# Superallowed Fermi Beta Decay Studies at TRIUMF-ISAC

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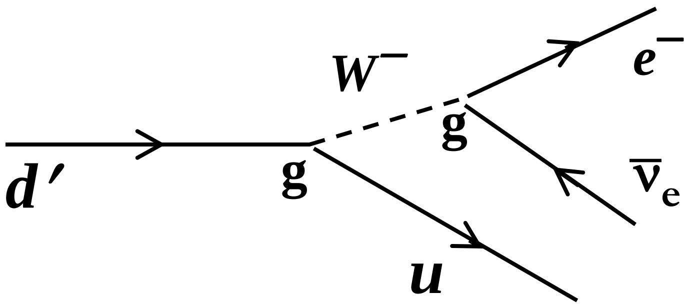
*Solvay Workshop,*
*Brussels,  Belgium*
*Sept 3 – 5, 2014*

# 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.

# $V_{ud}$ from Superallowed Fermi β Decay

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

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

- 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:

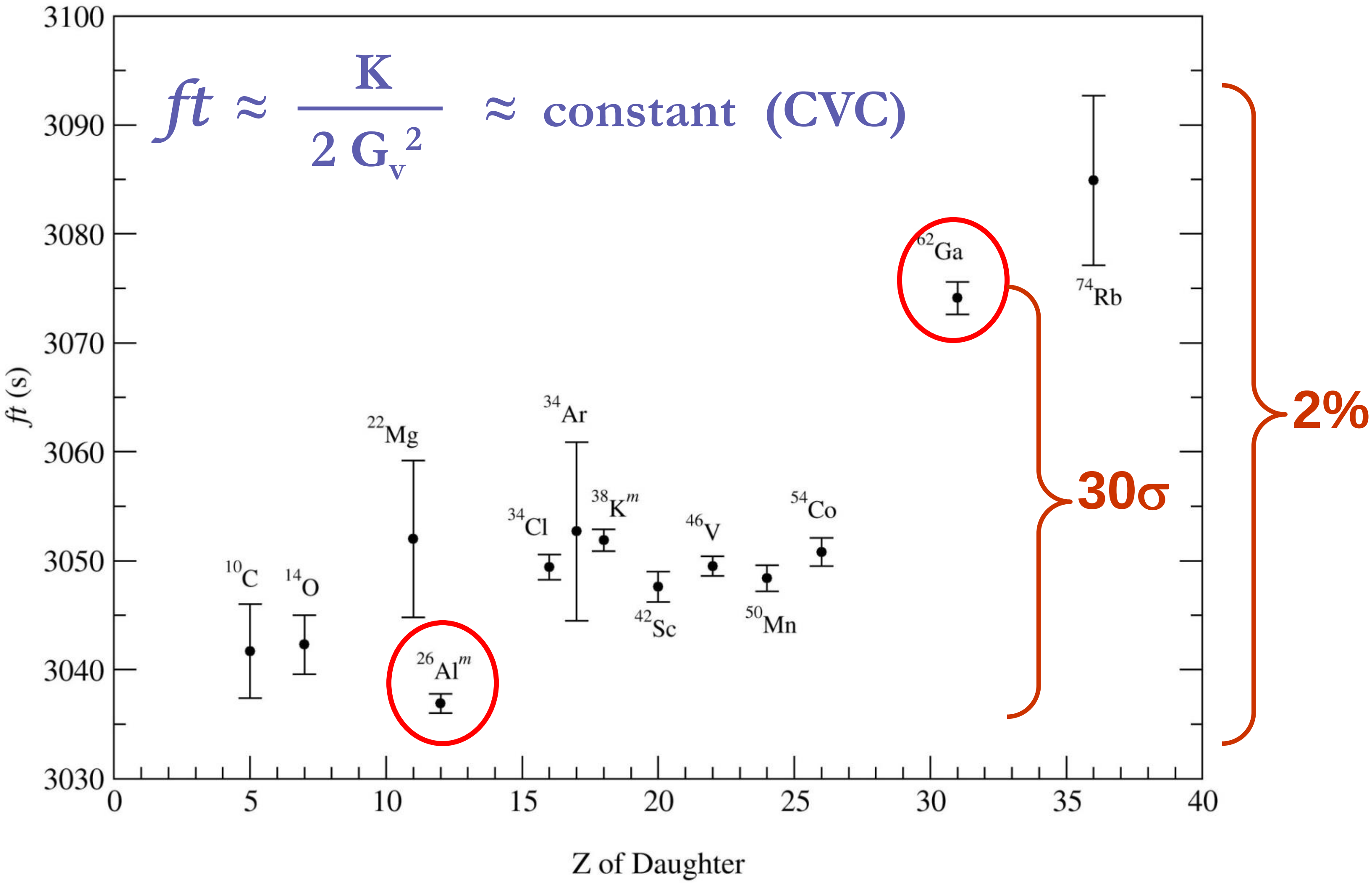
$$|M_{fi}|^2 = (T - T_Z)(T + T_Z + 1) = 2 \quad \text{(for T=1)}$$

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

# 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

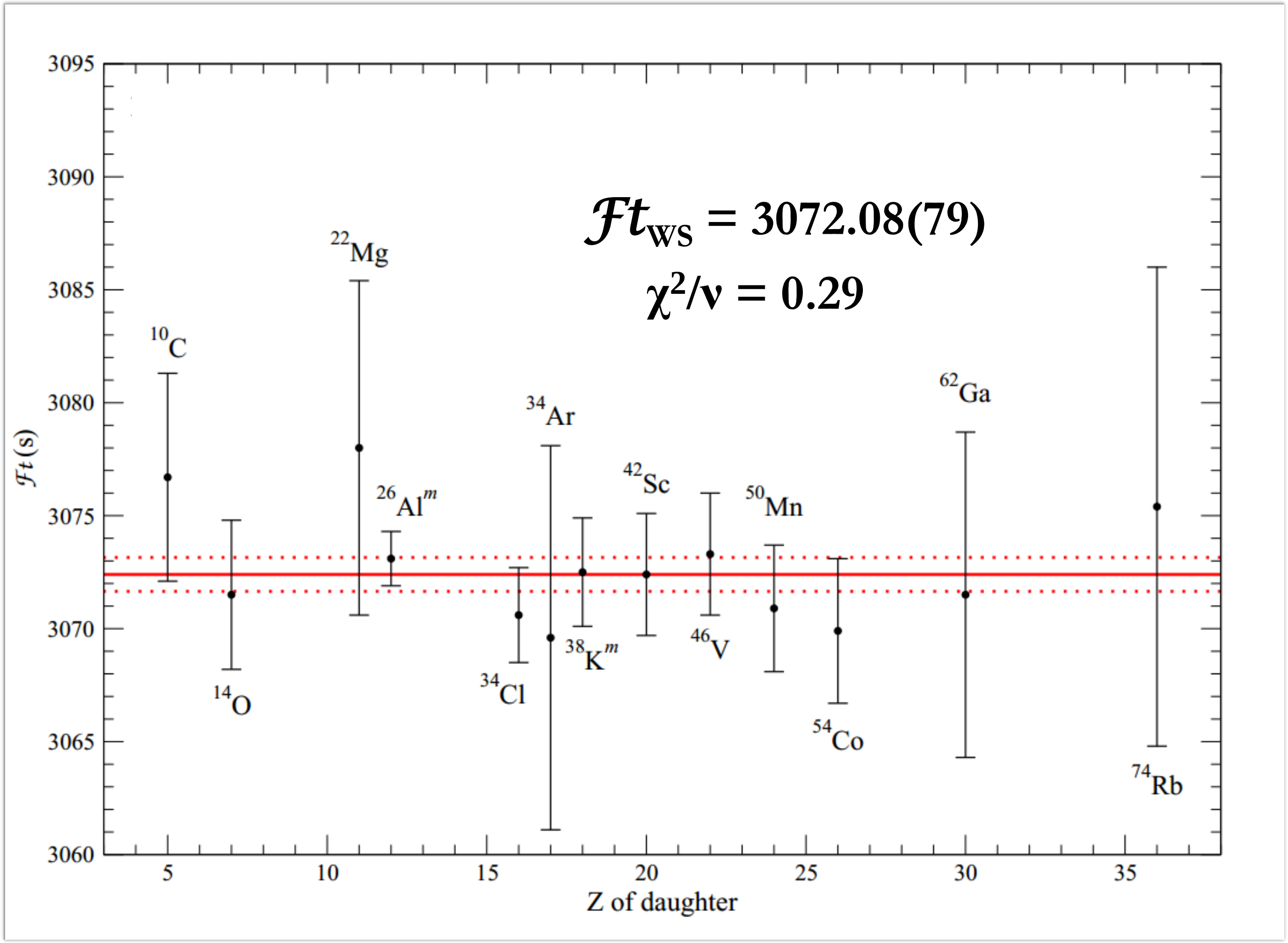
**$\Delta_R^V$ = nucleus independent inner radiative correction: 2.361(38)%**

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

**$\delta_{NS}$ = nuclear structure dependent radiative correction: -0.35% – 0.05%**

**$\delta_C$ = nucleus dependent isospin-symmetry-breaking correction: 0.2% – 1.6%**
**- strong nuclear structure dependence**

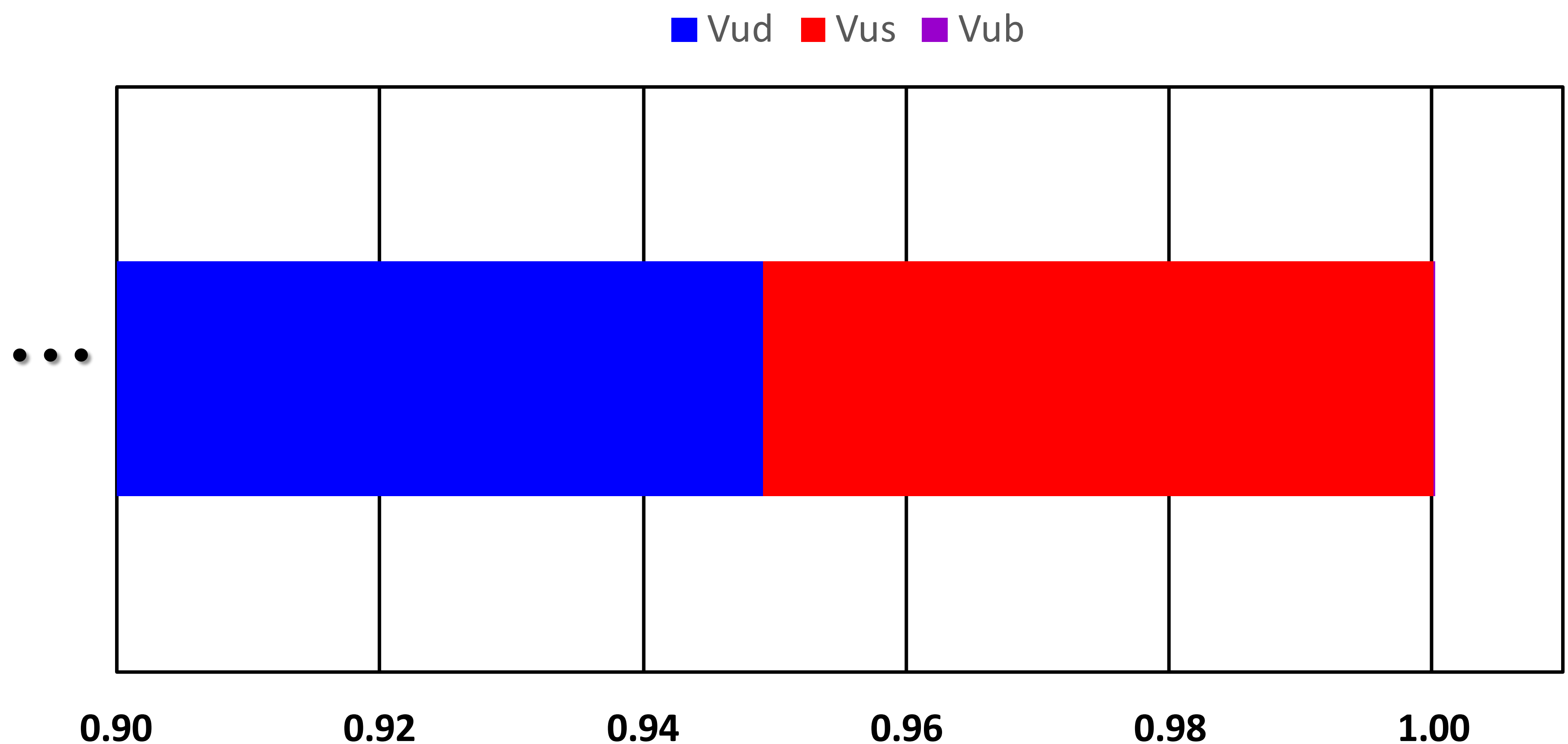
# Corrected Superallowed $\mathcal{F}t$ Values




**$|V_{ud}|$ = 0.97425 ± 0.00022**

**Hardy and Towner, Phys. Rev. C 79, 055502 (2009)**

# 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).

# Theoretical Treatment of $\delta_C$

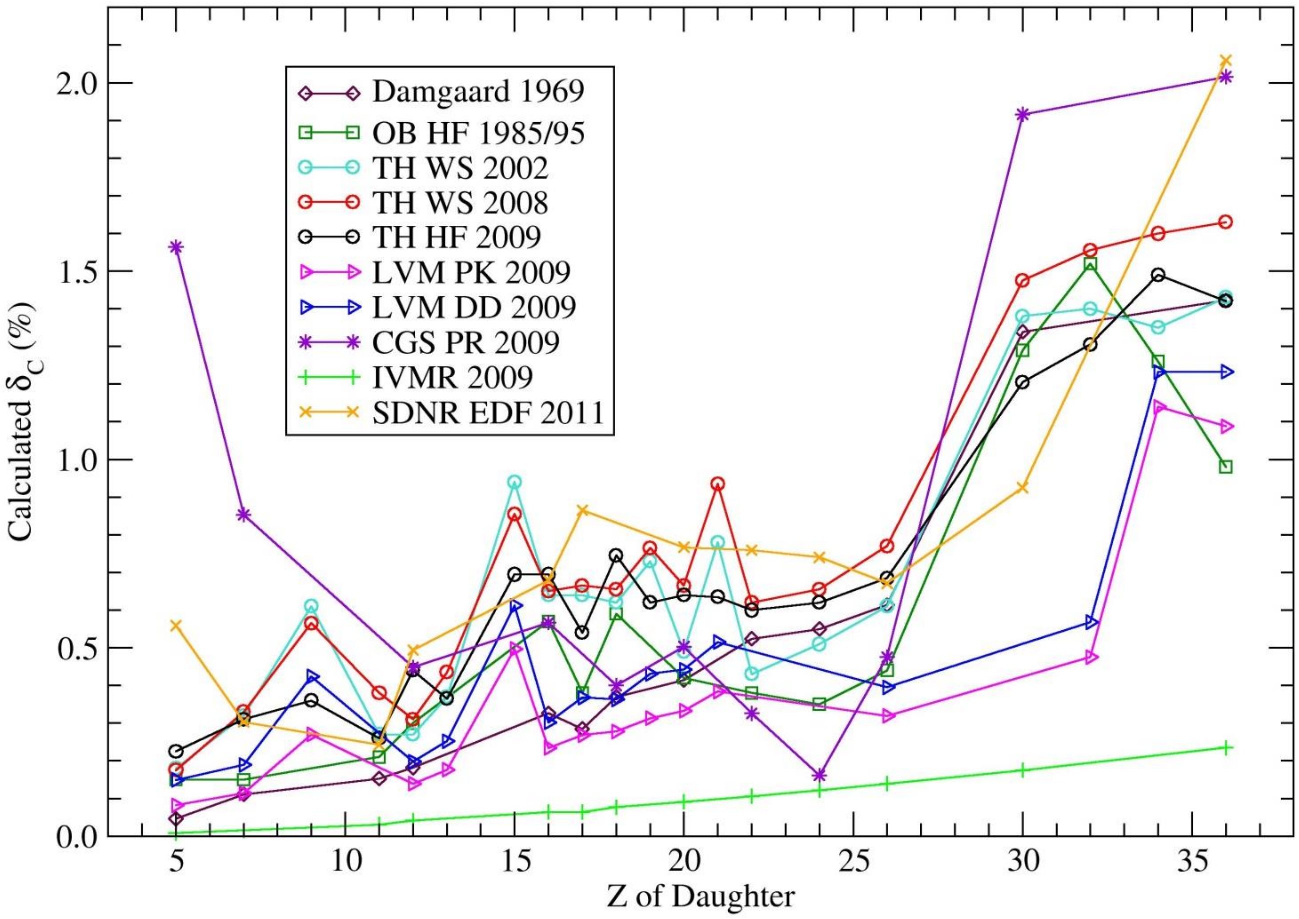
Many recent approaches to ISB corrections

→ Nuclear Shell Model

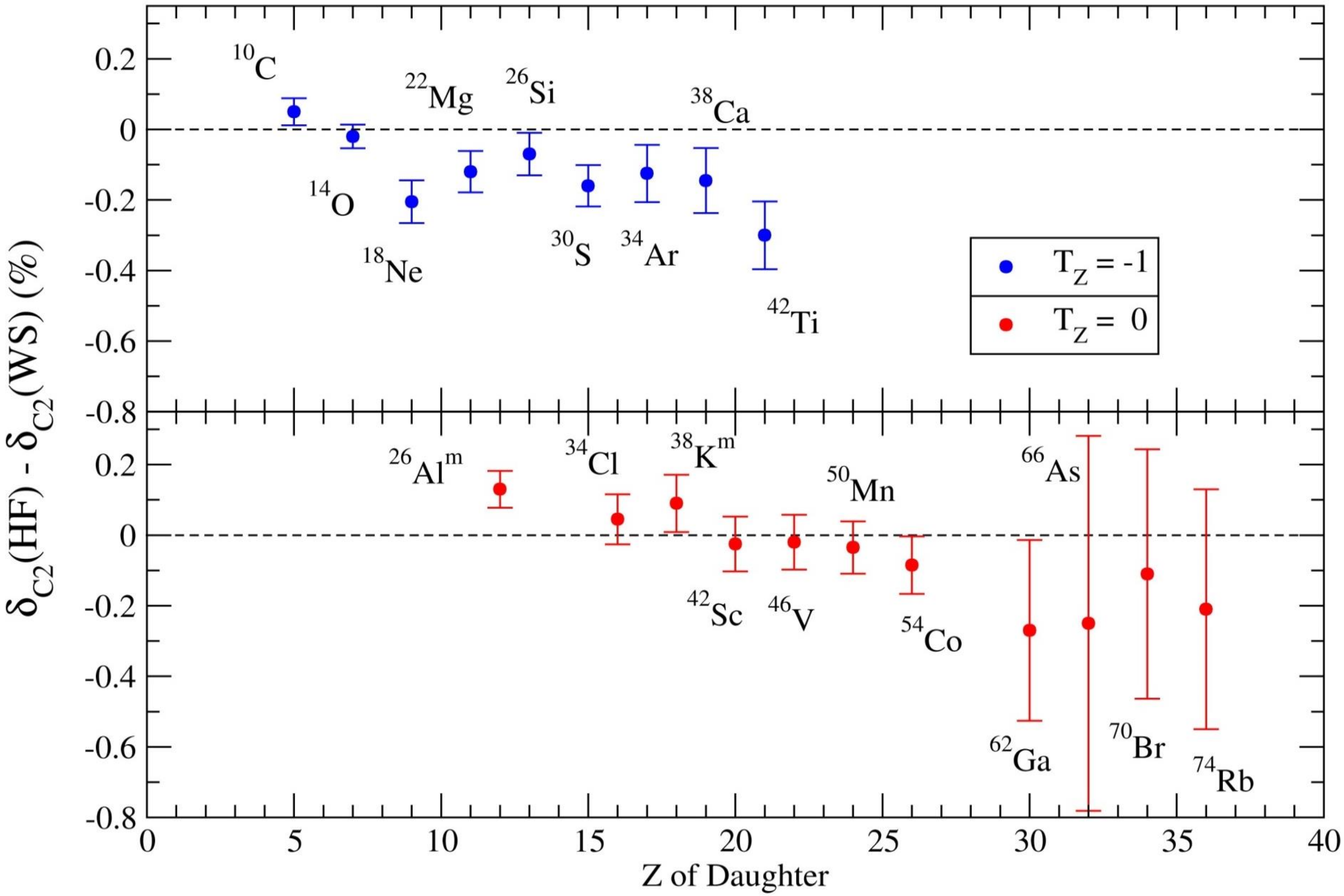
→ Relativistic Hartree-Fock

→ Random Phase Approximation

→ Energy Density Functional

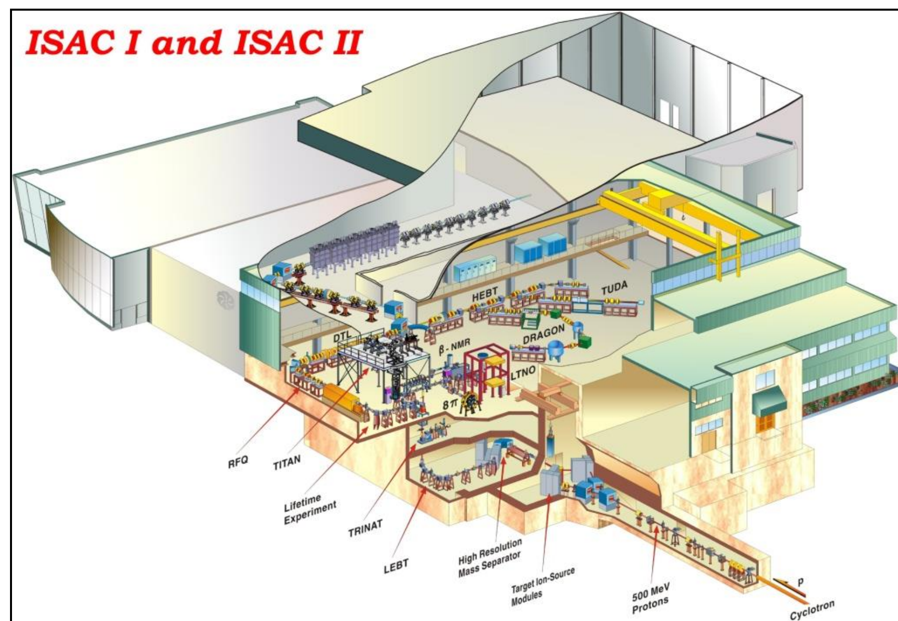


# Difference between Woods-Saxon and Hartree-Fock Radial Overlap Corrections



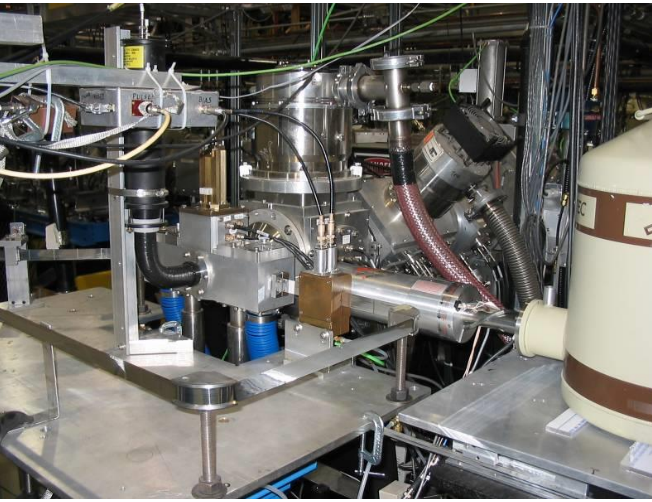
# TRIUMF-ISAC

**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.**

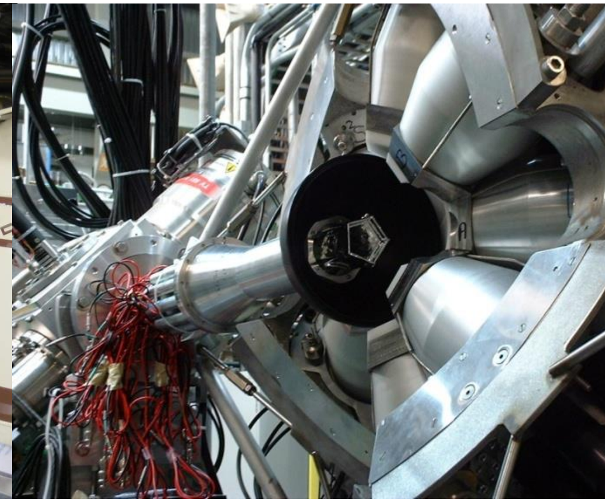


# Superallowed Fermi β Decay Studies at ISAC

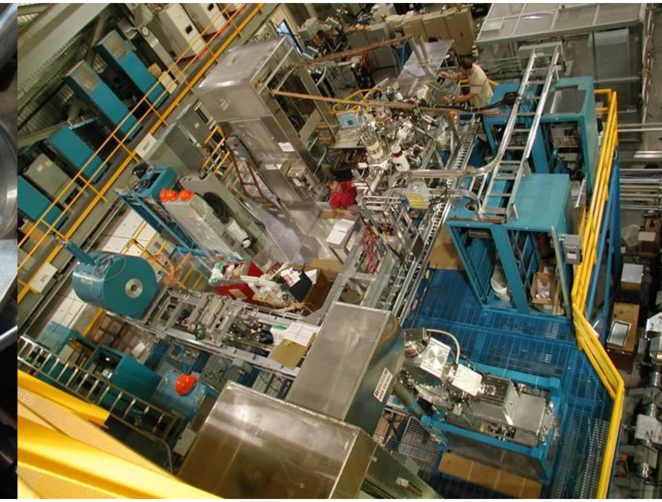
Halflives (GPS)



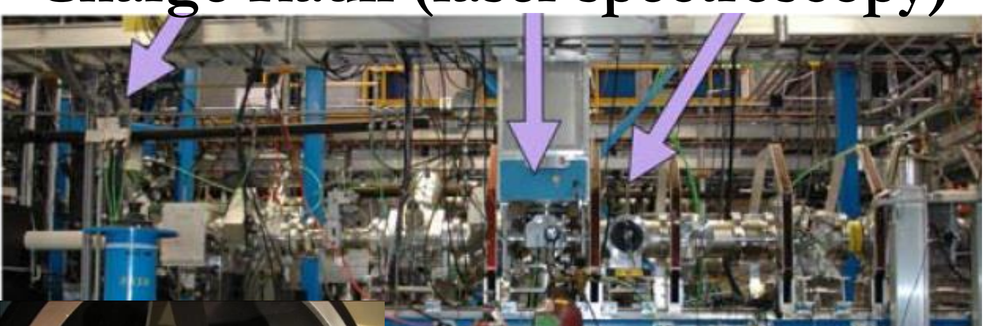
Branching ratios (8π)

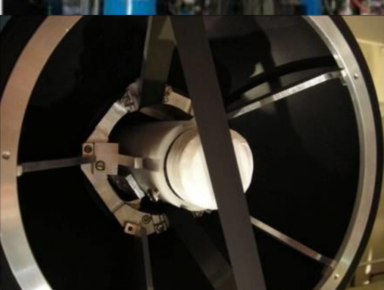


Masses (TITAN)



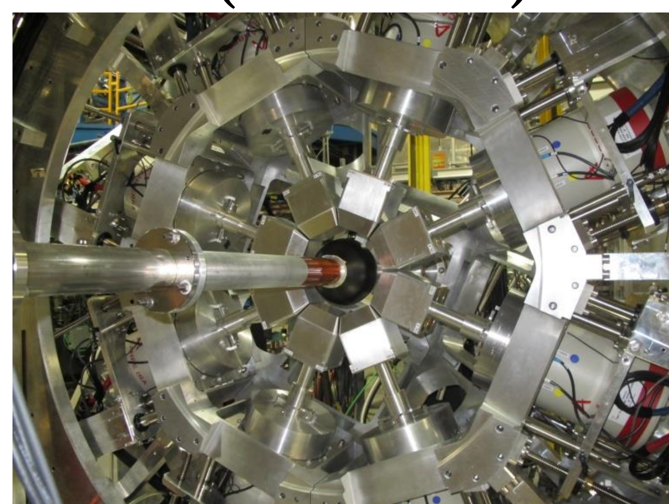
Charge Radii (laser spectroscopy)





Halflives (ZDS)

2014 (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)

$^{74}$Rb

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

$^{62}$Ga  $^{66}$As  $^{70}$Br

*$T_{½}$* and BR { $^{54}$Co, $^{50}$Mn

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

$^{46}$V

$^{38m}$K

*$T_{½}$* and BR $^{34}$Ar

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

$^{26m}$Al

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

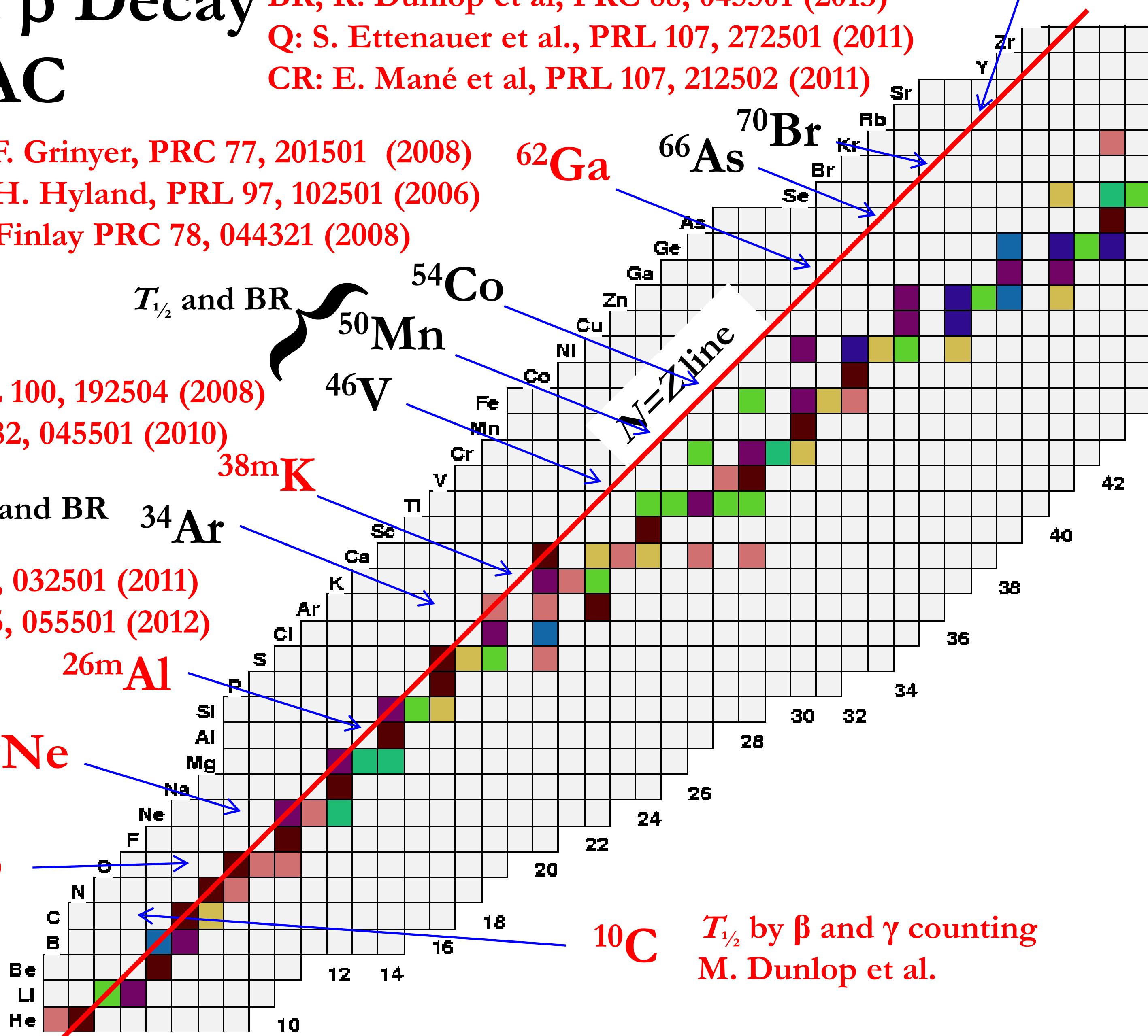
$^{18}$Ne

$^{14}$O

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

$^{10}$C

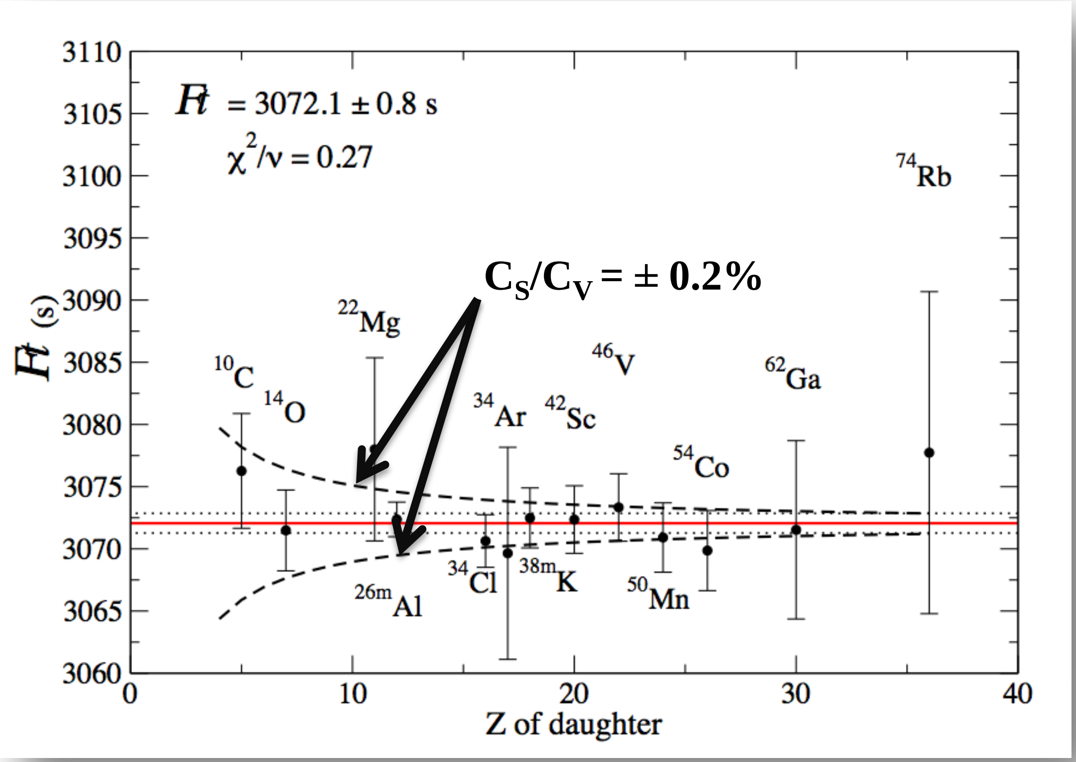
*$T_{½}$* by β and γ counting
M. Dunlop et al.



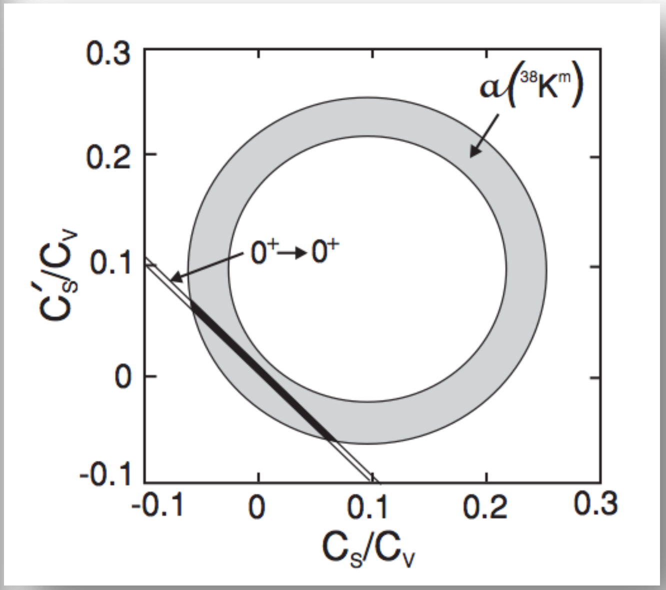
# Little b

**The superallowed data sets sensitive limits on b:**

- $C_S/C_V = -b_F/2 = +0.0011 \pm 0.0013$   (for $C_S = C'_S$)
- Ft values for $^{10}C$ and $^{14}O$ are the most important for constraining b.




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

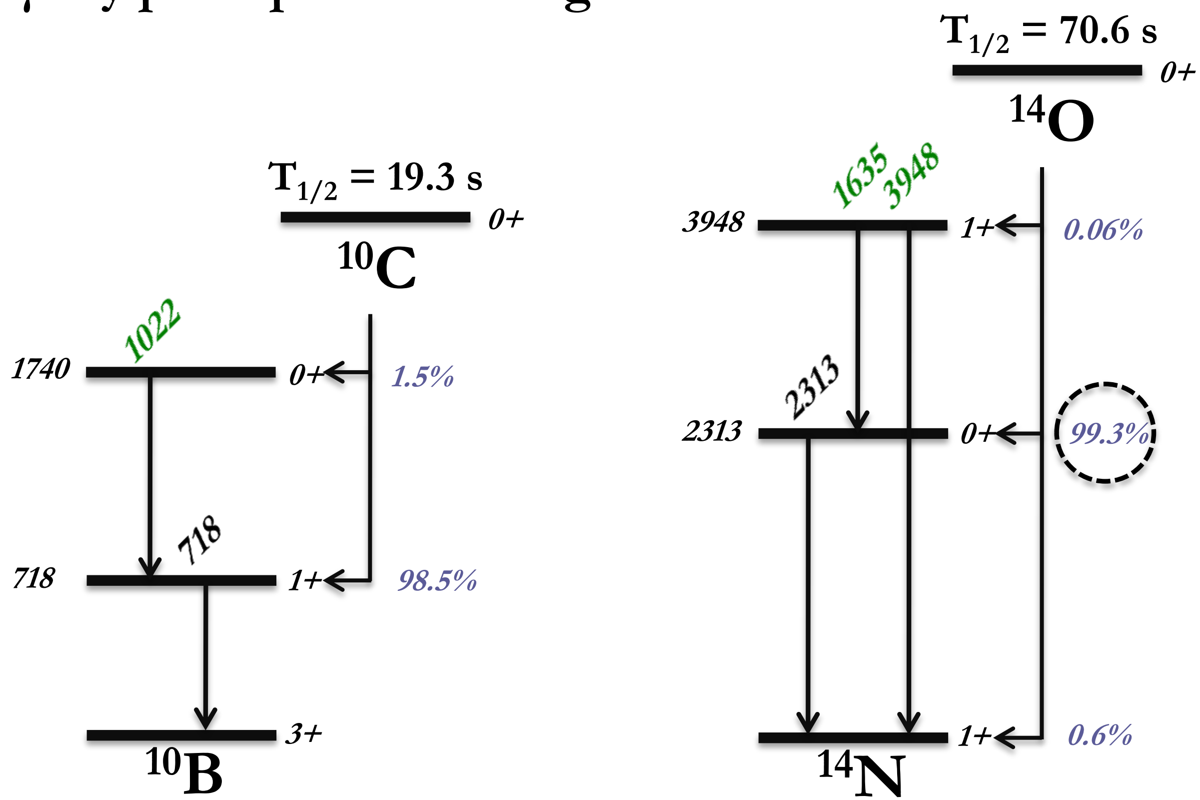



A. Gorelov et al.,
Phys. Rev. Lett 94 142501 (2005)

# Decay schemes of $^{10}C$ and $^{14}O$

**Nearly 100% of the β decays emit a characteristic γ ray**

- Half-life measurements can be performed either by direct β counting or by γ-ray photopeak counting.



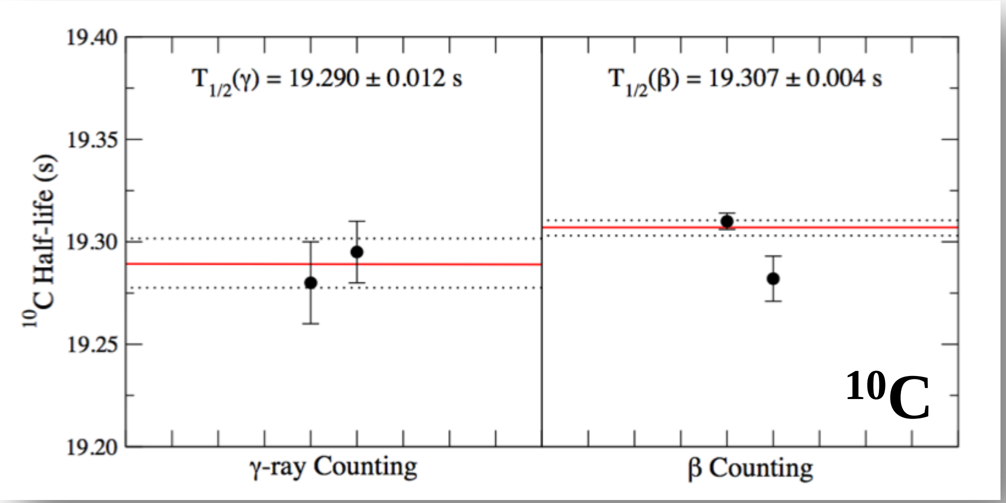
# Half-life measurements for $^{10}$C and $^{14}$O

β counting

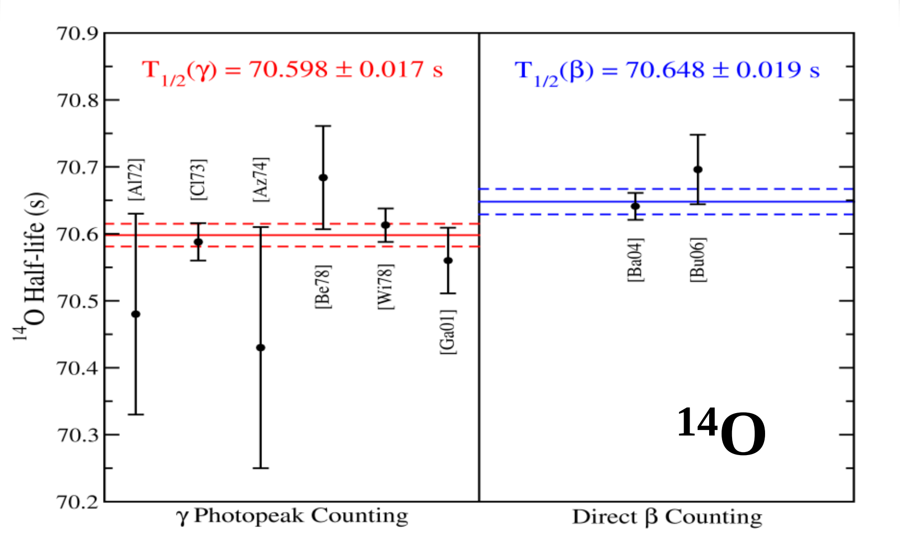
- High efficiency ✓
- No pile-up corrections ✓
- Not decay selective ✗

γ-ray photopeak counting

- Low efficiency ✗
- Pile-up corrections ✗
- Decay selective ✓




A small, but systematic, difference is observed for both $^{10}$C and $^{14}$O depending on the method that was used for the $T_{1/2}$ measurements.



# Precision γ-ray photopeak counting techniques with HPGe

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Nuclear Instruments and Methods in Physics Research A 579 (2007) 1005–1033

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

## Pile-up corrections for high-precision superallowed β decay half-life measurements via γ-ray photopeak counting

G.F. Grinyer[a,*], C.E. Svensson[a], C. Andreoiu[a], A.N. Andreyev[b], R.A.E. Austin[c], G.C. Ball[b], D. Bandyopadhyay[a,1], R.S. Chakrawarthy[b], P. Finlay[a], P.E. Garrett[a,b], G. Hackman[b], B. Hyland[a], W.D. Kulp[d], K.G. Leach[a], J.R. Leslie[e], A.C. Morton[b], C.J. Pearson[b], A.A. Phillips[a], F. Sarazin[f], M.A. Schumaker[a], M.B. Smith[b,2], J.J. Valiente-Dobón[a,3], J.C. Waddington[g], S.J. Williams[b], J. Wong[a], J.L. Wood[d], E.F. Zganjar[h]

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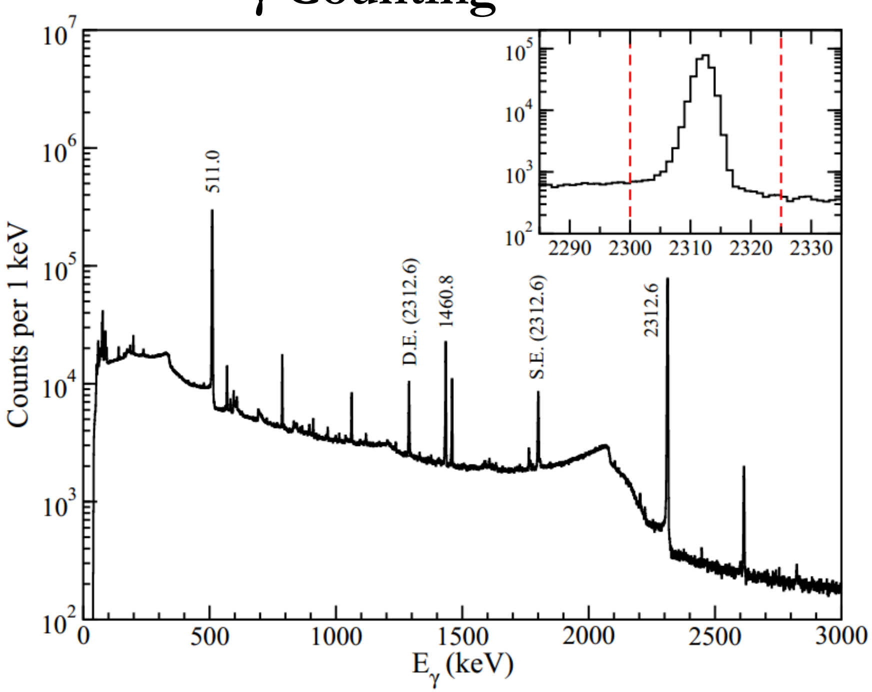
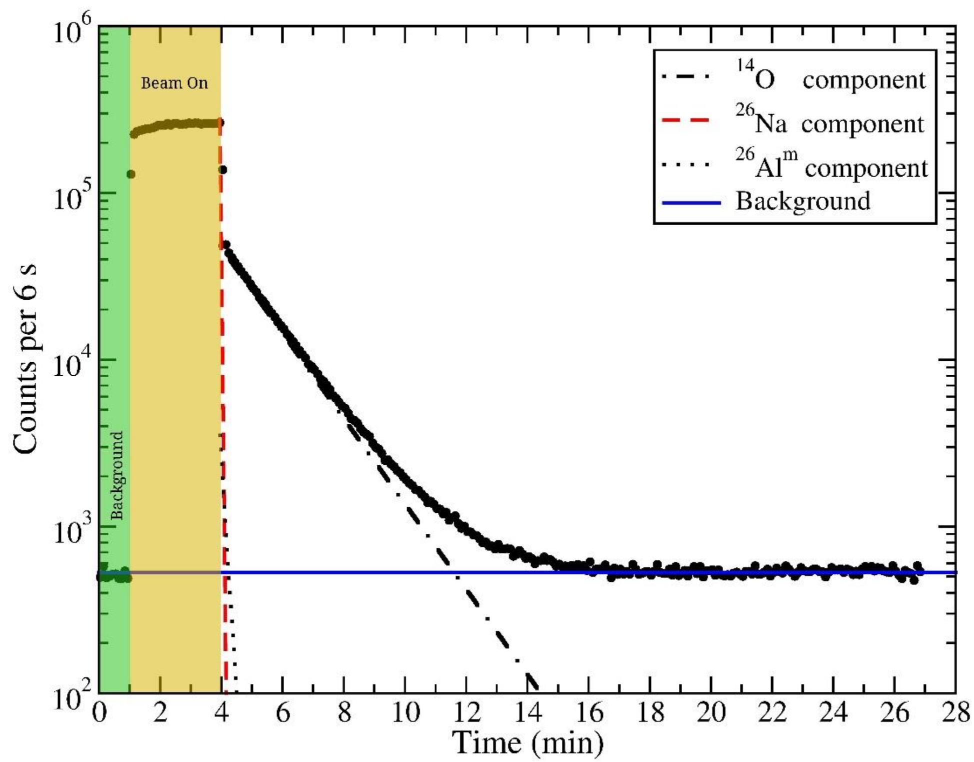
Available online 13 June 2007

# $^{14}O$ 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

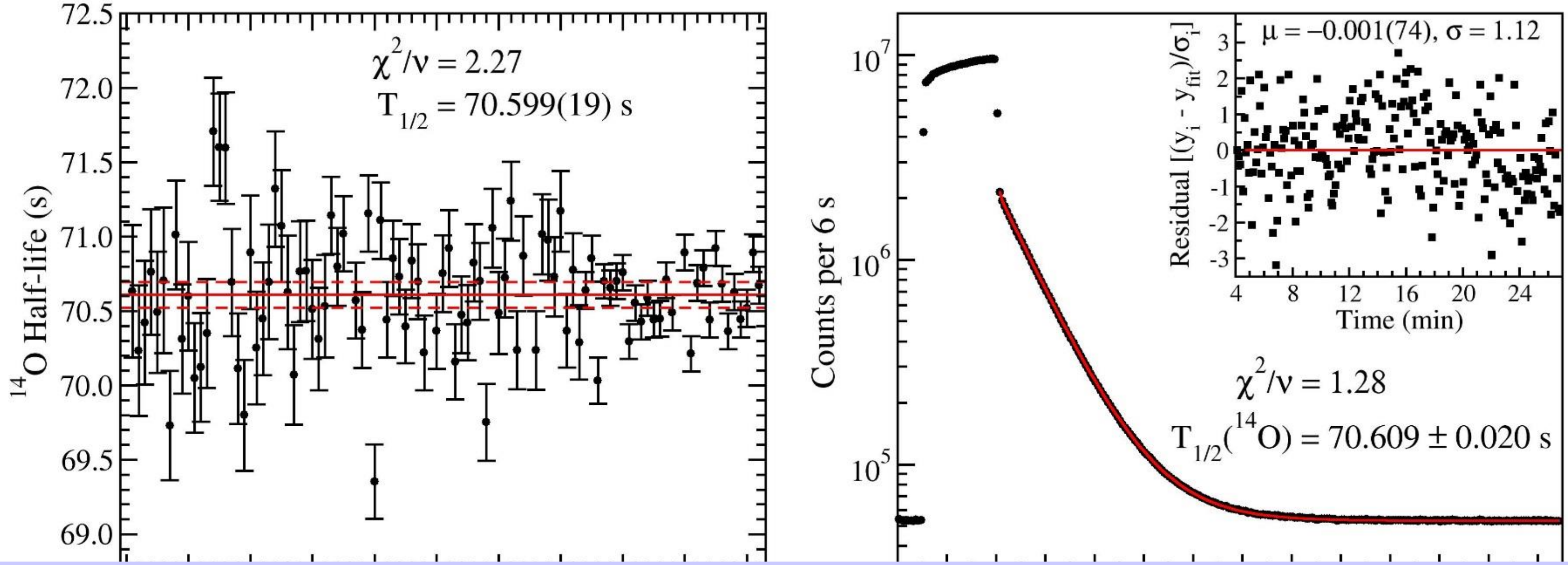
γ Counting



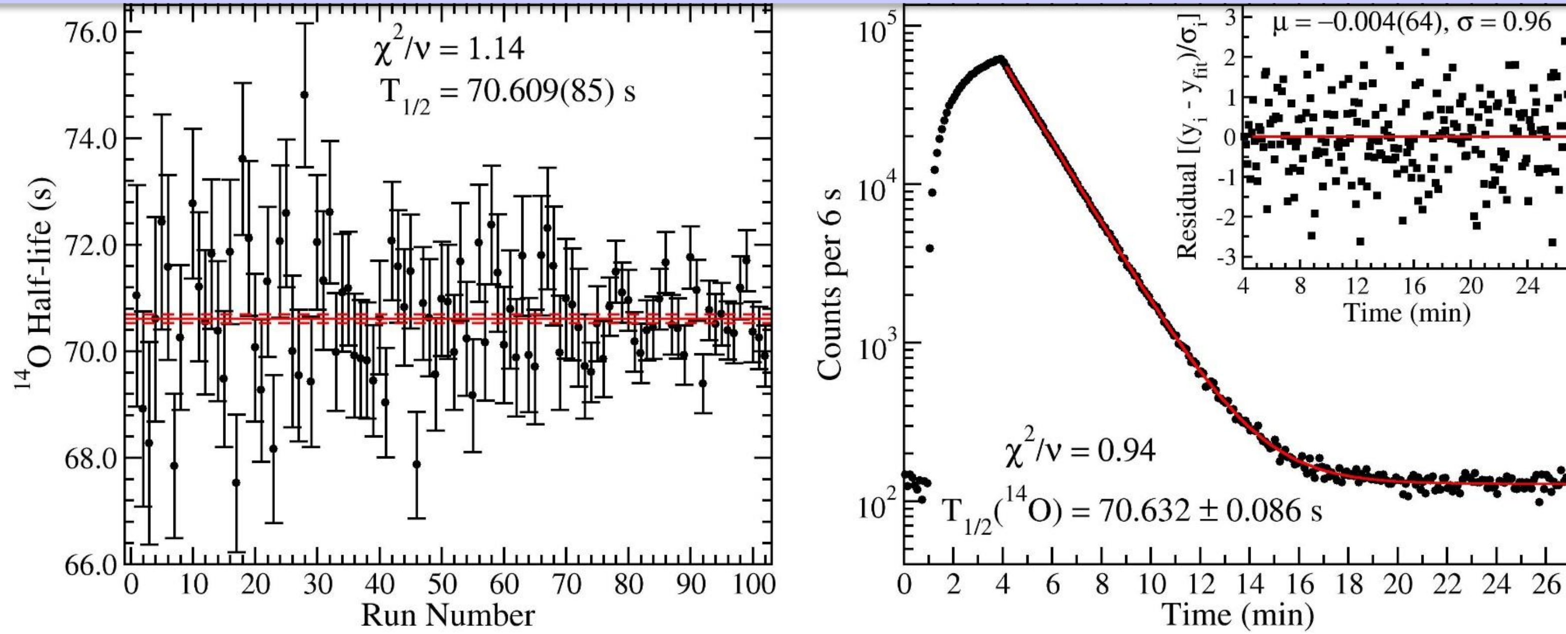

β Counting

**β**



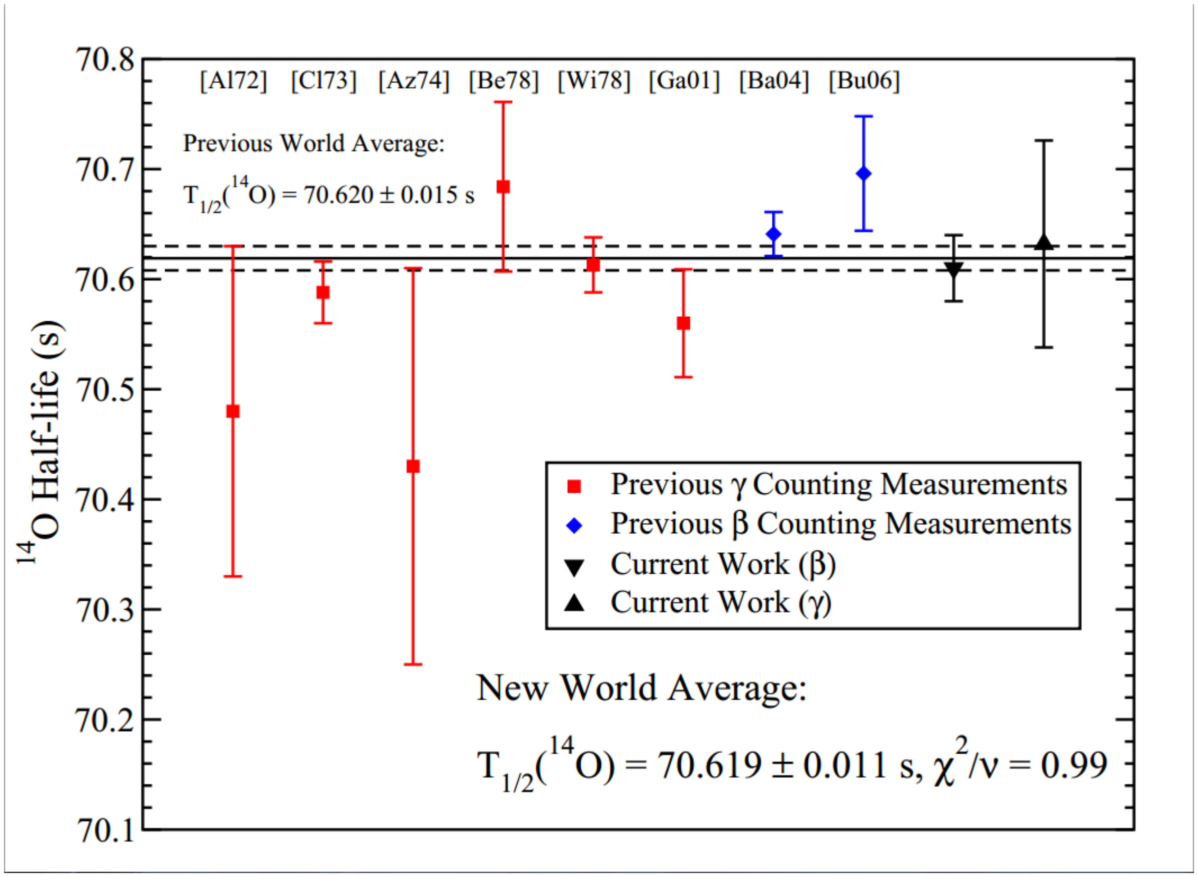
$\chi^2/\nu = 2.27$
$T_{1/2} = 70.599(19)$ s
$^{14}$O Half-life (s)
$\mu = -0.001(74)$, $\sigma = 1.12$
Residual $[(y_i - y_{fit})/\sigma_i]$
Time (min)
Counts per 6 s
$\chi^2/\nu = 1.28$
$T_{1/2}(^{14}O) = 70.609 \pm 0.020$ s


**γ**



$\chi^2/\nu = 1.14$
$T_{1/2} = 70.609(85)$ s
$^{14}$O Half-life (s)
Run Number
$\mu = -0.004(64)$, $\sigma = 0.96$
Residual $[(y_i - y_{fit})/\sigma_i]$
Time (min)
Counts per 6 s
$\chi^2/\nu = 0.94$
$T_{1/2}(^{14}O) = 70.632 \pm 0.086$ 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 $^{14}O$.**
- **Precision of the γ-ray counting technique is currently limited by the efficiency of the 8π spectrometer.**
- **GRIFFIN will increase this γ-ray detection efficiency by a factor of more than 20.**

# $^{74}$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:

$<r^2_{ch}>^{1/2} = 4.19(1)$ fm

Reduces uncertainty in theoretical $\delta_{C2}$ 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

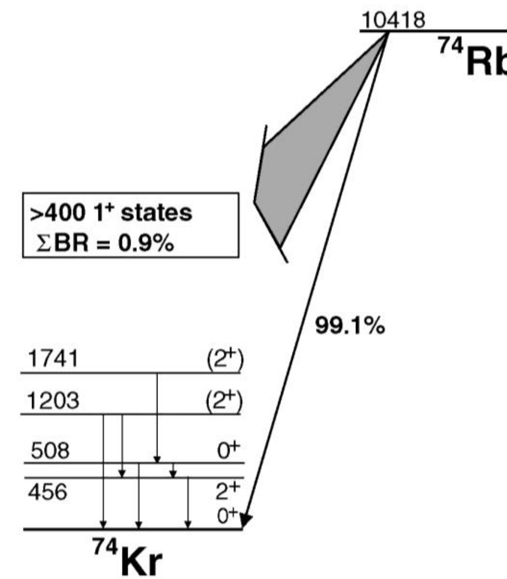
VOLUME 88, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 2002

**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 $\beta$ decay, leads to a violation of Cabibbo-Kobayashi-Maskawa unitarity by $2.2\sigma$. 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

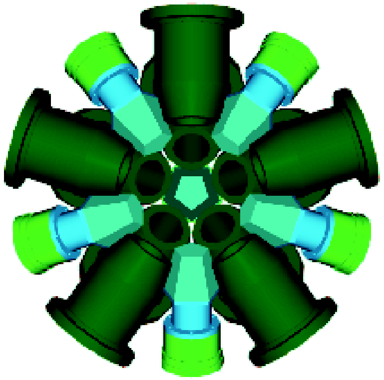
20 Compton-Suppressed HPGe detectors

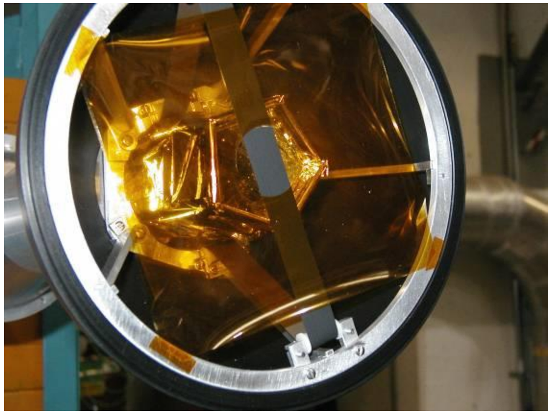
and 10 BaF2 detectors for γ-ray detection

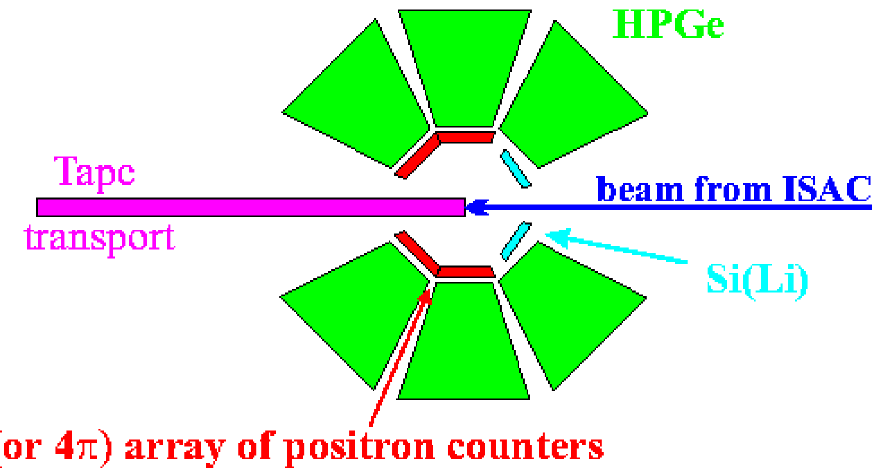
20 plastic scintillators for β detection

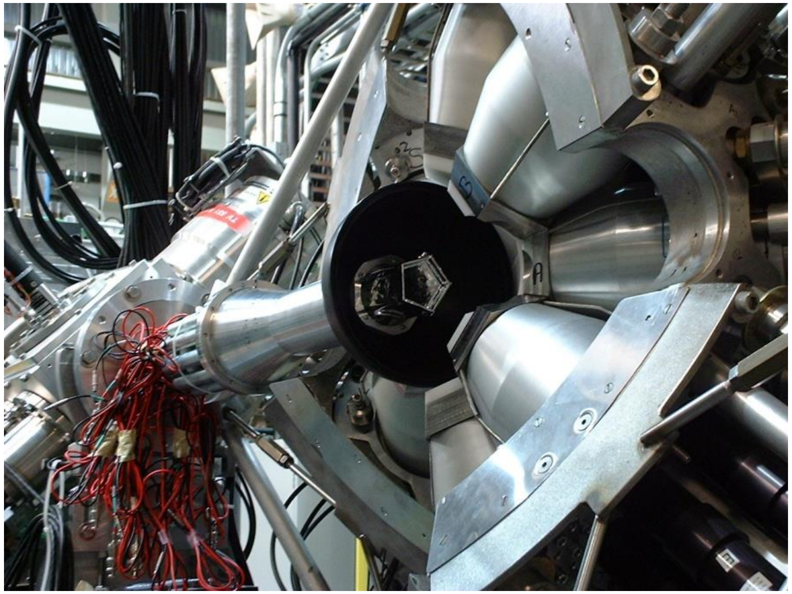
5 Si(Li) detectors for conversion electron spectroscopy

Fast, in-vacuum tape transport system



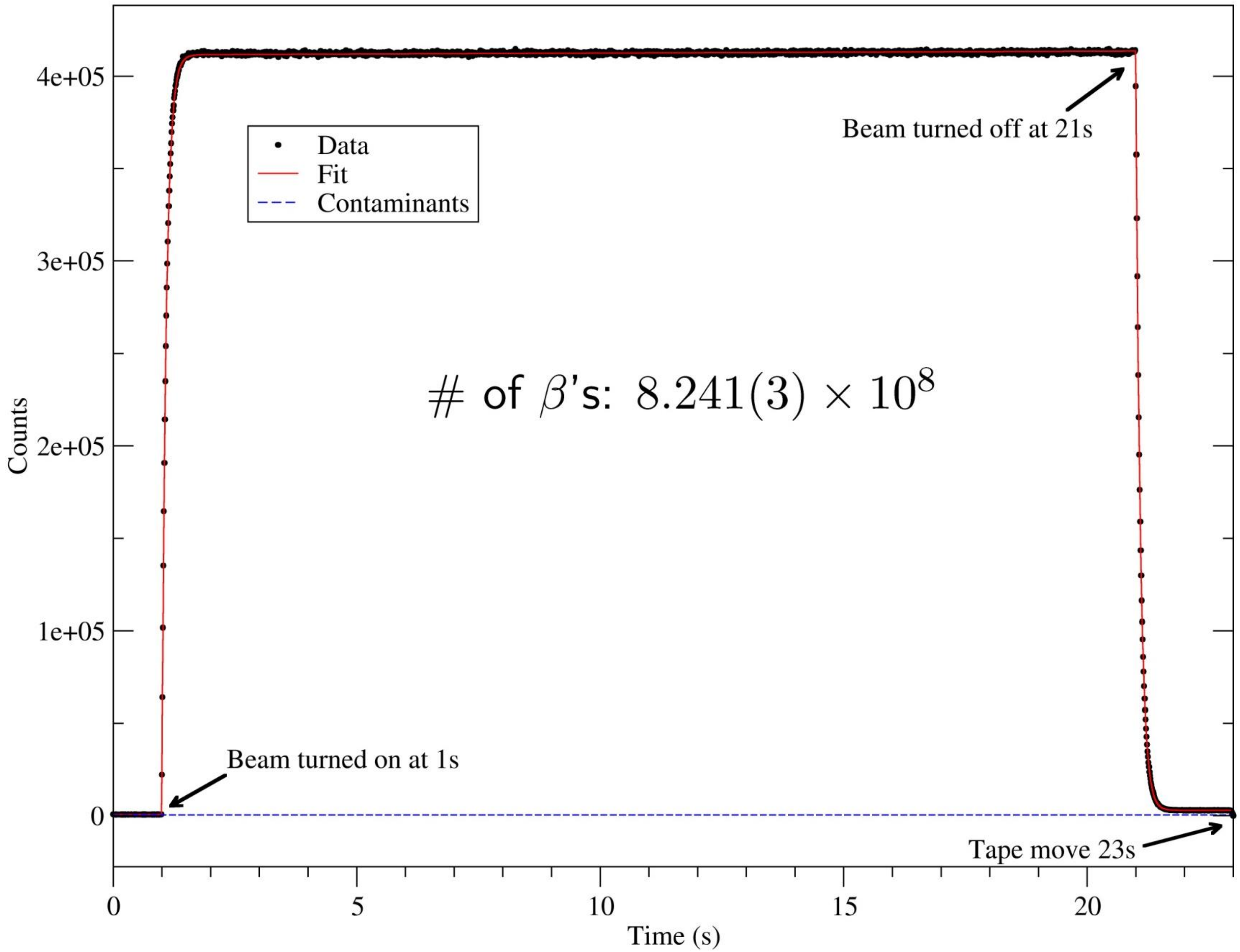




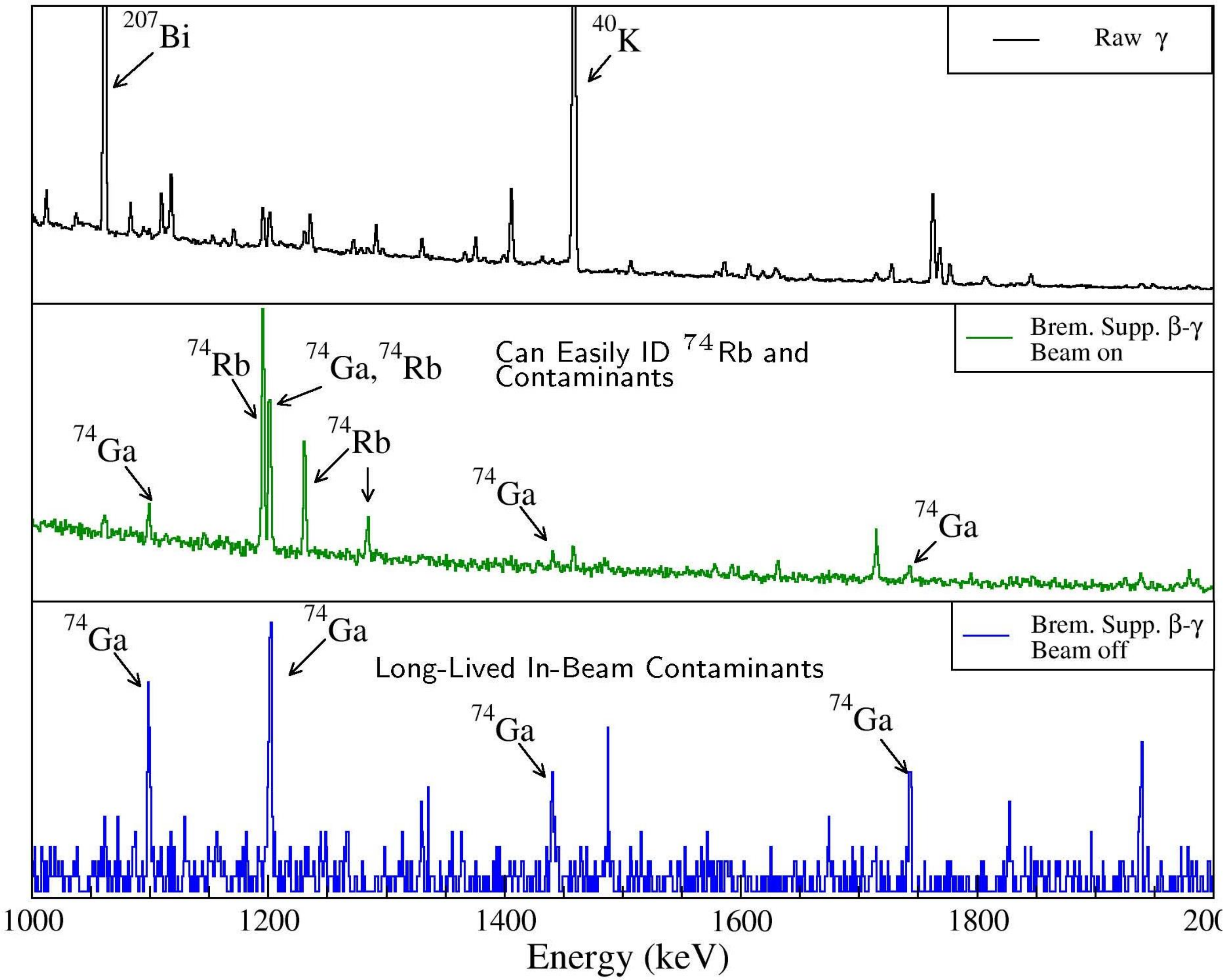



Simultaneous collection of γ-singles, γγ coincidences, β tagging, conversion electrons, and lifetime measurements

# Counting $^{74}$Rb β Decays with SCEPTAR



# Identifying γ-rays from $^{74}$Rb Decay

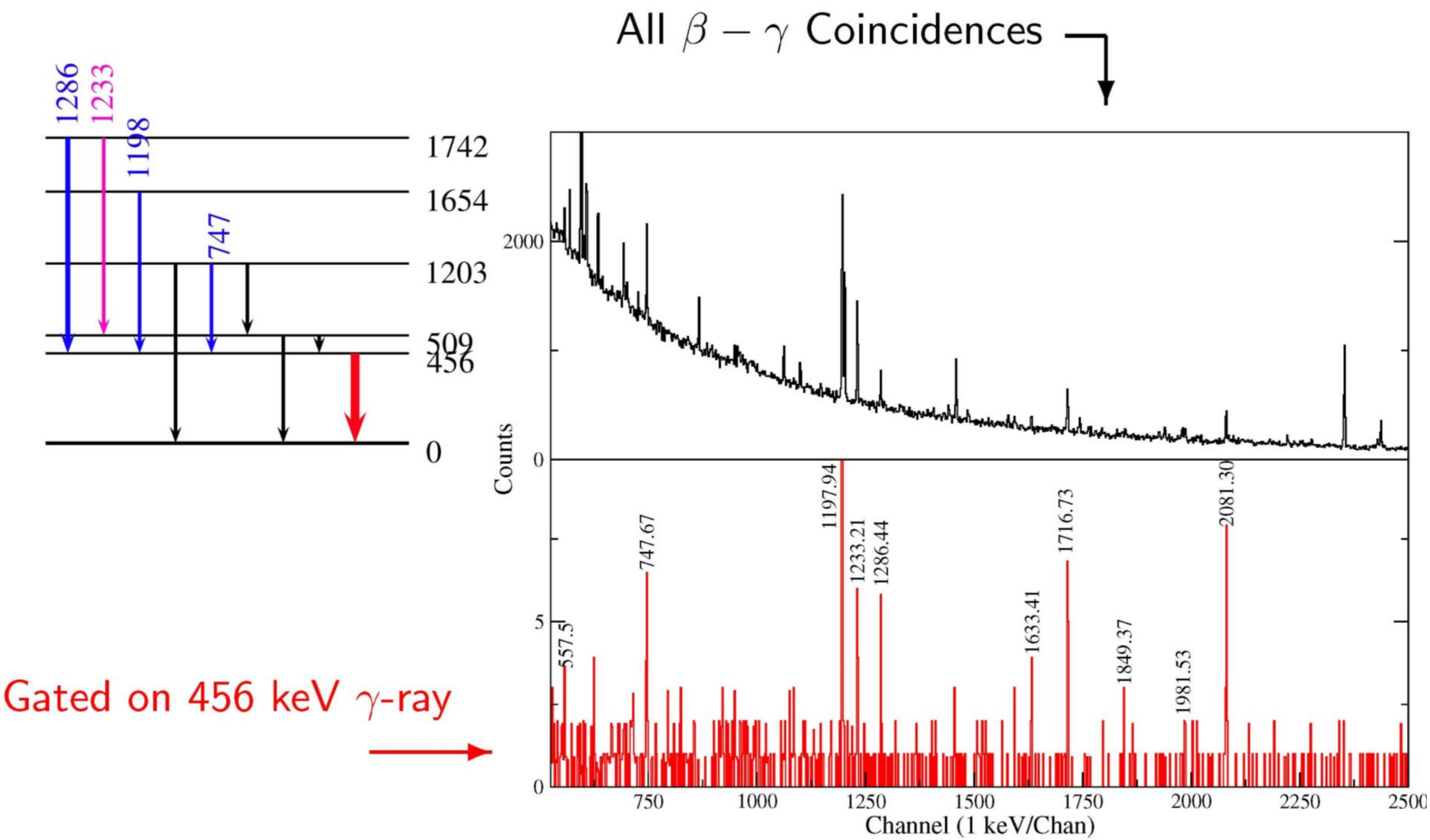



Raw γ-spectrum contains lines from room background and in-beam contaminants

β-γ coincidence, Bremsstralung suppression reduce background

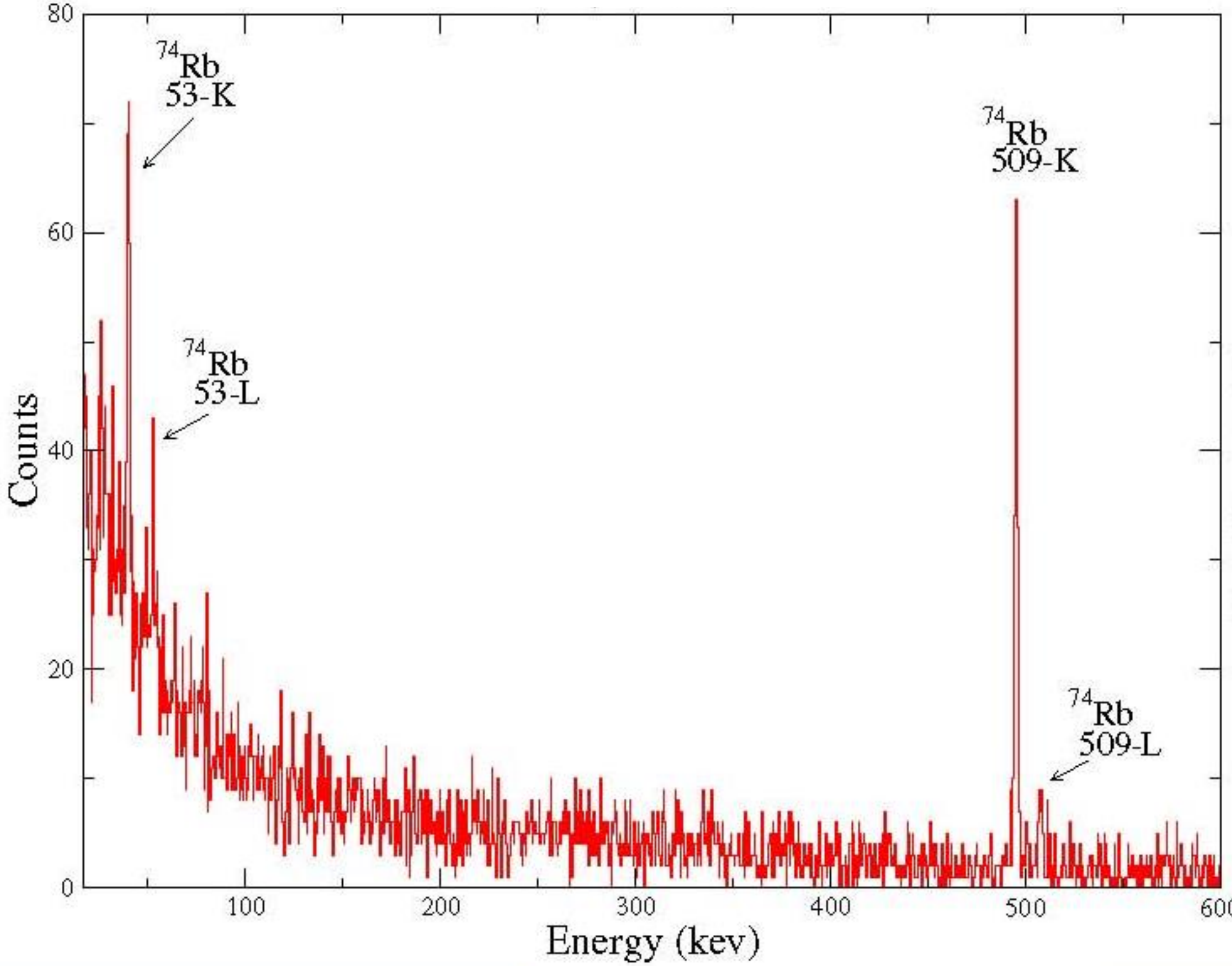
Spectrum during beam-off allows one to identify long-lived contaminants

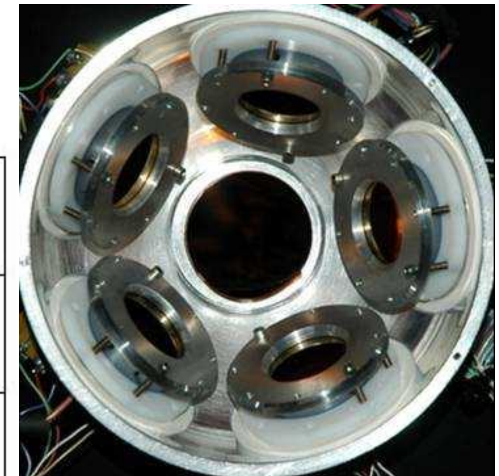
# γ–γ Coincidences following ppm β-decay branches of $^{74}$Rb

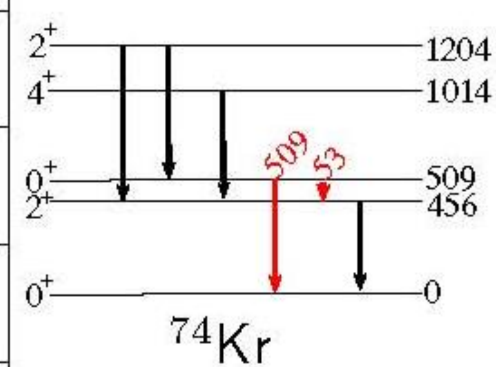


# Internal Conversion Decay of the $0^+_2$ State of $^{74}$Kr

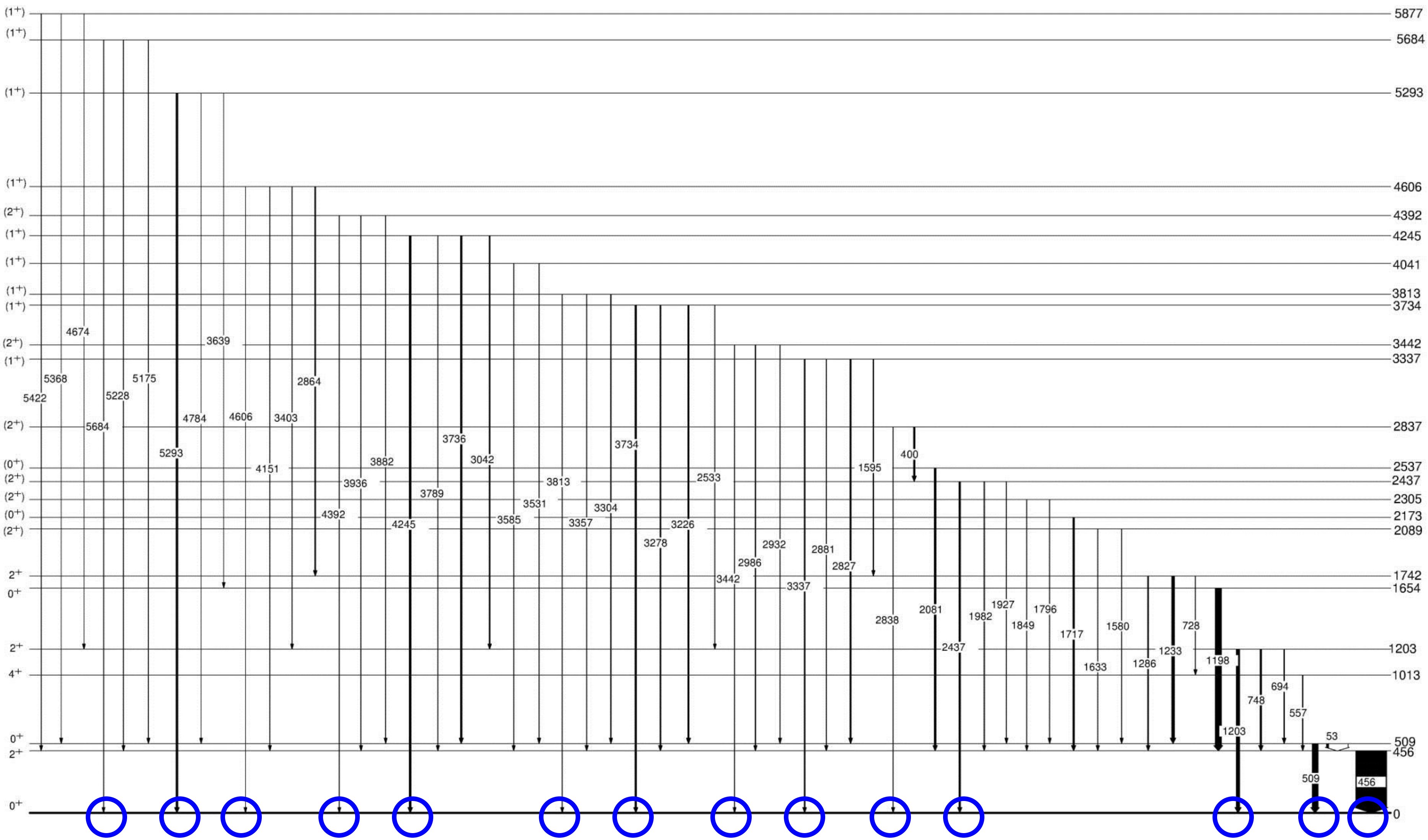
## β – γ – electron Coincidence Spectrum





# 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:

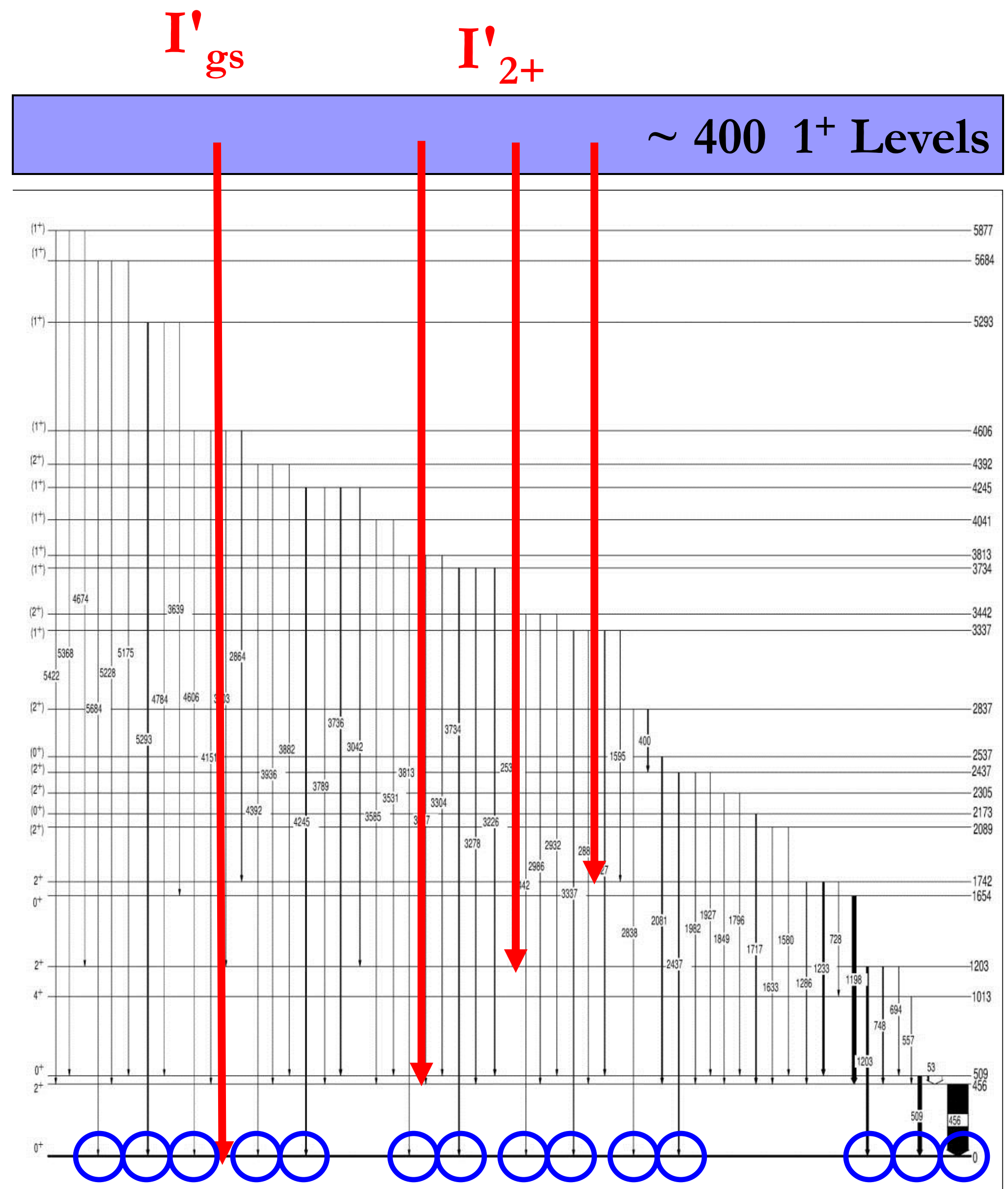
$B_{gs} = 0.33(11)$

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

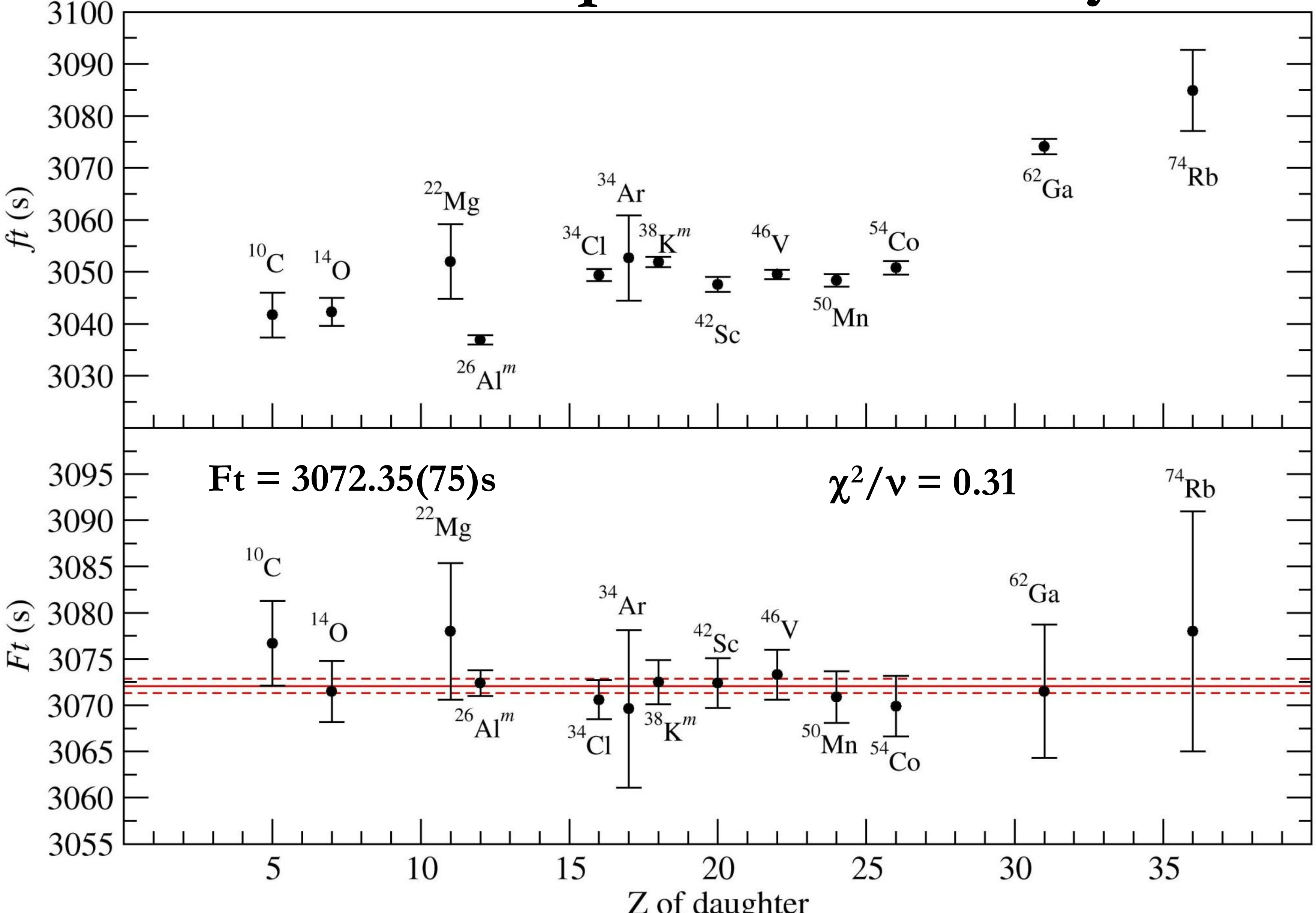
**Superallowed Branching Ratio:**

**$99.545 \pm 0.031$ %**

R. Dunlop PRC 88, 045501 (2013)



# $^{74}$Rb Superallowed Decay



# The near future …

GRIFFIN

***G**amma*

***R**ay*

***I**nfrastructure*

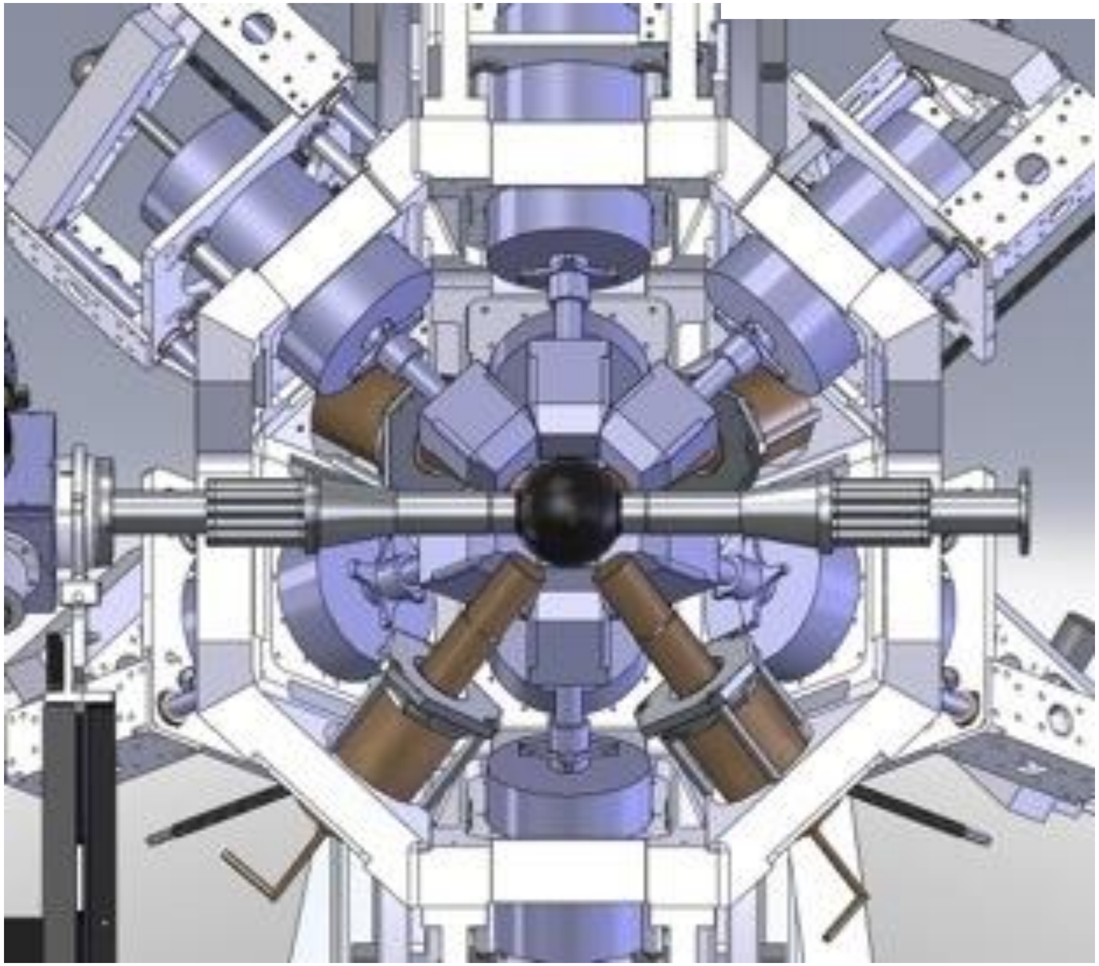
***F**or*

***F**undamental*

***I**nvestigations*

*of*

***N**uclei*

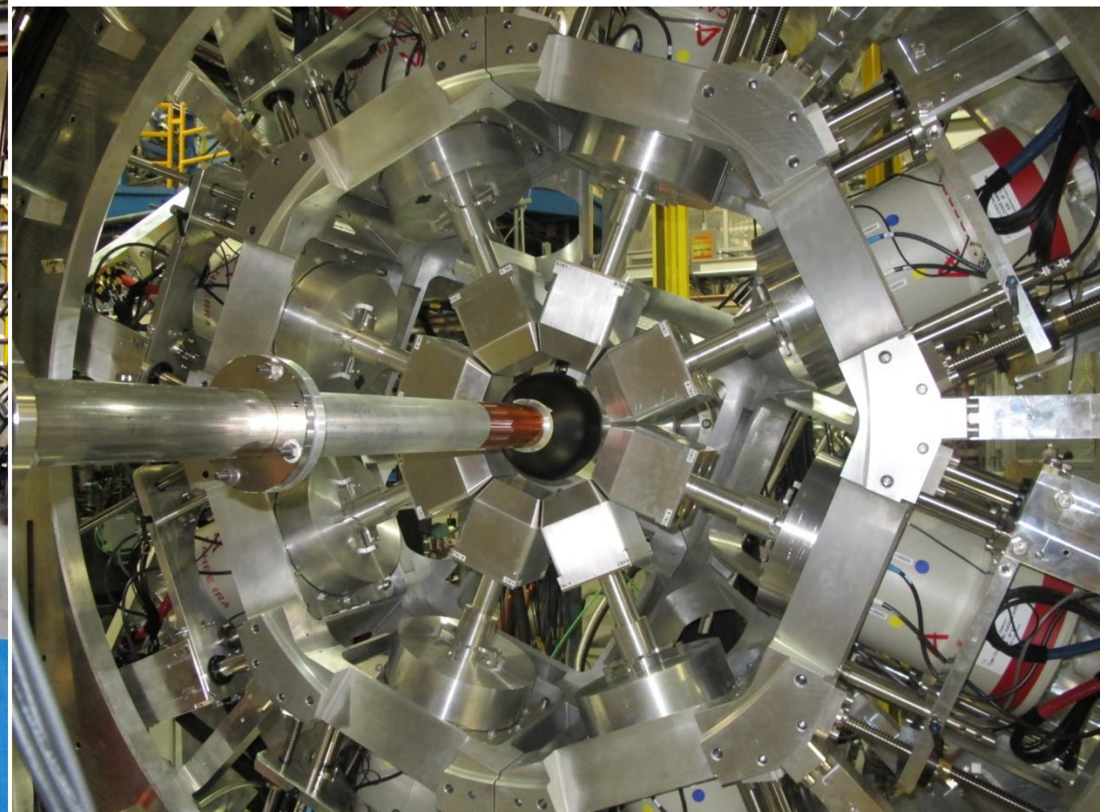


**A new high-efficiency decay spectroscopy facility for ISAC-I**

# GRIFFIN @ ISAC-I

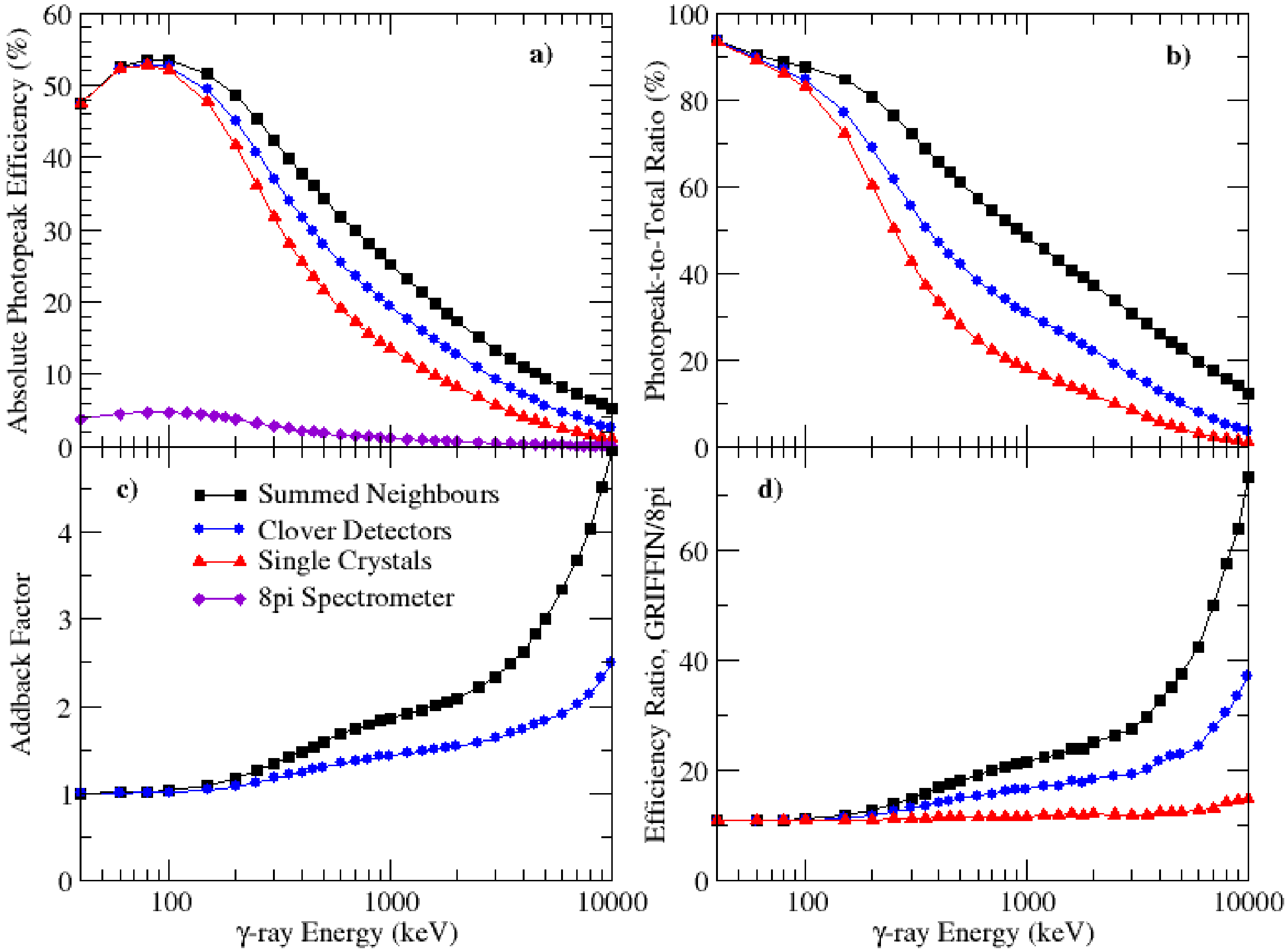
GRIFFIN


**July 25, 2014**



**First physics run at ISAC ($^{62}$Ga):**
**Sept. 30 – Oct 7, 2014**

# GRIFFIN Performance




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

# GRIFFIN Digital DAQ

**Custom Digital Electronics designed and built at Université de Montreal and TRIUMF**

Programmable Logic Pulse Generator

32 Channels
NIM or TTL

Clock Distribution Module

10MHz Atomic Clock
Low-jitter fan-out to all modules

GRIF-16 Module

16 chans
100MHz,
14bit

GRIF-4G Module

4 chans
1GHz,
14bit

Master and Collector Module

650MB/s link to each digitizer
2GB RAM with peak transfer of 8.5Gb/s.

# GRIFFIN Program at ISAC

Nuclear Structure:

- Shell structure evolution in neutron-rich nuclei
- Octupole deformation/collectivity in odd-A actinide nuclei (RnEDM)

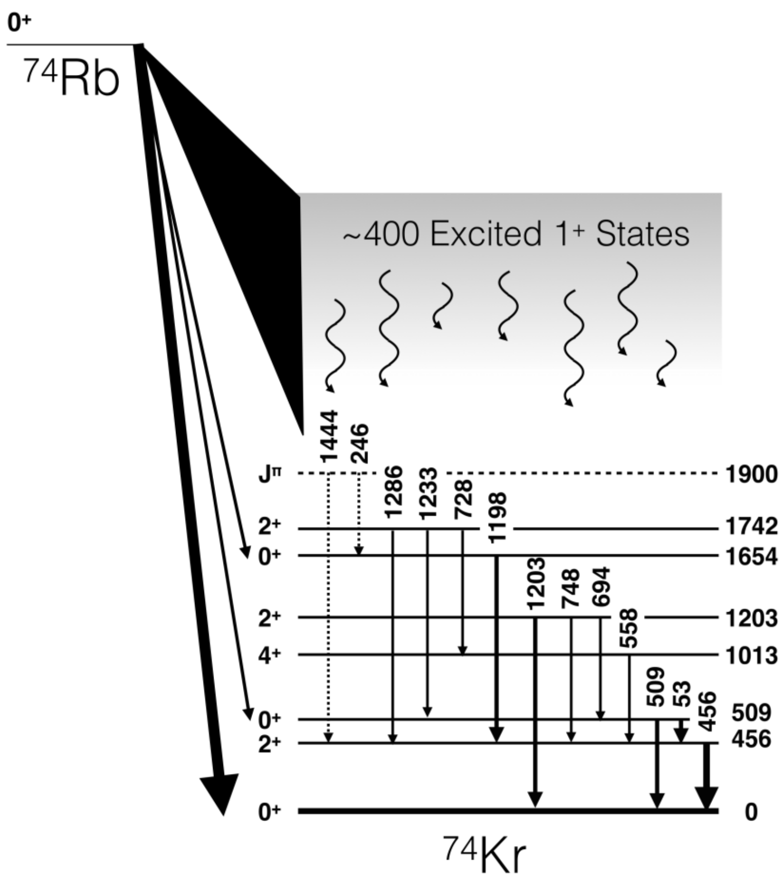
Nuclear Astrophyics:

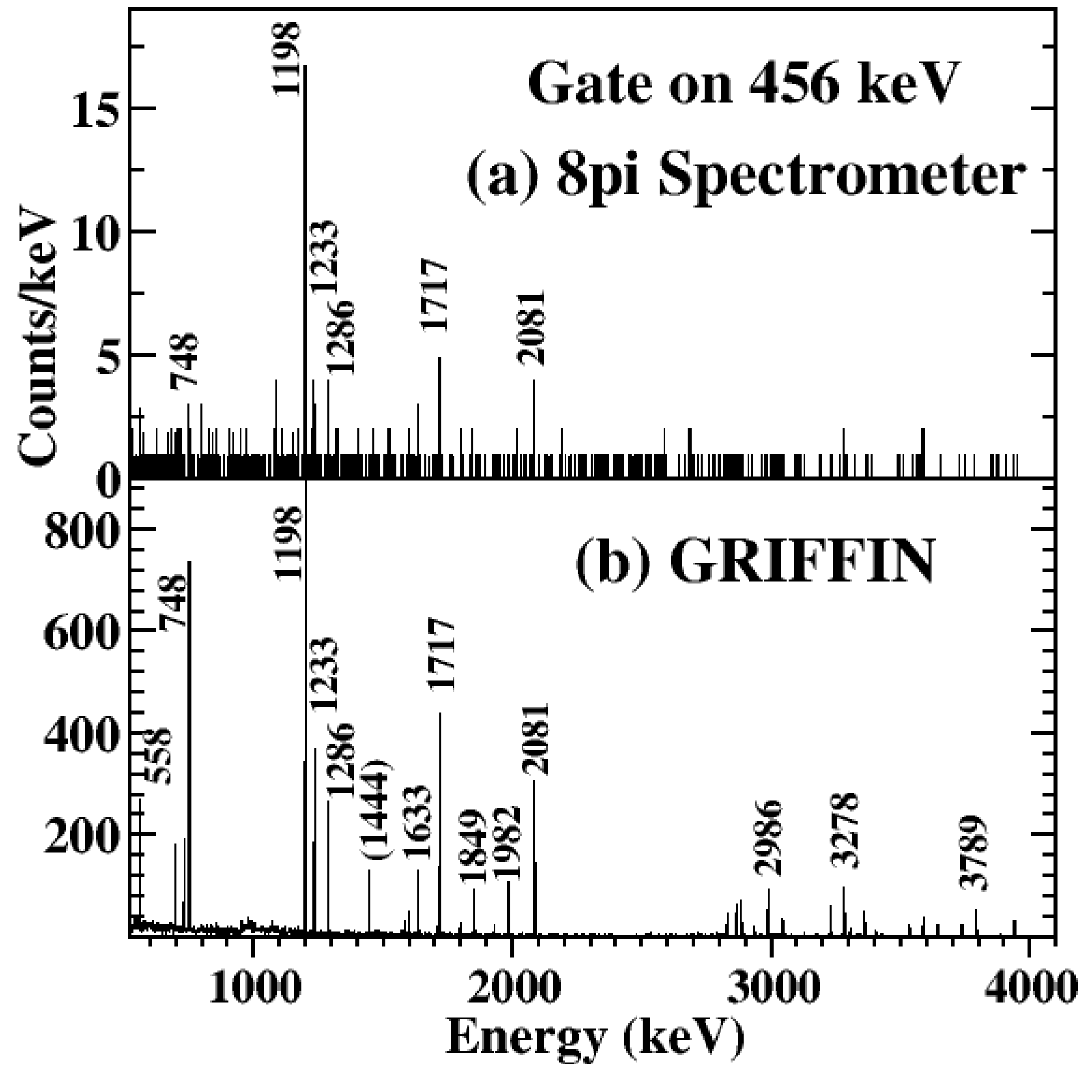
- r-process
- $\beta$-delayed neutron emission

Symmetries (Superallowed and mirror beta decays):

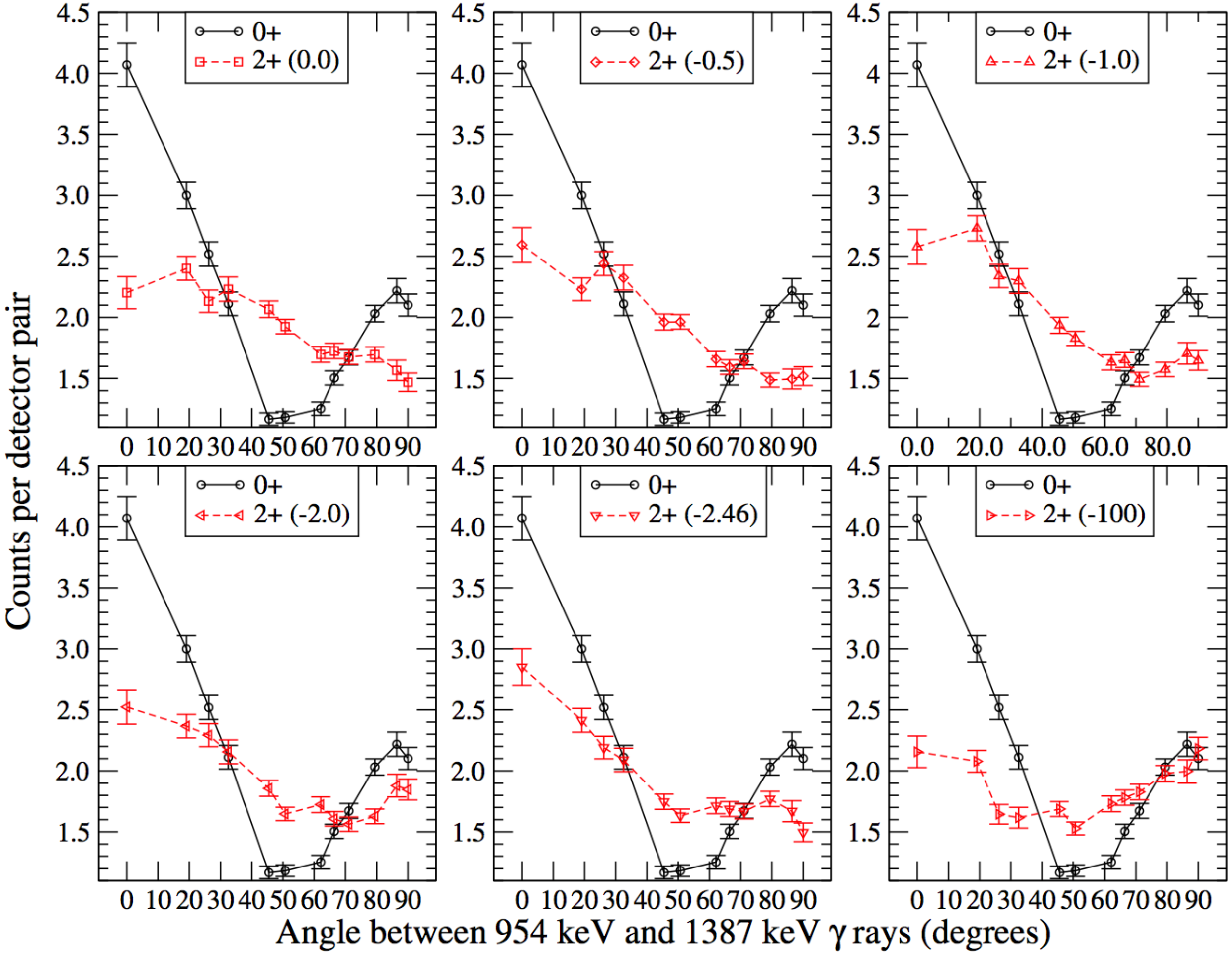
- non-analogue $0^+ \rightarrow 0^+$ branches in $A \geq 62$ decays to test large-scale shell model calculation of $\delta_C$
- $\gamma$–$\gamma$ angular correlation measurements to assign $J^\pi$ values of excited states
- high-precision $\gamma$-ray based lifetime measurements for superallowed emitters ($^{10}$C, $^{14}$O, $^{18}$Ne, $^{34}$Ar, …)
- mirror decay branching ratios ($^{35}$Ar, $^{37}$K, …)

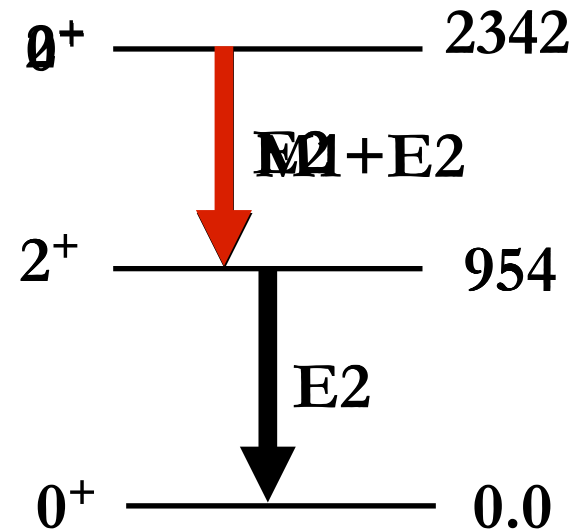
# $^{74}$Rb Superallowed Decay with GRIFFIN



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




**Using GRIFFIN we will determine the spin of the 2342 keV state in $^{62}$Zn**

# Conclusions

The CVC test is being extended to high-Z where the isospin symmetry breaking corrections are large (~ 1.5%).

A high-precision experimental superallowed *ft* value has been achieved for $^{62}Ga$ and can be expected for $^{74}Rb$ in the near future with high-precision charge state Penning trap mass measurements.

The uncertainty in the corrected $\mathcal{F}t$ values for these A ≥ 62 superallowed decays will then be dominated entirely by the nuclear structure uncertainties in the theoretical isospin symmetry breaking corrections, providing strong motivation to expand the model spaces and improve the interactions used in these calculations.

- e.g. $^{62}Ga$ $(p_{3/2}f_{5/2}p_{1/2})^6 \quad \rightarrow \quad (f_{7/2}p_{3/2}f_{5/2}p_{1/2})^{22}$

Guidance to these theoretical developments will be provided by additional experimental measurements:

- charge radii, (d,t) and (p,t) transfer reactions for spectroscopic factors

- non-analogue Fermi branching ratios (i.e. experimental $\delta^i_{C1}$) provide sensitive tests of the 0+ wavefunctions in the parent and daugter nuclei

# Conclusions

**Ultimately, more stringent tests of isospin symmetry breaking calculations for the high-Z superallowed decays will require the radiative corrections to be calculated at higher order:.**

**e.g. ($^{62}$Ga):**

$$\delta_C = 1 - \frac{\overline{F}t}{ft\left(1+\delta_R\right)}$$

**$\delta_C^{\,exp}(^{62}\text{Ga}) = 1.41\ (4)_{ft}(3)_{Ft}(2)_{\delta NS}(9)_{\delta R'}\ \%$**

**is now completely dominated by the uncertainty in the outer radiative correction $\delta_R$ (<u>estimated</u> at order $Z^2\alpha^3$).**

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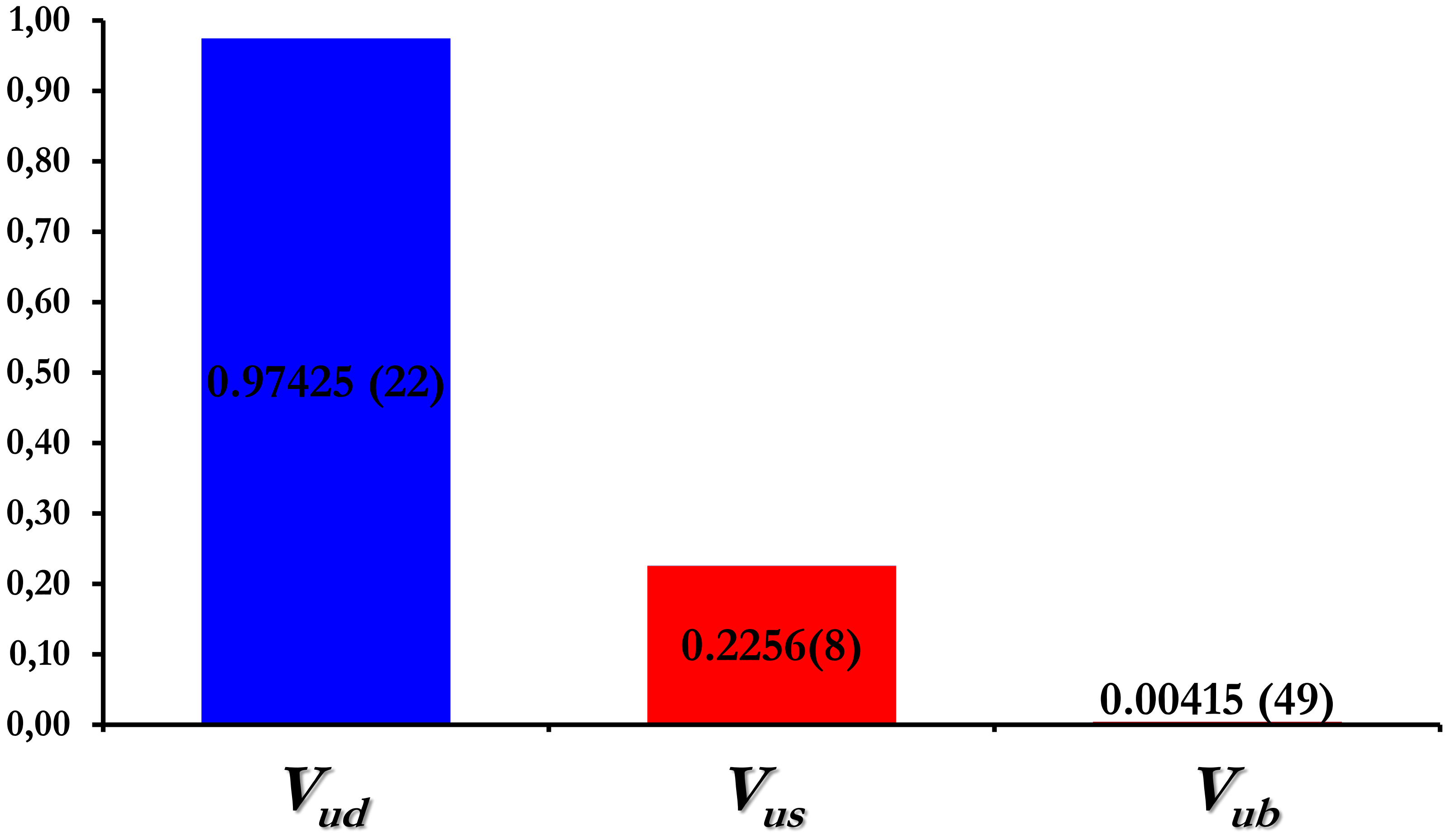
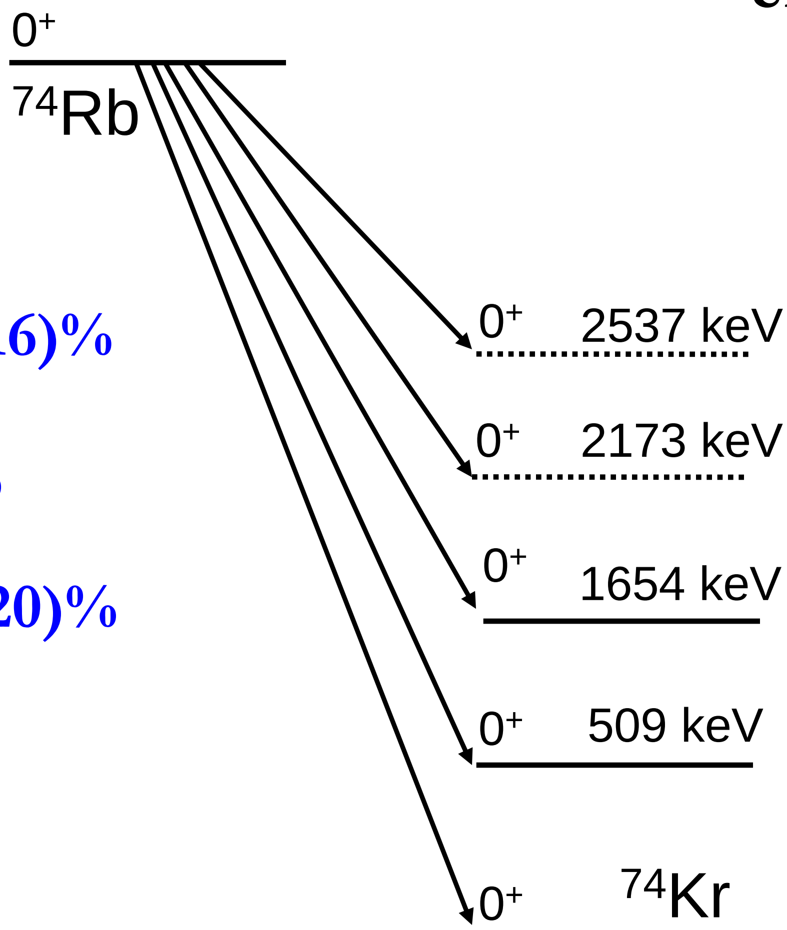
# CKM Unitarity




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

# Isospin Mixing Component: $^{74}$Rb

$\delta_{c1} \approx \delta^1_{c1} + \delta^2_{c1} + \ldots$ $\delta^n_{c1} \approx (f_0/f_n)BR_n$




**Experiment**

$\delta^4_{c1} = 0.024(16)\%$

$\delta^3_{c1} \leq 0.011\%$

$\delta^2_{c1} = 0.080(20)\%$

$\delta^1_{c1} \leq 0.021\%$

**Theory**

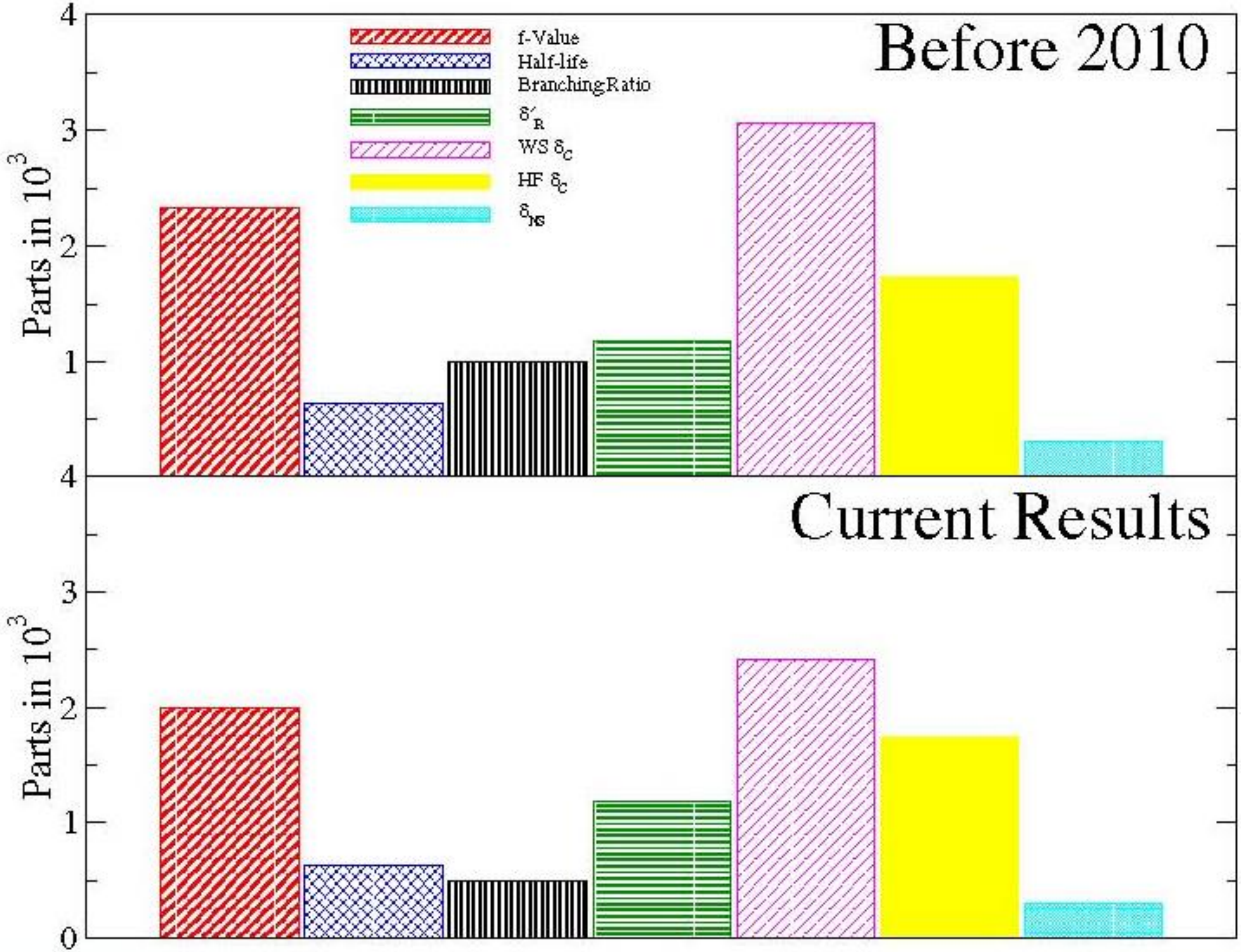
0.003(30)%

0.005(30)%

0.060(30)%

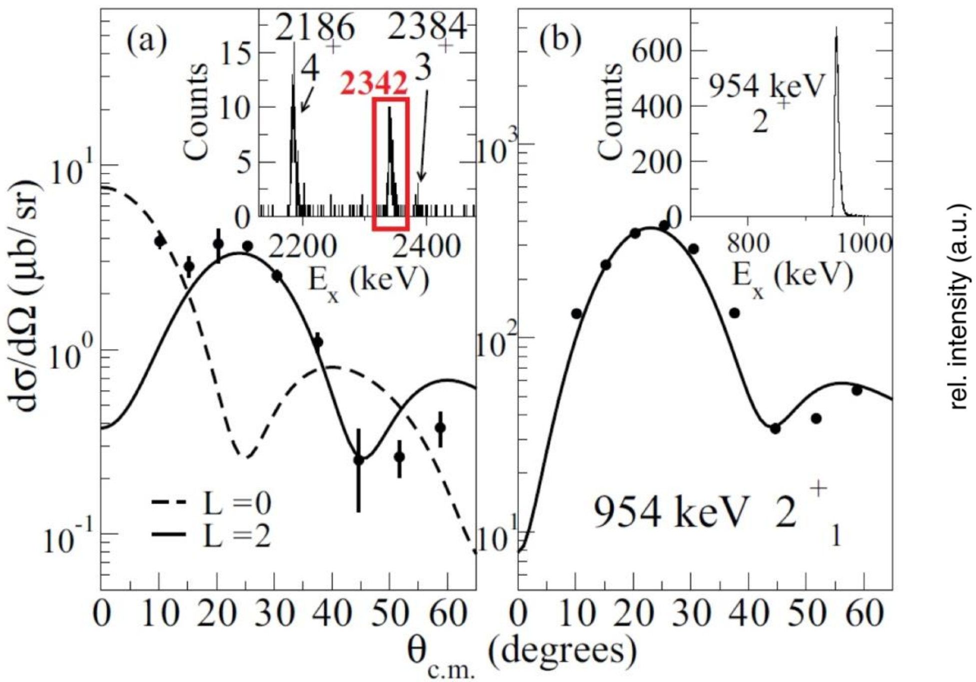
0.050(30)%

# $^{74}$Rb Superallowed Error Budget

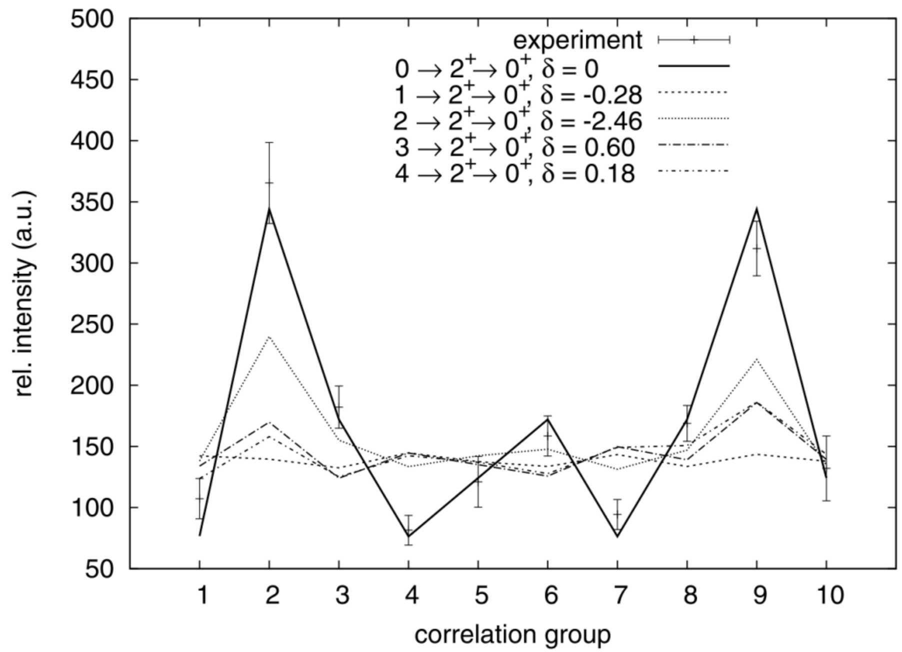


# 2342 keV ($0^+$?) State

## $^{64}Zn(p,t)^{62}Zn$
## Claim: $2^+$




## $^{61}Ni(^3He,2n\gamma)^{62}Zn$
## Claim: $0^+$

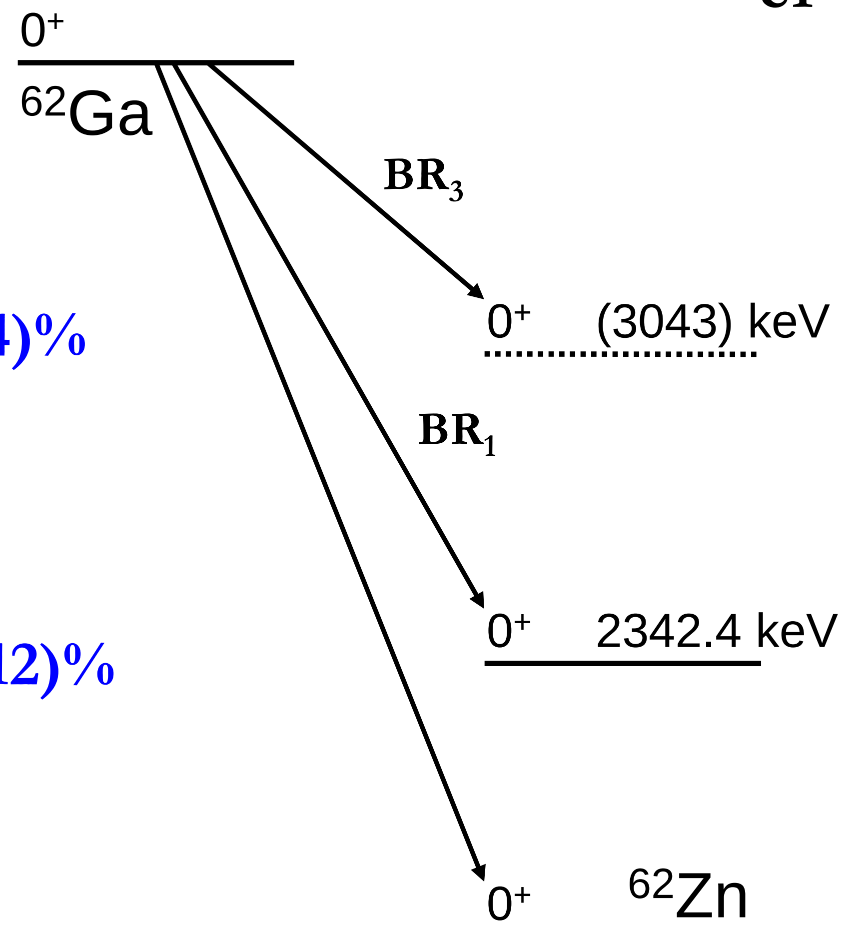



K.G. Leach et al., Phys. Rev. C 88, 031306(R) (2013)

M. Albers et al., Nucl. Phys. A847, 180 (2010)

# Isospin Mixing Component: $^{62}$Ga

$$\delta_{c1} \approx \delta^{1}_{c1} + \delta^{2}_{c1} + \ldots \qquad \delta^{n}_{c1} \approx (f_0/f_n)BR_n$$




**Experiment**

$\delta^{3}_{c1} \leq 0.011(4)\%$

$\delta^{1}_{c1} = 0.026(12)\%$

**Theory**

- 0.203% (TH MSDI)

- 0.083(20)% (TH MSDI)
- 0.158 % (TH GXPF1)
- 0.079% (OB FPVH)
- 0.169% (OB FPD6*)

**All shell-model calculations of isospin symmetry breaking in $^{62}$Ga to date assume a closed $^{56}$Ni core, and all significantly overestimate the isospin mixing components.**

# 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)

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

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