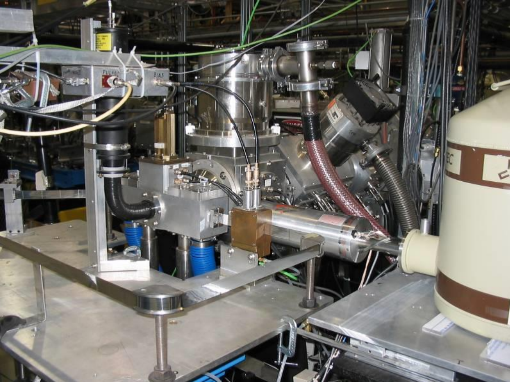
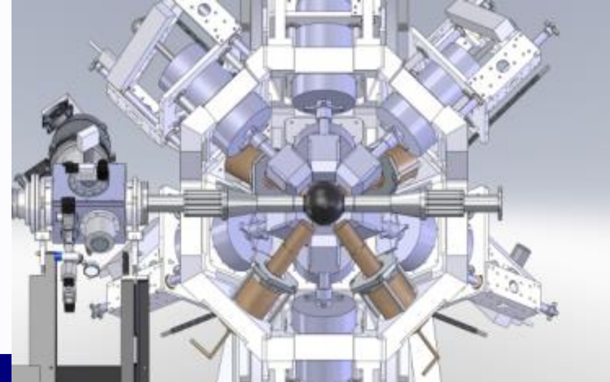
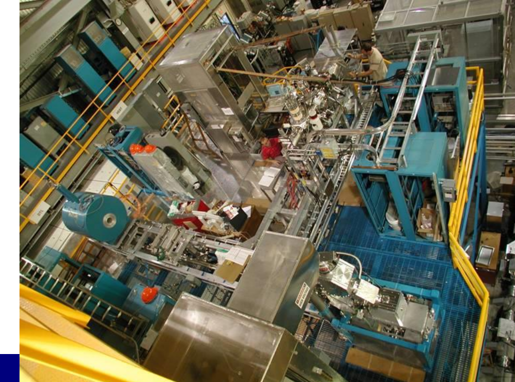
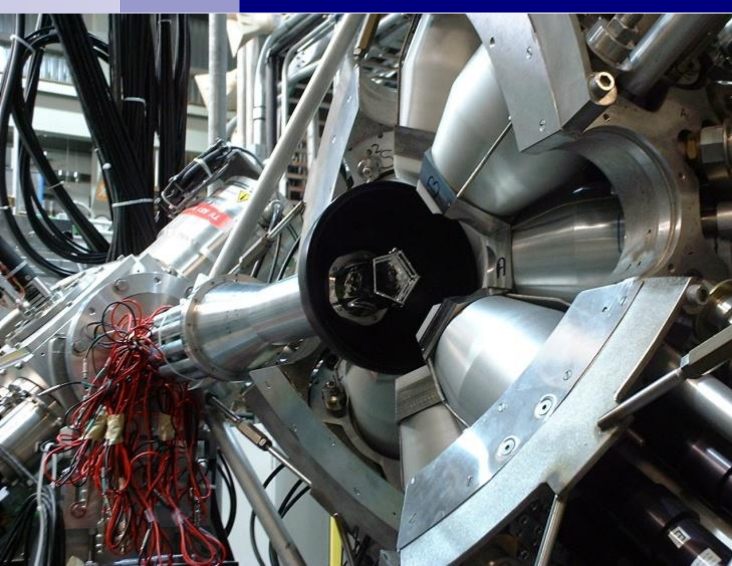


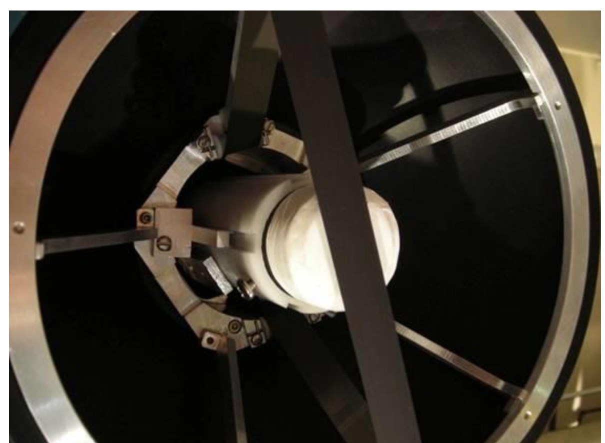




Superallowed Fermi Beta Decay Studies at TRIUMF-ISAC

C.E. Svensson, University of Guelph





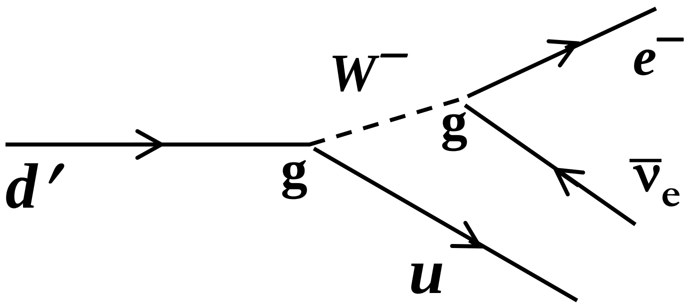
CAP Congress,
Sudbury, Ontario
June 16 – 20, 2014

The Cabibbo-Kobayashi-Maskawa (CKM) matrix

The CKM matrix plays a central role in the Standard Model

and underpins all quark flavour-changing interactions:

weak interaction eigenstates ≠ quark mass eigenstates



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

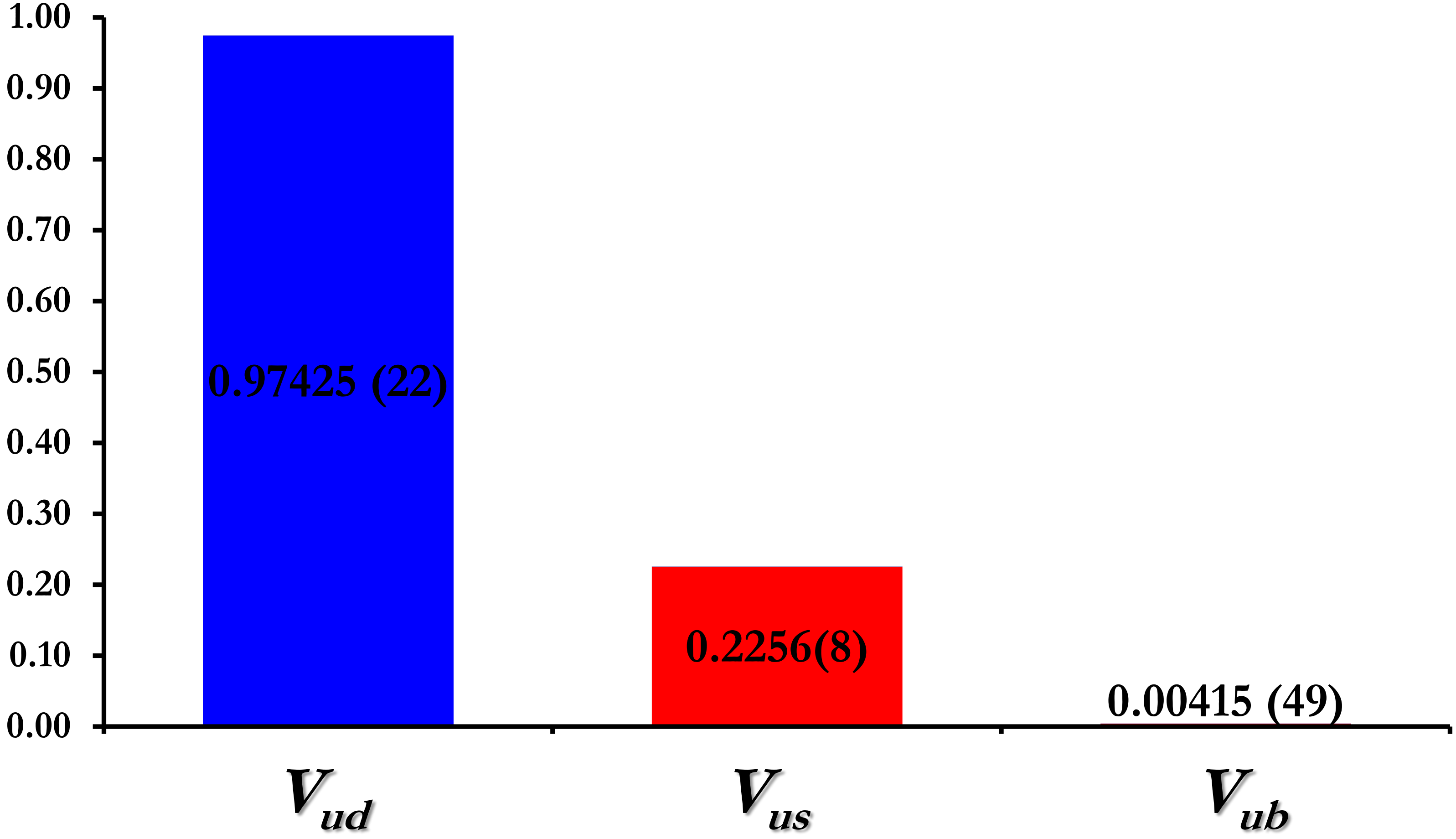
$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle + V_{ub}|b\rangle$$

In the Standard Model the CKM describes a unitary transformation.

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

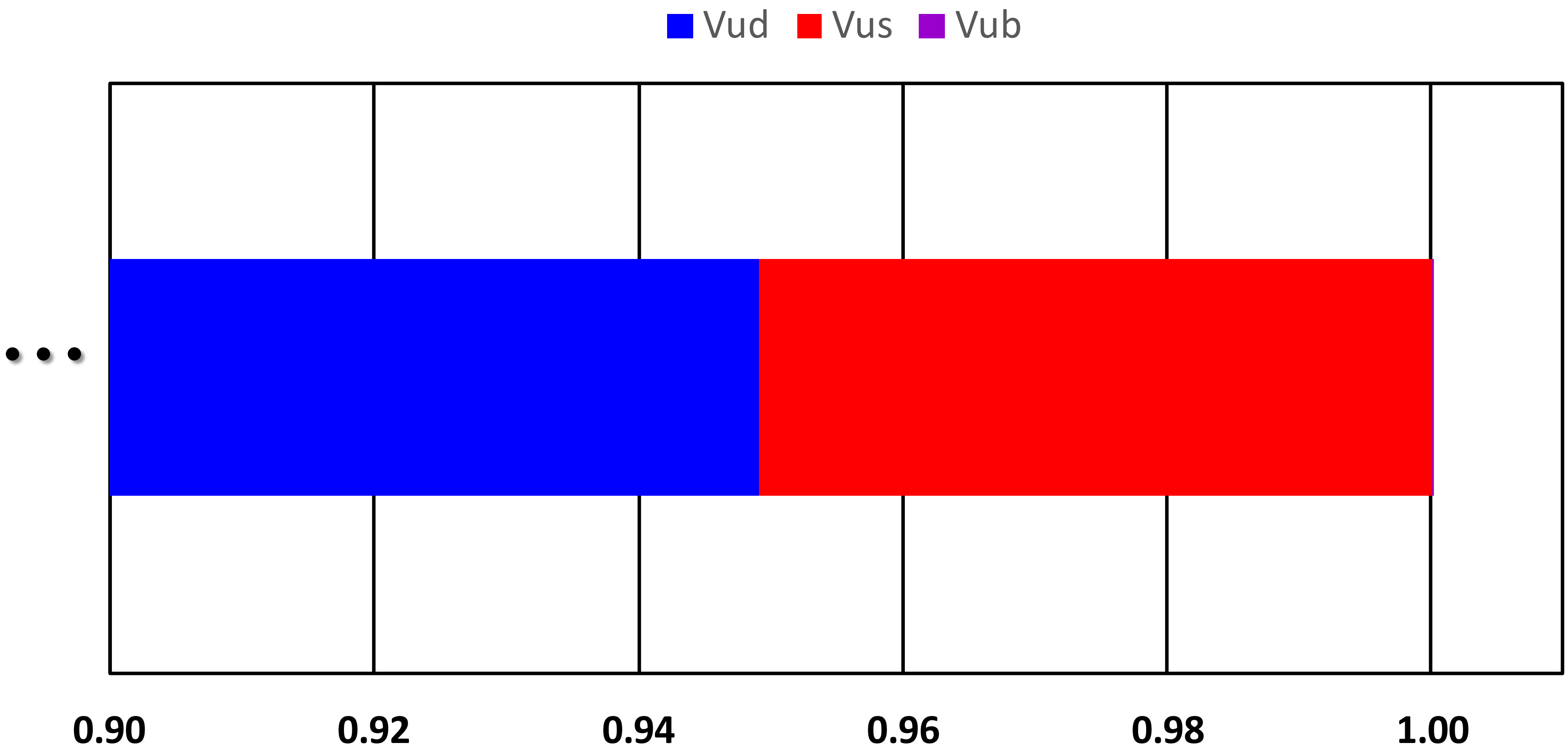
The first row of the CKM matrix provides, by far, the most demanding experimental test of this unitarity condition.

CKM Unitarity



J.C. Hardy and I.S. Towner, Ann. Phys. (Berlin) 525, 443 (2013).

CKM Unitarity



$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.00008(43)_{Vud}(36)_{Vus}$$

J.C. Hardy and I.S. Towner, Ann. Phys. (Berlin) 525, 443 (2013).

New Lattice QCD Form Factor Calculations for V_{us}

R.J. Dowdall et al., Phys. Rev. D 88, 074504 (2013)

$K^+ \to l\nu \,/\, \pi^+ \to l\nu$ (HPQCD Collaboration)

$$|V_{us}| = 0.22564(53)$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.00009(43)_{Vud}(24)_{Vus}$$

A. Bazavov et al., Phys. Rev. Lett. 112, 112001 (2014)

$K^+ \to \pi^+ l\nu$ (Fermilab Lattice and MILC Collaborations)

$$|V_{us}| = 0.22290(90)$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99885(43)_{Vud}(40)_{Vus}$$

V_{ud} from Superallowed Fermi β Decay

To first order, β decay ft values can be expressed as:

$$f\,t = \frac{K}{|M_{fi}|^2 g^2}$$

- phase space (Q-value) → f
- half-life, branching ratio → t
- constants → K
- matrix element → $|M_{fi}|^2$
- Weak coupling strength → g^2

For the special case of $0^+ \rightarrow 0^+$ (pure Fermi) β decays between isobaric analogue states (superallowed) the matrix element is that of an isospin ladder operator:

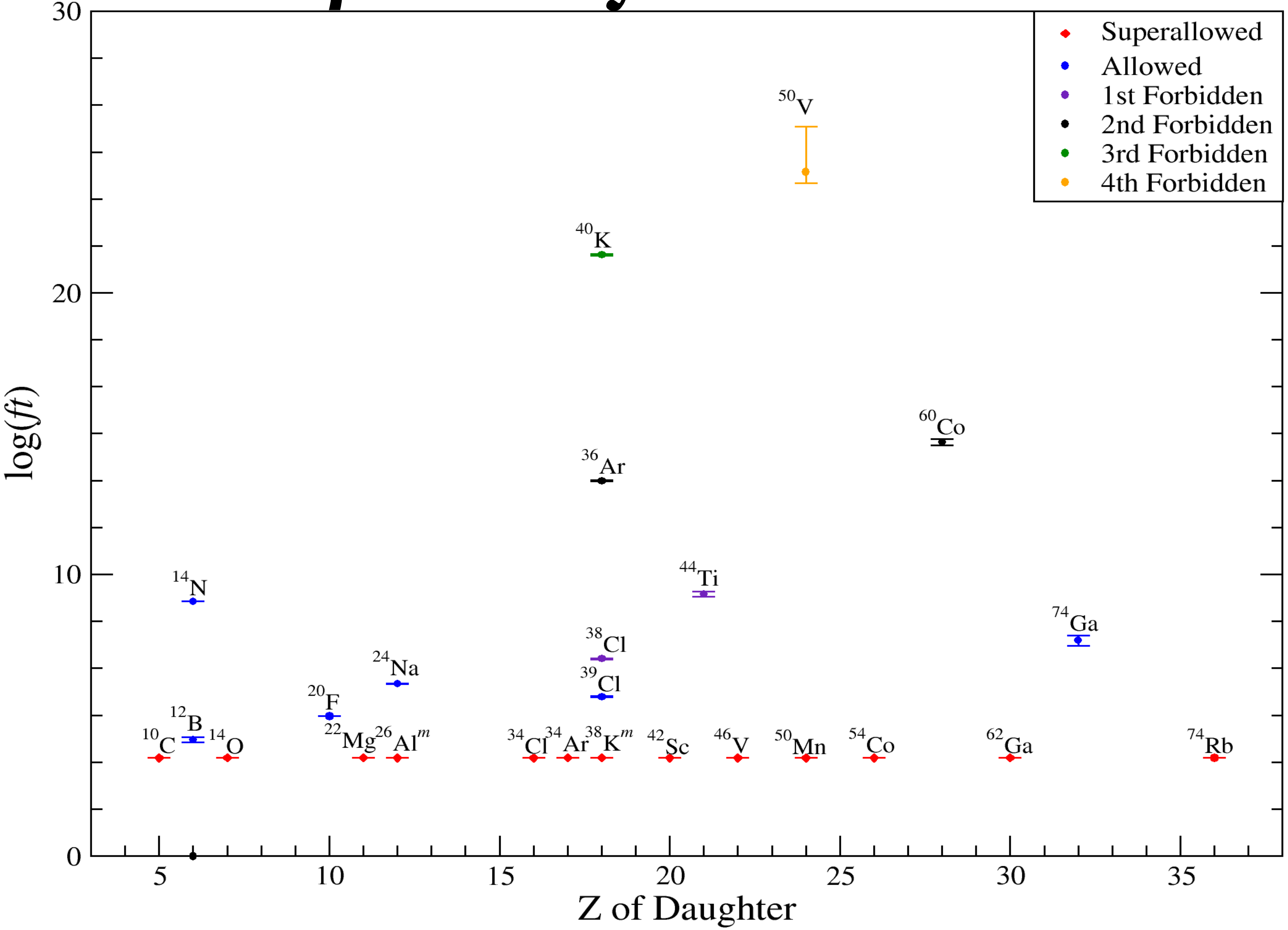
$$|M_{fi}|^2 = (T - T_Z)(T + T_Z + 1) = 2 \quad (\text{for } T=1)$$

Strategy: Measure superallowed ft-values, deduce G_V and V_{ud}:

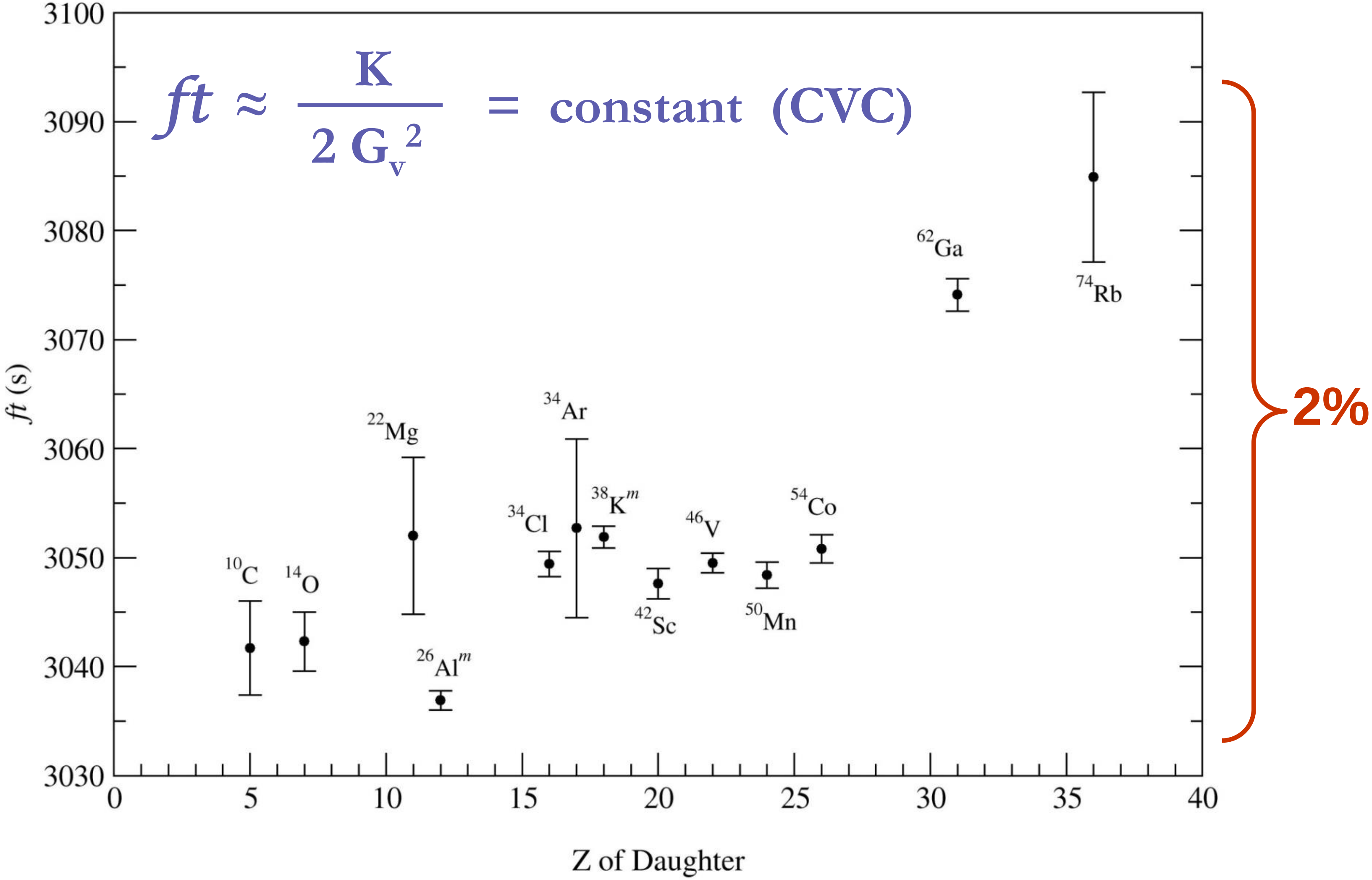
Vector coupling constant → $$G_V^2 = \frac{K}{2\,ft}$$

$$|V_{ud}| = G_V / G_F$$ ← Fermi coupling constant

β decay ft-values



Superallowed *ft*-values



Superallowed Fermi β Decay: Corrections

$$\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} = \text{constant}$$

"Corrected" ft value

Experiment

Calculated corrections (~1%)
(nucleus dependent)

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

CVC Hypothesis

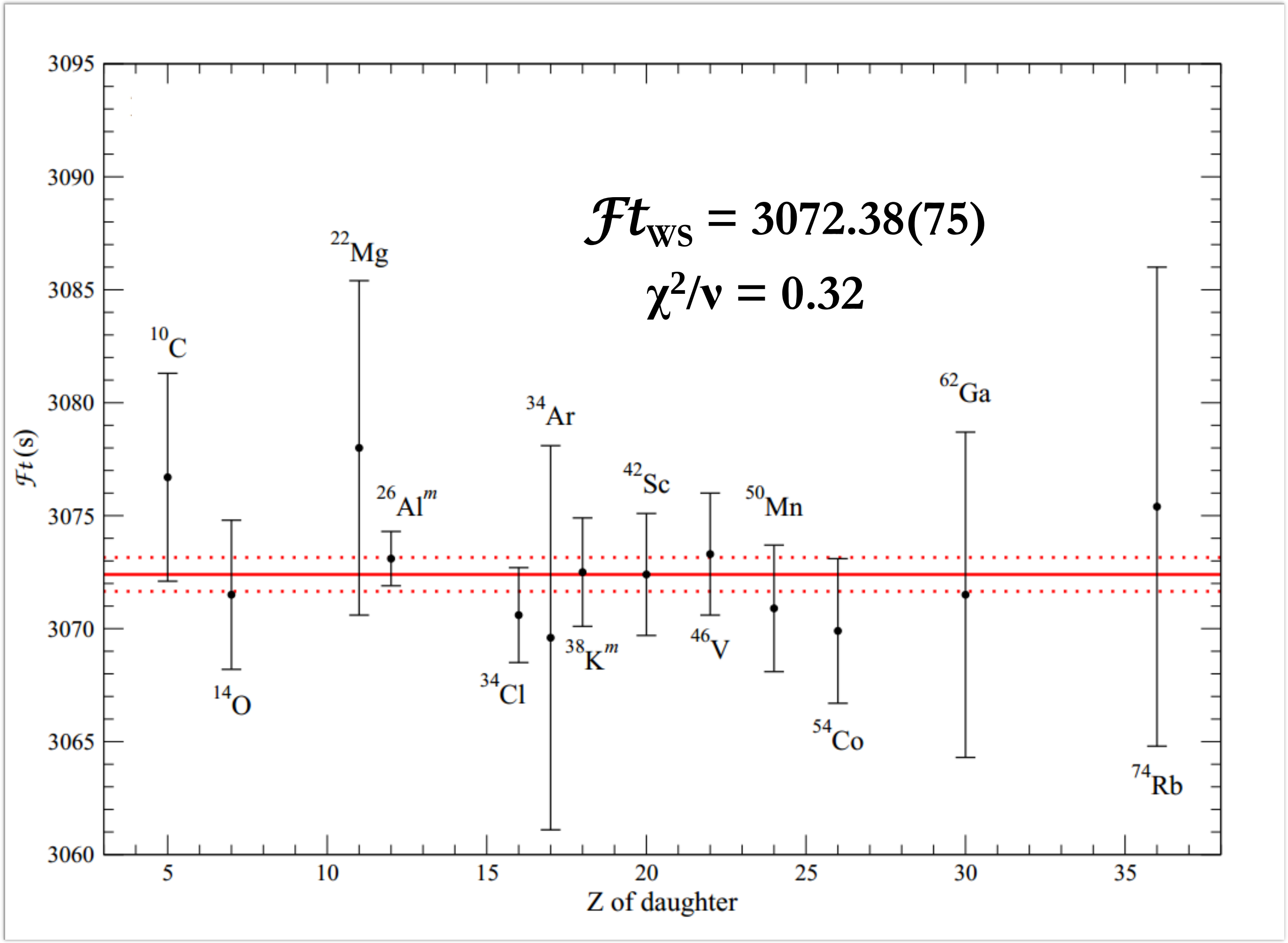
Δ_R^V = nucleus independent inner radiative correction: 2.361(38)%

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% – 0.03%

δ_C = nucleus dependent isospin-symmetry-breaking correction: 0.2% – 1.5%
- strong nuclear structure dependence

Corrected Superallowed $\mathcal{F}t$ Values



P. Finlay, *et al.*, Phys. Rev. Lett. 106, 032501 (2011)
R. Dunlop, *et al.*, Phys. Rev. C 88, 045501 (2013)

Theoretical Treatment of δ_C

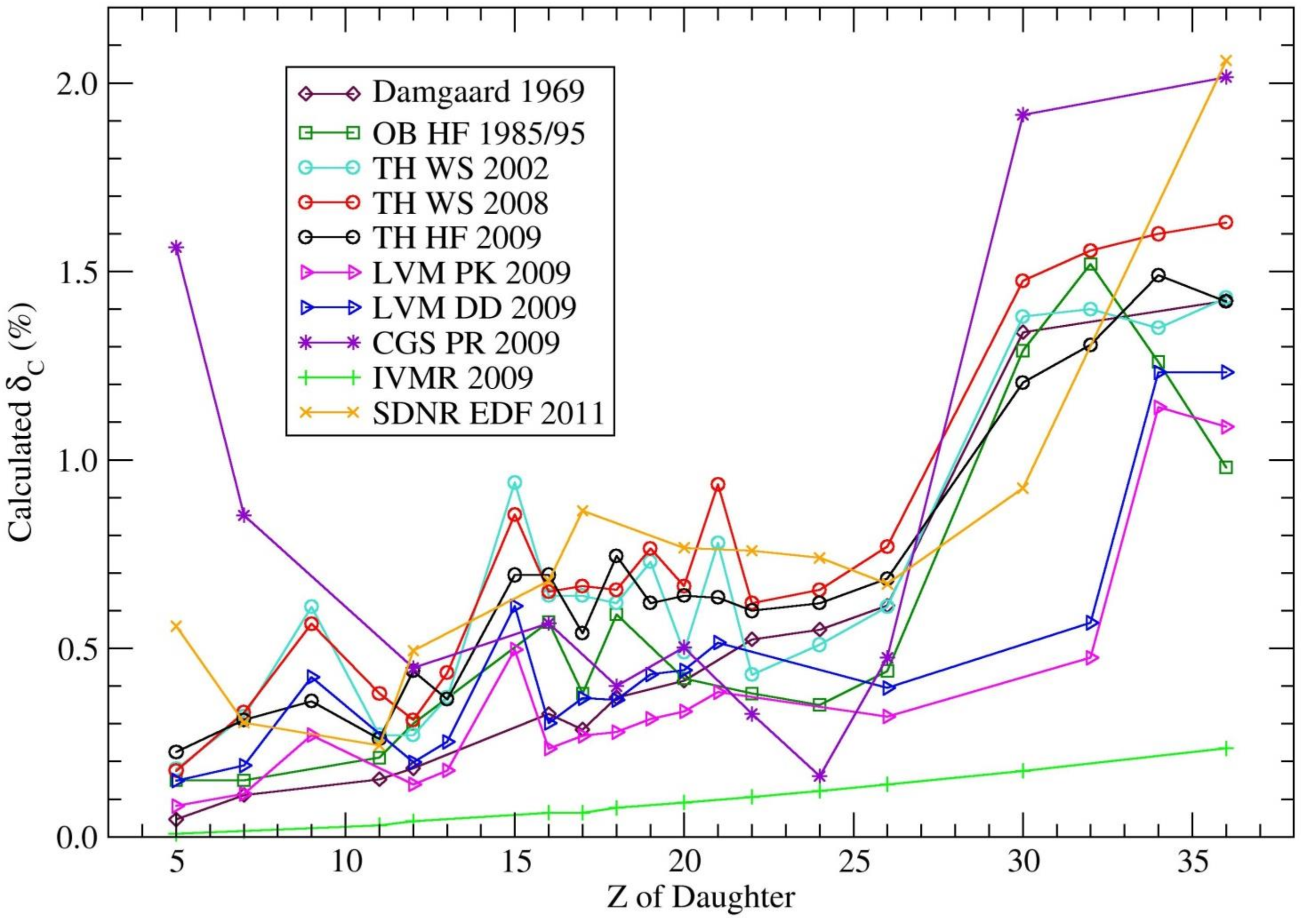
Many recent approaches to ISB corrections

→ Nuclear Shell Model

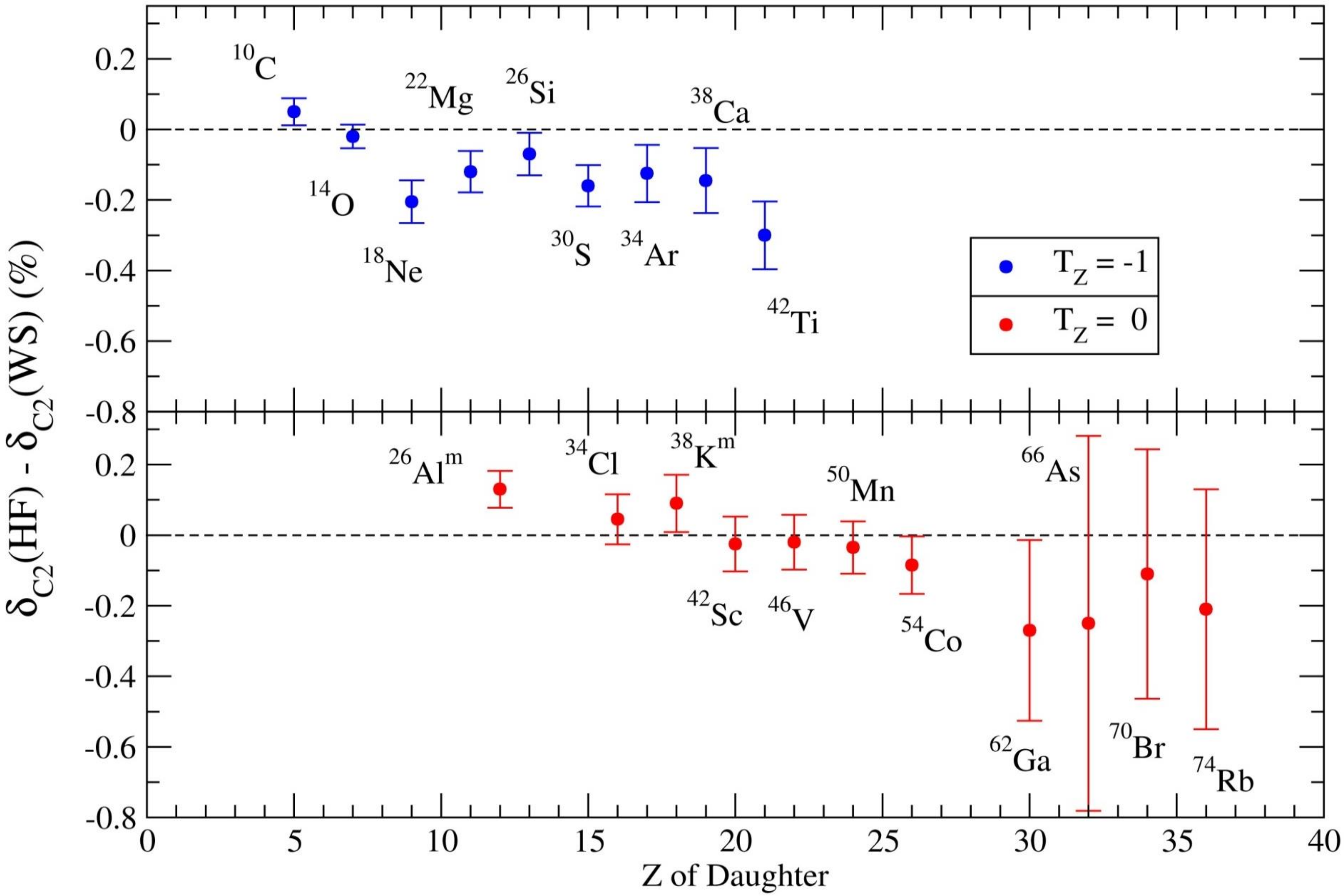
→ Relativistic Hartree-Fock

→ Random Phase Approximation

→ Energy Density Functional

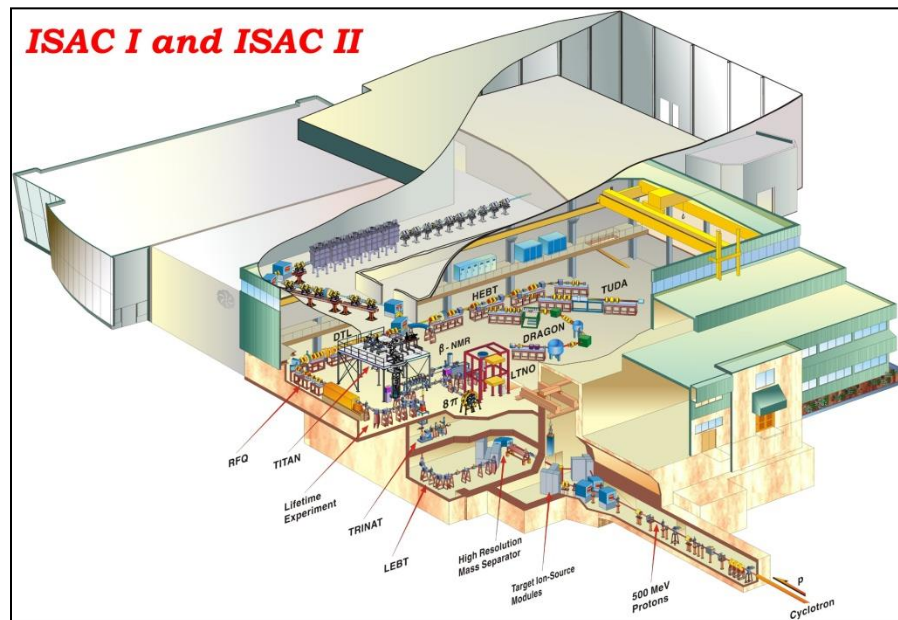


Difference between Woods-Saxon and Hartree-Fock Radial Overlap Corrections



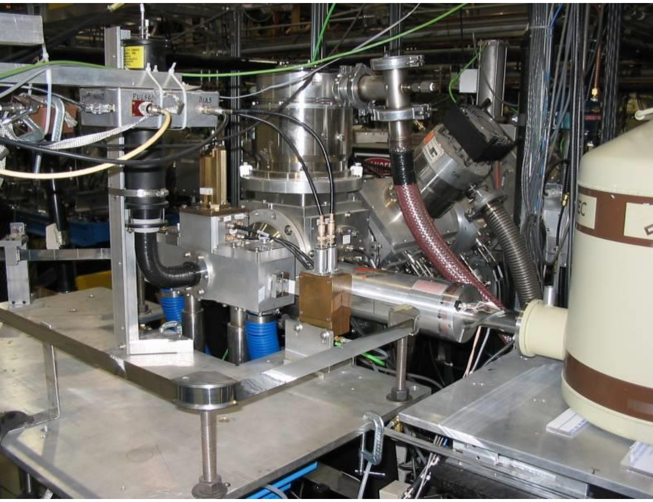
TRIUMF-ISAC

Up to 100 μA, 500 MeV proton beams from the TRIUMF main cyclotron produce high-intensity secondary beams of many of the superallowed emitters by the ISOL technique.

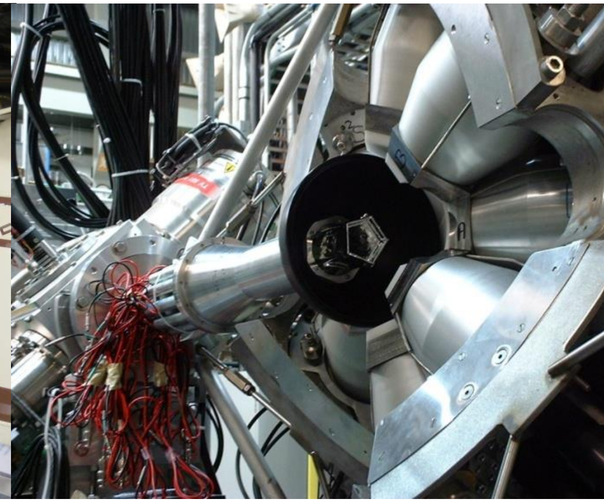


Superallowed Fermi β Decay Studies at ISAC

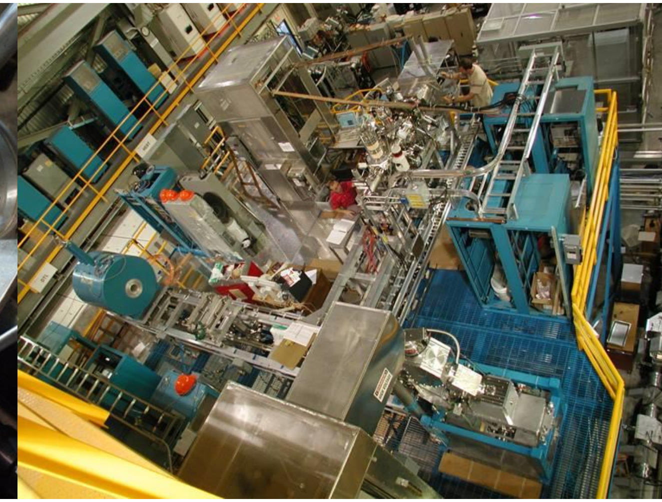
Halflives (GPS)



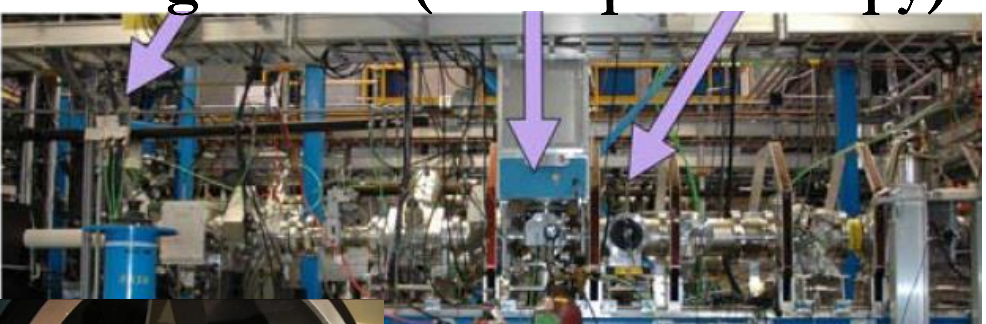
Branching ratios (8π)

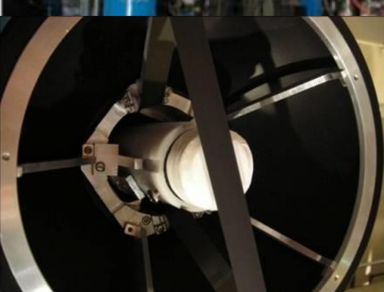


Masses (TITAN)



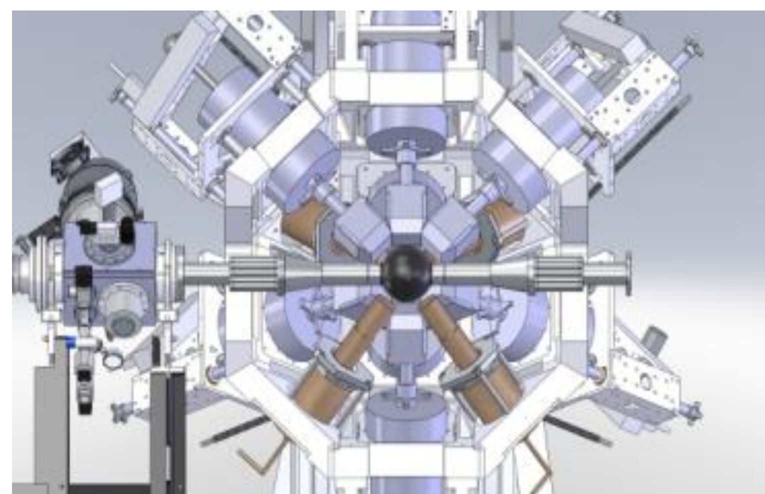
Charge Radii (laser spectroscopy)





Halflives (ZDS)

Near Future (GRIFFIN)



Superallowed β Decay Studies at ISAC

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

$T_{½}$, G.F. Grinyer, PRC 77, 201501 (2008)
BR, B.H. Hyland, PRL 97, 102501 (2006)
BR, P. Finlay PRC 78, 044321 (2008)

$T_{½}$ and BR

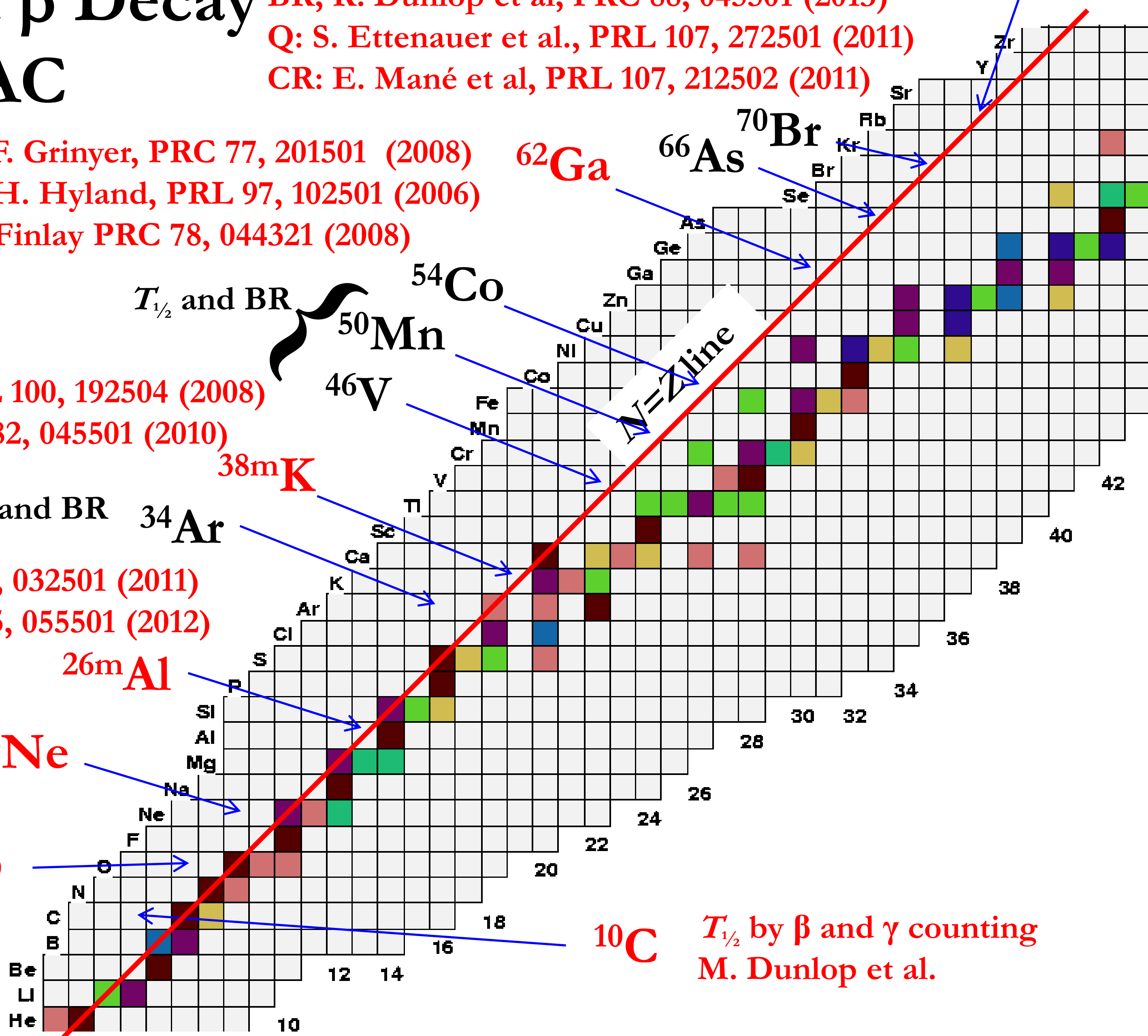
BR, K.G. Leach et al., PRL 100, 192504 (2008)
$T_{1/2}$, G.C. Ball *et al*, PRC 82, 045501 (2010)

$T_{½}$ and BR

$T_{½}$ P. Finlay et al, PRL 106, 032501 (2011)
BR, P. Finlay et al, PRC 85, 055501 (2012)

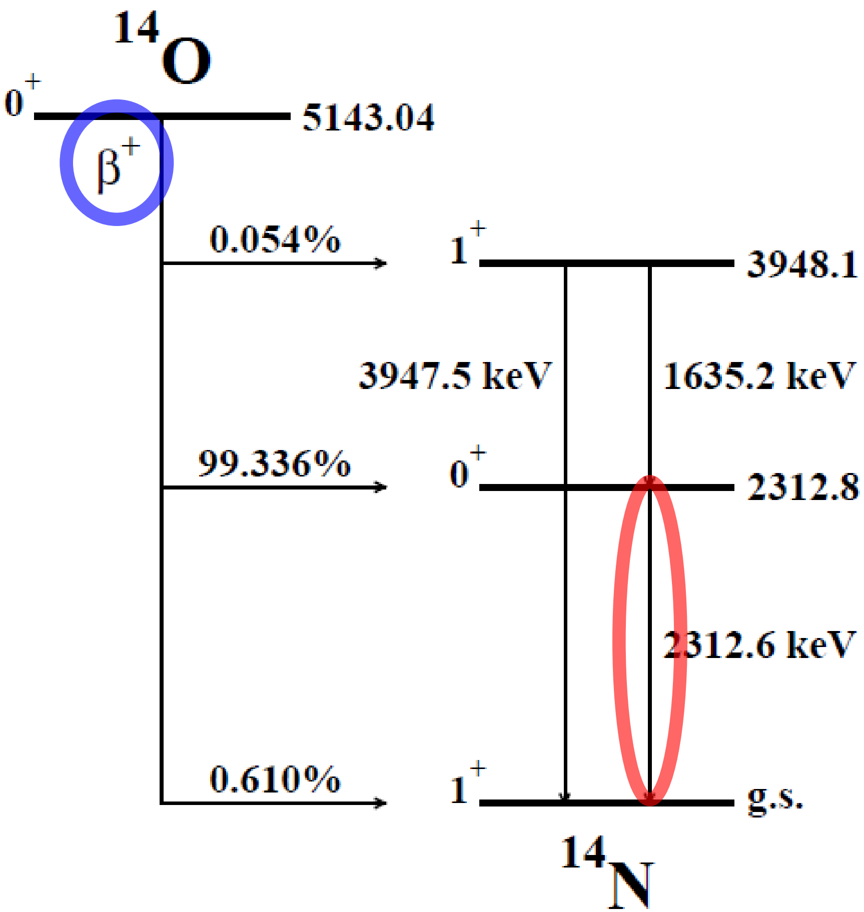
$T_{½}$, G.F. Grinyer et al,
PRC 76, 025503 (2007)
PRC 87, 045502 (2013)

$T_{½}$, A.T. Laffoley et al,
PRC 88, 015501 (2013)



$T_{½}$ by β and γ counting
M. Dunlop et al.

^{14}O Half-Life Measurement



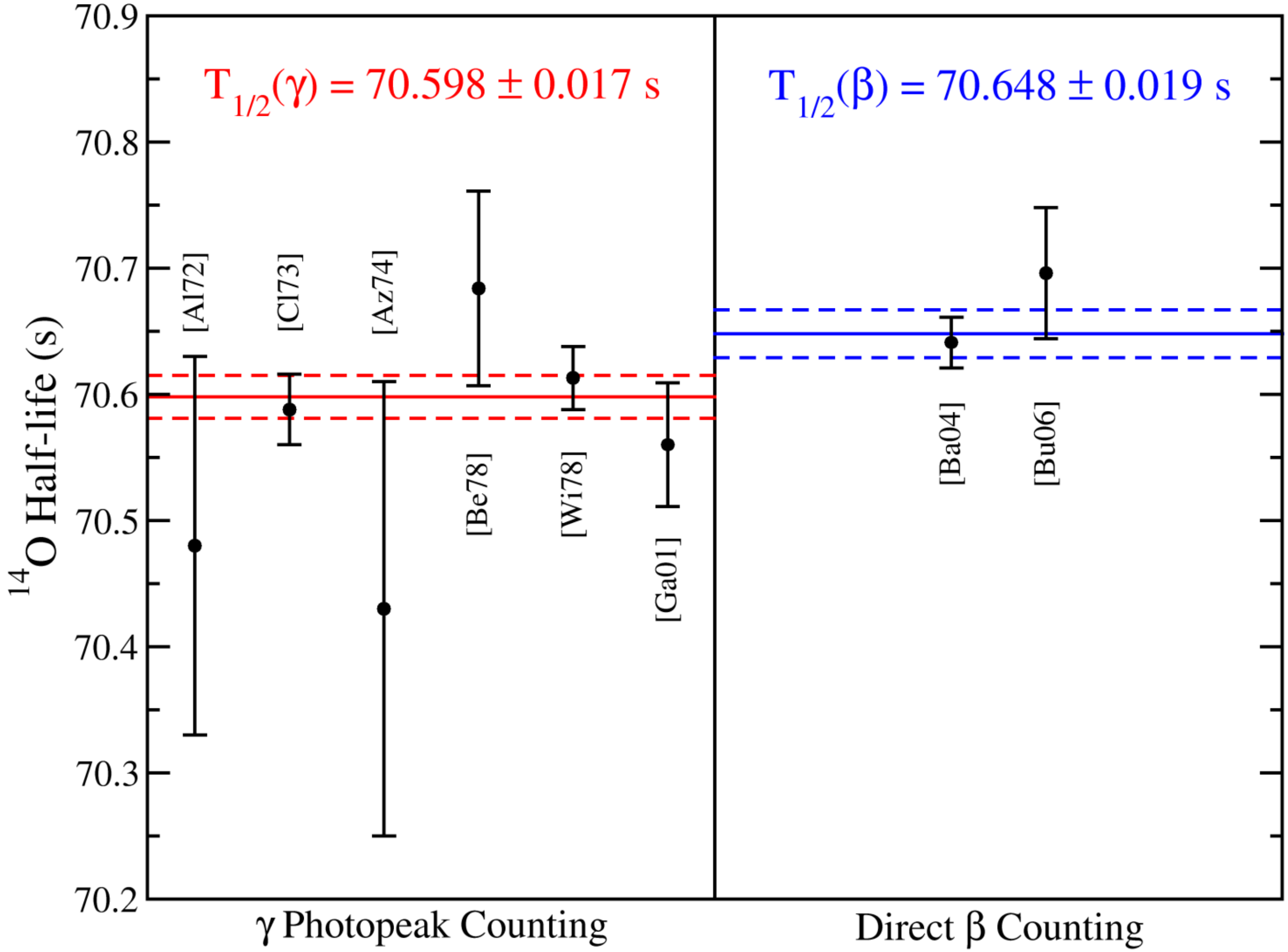
Simultaneous independent direct β and γ-ray counting experiments using the 8π spectrometer and the Zero-Degree Scintillator.

γ Counting:
- Decay Selective
- Slow & Inefficient

β Counting:
- Fast & Efficient
- Not Decay Selective

Previous measurements reveal a systematic discrepancy between detection method

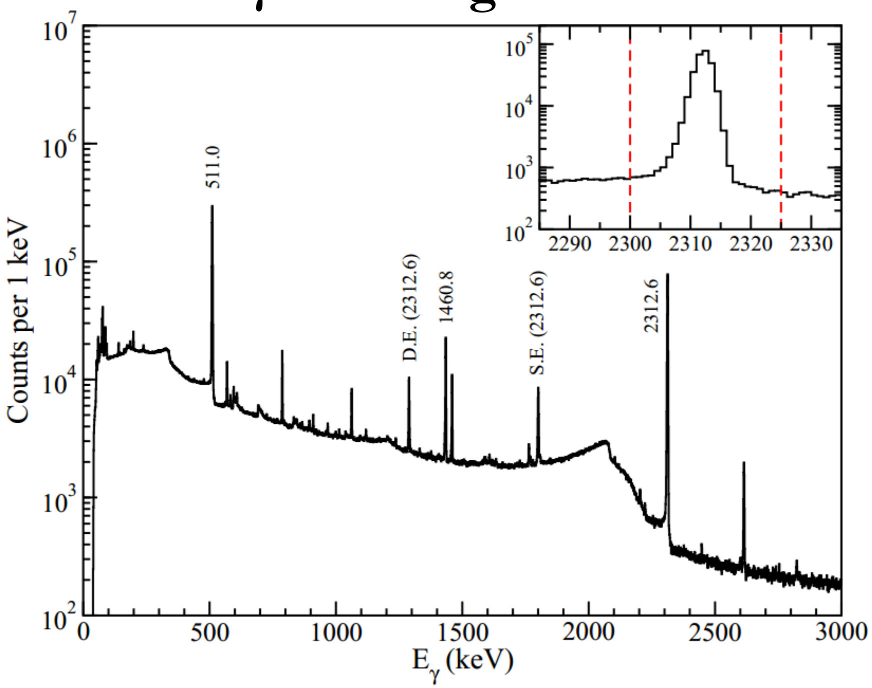
^{14}O Half-Life *vs* Detection Method

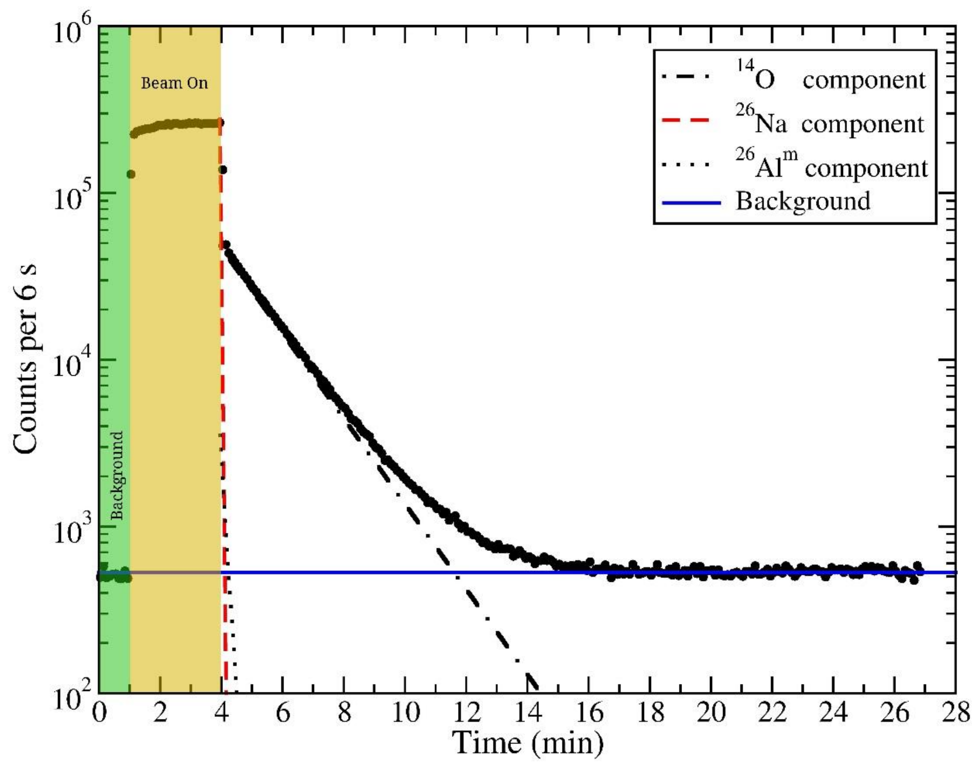


^{14}O Half-Life Measurement at ISAC

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

γ Counting

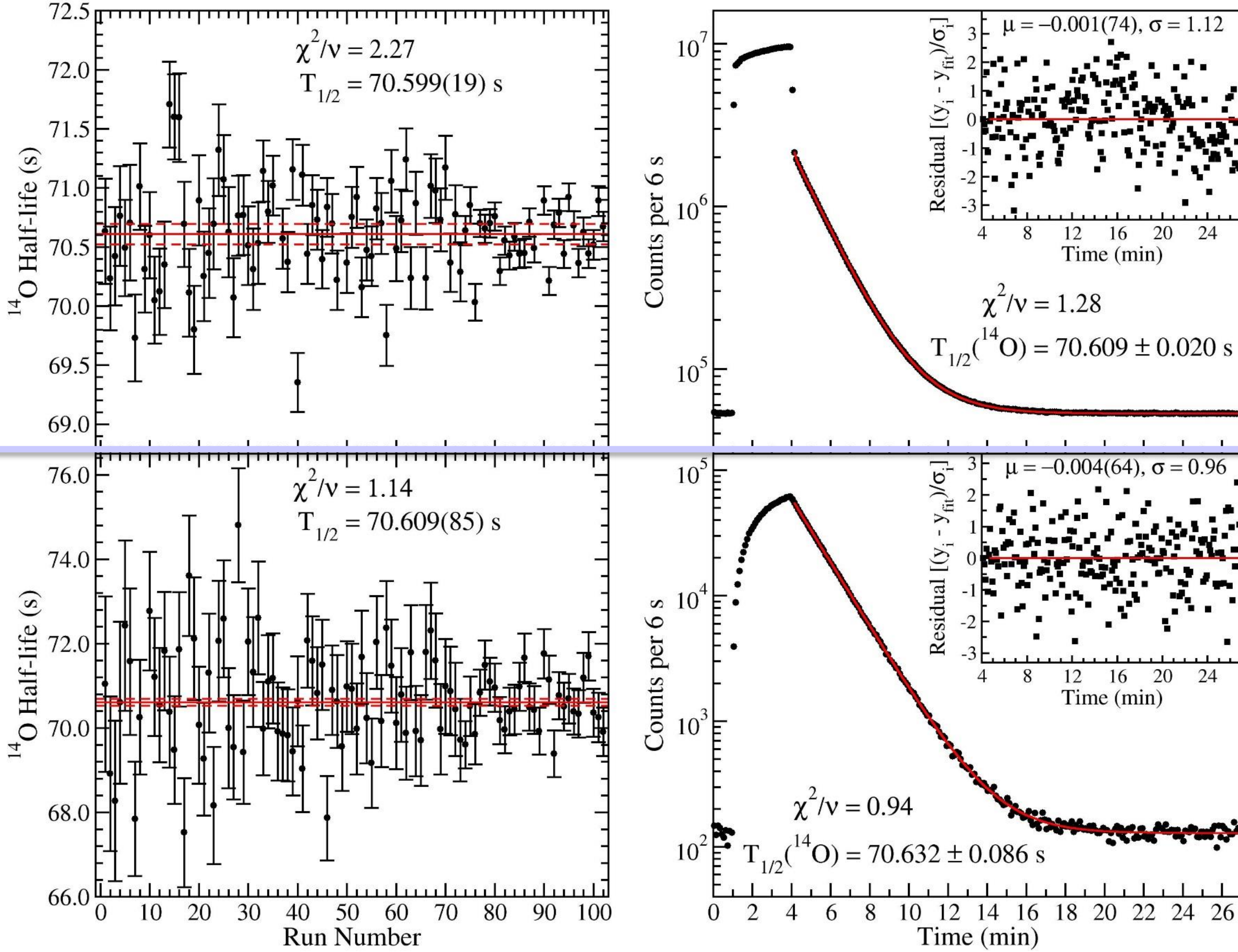




β Counting

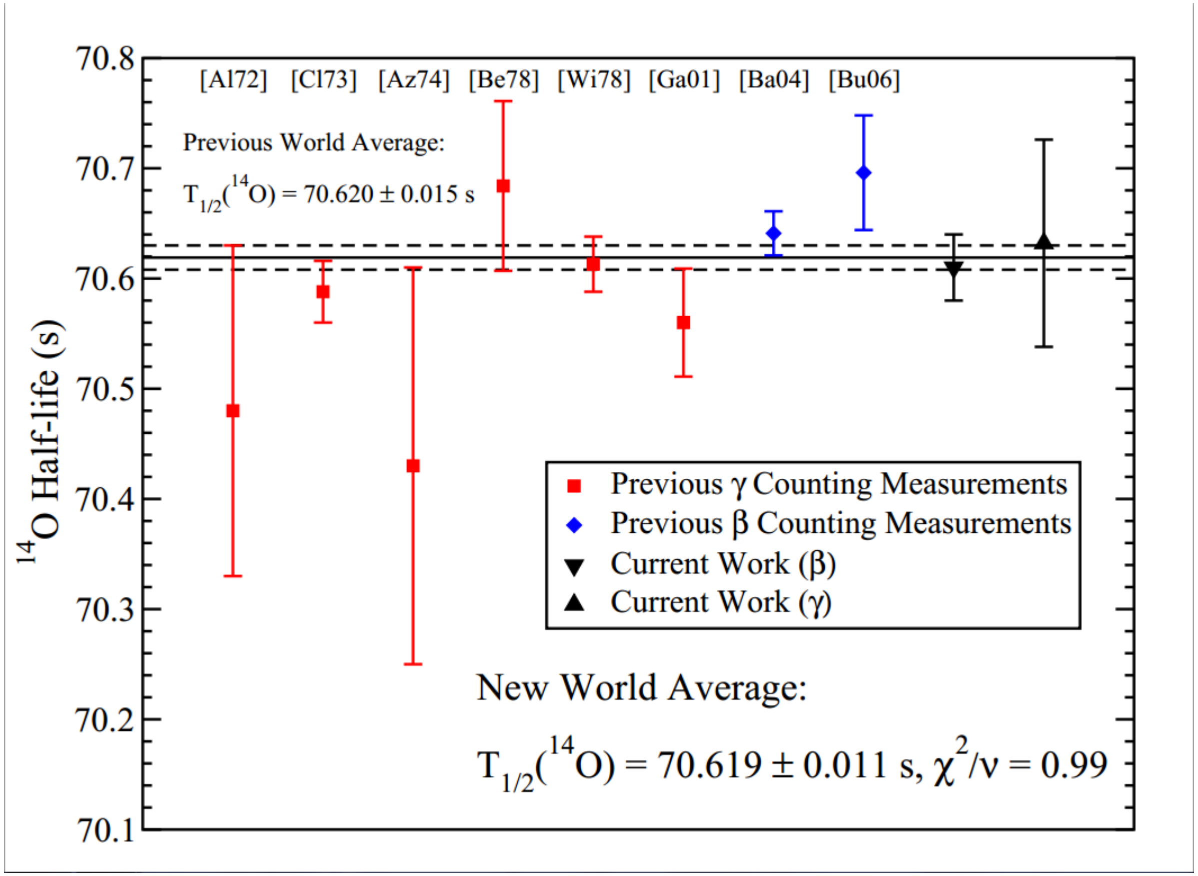
β

γ



χ²/ν = 2.27
T1/2 = 70.599(19) s
14O Half-life (s)
χ²/ν = 1.14
T1/2 = 70.609(85) s
Run Number
Counts per 6 s
μ = −0.001(74), σ = 1.12
Residual [(yi - yfit)/σi]
Time (min)
χ²/ν = 1.28
T1/2(14O) = 70.609 ± 0.020 s
μ = −0.004(64), σ = 0.96
χ²/ν = 0.94
T1/2(14O) = 70.632 ± 0.086 s
Time (min)

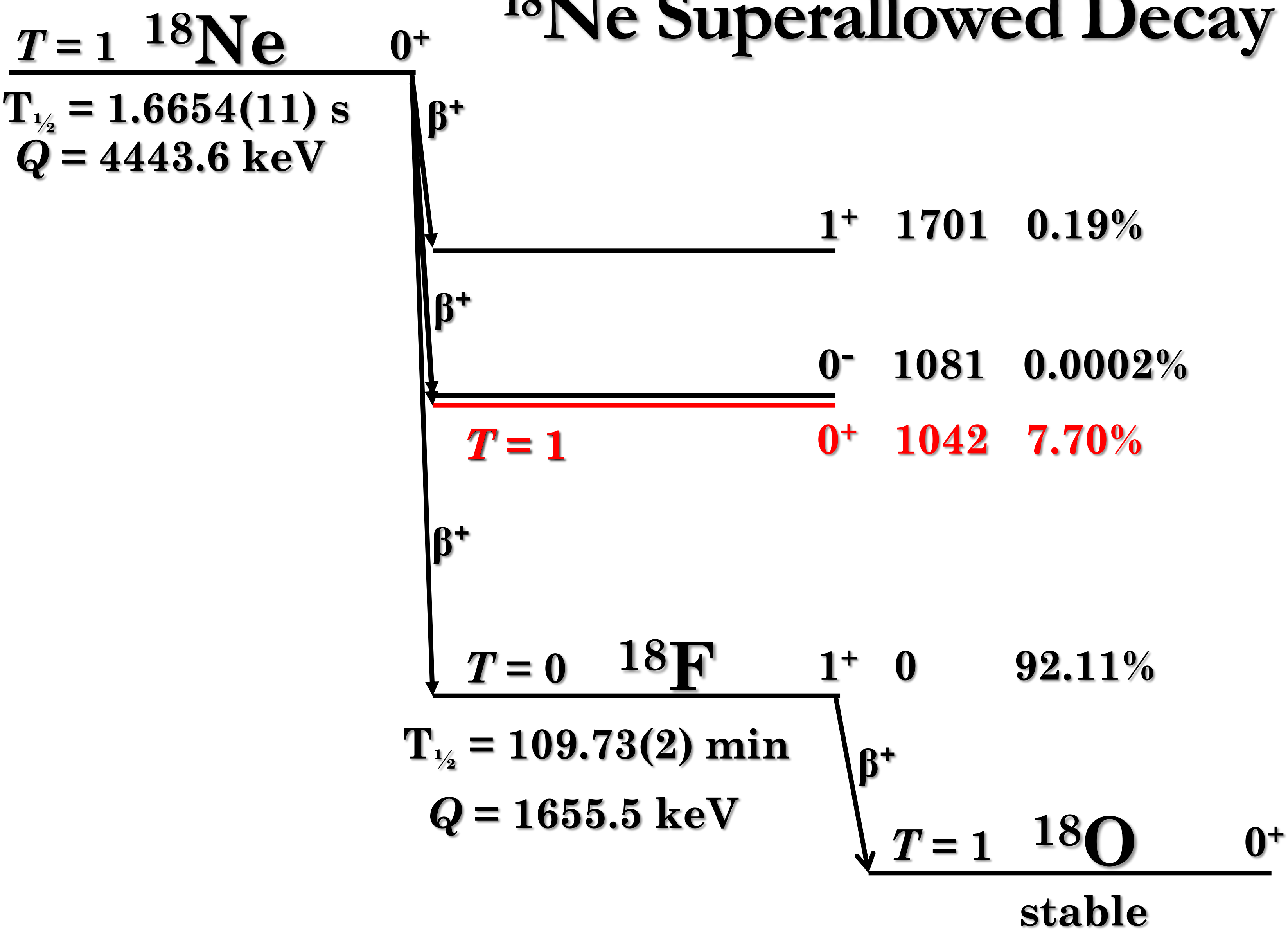
^{14}O Half-Life



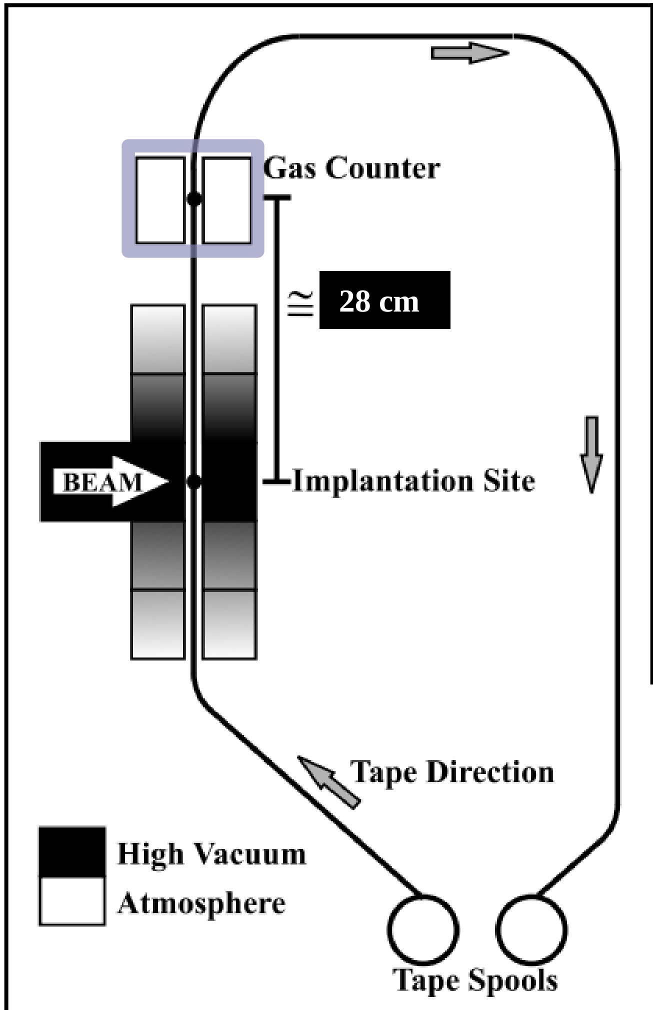
A.T. Laffoley *et al.*, Phys. Rev. C **88**, 015501 (2013)

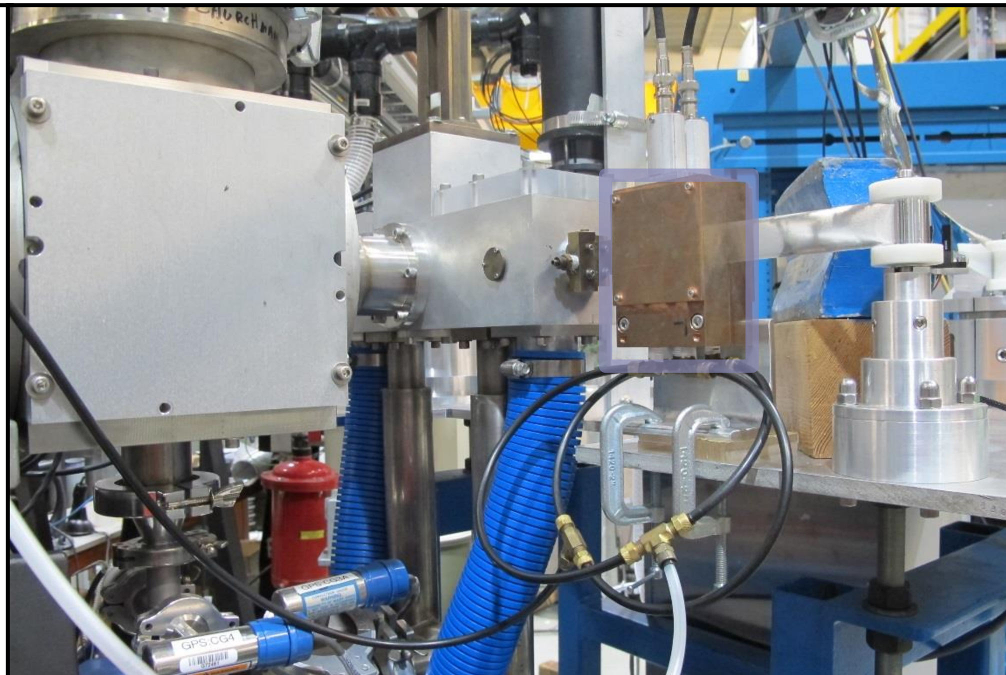
- **Initial experiment shows consistency between β and γ half-life measurements for ^{14}O.**
- **A follow-up experiment is scheduled for July, 2014 to push to 0.01% precision.**
- ***ft* measurements for light superallowed Fermi β emitters are required to constrain scalar currents in the weak interaction.**

^{18}Ne Superallowed Decay



4π Gas Counter and Thick Tape Transport



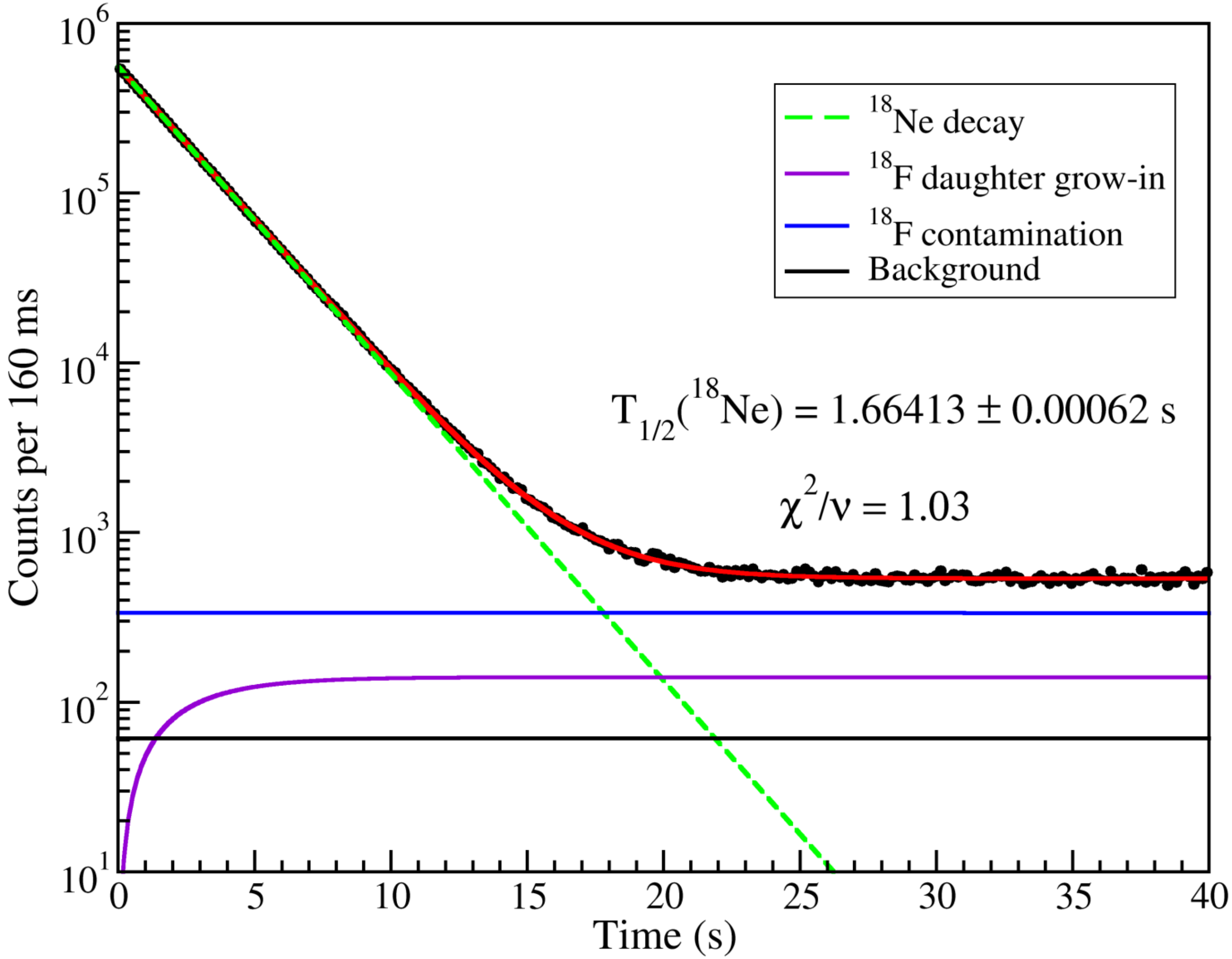


- 4π continuous-flow gas-proportional counter and tape transport system
- Methane (CH_4) gas
- ~ 100% efficient β counter
- Very low background rates

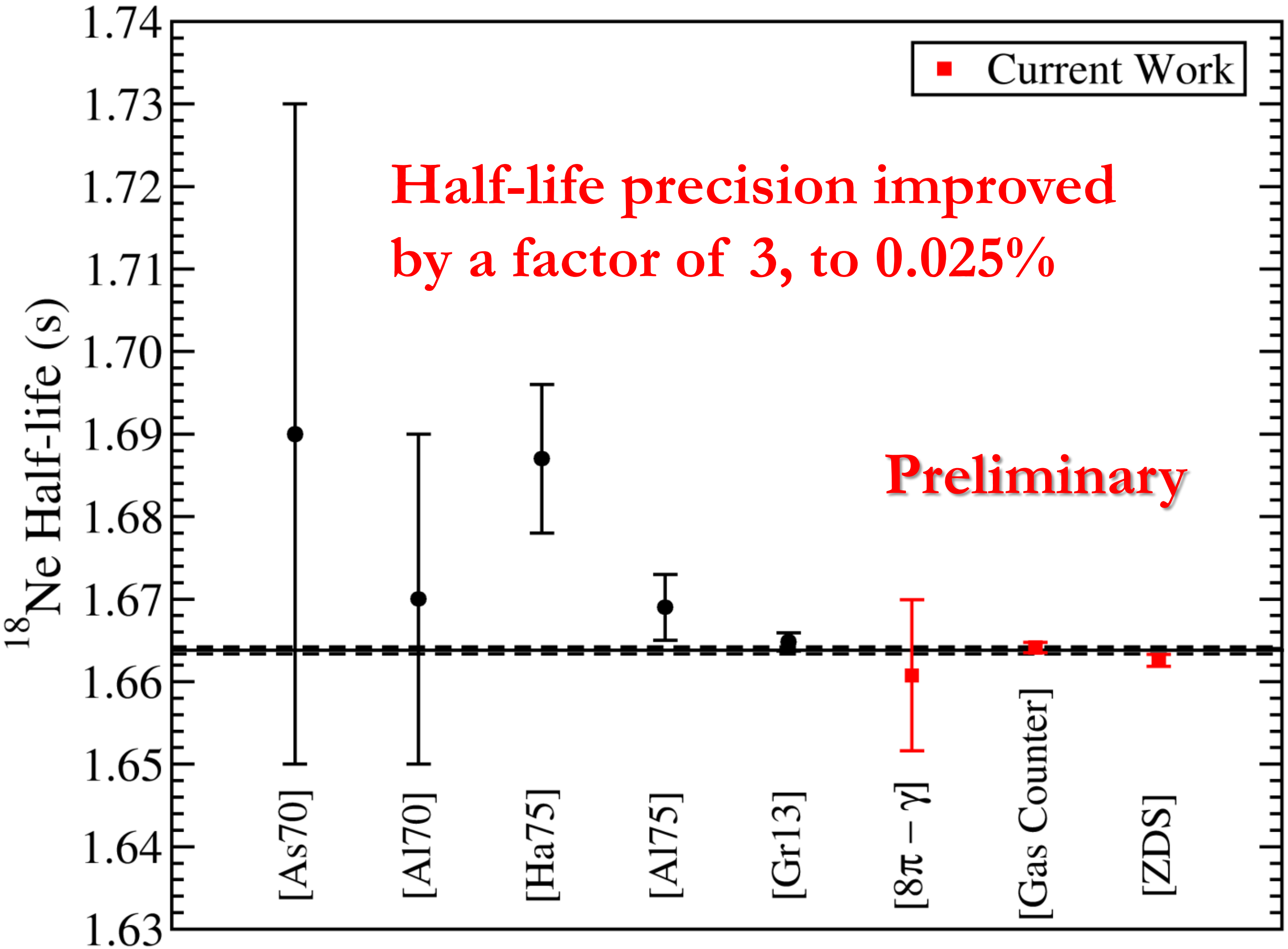
LOUISIANA STATE UNIVERSITY

E. F. Zganjar

^{18}Ne Sample Data – Gas Counter



Status of ^{18}Ne Half-life



^{74}Rb Superallowed Decay ($T_{1/2}$ ~ 65 ms)

Halflife: Measured with the GPS 4π gas proportional counter at ISAC.

$T_{1/2}$ = 64.761(31) ms

G.C. Ball et al., Phys. Rev. Lett. 86, 1454 (2001).

Mass: First demonstration of a high charge state mass measurement for a short-lived isotope with the TITAN Penning trap.

S. Ettenauer et al., Phys. Rev. Lett. 107, 272501 (2011).

Charge Radius: Measured via collinear laser spectroscopy:

$\langle r^2_{ch} \rangle^{1/2}$ = 4.19(1) fm

Reduces uncertainty in theoretical δ_{C2} by ~ 20%

E. Mané et al., Phys. Rev. Lett. 107, 212502 (2011).

Branching Ratio: Measured with the 8π Spectrometer to ± 0.03%

BR = 99.545 (31) %

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

Superallowed β Branching Ratios for A ≥ 62 and the Pandemonium Effect

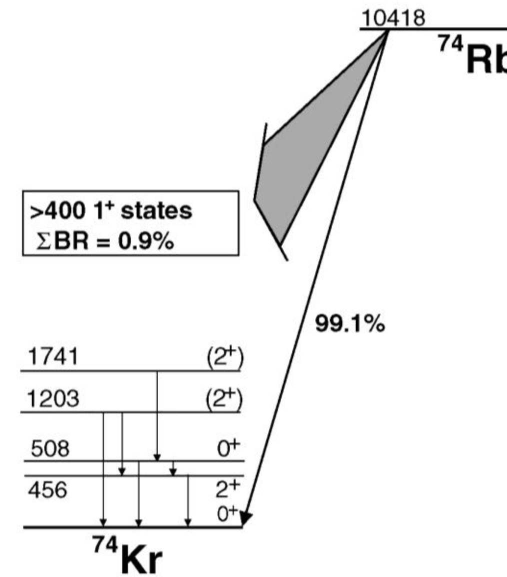
VOLUME 88, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 2002

Superallowed Beta Decay of Nuclei with $A \geq 62$: The Limiting Effect of Weak Gamow-Teller Branches

J. C. Hardy and I. S. Towner*
Cyclotron Institute, Texas A & M University, College Station, Texas 77843
(Received 16 January 2002; published 6 June 2002)

The most precise value of V_{ud}, which is obtained from superallowed nuclear β decay, leads to a violation of Cabibbo-Kobayashi-Maskawa unitarity by 2.2σ. Experiments are underway on two continents to test and improve this result through decay studies of odd-odd $N = Z$ nuclei with $A \geq 62$. We show, in a series of illustrative shell-model calculations, that numerous weak Gamow-Teller branches are expected to compete with the superallowed branch in each of these nuclei. Though the total Gamow-Teller strength is significant, many of the individual branches will be unobservably weak. Thus, new techniques must be developed if reliable ft values are to be obtained with 0.1% precision for the superallowed branches.

DOI: 10.1103/PhysRevLett.88.252501 PACS numbers: 23.40.Hc, 21.60.Cs, 27.50.+e



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.

In the subsequent γ decay, many individual γ-rays may be too weak to identify.

The sum of these unobserved γ intensities will, however, generally be sufficient to prevent precision determination of β decay branching ratios through γ-ray spectroscopy.

8π Spectrometer – Decay Spectroscopy at ISAC-I

8π Spectrometer at ISAC

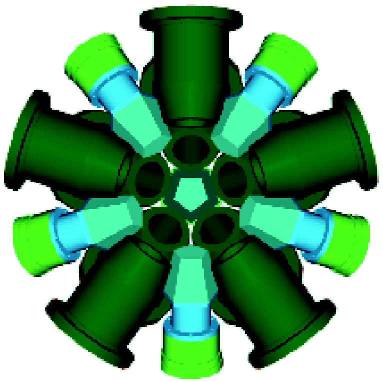
20 Compton-Suppressed HPGe detectors

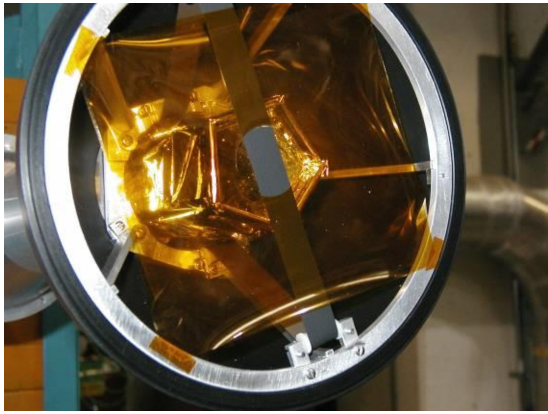
and 10 BaF2 detectors for γ-ray detection

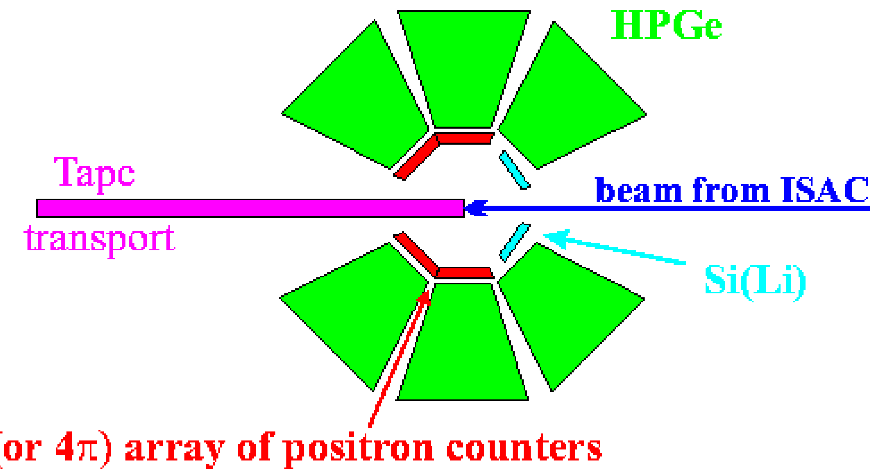
20 plastic scintillators for β detection

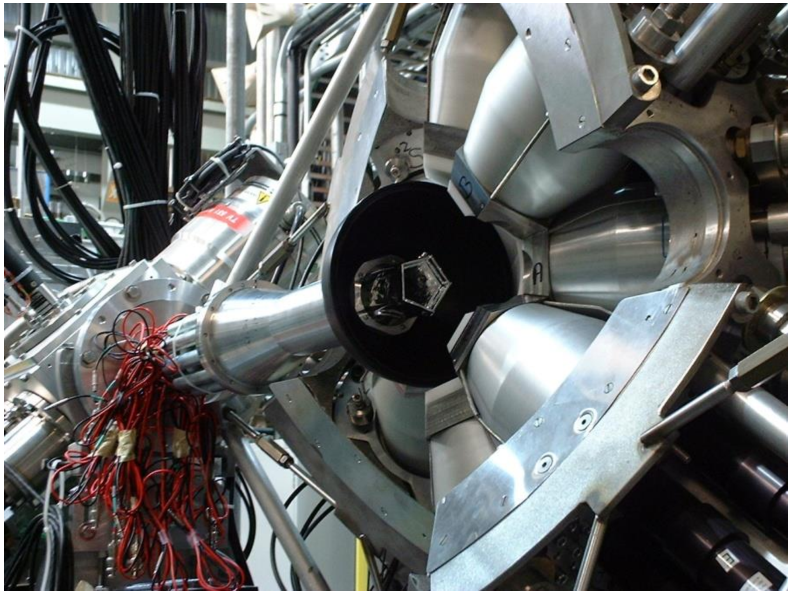
5 Si(Li) detectors for conversion electron spectroscopy

Fast, in-vacuum tape transport system



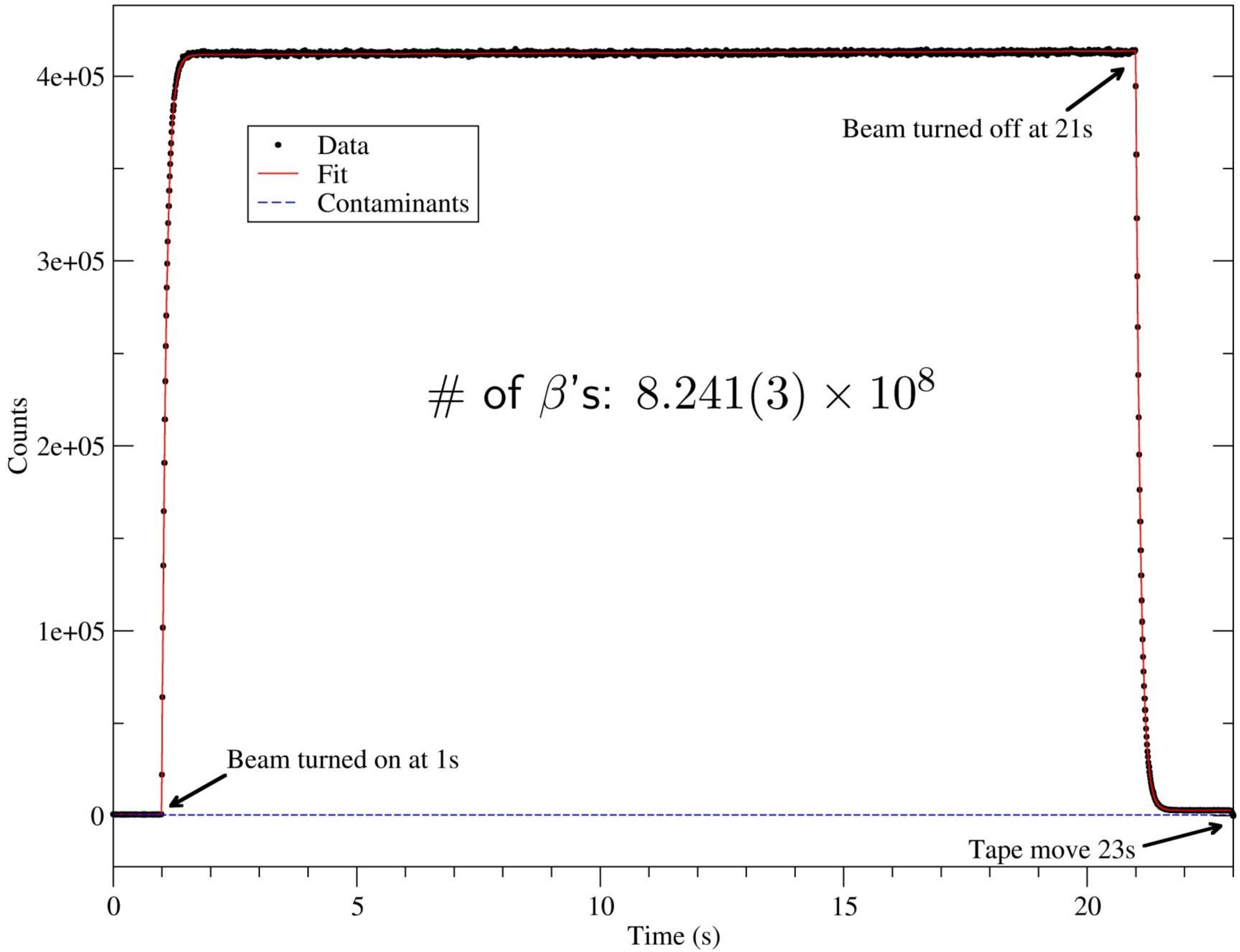




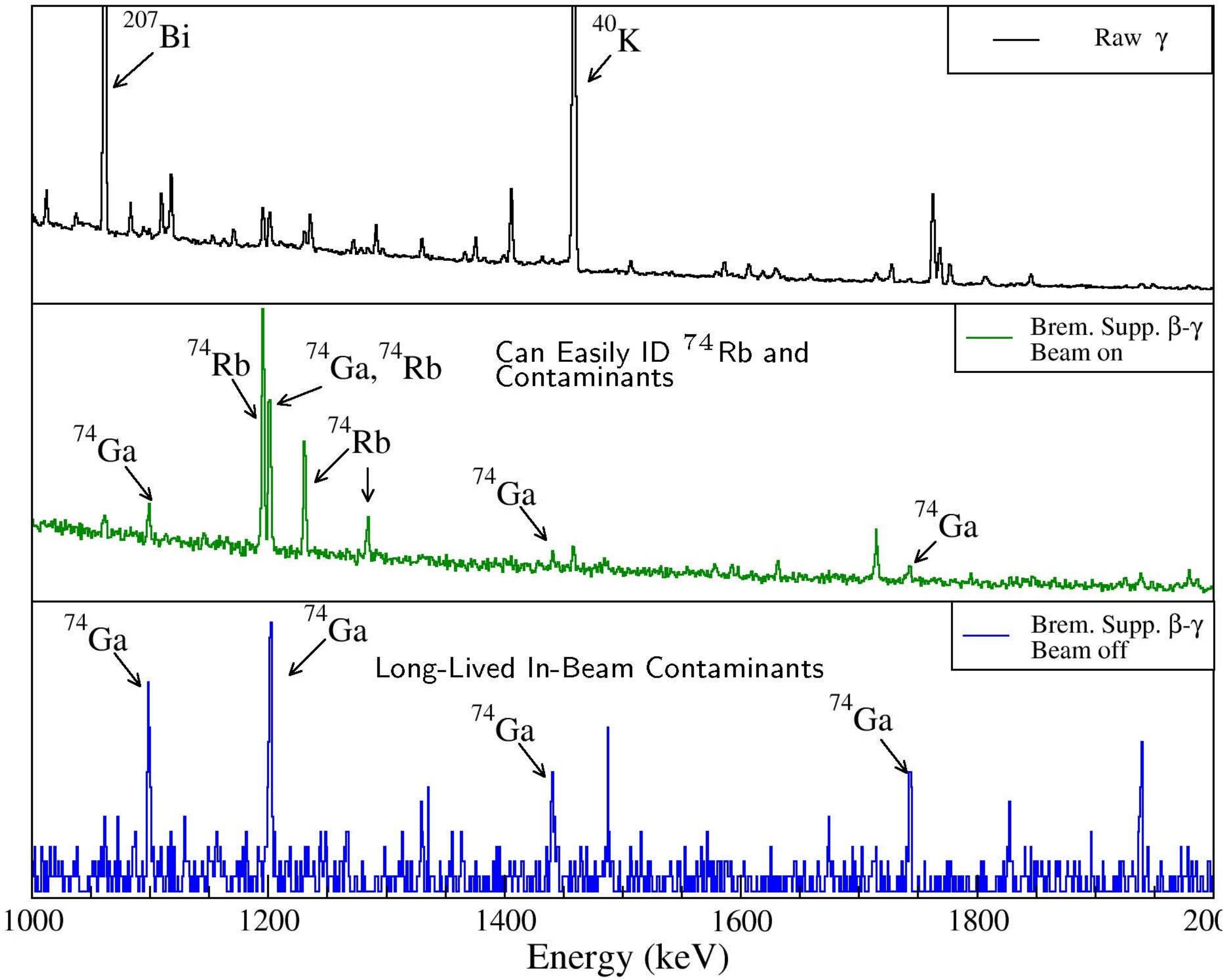


Simultaneous collection of γ-singles, γγ coincidences, β tagging, conversion electrons, and lifetime measurements

Counting ^{74}Rb β Decays with SCEPTAR



Identifying γ-rays from ^{74}Rb Decay

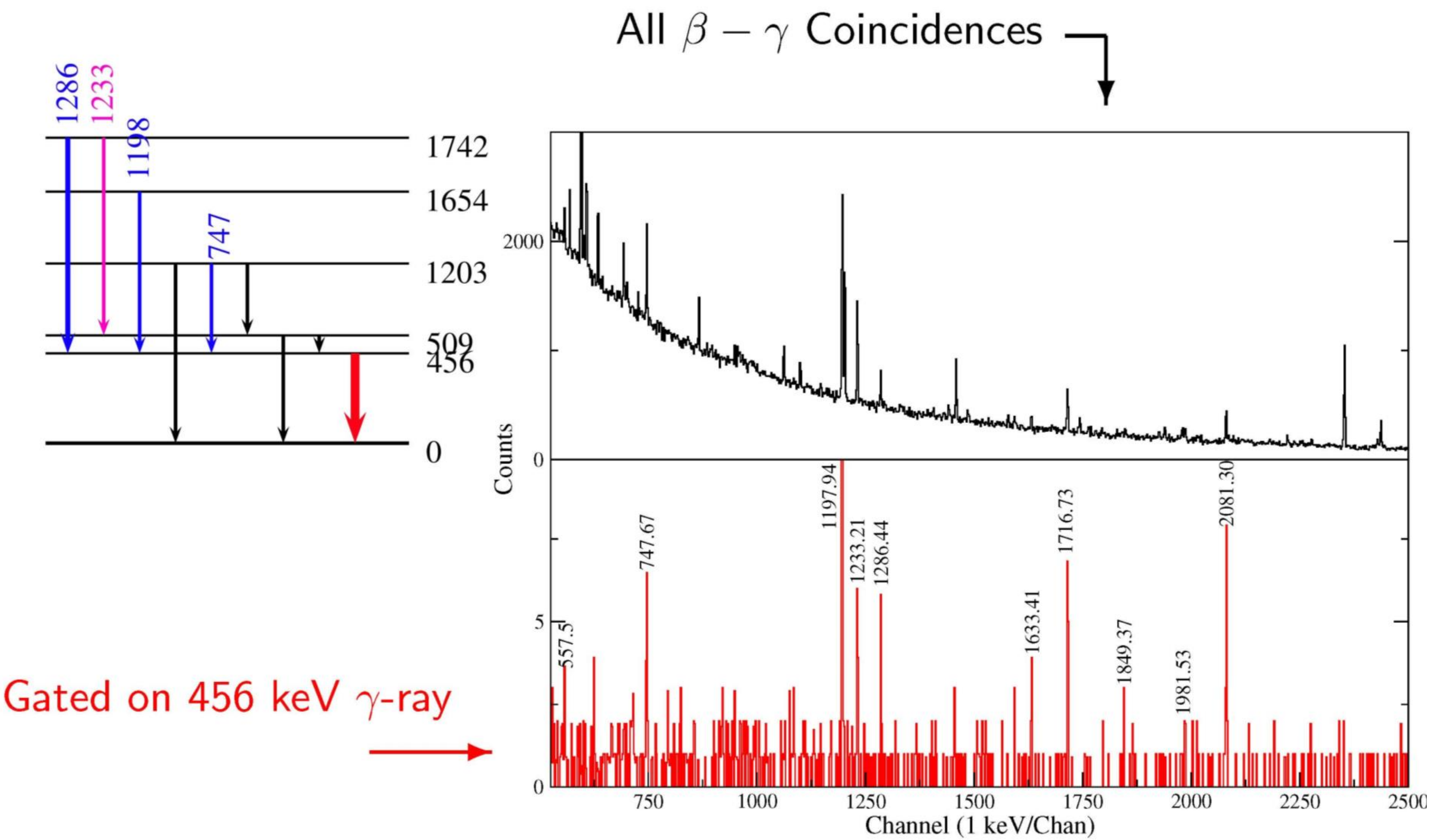


Raw γ-spectrum contains lines from room background and in-beam contaminants

β-γ coincidence, Bremsstralung suppression reduce background

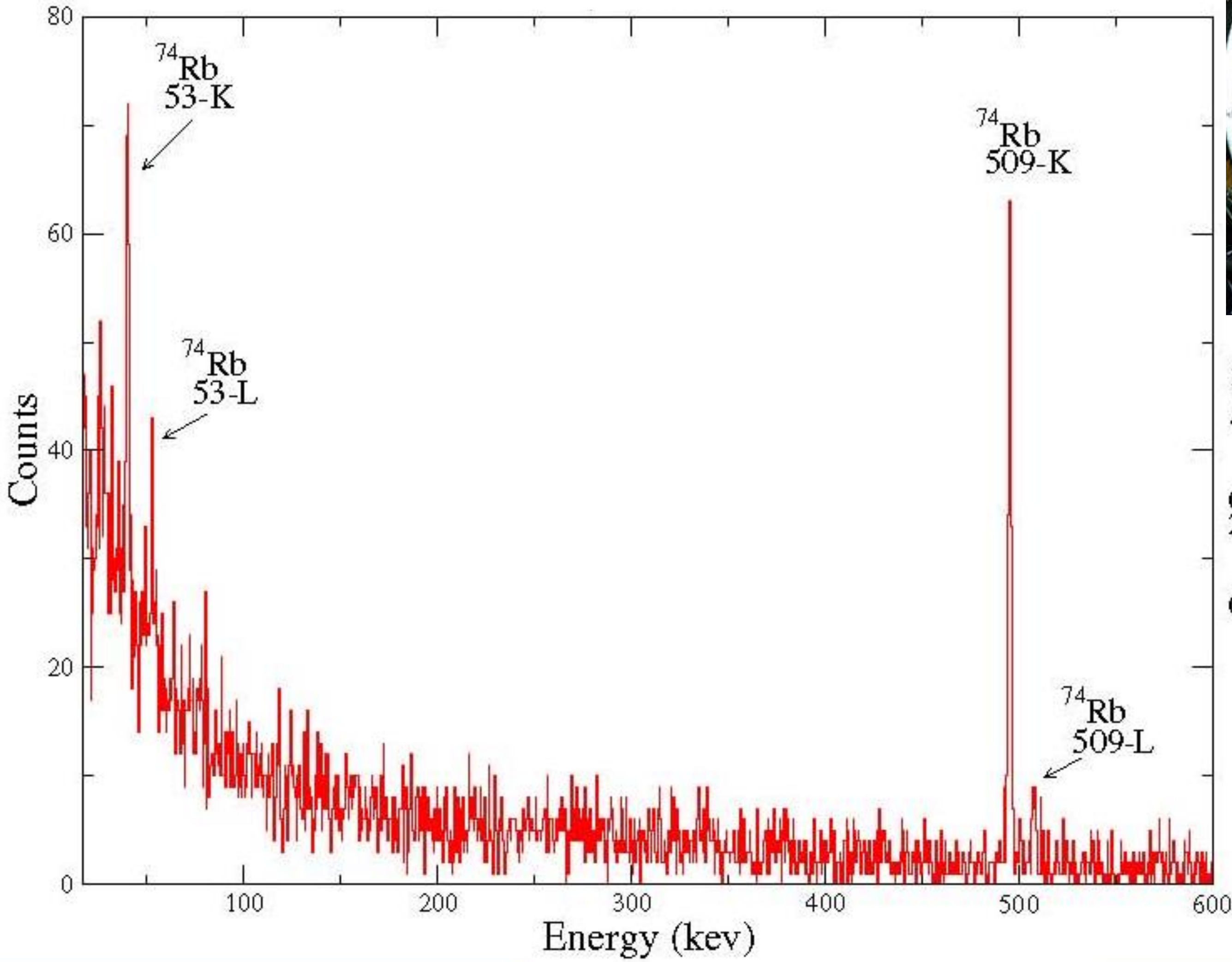
Spectrum during beam-off allows one to identify long-lived contaminants

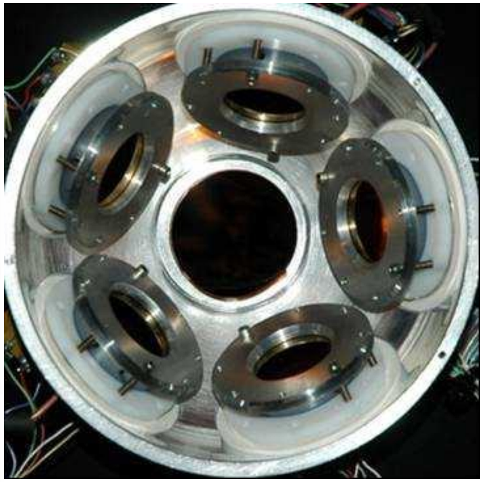
γ–γ Coincidences following ppm β-decay branches of ^{74}Rb

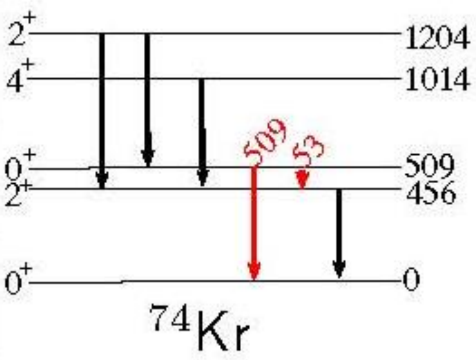


Internal Conversion Decay of the 0^+_2 State of ^{74}Kr

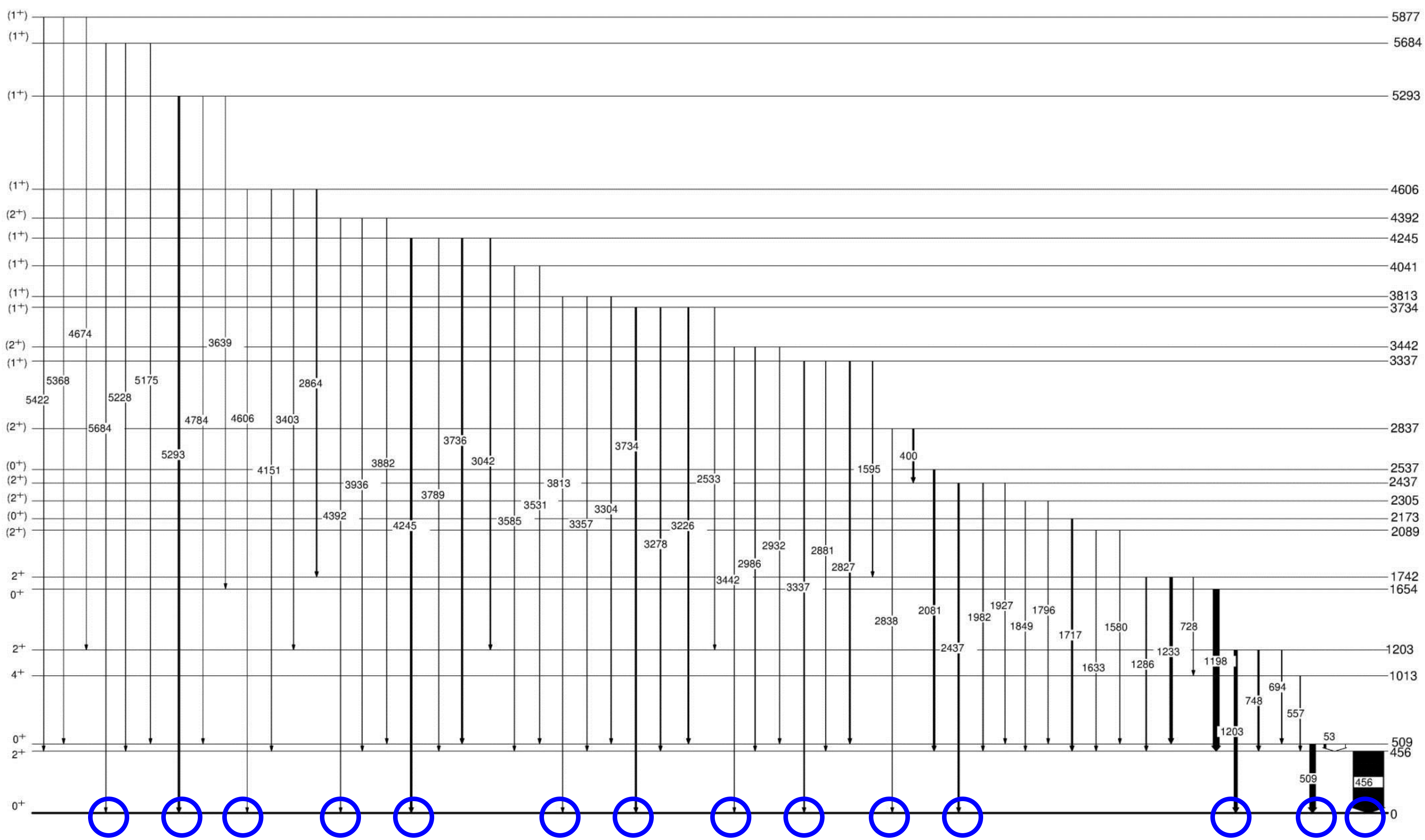
β – γ – electron Coincidence Spectrum







57 γ-ray transitions identified following ^{74}Rb decay



Ground-state γ-feeding of I_{gs} = 3950(70) ppm identified.

Controlling Pandemonium via 2^+ "Collector" States

$I_{gs} = 3950(70)$ ppm

Direct β feeding of 2^+ states is negligible

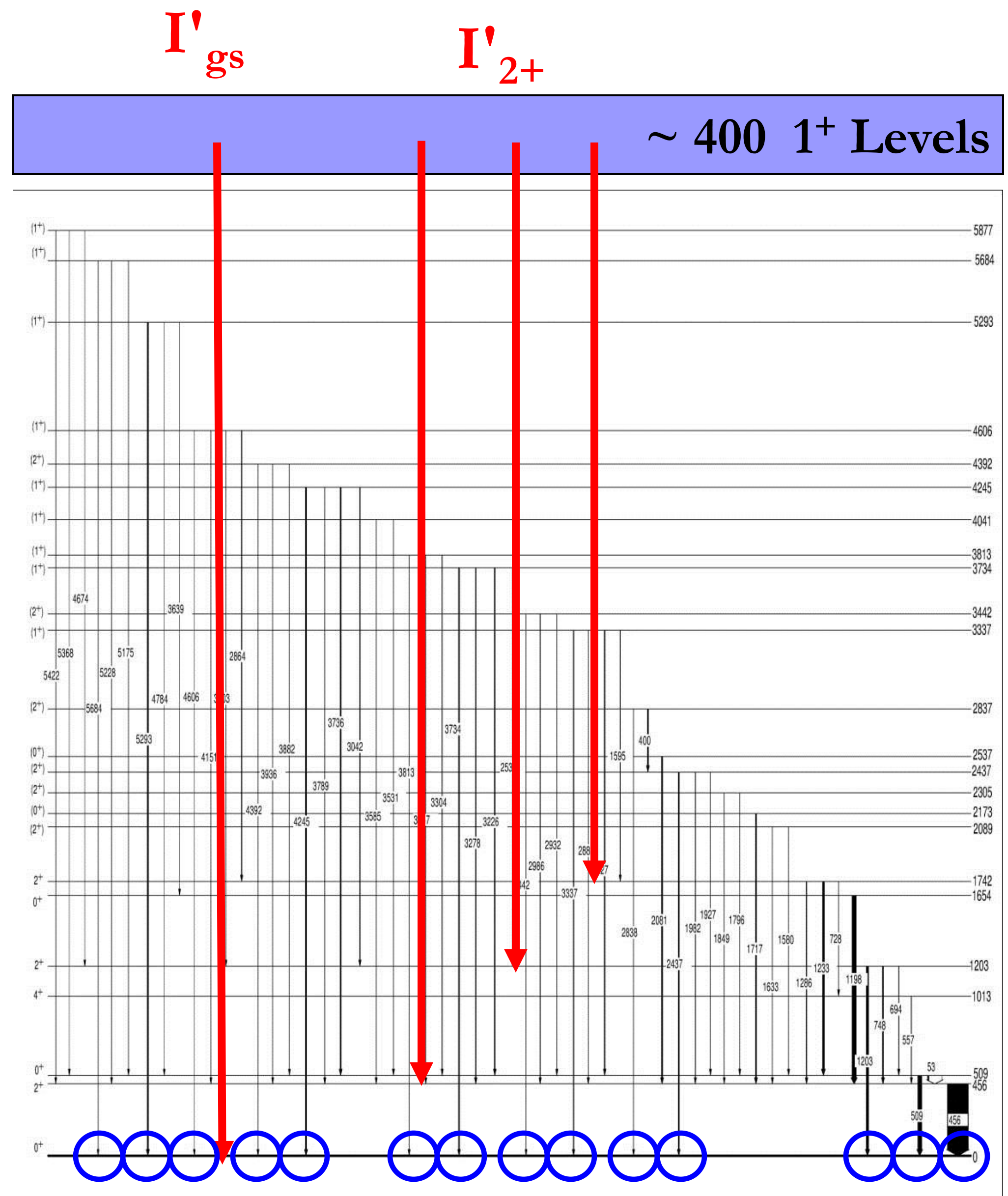
$I'_{2+} = 1225(57)$ ppm

$B_{gs} = I'_{gs} / (I'_{gs} + I'_{2+})$

Expt + Shell Model:

$B_{gs} = 0.33(11)$

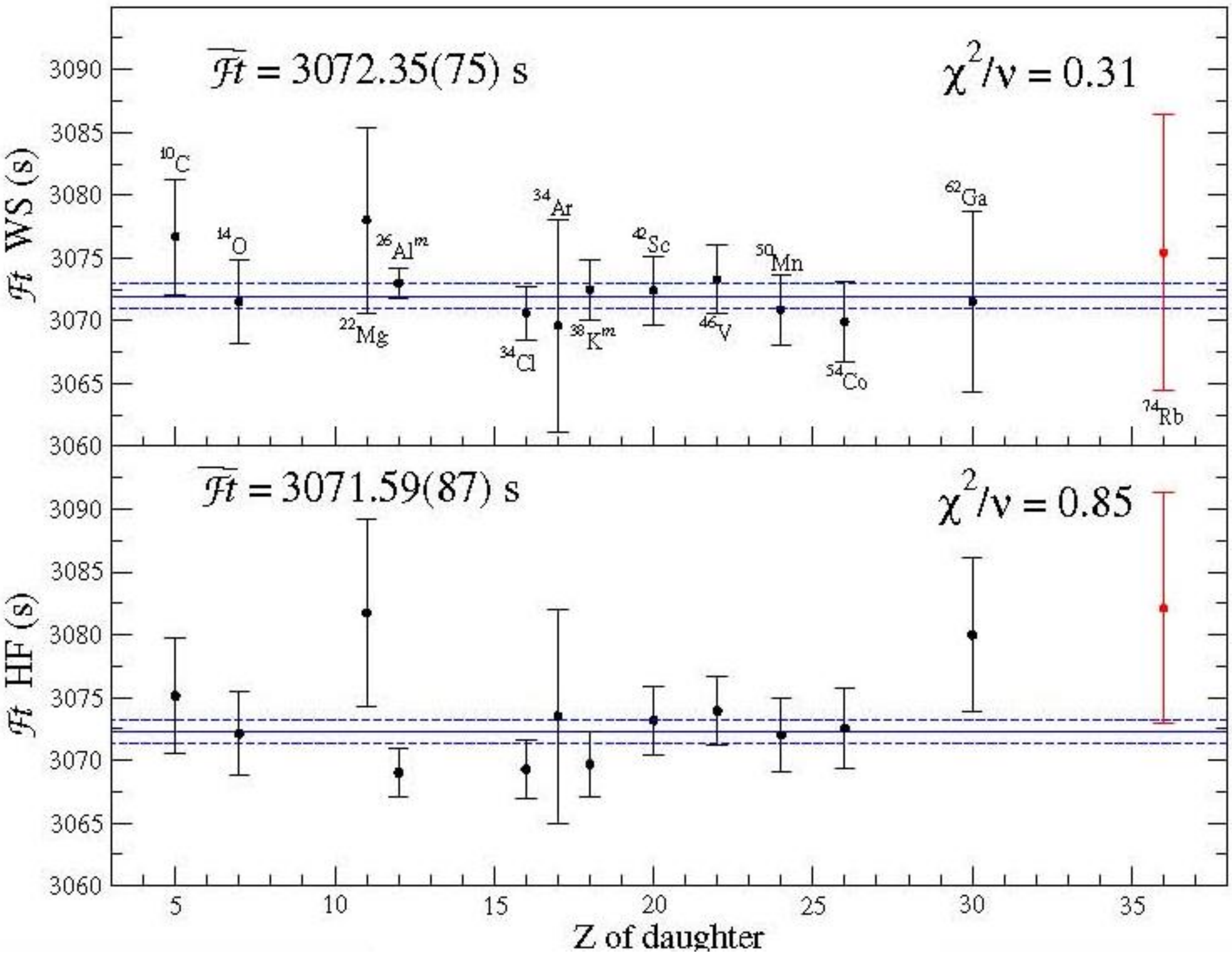
$I'_{gs} = 600(300)$ ppm



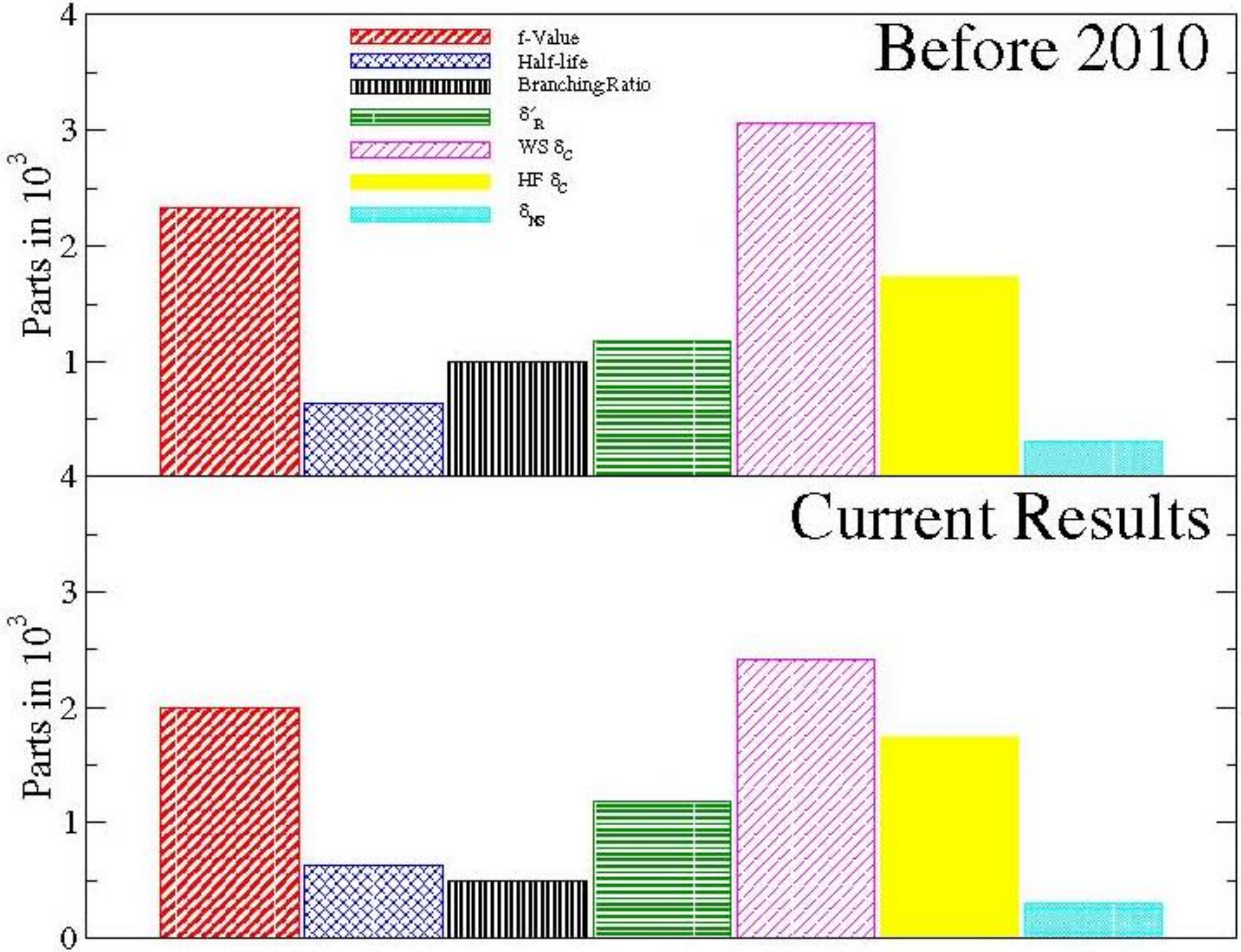
Superallowed Branching Ratio:
99.545 ± 0.031 %

R. Dunlop PRC 88, 045501 (2013)

^{74}Rb Superallowed Decay



^{74}Rb Superallowed Error Budget



The Future …

***G**amma*

***R**ay*

***I**nfrastructure*

***F**or*

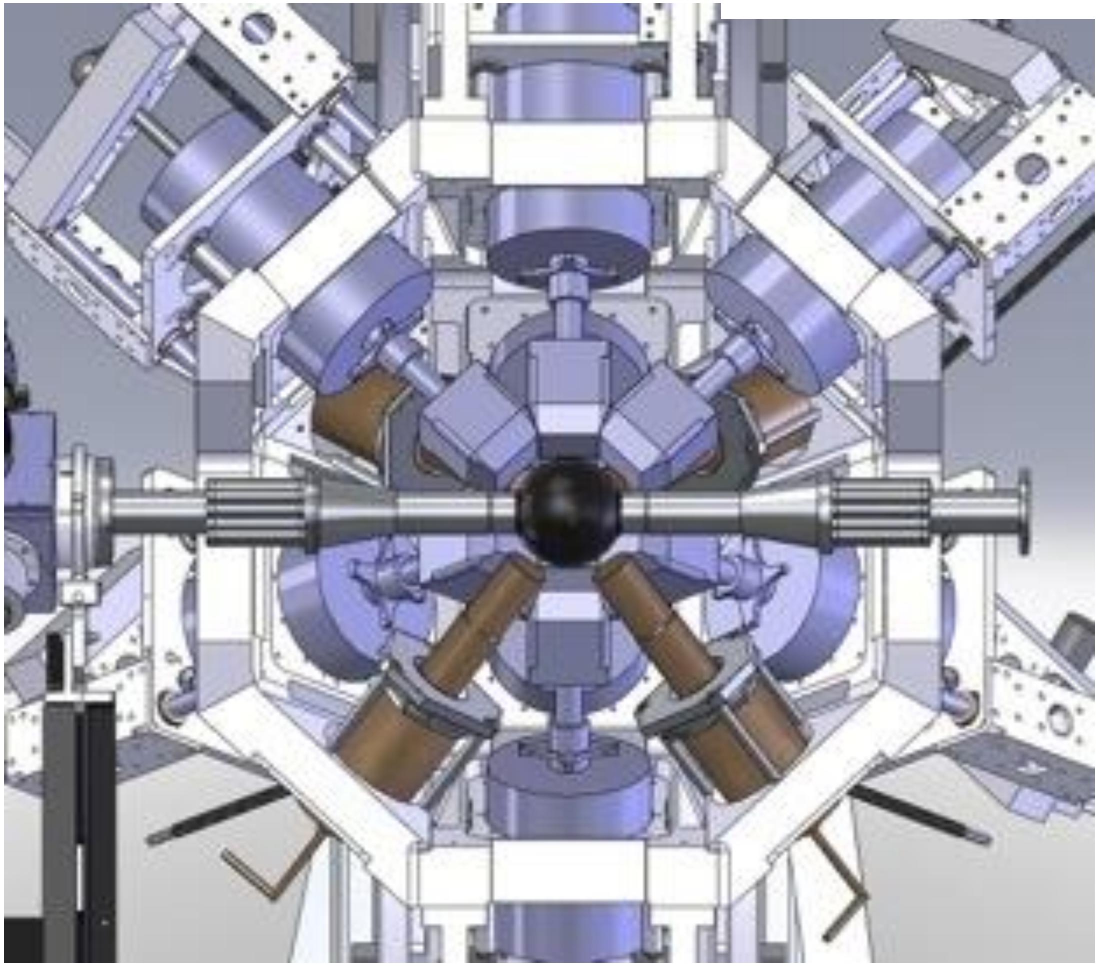
***F**undamental*

***I**nvestigations*

of

***N**uclei*

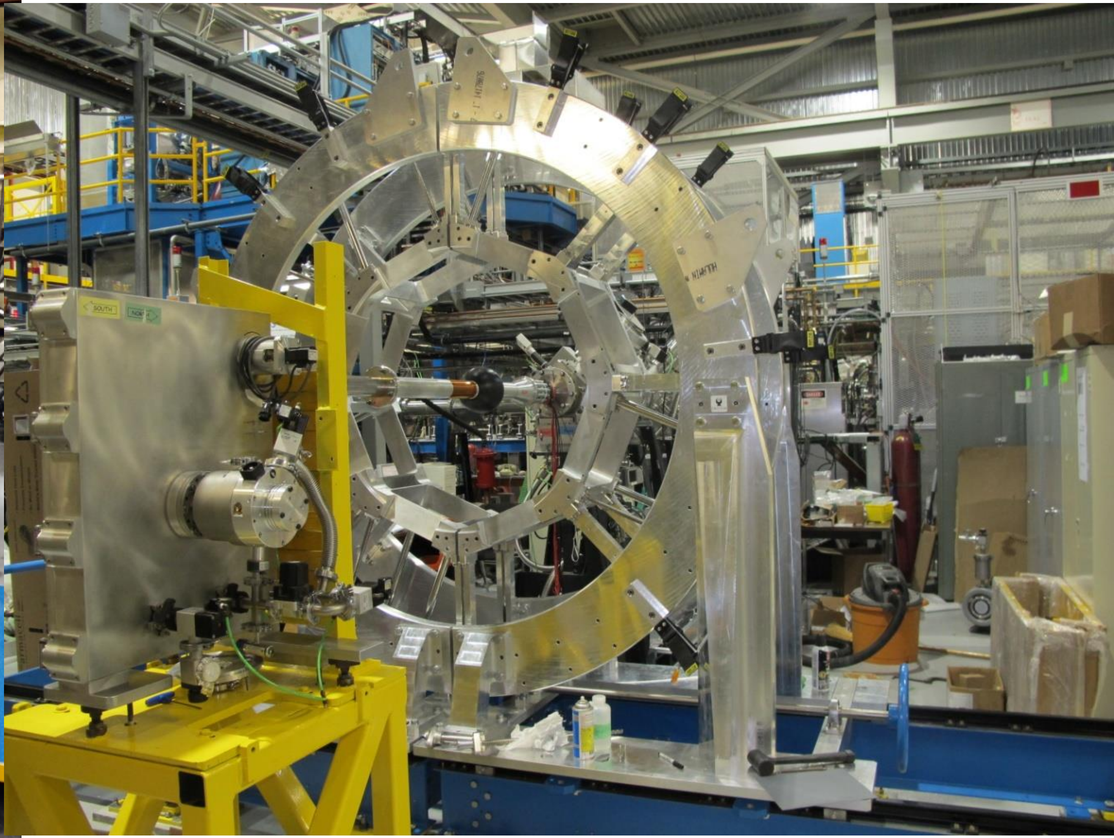
GRIFFIN



A new high-efficiency decay spectroscopy facility for ISAC-I

GRIFFIN @ ISAC-I

GRIFFIN



June 14, 2014

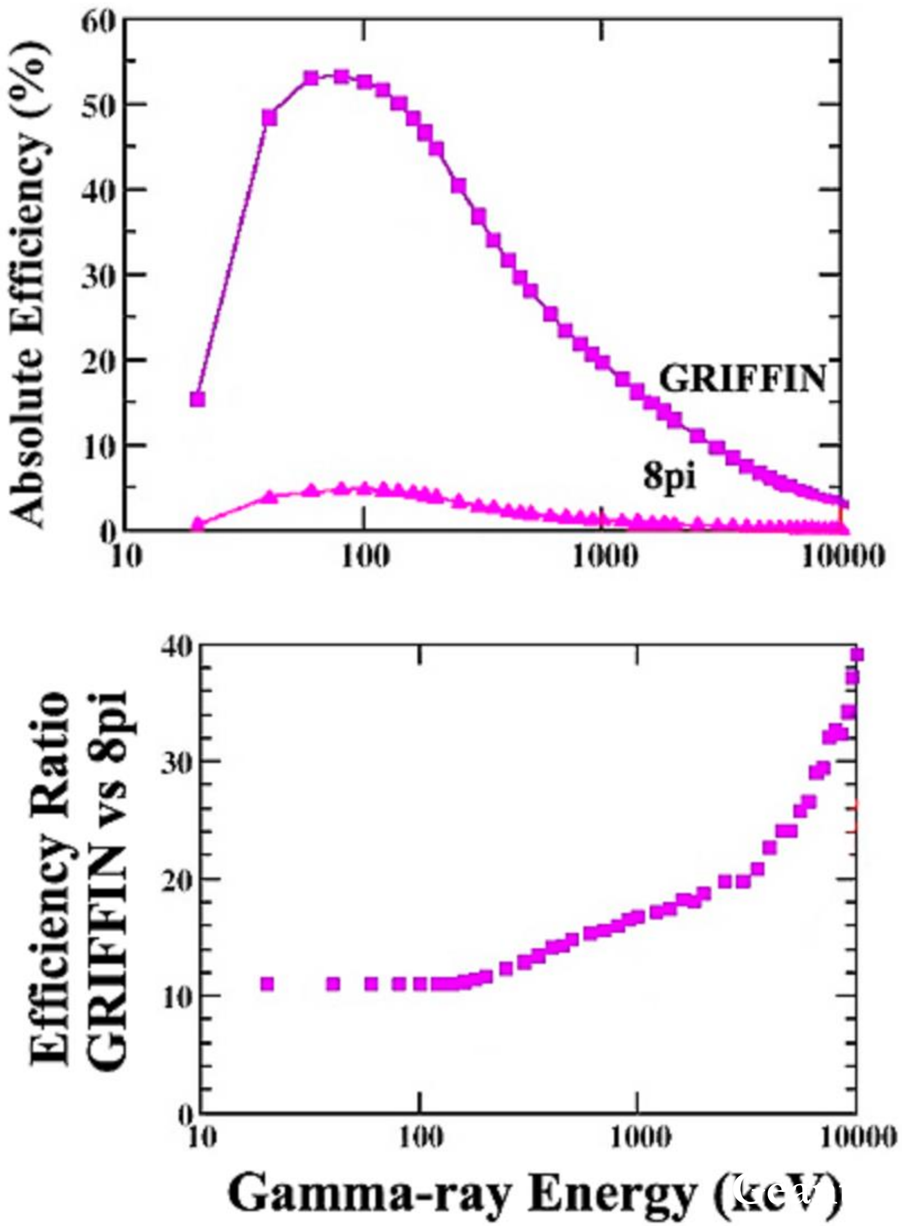
GRIFFIN

16 large-volume clover-type HPGe γ-ray detector

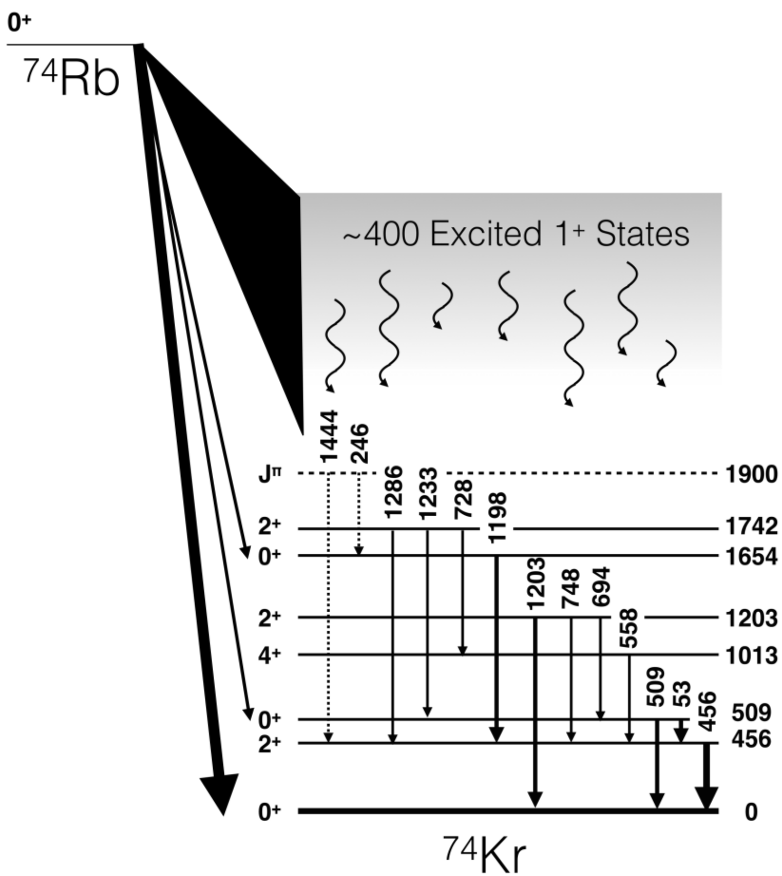
17 times the efficiency of the 8π at $E_\gamma = 1$ MeV

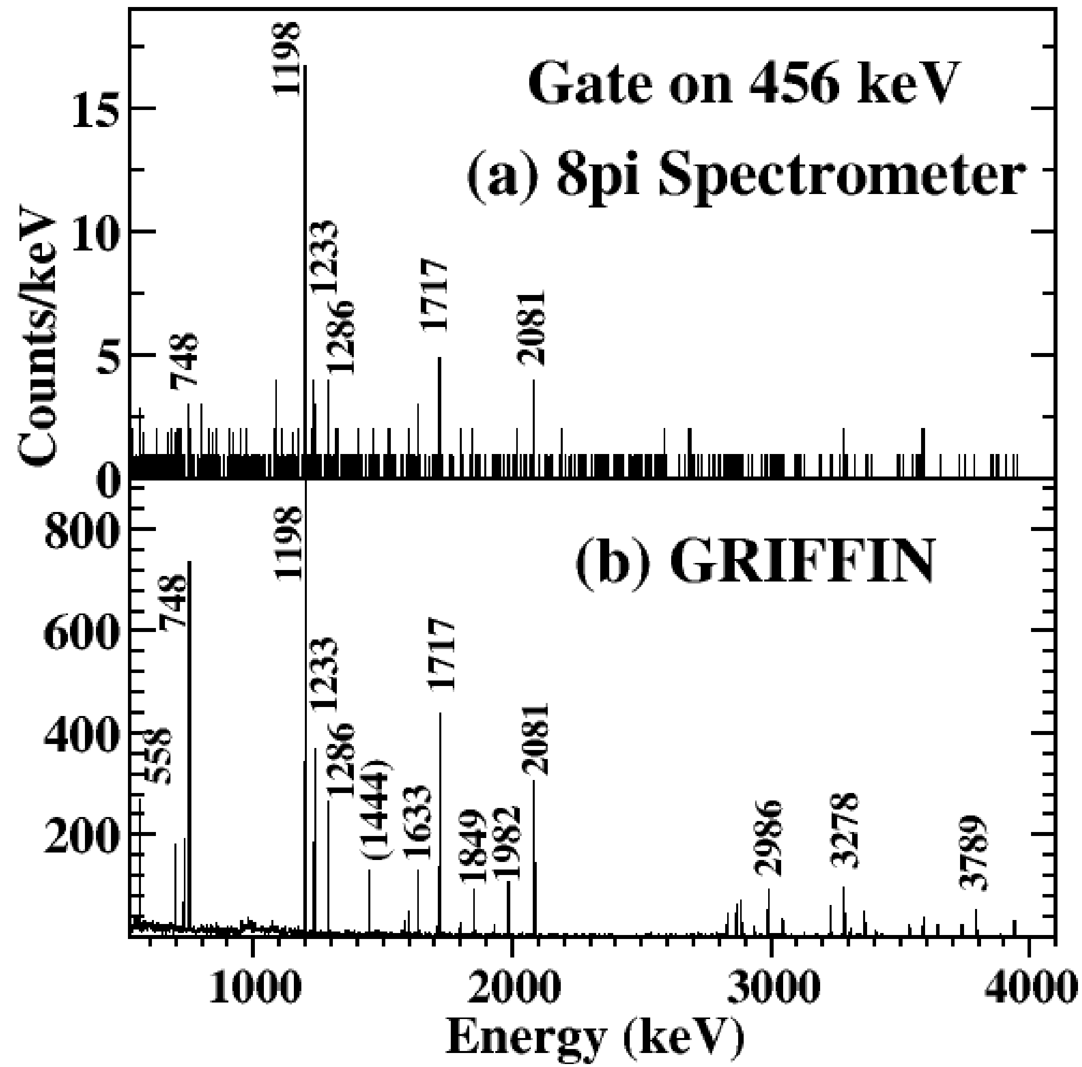
Efficiency improvement increases with γ-ray energy

~300x the γ-γ efficiency of the 8π

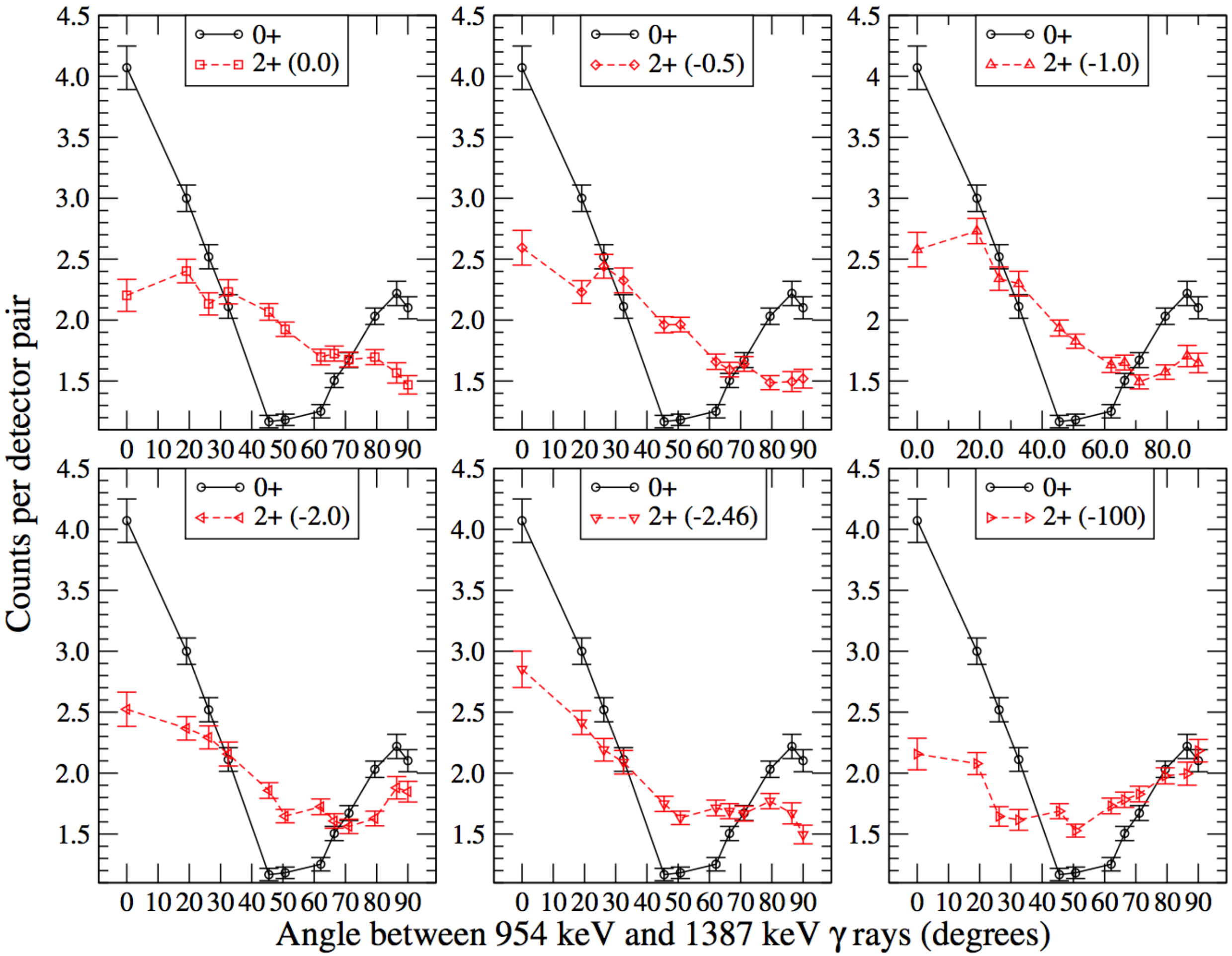


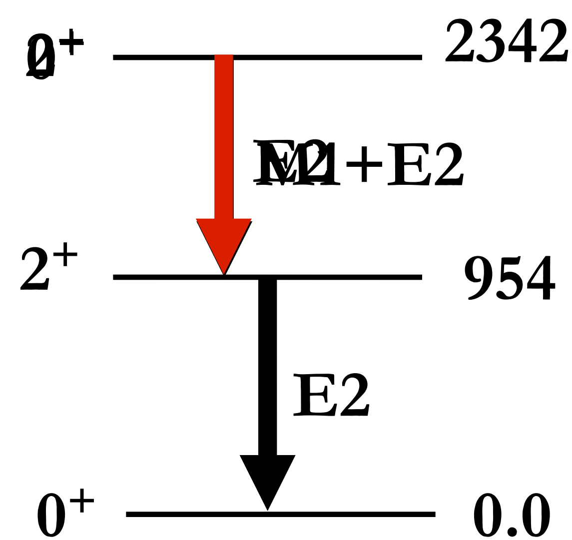
^{74}Rb Superallowed Decay with GRIFFIN





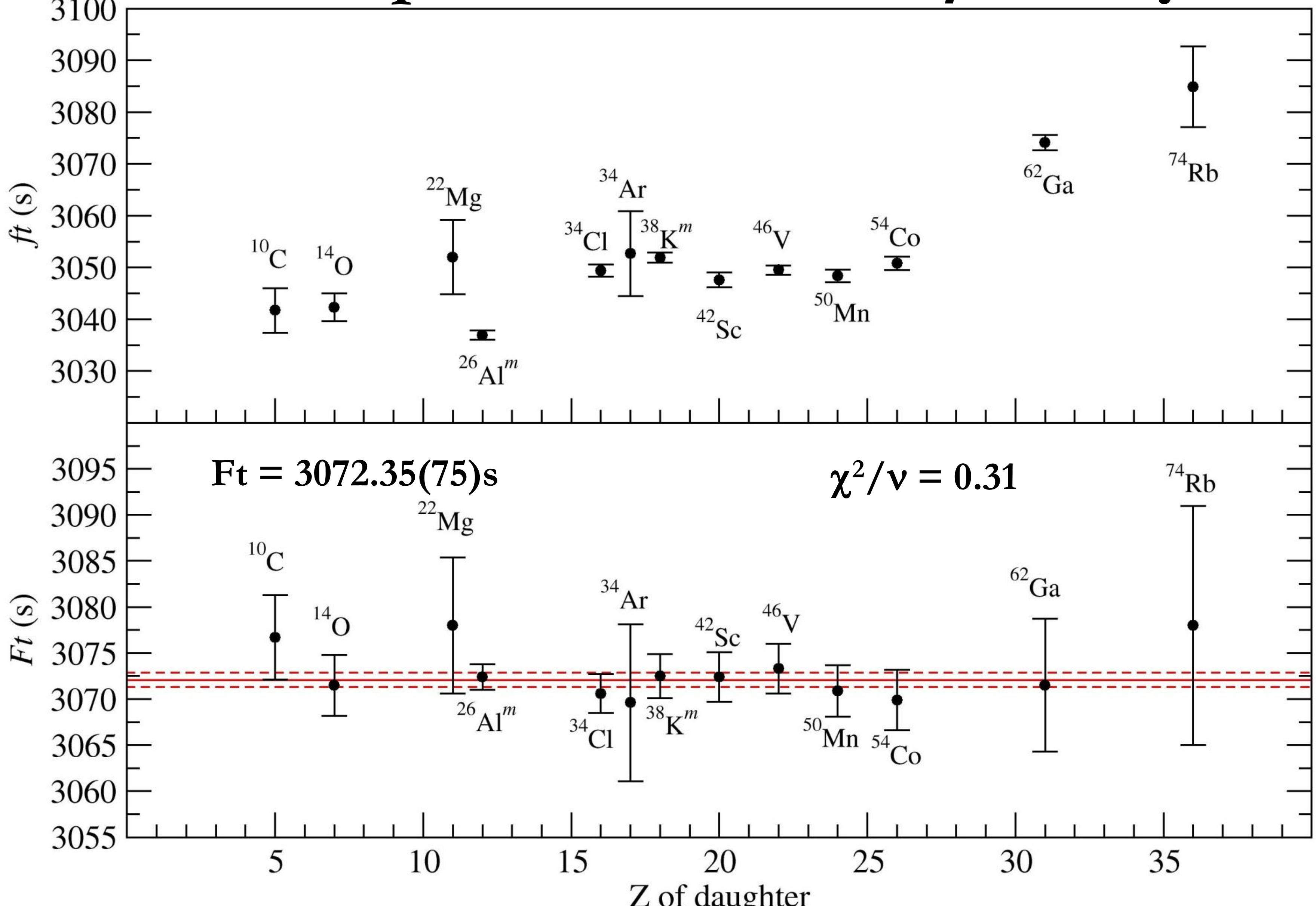
Angular Correlation Measurements with GRIFIFN (S1518: ^{62}Ga superallowed decay)





Using GRIFFIN we can determine the spin-parity of the 2342 keV state

World Superallowed Fermi β Decay Data



World Superallowed Fermi β Decay Data

CVC hypothesis confirmed to ± 0.013%

Set limits on maximally parity violating weak scalar currents:

$$C_S/C_V = 0.0011 \pm 0.0013$$

V_{ud} determined from the superallowed data is, by far, the most precisely determined element of the CKM quark-mixing matrix:

$$|V_{ud}| = 0.97425 \pm 0.00022$$

and together with V_{us} (and V_{ub}) provides the most demanding experimental test of the unitarity of the CKM matrix:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.00008 \pm 0.00056$$

Model-dependence of the strongly nuclear structure dependent isospin symmetry breaking corrections in superallowed Fermi β decays remains a key focus of research for both the theoretical and experimental communities.

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Superallowed β Decay Studies at ISAC

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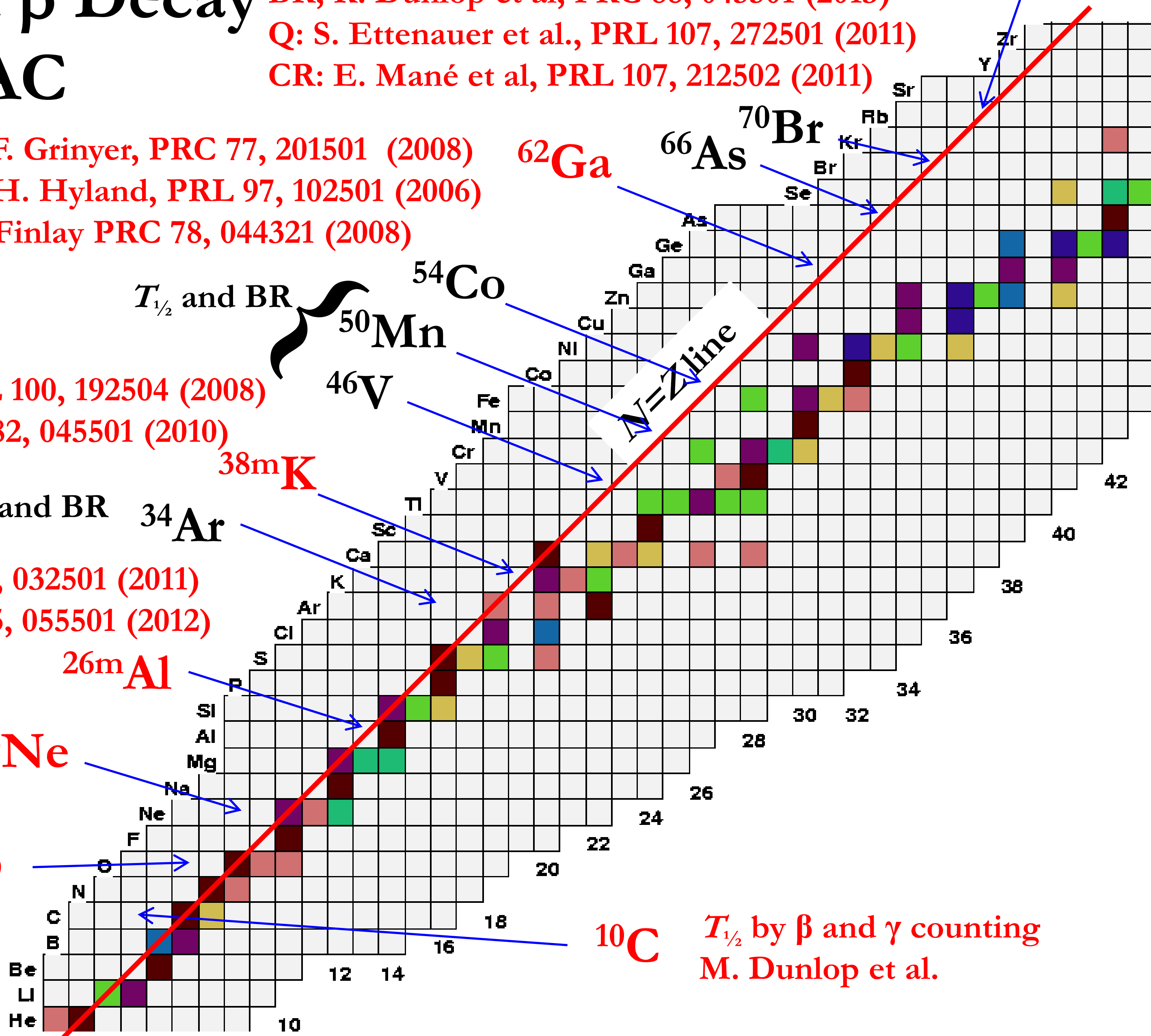

$T_{1/2}$ by β and γ counting
M. Dunlop et al.