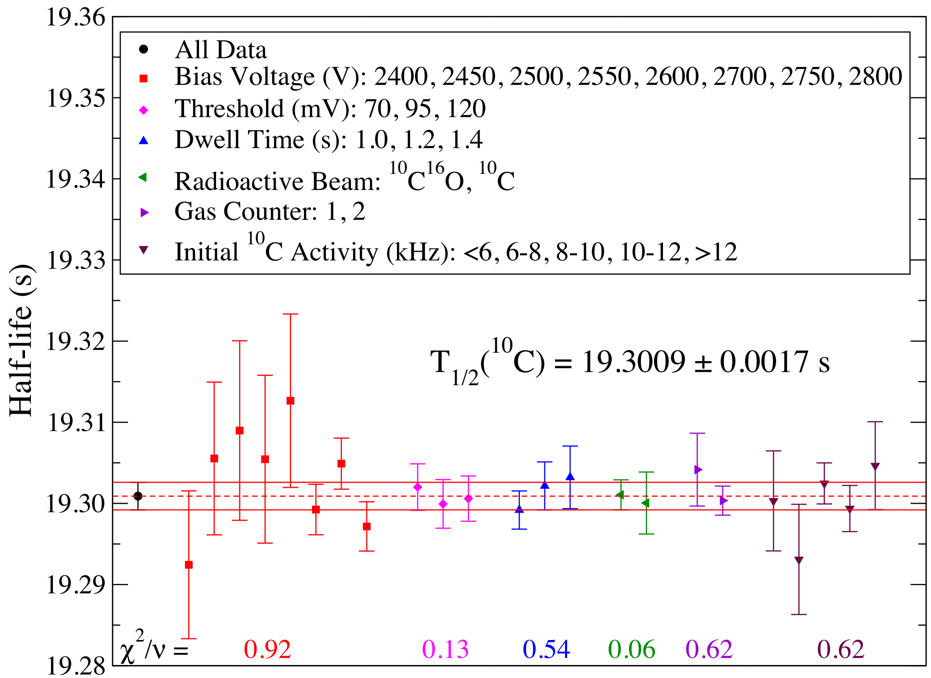
- $^{13}N_2$ (mass diff. to $^{10}C^{16}O$ ~10 ppm)
- $HC^{13}N$ (mass diff. ~70 ppm), etc…

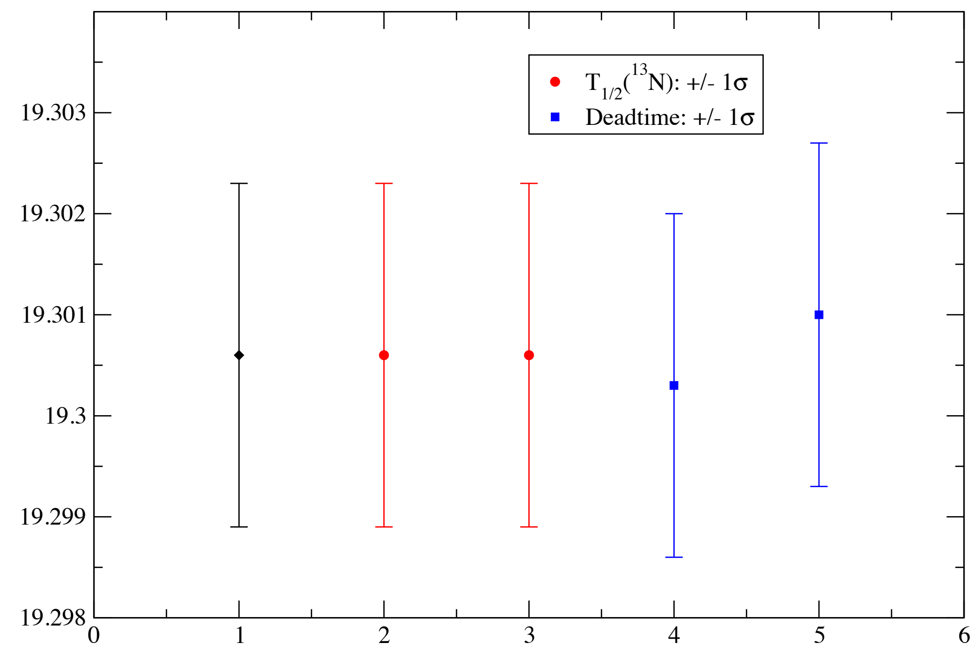




β Counting — Systematics

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

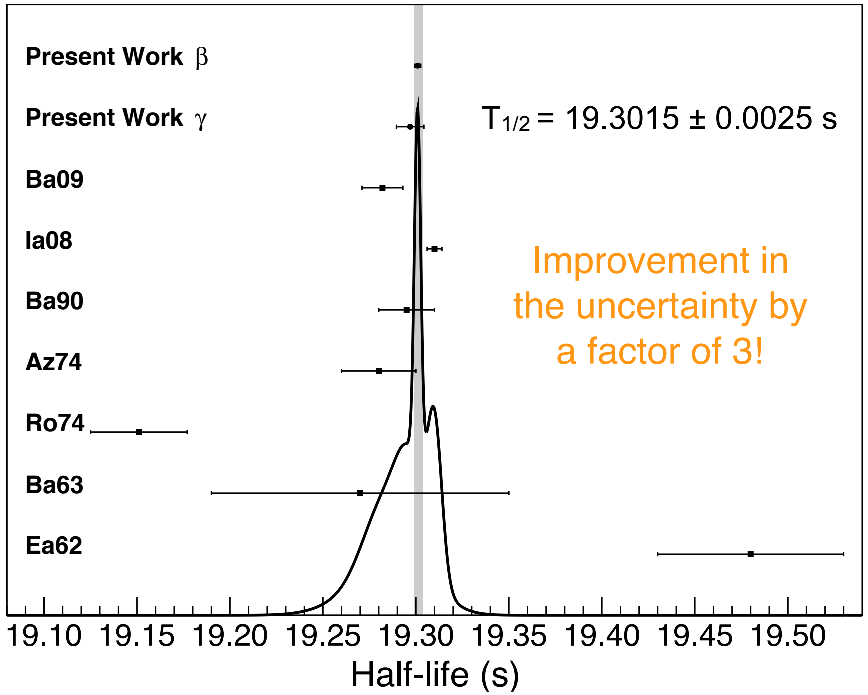


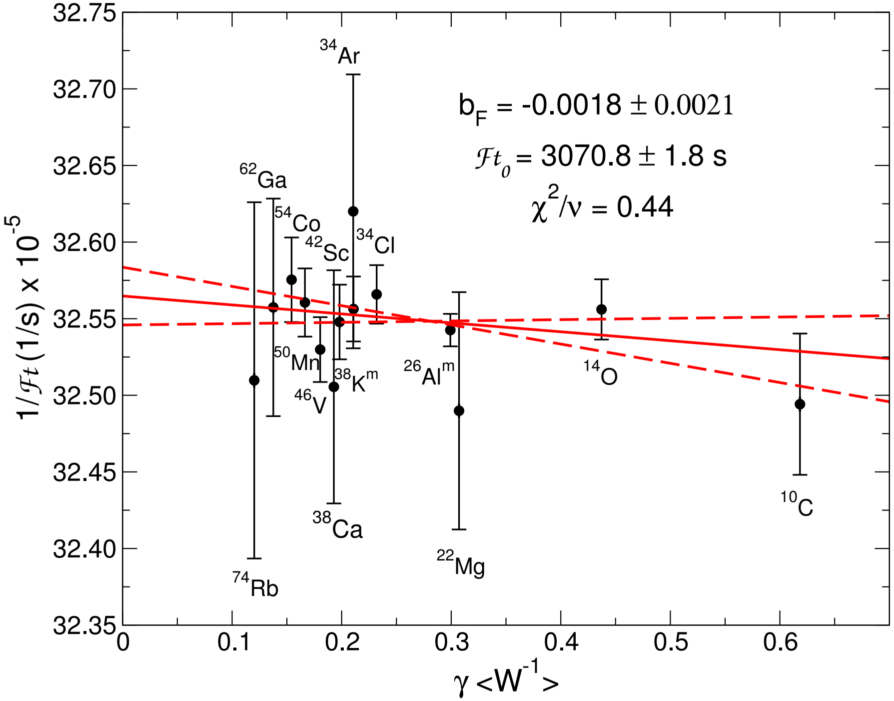


$T_{1/2,\beta}(^{10}C) = 19.3009 \pm 0.0017$ s

The most precise (0.009%) superallowed $T_{1/2}$ reported to date!

Results — ^{10}C Half-life





- Updated ^{10}C half-life
- Updated ^{14}O Q-value (A. A. Valverde *et al.*, Phys. Rev. Lett. 114, 232502 (2015))
- Updated ^{14}O branching ratio (P. A. Voytas *et al.* Phys. Rev. C 92, 065502 (2015))

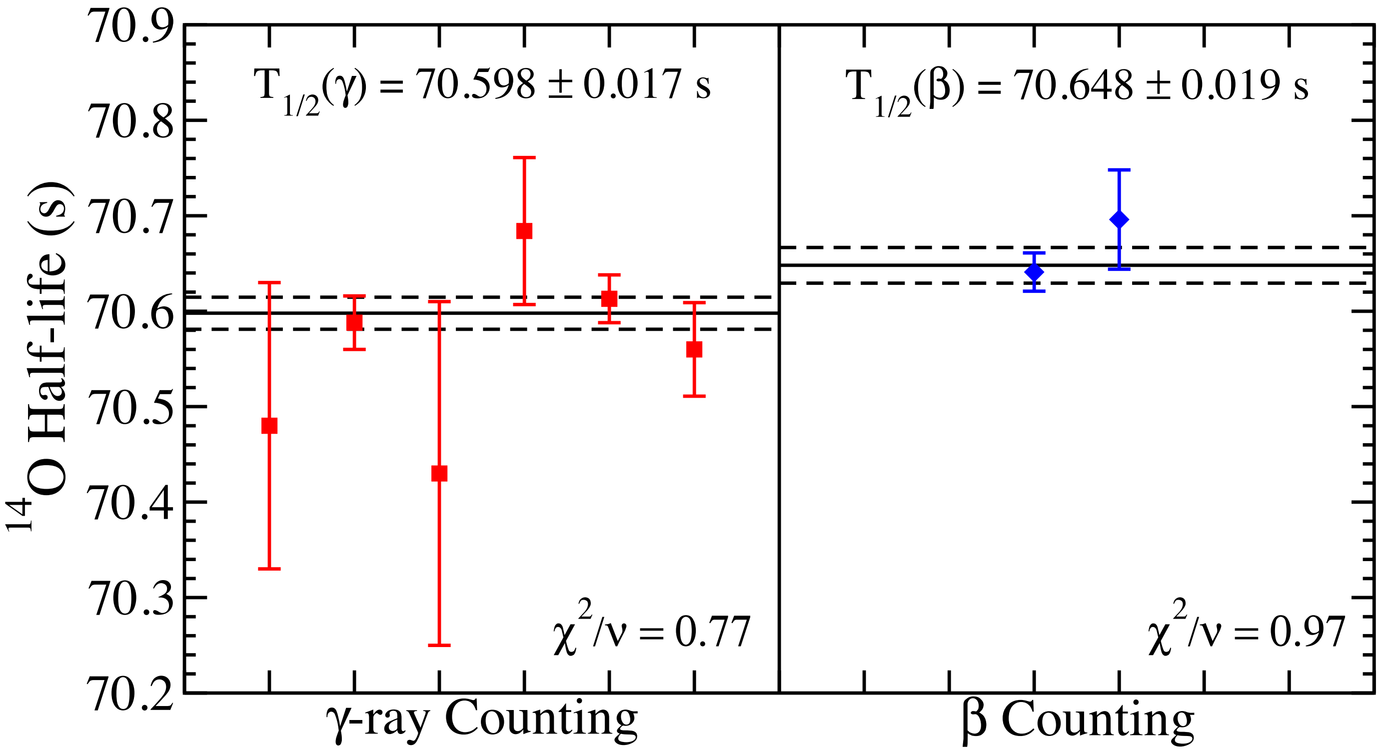
$b_F = -0.0018(21)$

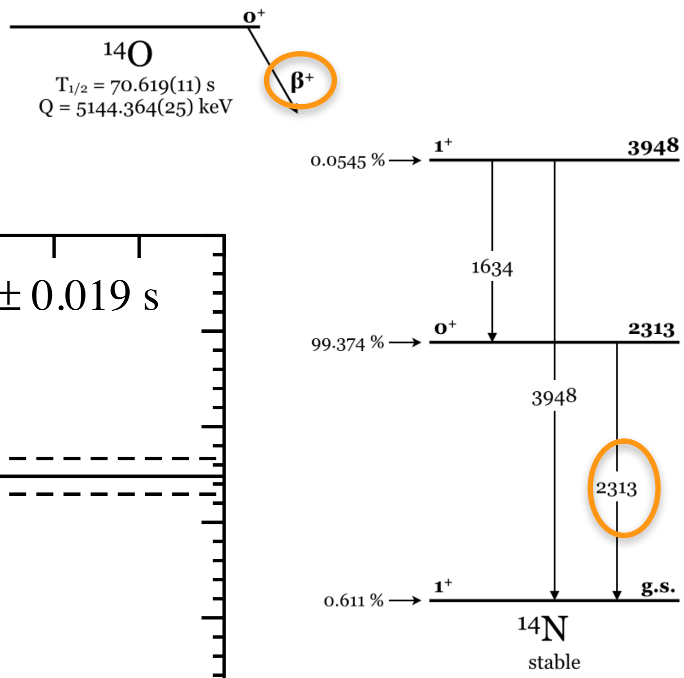
and

$C_S/C_V = -b_F/2 = 0.0009(11)$

M. R. Dunlop *et al.*, Phys. Rev. Lett. **116**, 172501 (2016)

^{14}O Half-life Measurements

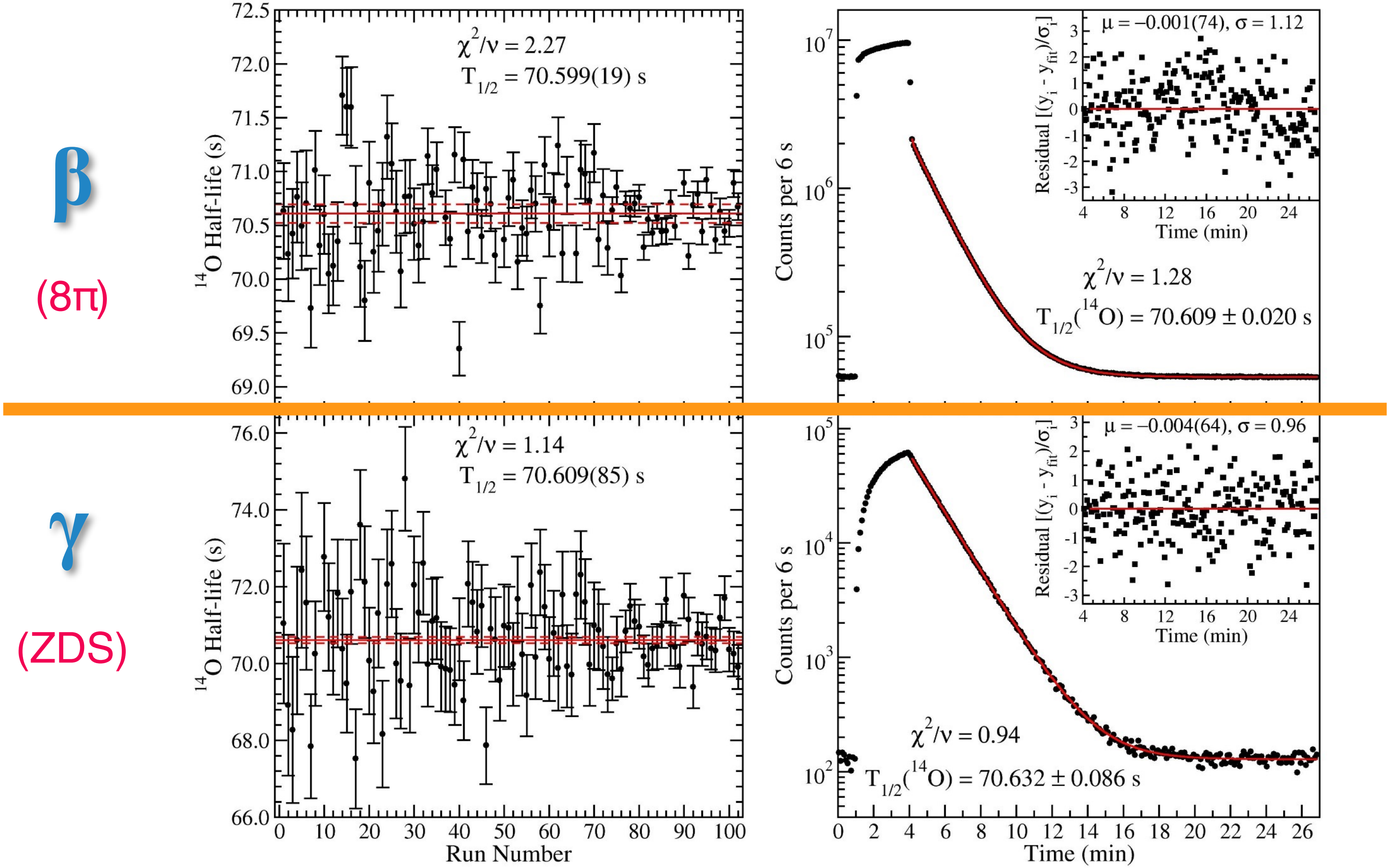




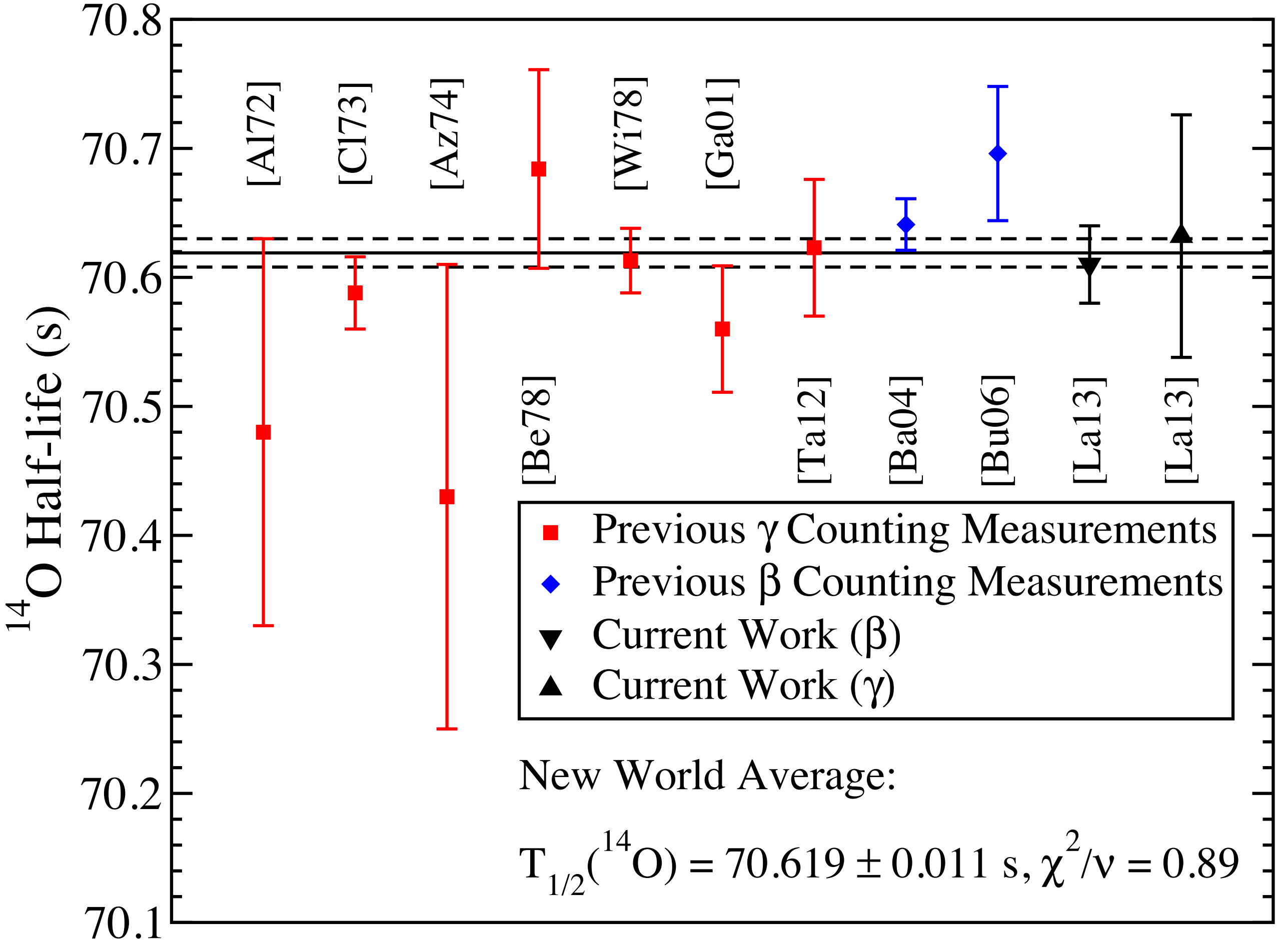
Grouping the previous ^{14}O half-life measurements based on detection method (direct β counting or detecting the 2313 keV γ-ray) yields half-lives that disagree at the 2σ level.

^{14}O Half-life Measurements

Beam:
$^{12}C^{14}O$: $T_{1/2} = 70.620$ s
$^{26}Al^{m}$: $T_{1/2} = 6.3465$ s
^{26}Na: $T_{1/2} = 1.072$ s



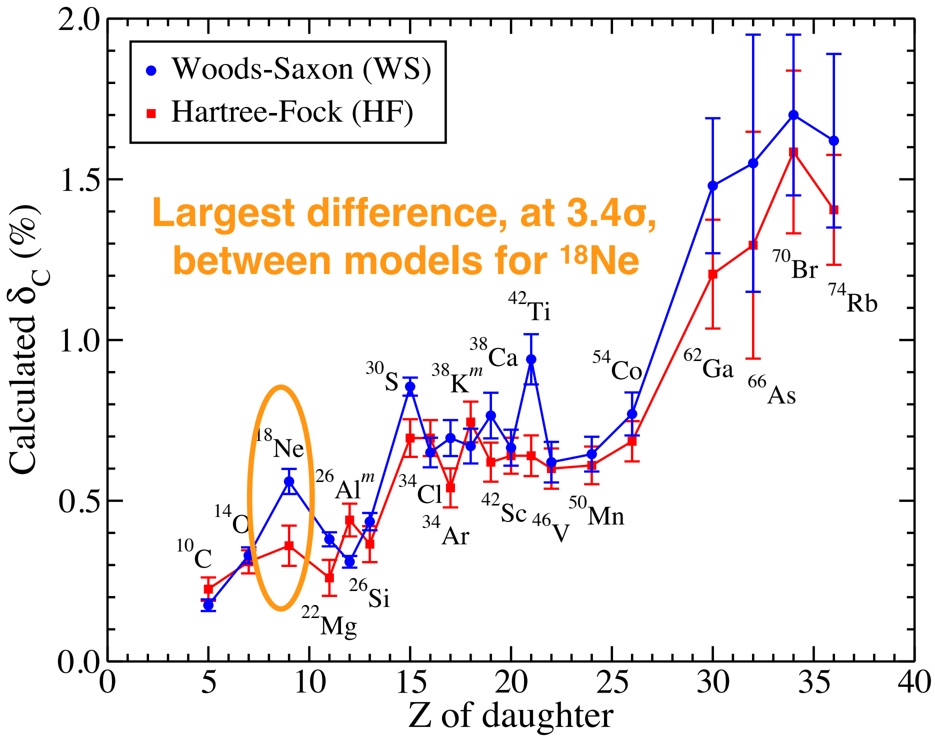
^{14}O Half-life Measurements



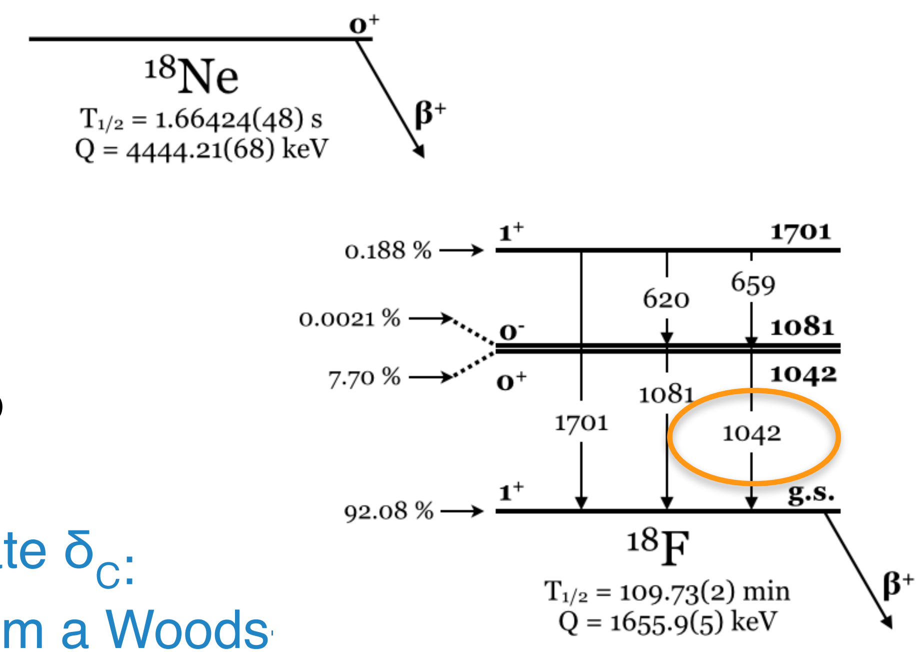
A.T. Laffoley *et al.*, PRC **88**, 015501 (2013)

- The half-life measurements for ^{14}O now form a consistent data set.
- A more precise measurement is still desired and can be performed at ISAC using the 4π gas counter.

^{18}Ne Half-life Measurements



J. C. Hardy and I. S. Towner, Phys. Rev. C **91**, 025501 (2015)
J. C. Hardy and I. S. Towner, Phys. Rev. C **79**, 055502 (2009)

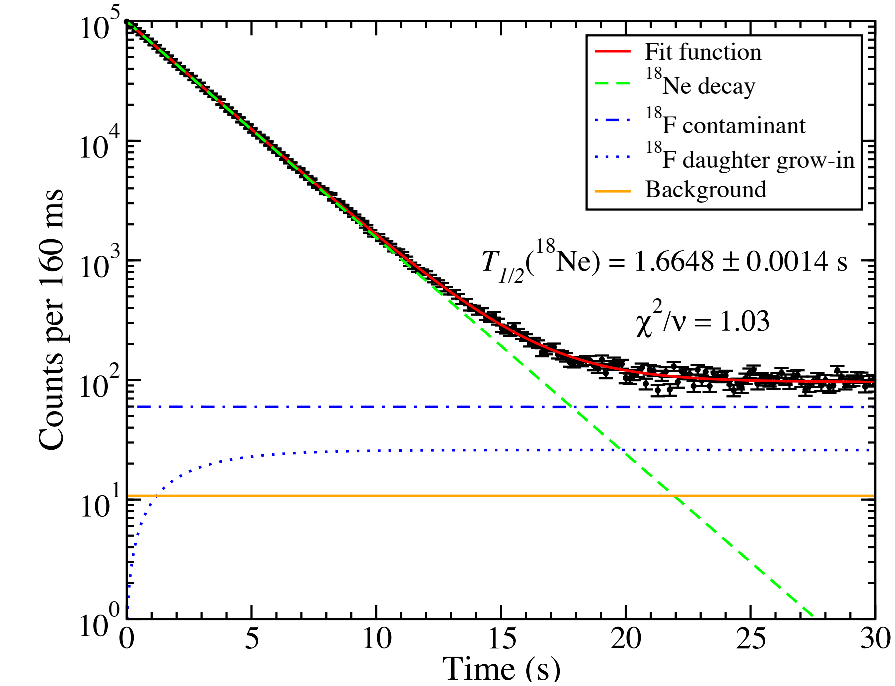


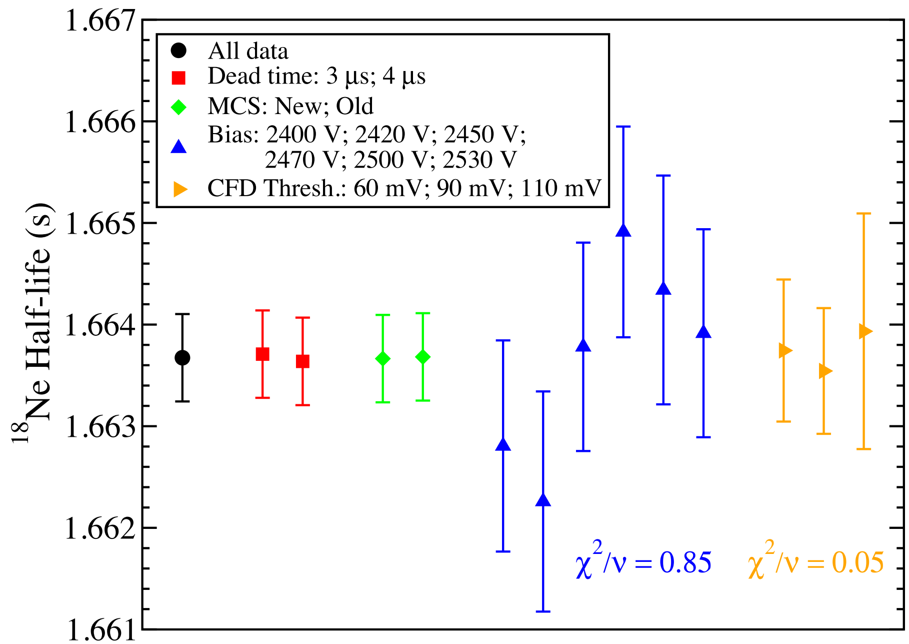
Two Shell Model approaches to calculate δ_C:

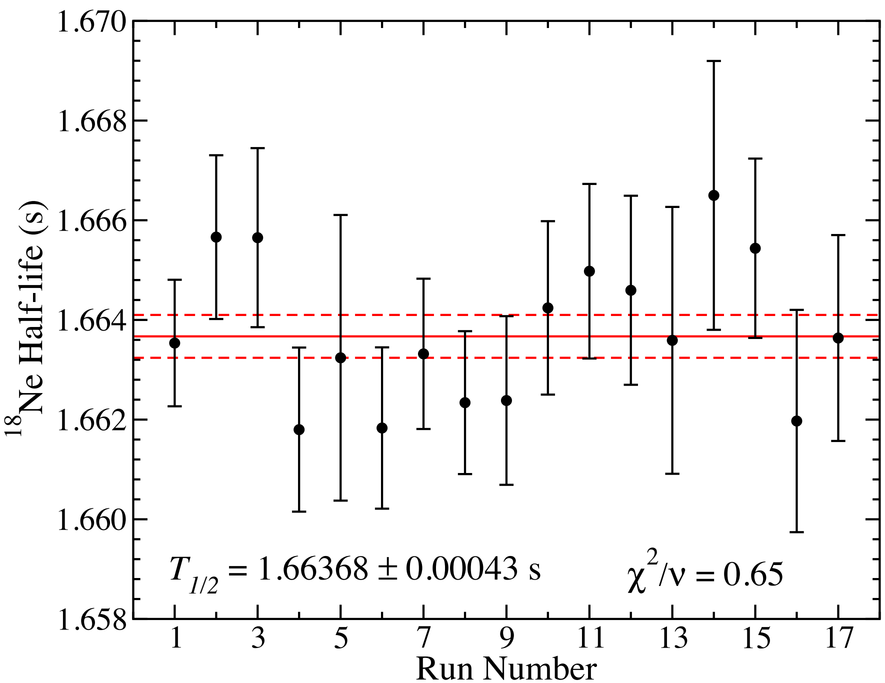
- Use radial wave functions derived from a Woods-Saxon (WS) potential,
- Use self-consistent Hartree-Fock (HF) eigenfunctions.

Can use experimentally determined Ft values to constrain δ_C

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

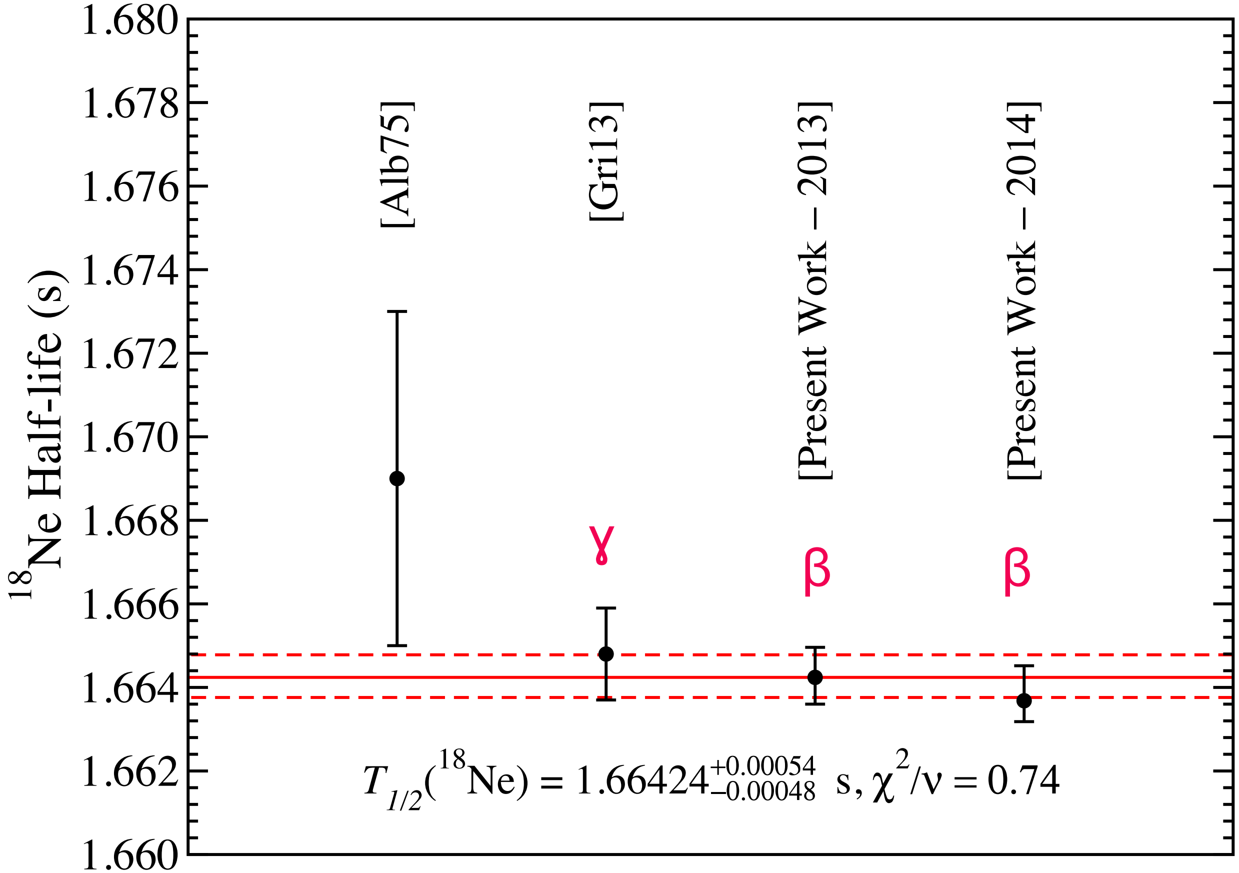






Cycle:
0.5–2 s implant
2.3–3.9 s cooling/tape move
40 s decay counting

^{18}Ne Half-life Measurements

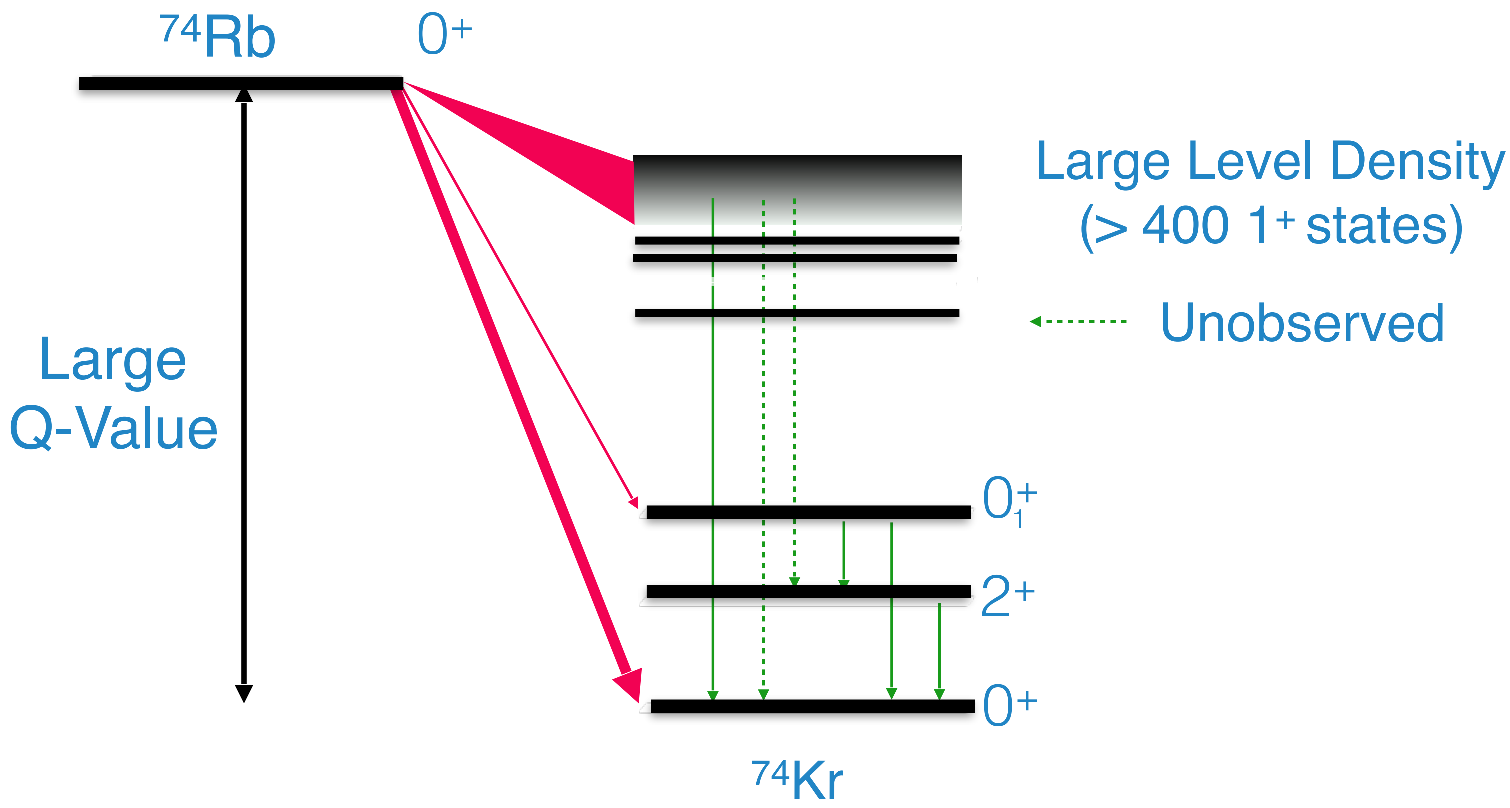


G. F. Grinyer *et al.*, Phys. Rev. C **87**, 045502 (2013)
A.T. Laffoley *et al.*, PRC **92**, 025502 (2015)

- Half-life measured to 0.03%, world average improved by a factor of 2
- The half-life has now been determined to the level needed for the ft high-precision cases. An improvement in the branching ratio in needed order to include the ^{18}Ne ft value among the high-precision cases.

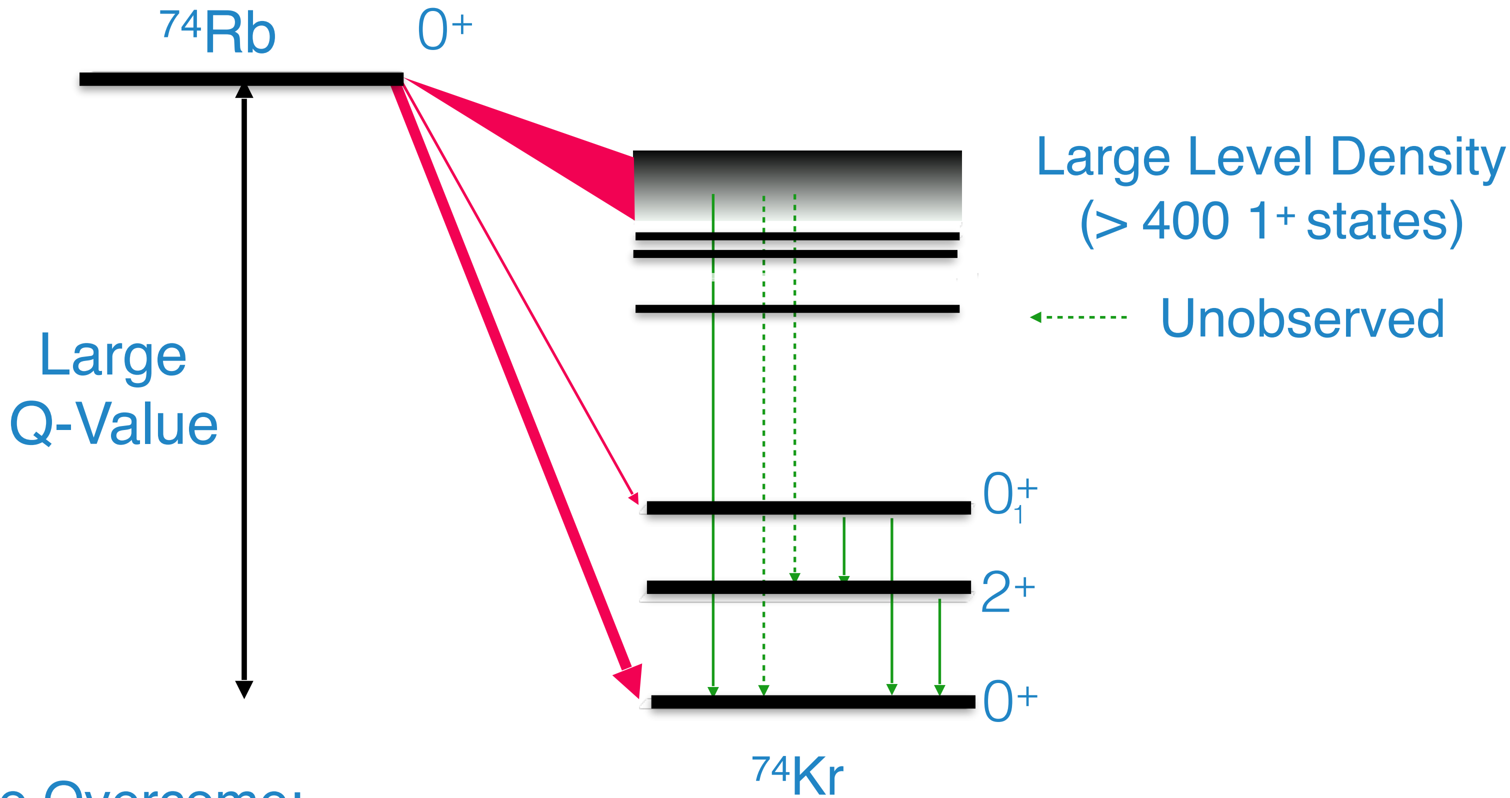
High-Precision Branching Ratio Measurements

A ≥ 62 Superallowed Decays: Pandemonium



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

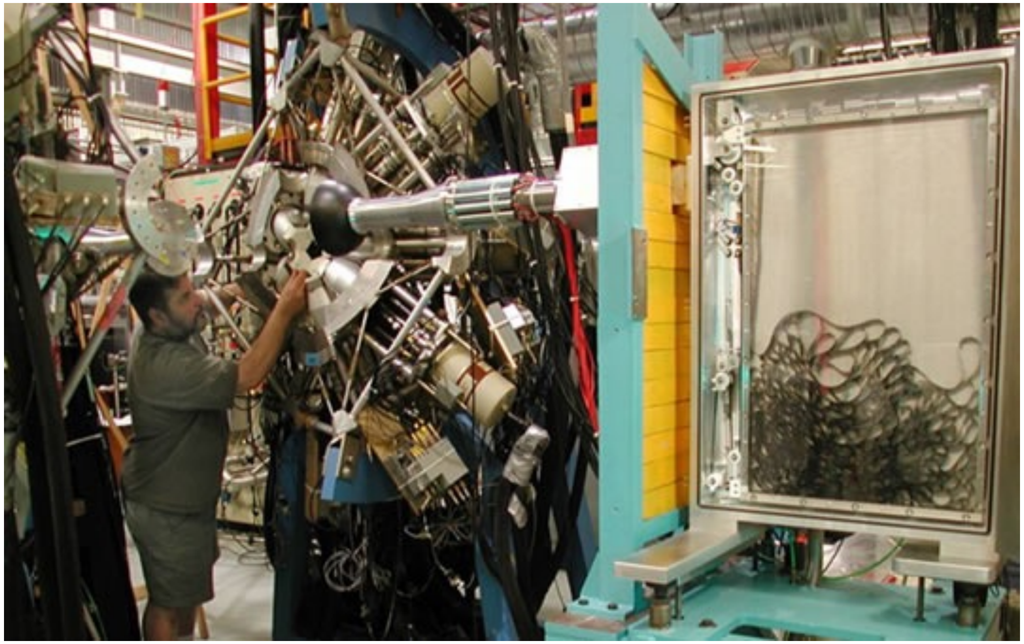
Overcoming the Pandemonium Effect

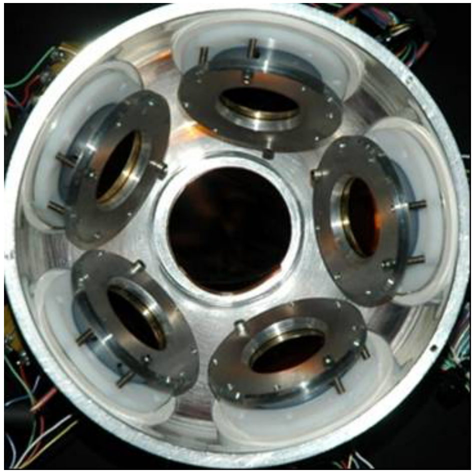


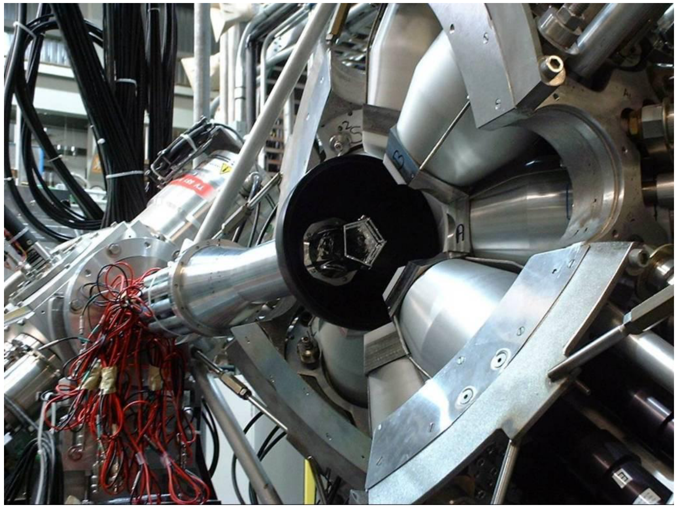
- How to Overcome:
  - 2+ states are β 2nd-forbidden $$I'_2 = I_{out} - I_{in}$$
  - Theory can estimate relative gamma-ray BR $$\bar{B}_{gs} = \frac{I'_{gs}}{I'_{gs} + I'_2}$$

⇒ Estimate of unobserved intensities, I'_{gs}

Branching Ratio Measurements: The 8π, PACES, and SCEPTAR



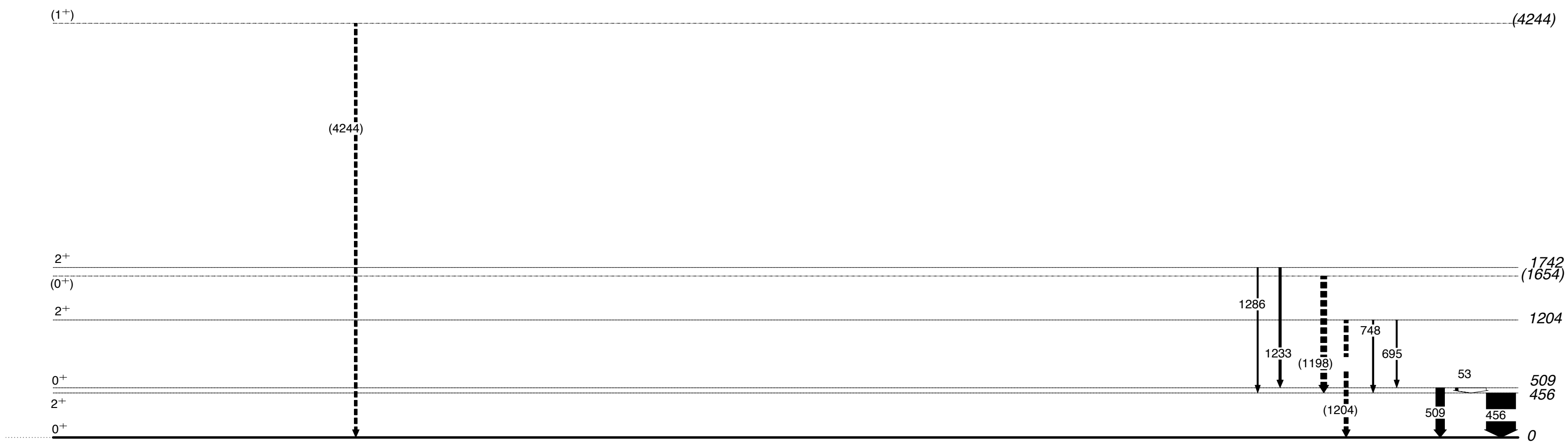




- PACES — 5 Si(Li) detectors used to measure conversion electrons
- SCEPTAR — 10 plastic scintillators used to tag the beta particles

^{74}Rb Branching Ratio

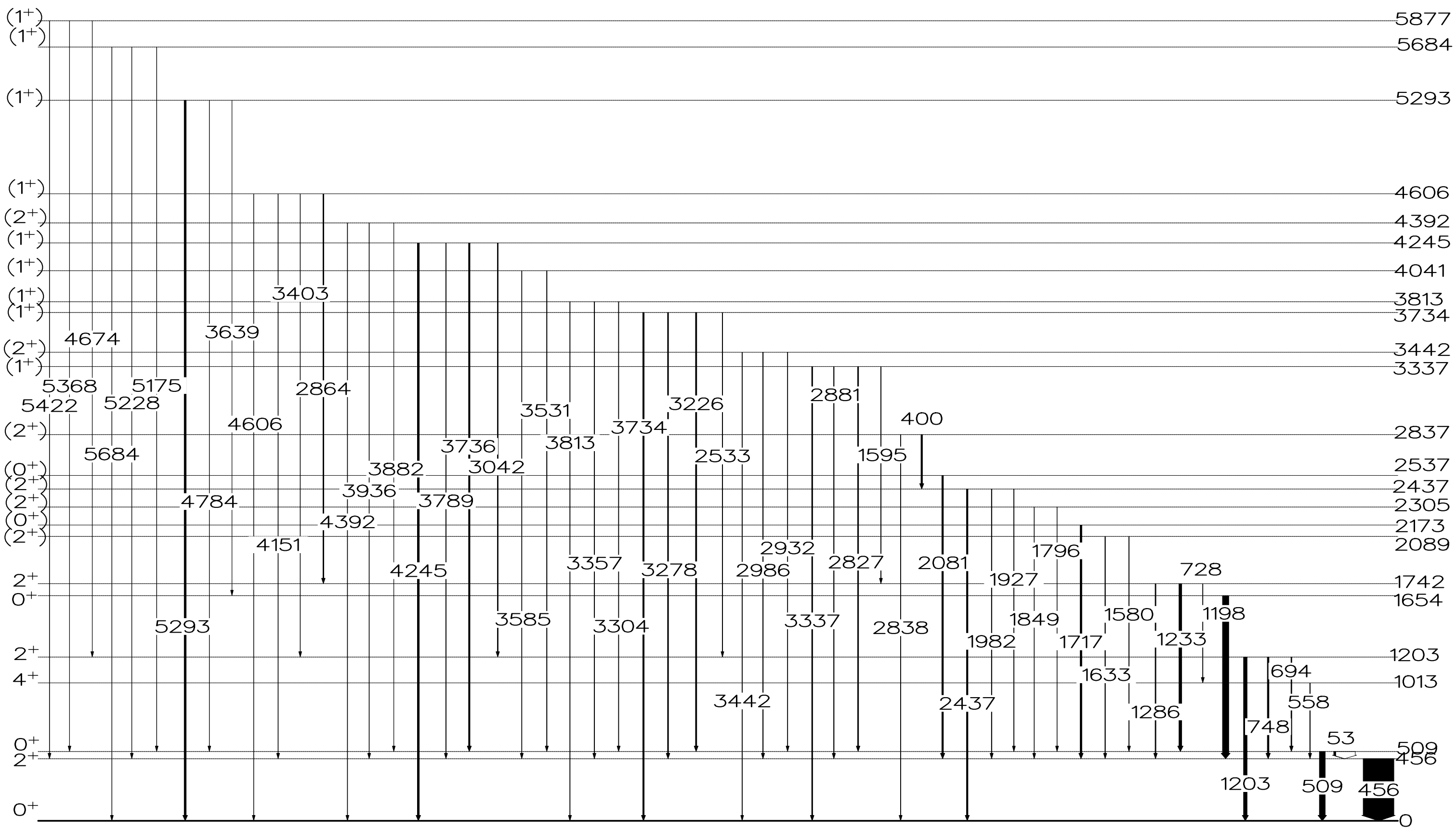
- Previously known decay scheme included 7 levels and 10 transitions



A. Piechaczek *et al.*, Phys. Rev. C. **67**, 051305 (2003)

^{74}Rb Branching Ratio

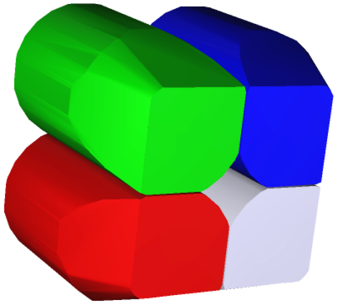
R. Dunlop *et al.*, Phys. Rev. C. **88**, 045501 (2013)

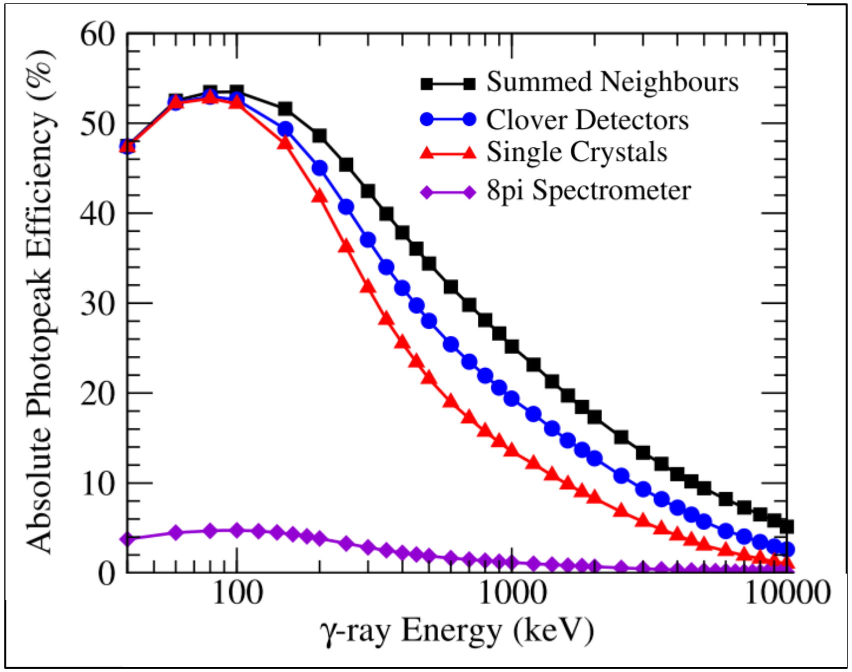


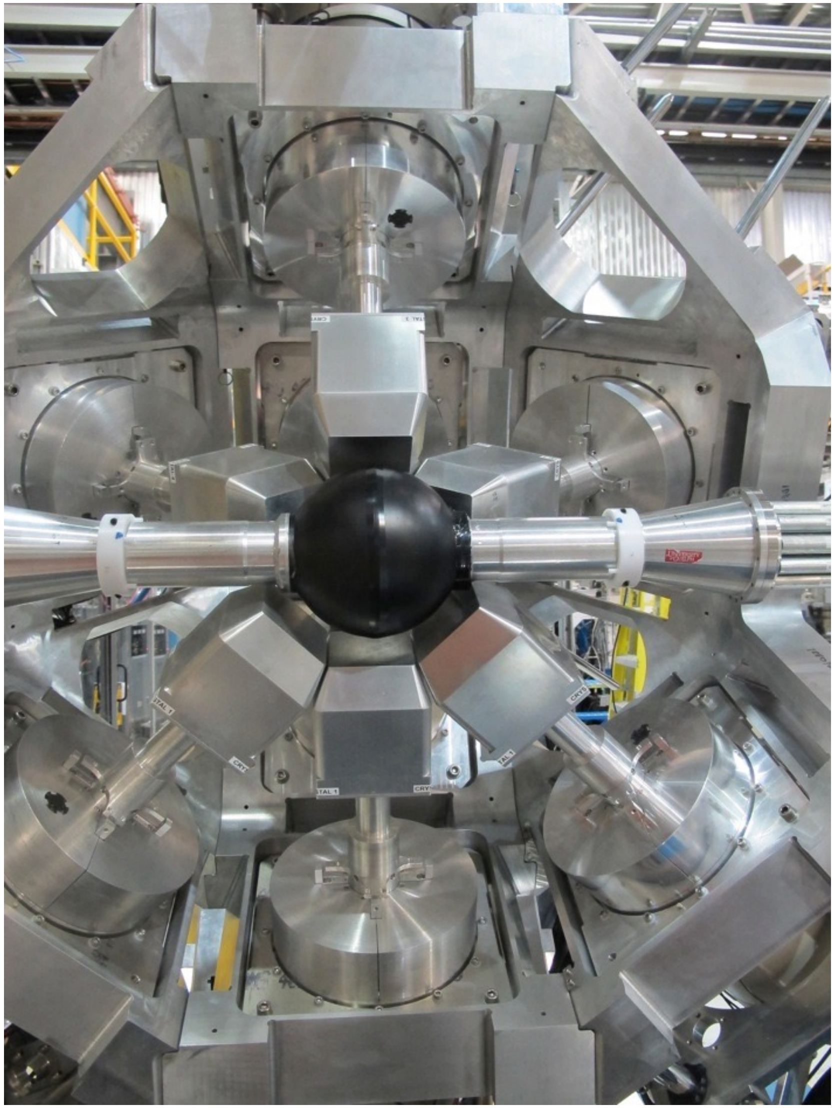
- 23 excited states identified in ^{74}Kr were identified.
- 58 new ɣ-ray and electron transitions were identified.
- Improvement in the branching ratio measurement by a factor of 3.

Branching Ratio Measurements with GRIFFIN

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

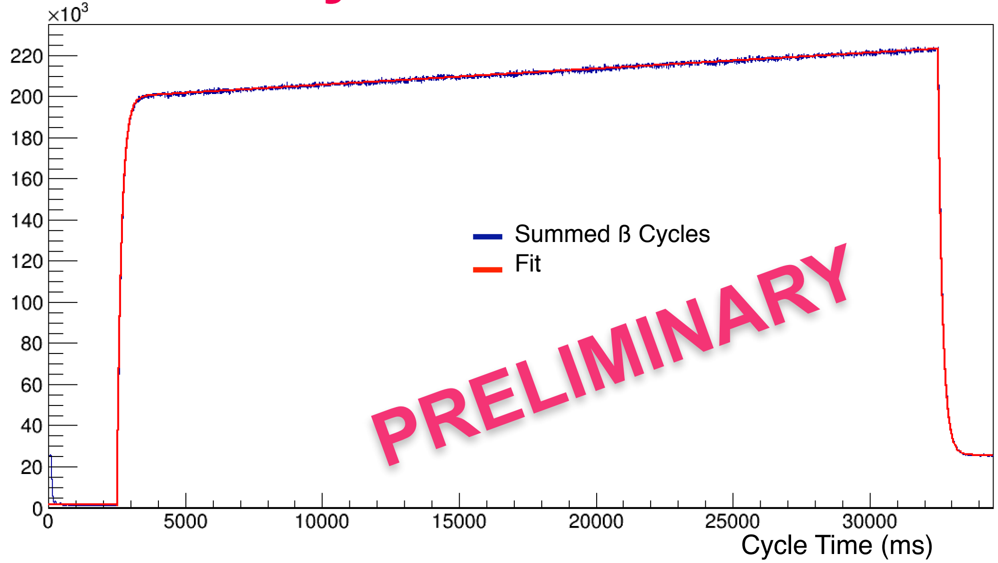


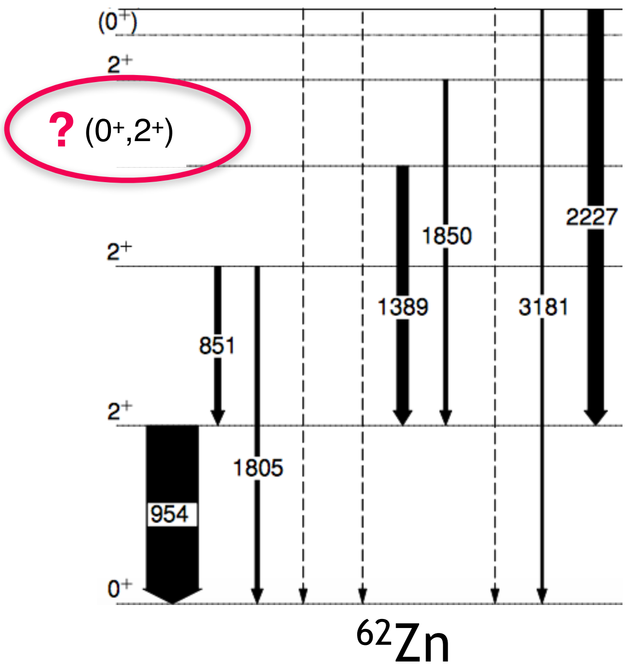


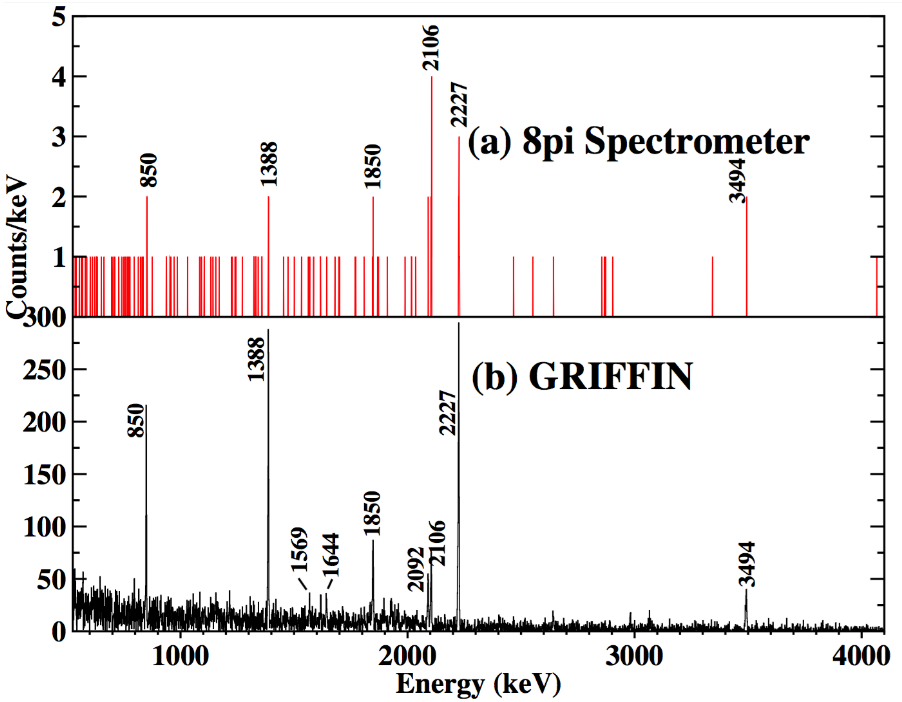


~ 300-500 times the γ-γ coincidence efficiency of the 8π spectrometer

Preliminary ^{62}Ga Branching Ratio



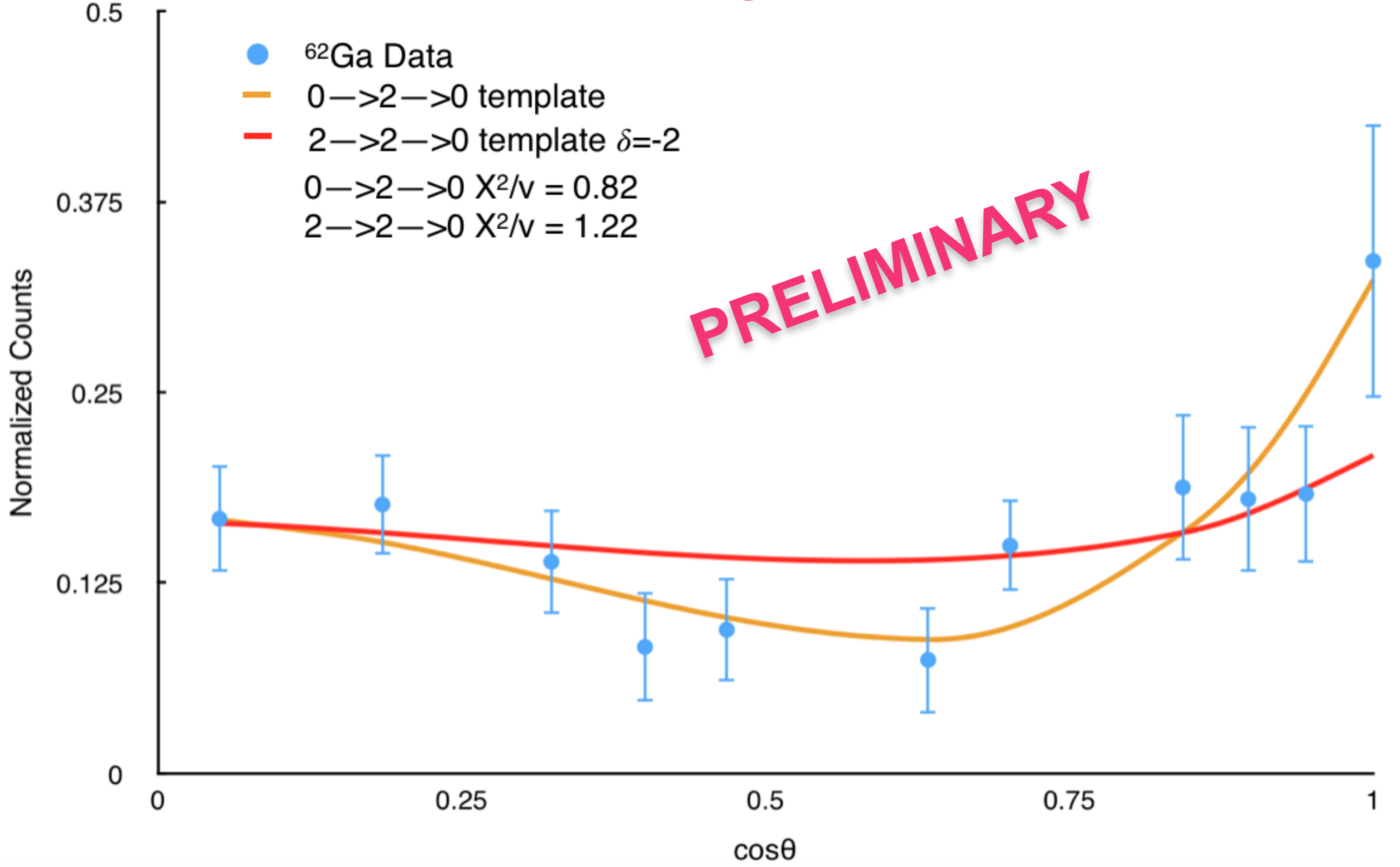




- GRIFFIN: ~3x10⁸ decay
- 8π: ~6x10⁸ decays
- With half of the decays we have much higher statistics with the high-efficiency GRIFFIN array!

Gate set on 954 keV γ-ray.

Preliminary ^{62}Ga Angular Correlations



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

Conclusions

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

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

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

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

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

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

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