HIGH-PRECISION HALF-LIFE AND BRANCHING-RATIO MEASUREMENTS FOR THE SUPERALLOWED β^+ EMITTER $^{26}Al^m$

UNIVERSITY of GUELPH

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Overview

- Introduction
  - Superallowed Fermi β decay – Why $^{26}Al^m$?
- Experiment
  - Half-life of $^{26}Al^m$
  - Branching Ratios for $^{26}Al^m$ Decay
- Results and Discussion
  - The $^{26}Al^m$ ft and $\mathcal{F}t$ values
  - Impact
- Future Work

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 — $\mathcal{F}t$

Experiment — ft

Calculated corrections (~1%) (nucleus dependent) — δ_R', δ_{NS}, δ_C

Inner radiative correction (~2.4%) (nucleus independent) — Δ_R^V

CVC Hypothesis — constant

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

$\delta_C = \delta_{C1} + \delta_{C2}$ (isospin mixing plus radial overlap)

Theoretical treatment of δ_C

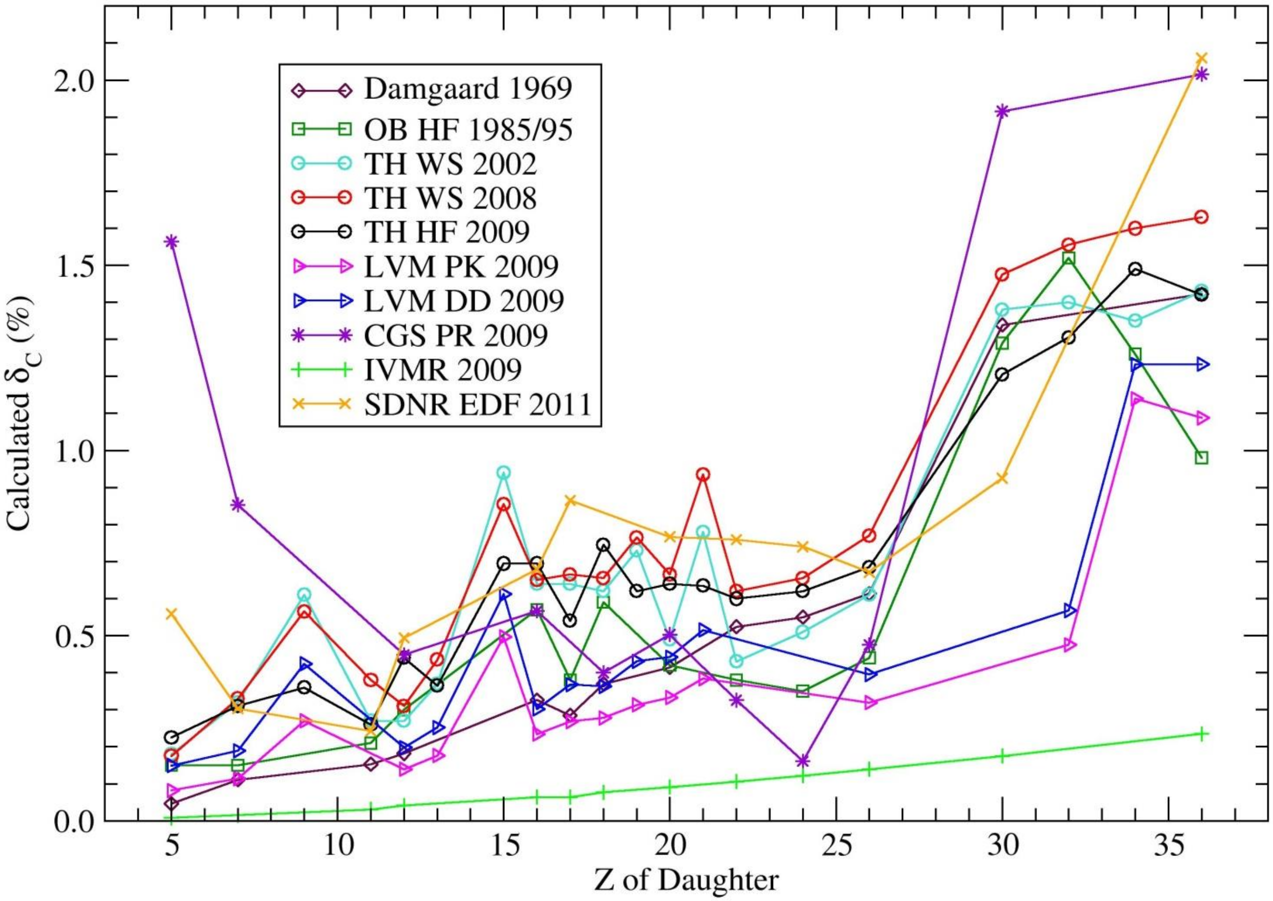
Several approaches to ISB corrections

→ Nuclear Shell Model

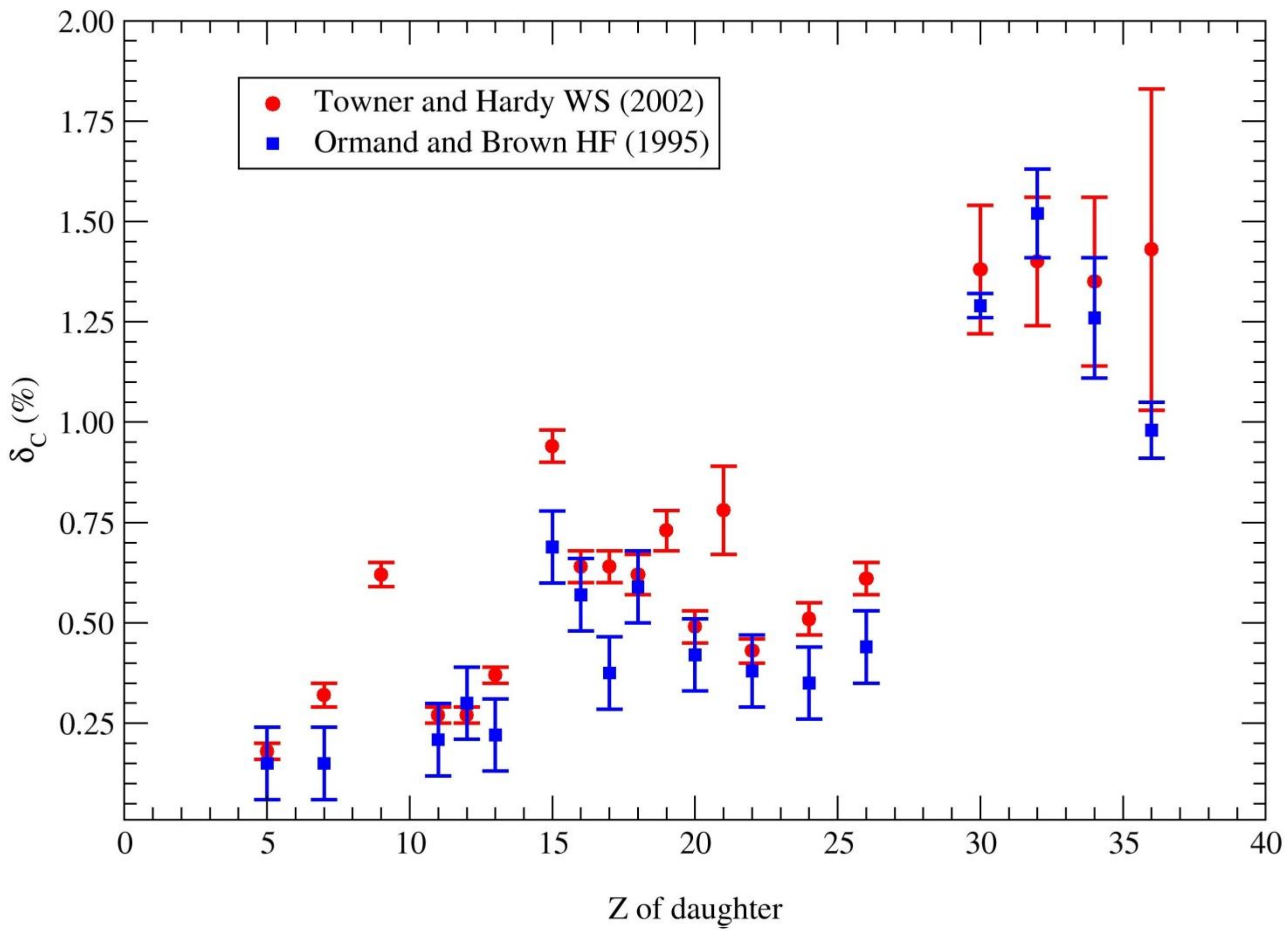
→ Relativistic Hartree-Fock

→ Random Phase Approximation

→ Energy Density Functional theory



Isospin-Symmetry-Breaking Corrections



Two approaches to δ_{C2}

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

W.E. Ormand and B.A. Brown, Physical Review C **52**, 2455 (1995)
I.S. Towner and J.C. Hardy, Physical Review C **66**, 035501 (2002)

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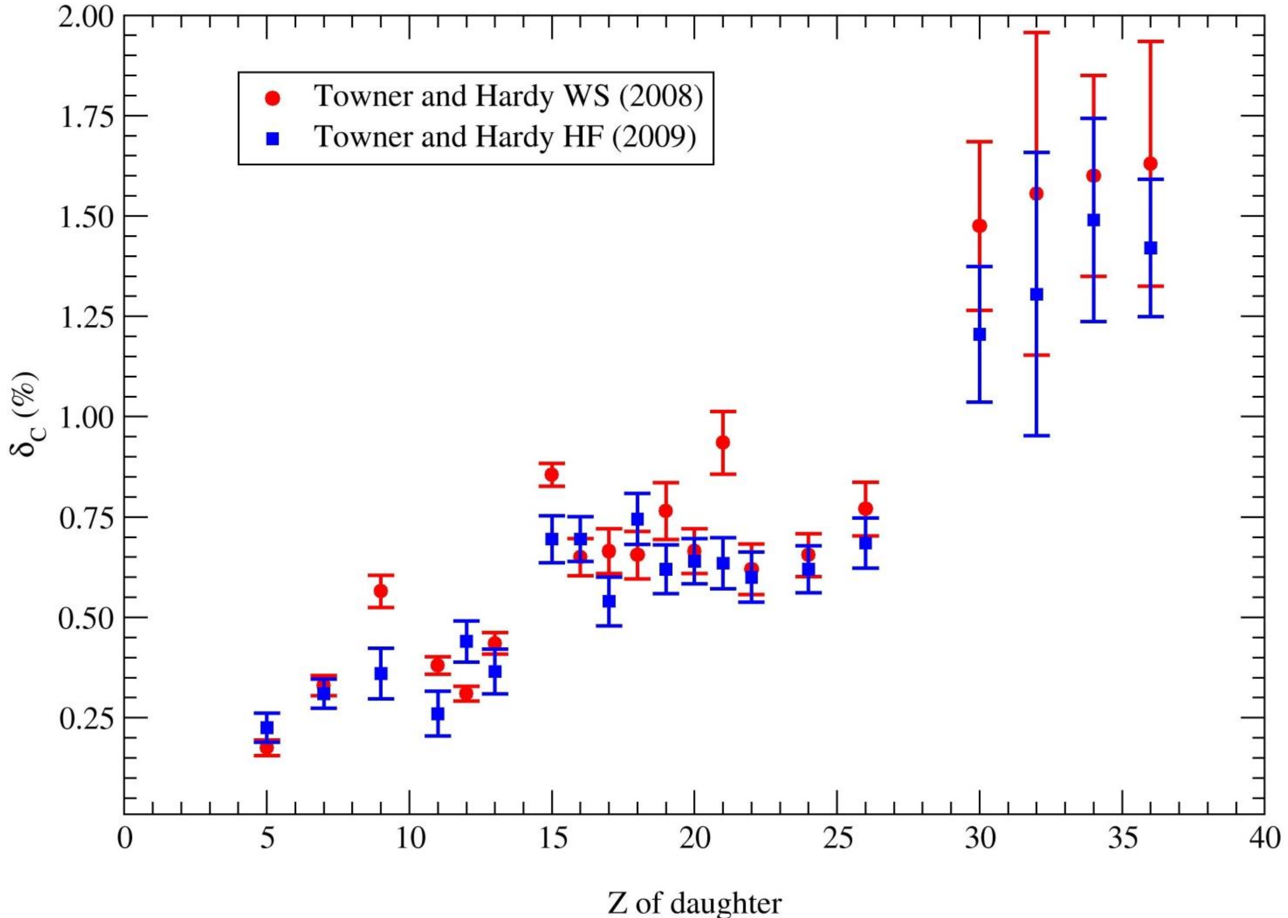
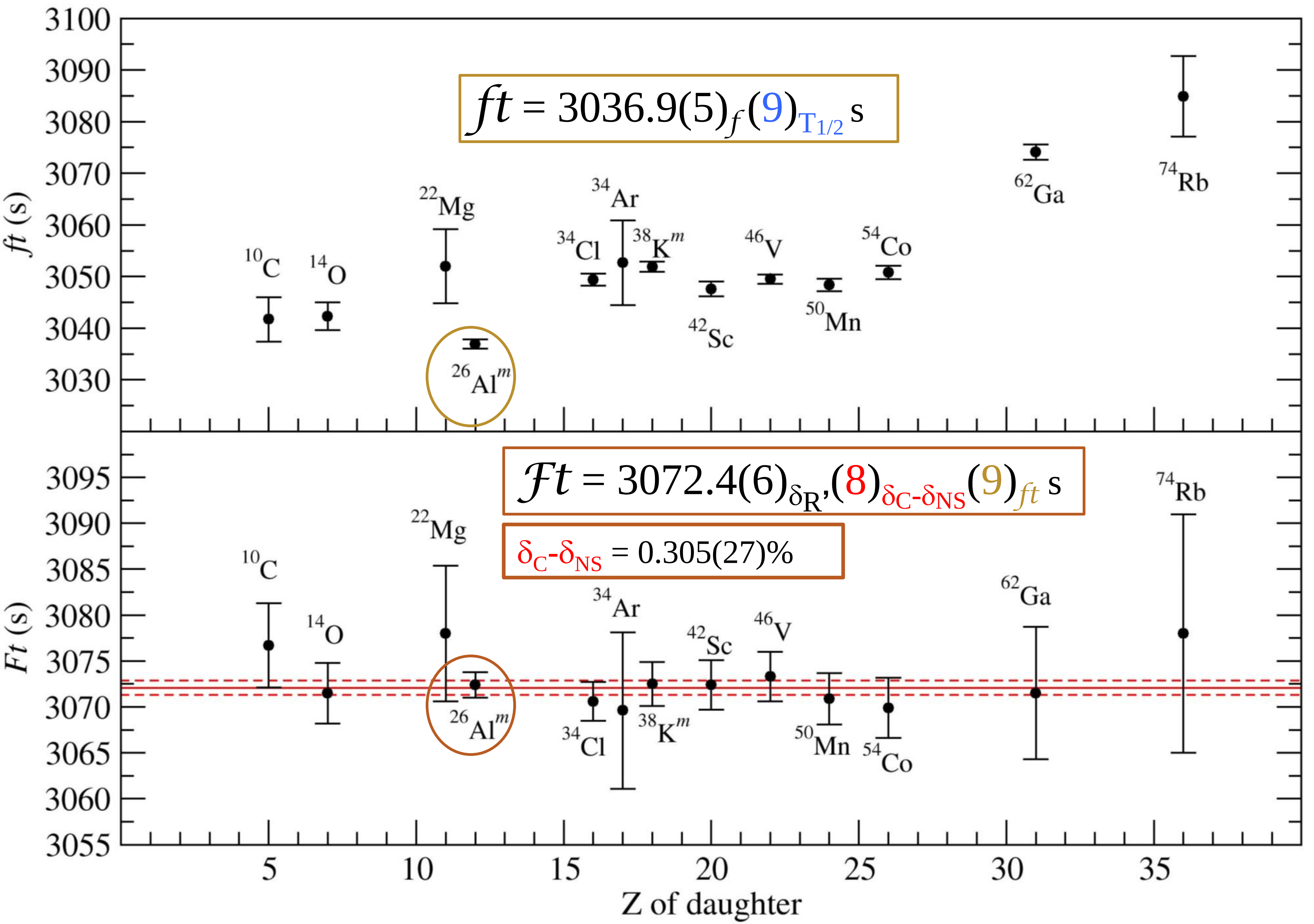


Two approaches to δ_{C2}

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

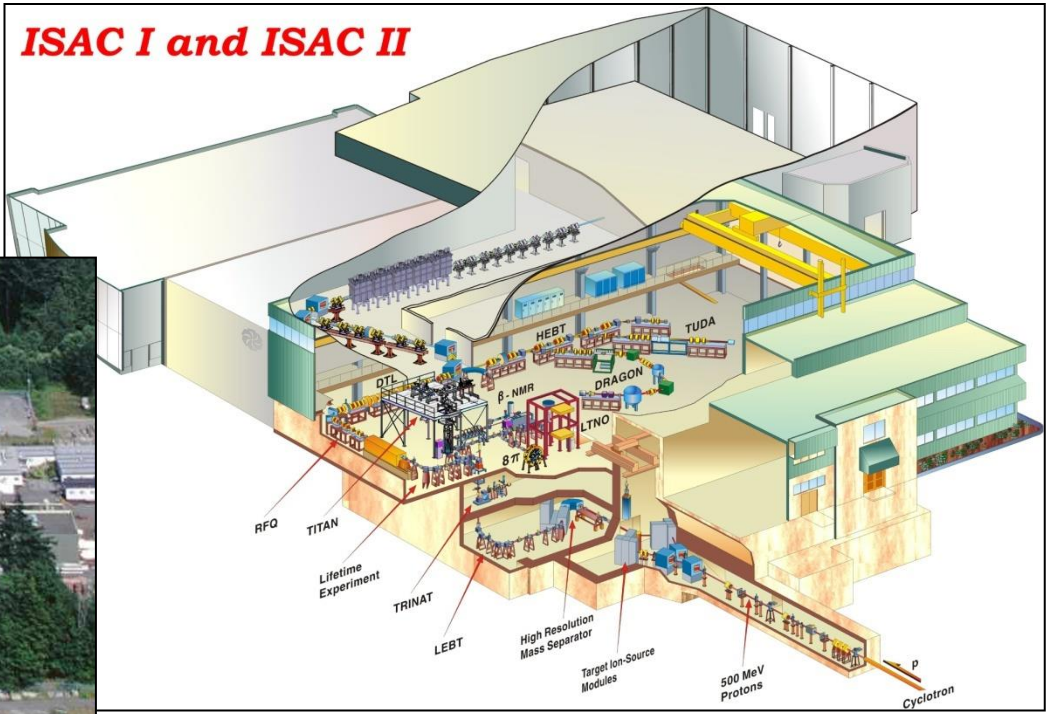
$\overline{\mathcal{F}t} = 3071.81 \pm 0.79_{stat} \pm 0.27_{syst}$ s

I.S. Towner and J.C. Hardy, Physical Review C **77**, 055501 (2008)
J.C. Hardy and I.S. Towner, Physical Review C **79**, 055502 (2009)

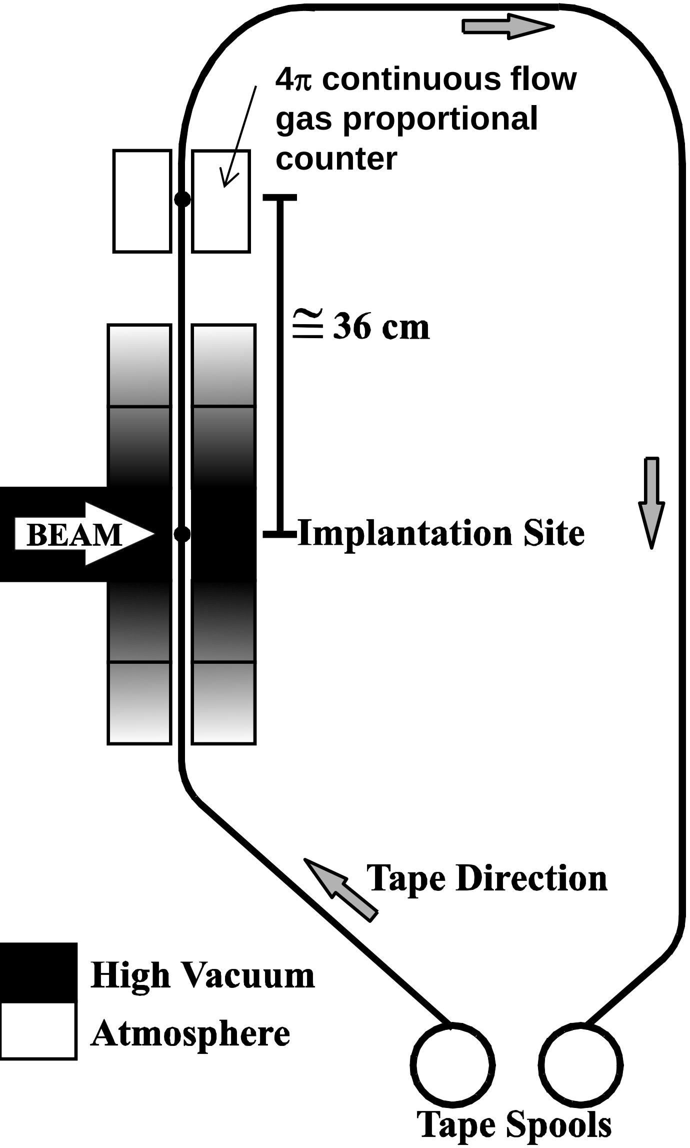


J.C. Hardy and I.S. Towner, Physical Review C **79**, 055502 (2009)

TRIUMF: *Canada's National Laboratory for Nuclear and Particle Physics Research*



Measuring Superallowed Half Lives

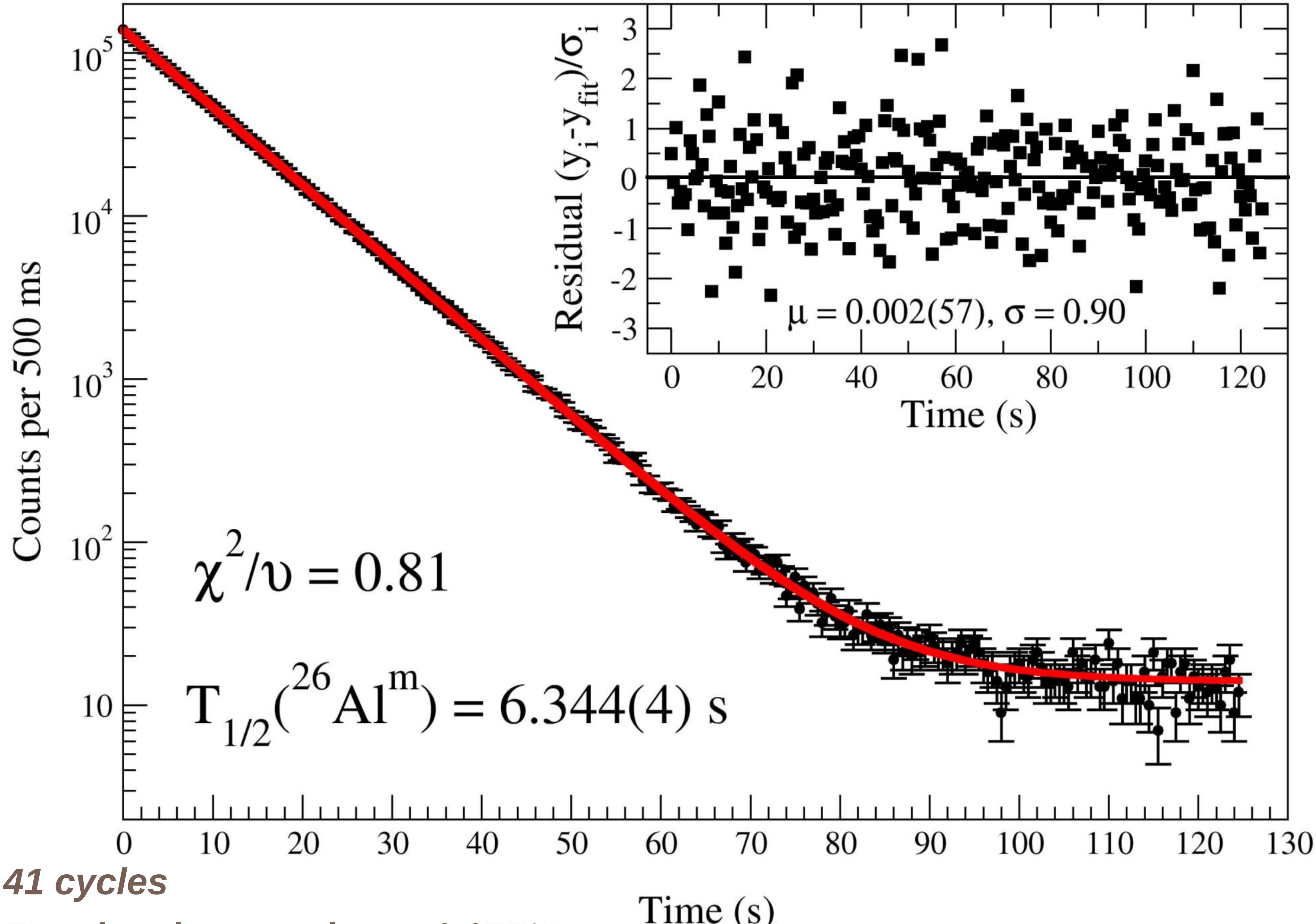


Beam

- $^{26}Al^{m}$: $T_{1/2}$ = 6.3465 s
- ^{26}Na: $T_{1/2}$ = 1.072 s
- $^{26}Al^{g}$: $T_{1/2}$ = 7.4×10^{5} yrs

Cycle

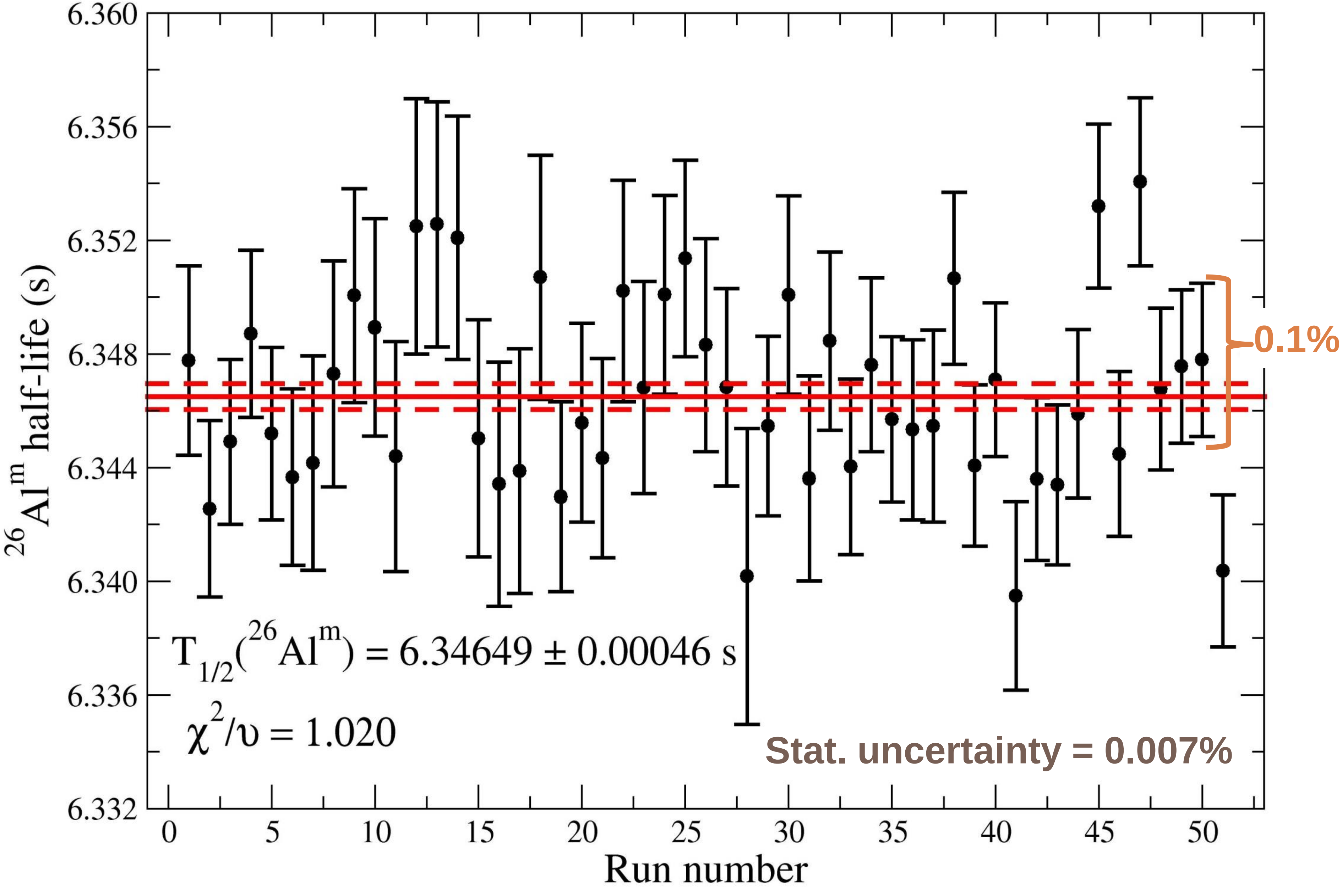
- Implant 6-14 s
- Allow ^{26}Na to decay 26-34 s
- Move tape to detector and count $^{26}Al^{m}$ decays for ~20, 25, 30 half-lives, then repeat.
- Change detector voltage, discriminator setting, and swap fixed, nonextendable dead times between two MCS units to investigate systematic effects.



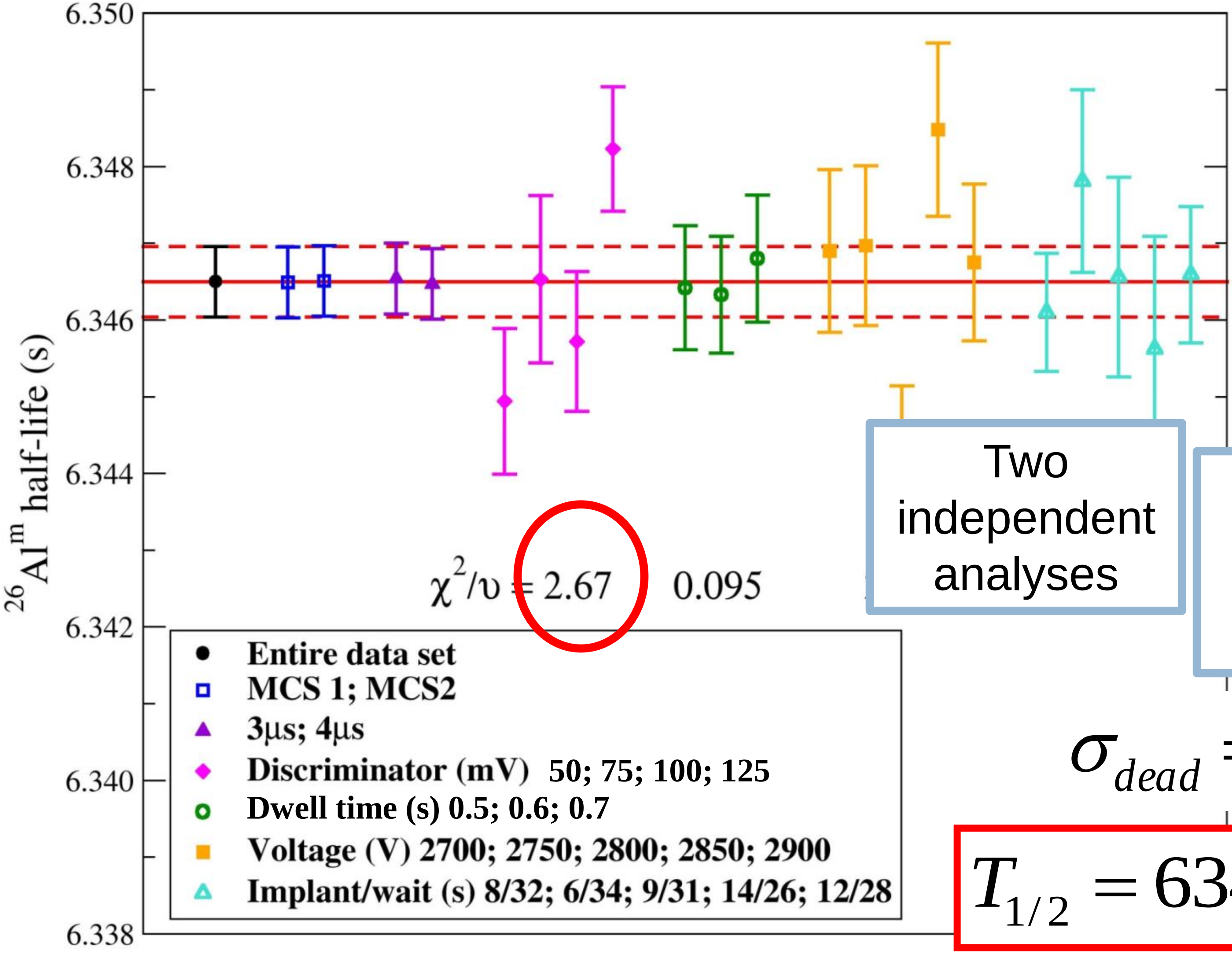
41 cycles

Fractional uncertainty = 0.077%

2008 cycles spanning 51 runs



Assigning a systematic uncertainty



$$\sigma = \sqrt{2.67}\sigma_{stat.}$$

= 0.75 ms

$$\sigma_{stat.} = 0.46ms$$

$$\sigma_{syst.} = 0.59ms$$

Two independent analyses

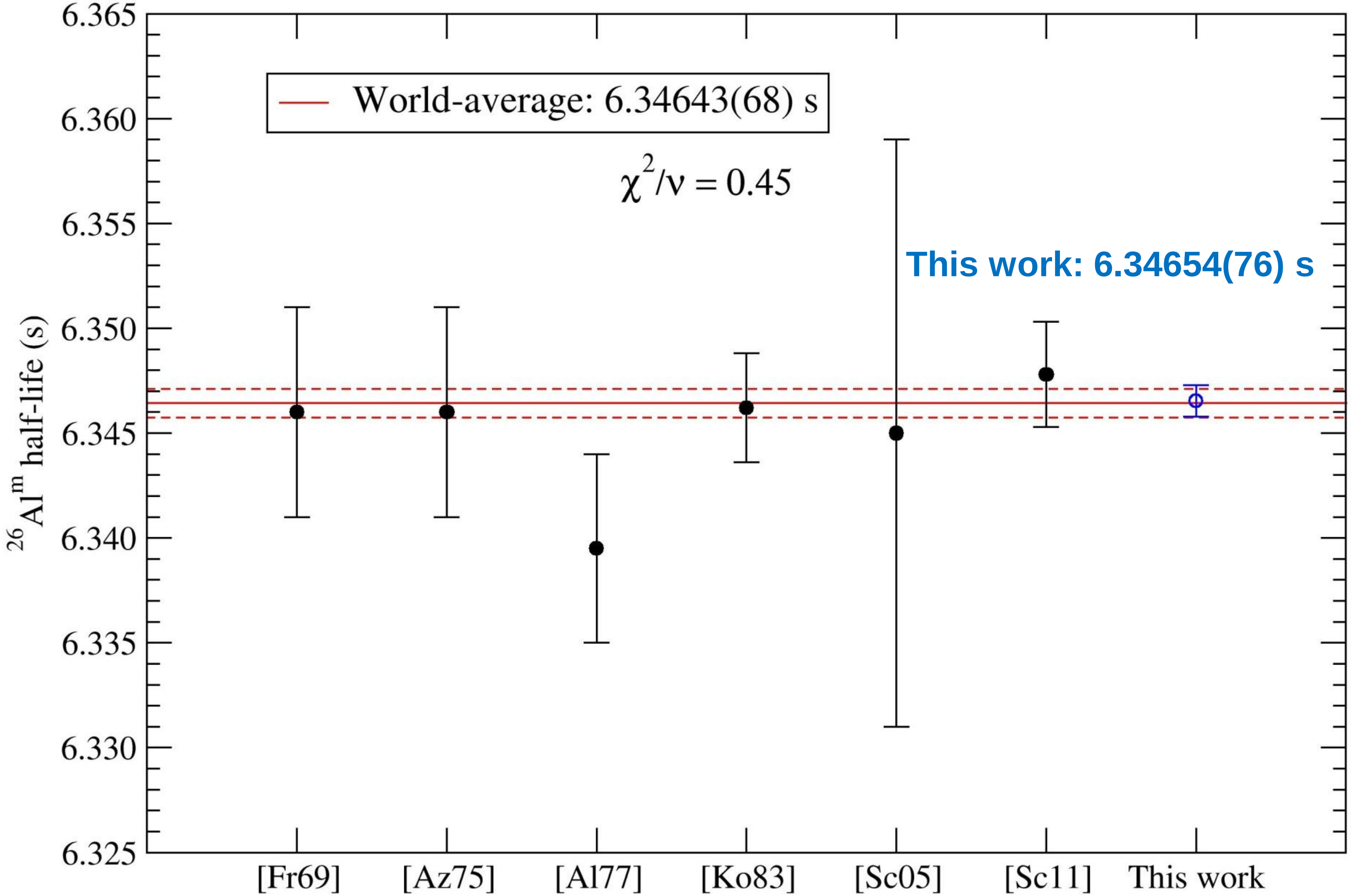
1) 6346.59 ms
2) 6346.49 ms

σ_{ind} = 0.05 ms

$$\sigma_{dead} = 0.045ms$$

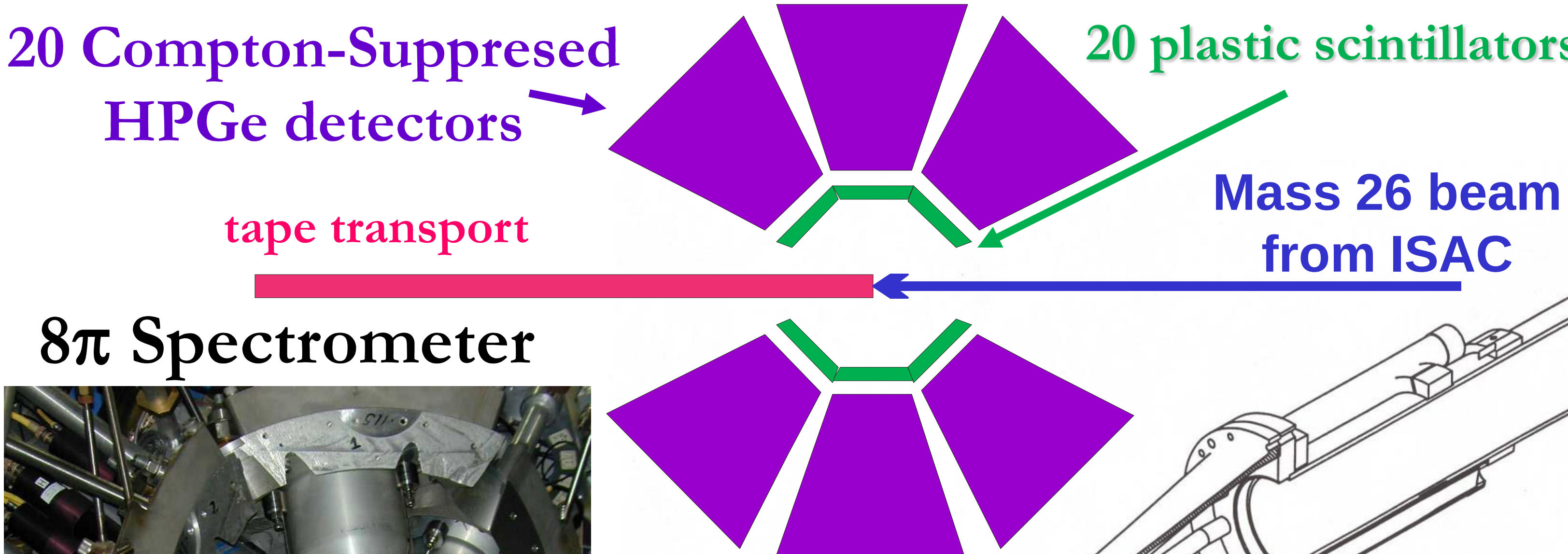
$$T_{1/2} = 6346.54(76)ms$$

Comparison with previous results

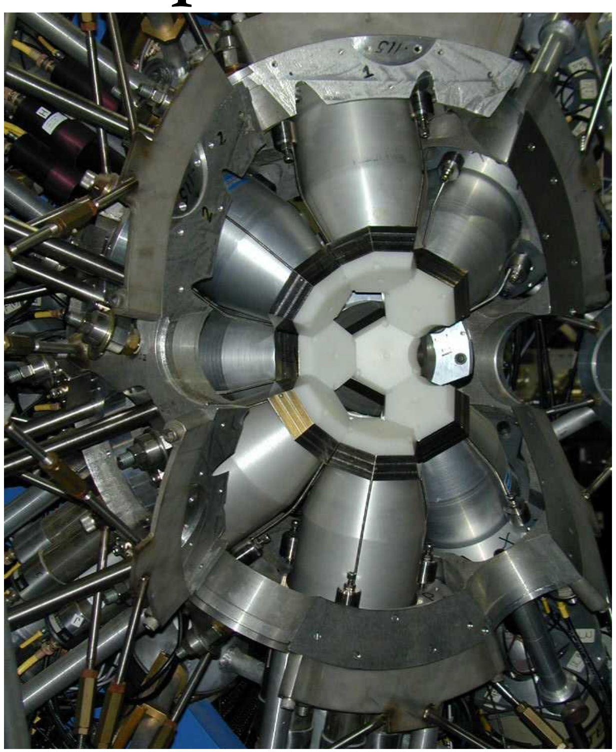


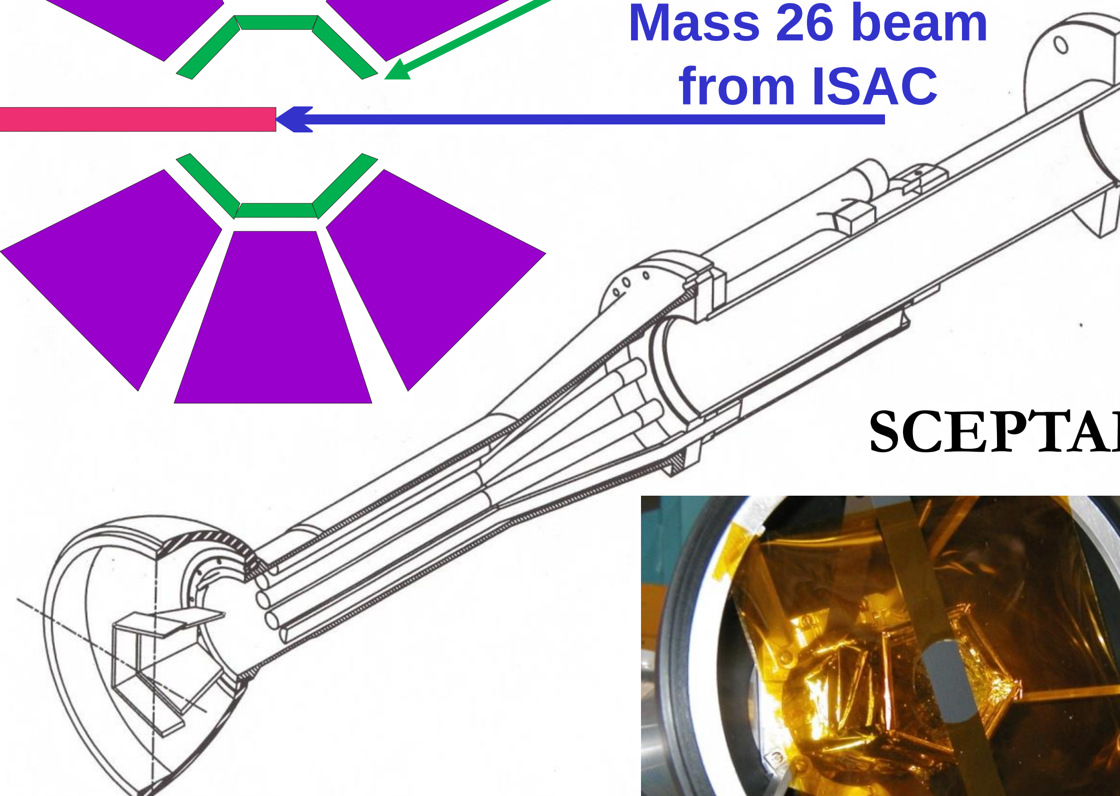
P. Finlay *et al.*, Phys. Rev. Lett. **106**, 032501 (2011)

The 8π Spectrometer and SCEPTAR at ISAC-I

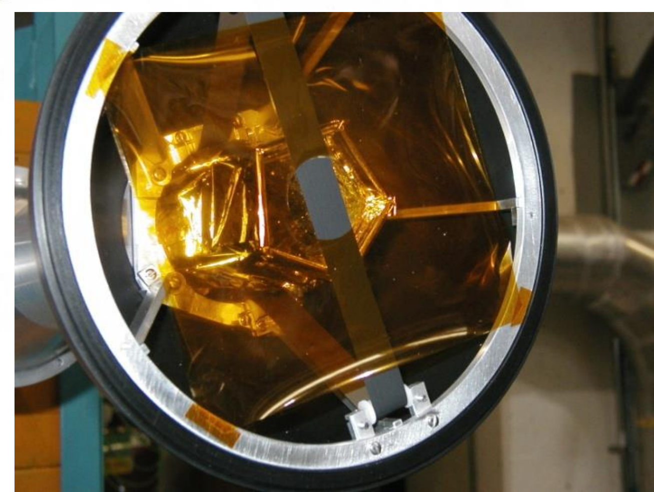


8π Spectrometer

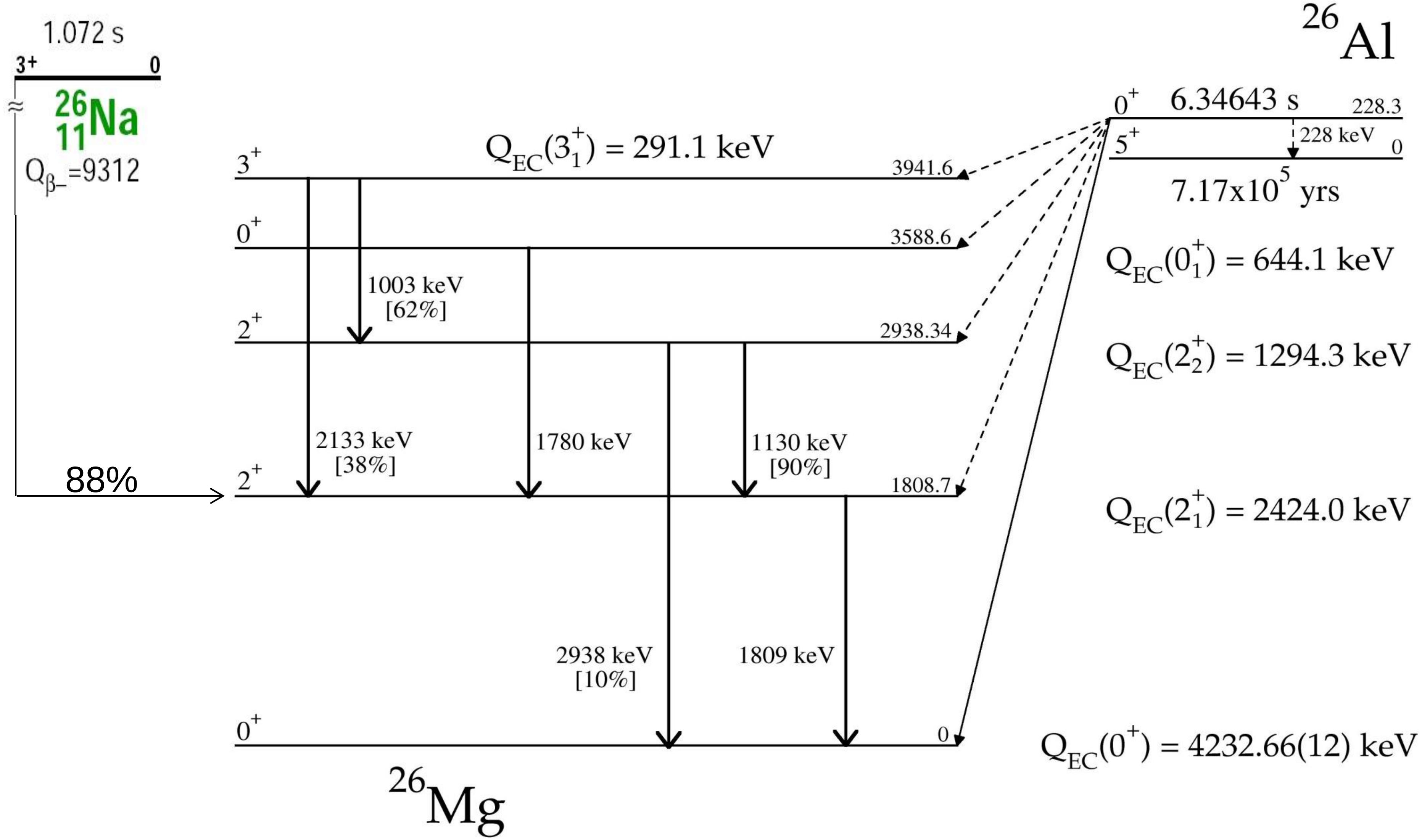




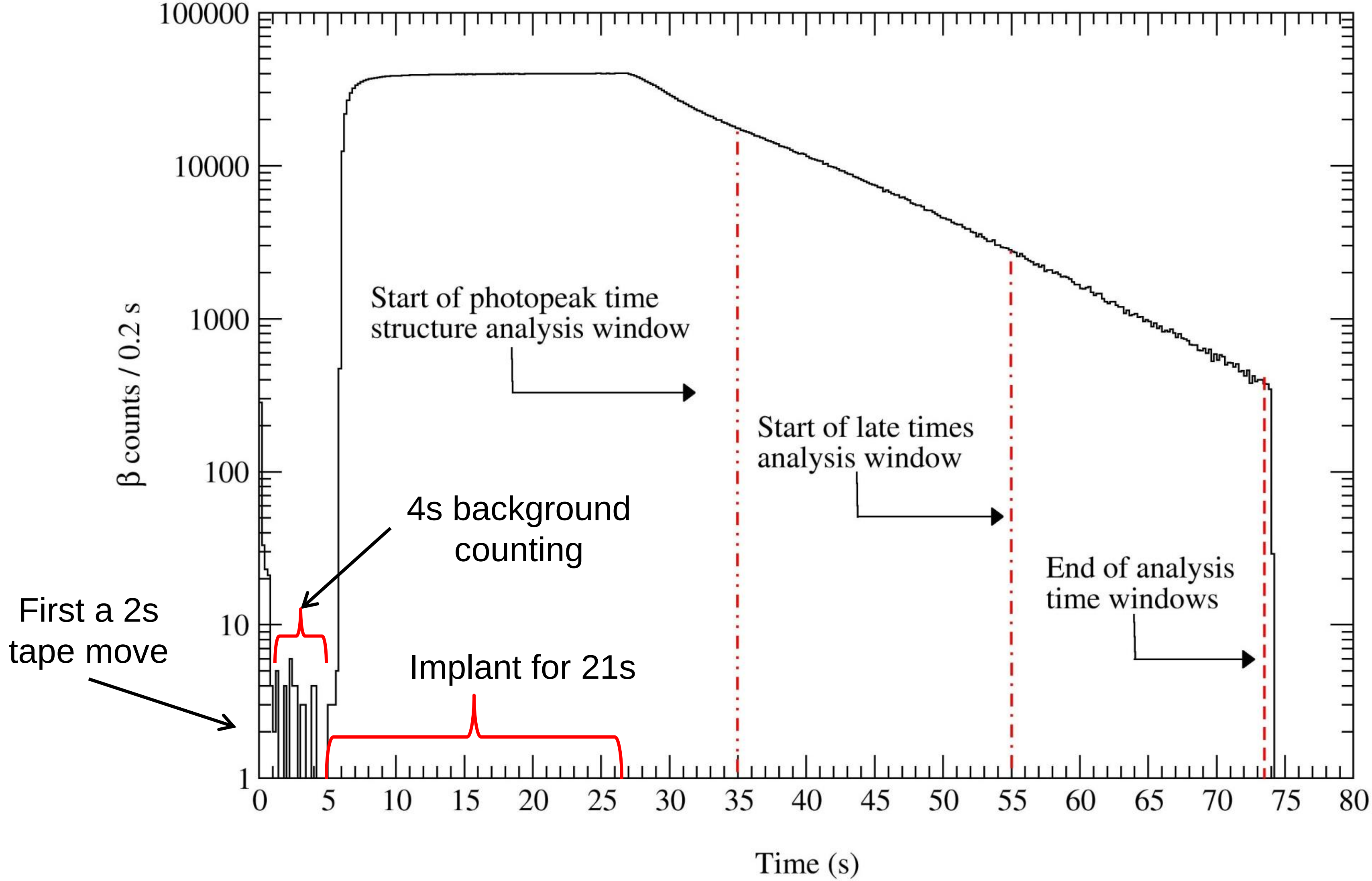
SCEPTAR



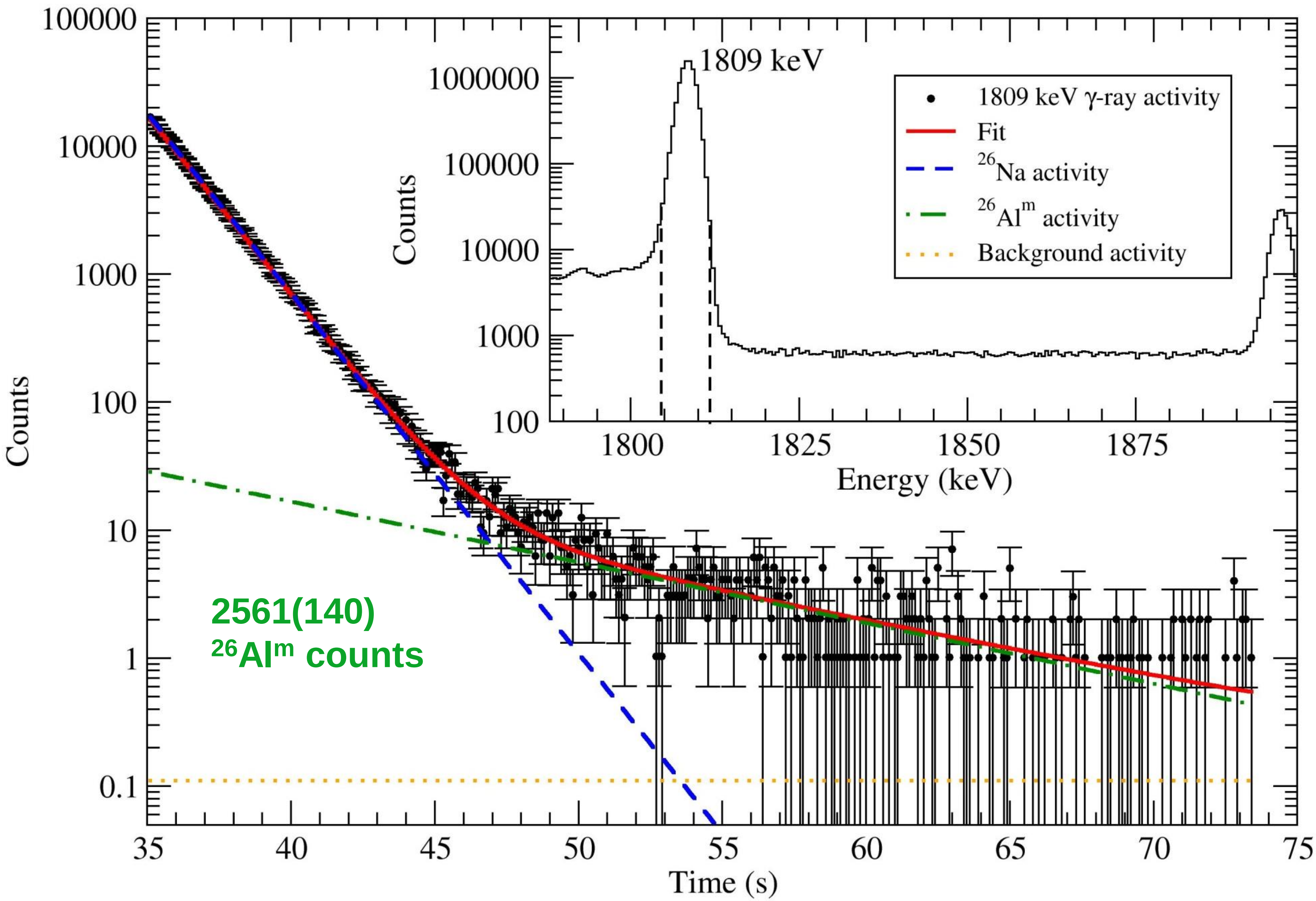
Branching Ratios for $^{26}Al^{m}$ Decay



Cycle Structure



Determining $^{26}Al^{m}$ non-analog intensity



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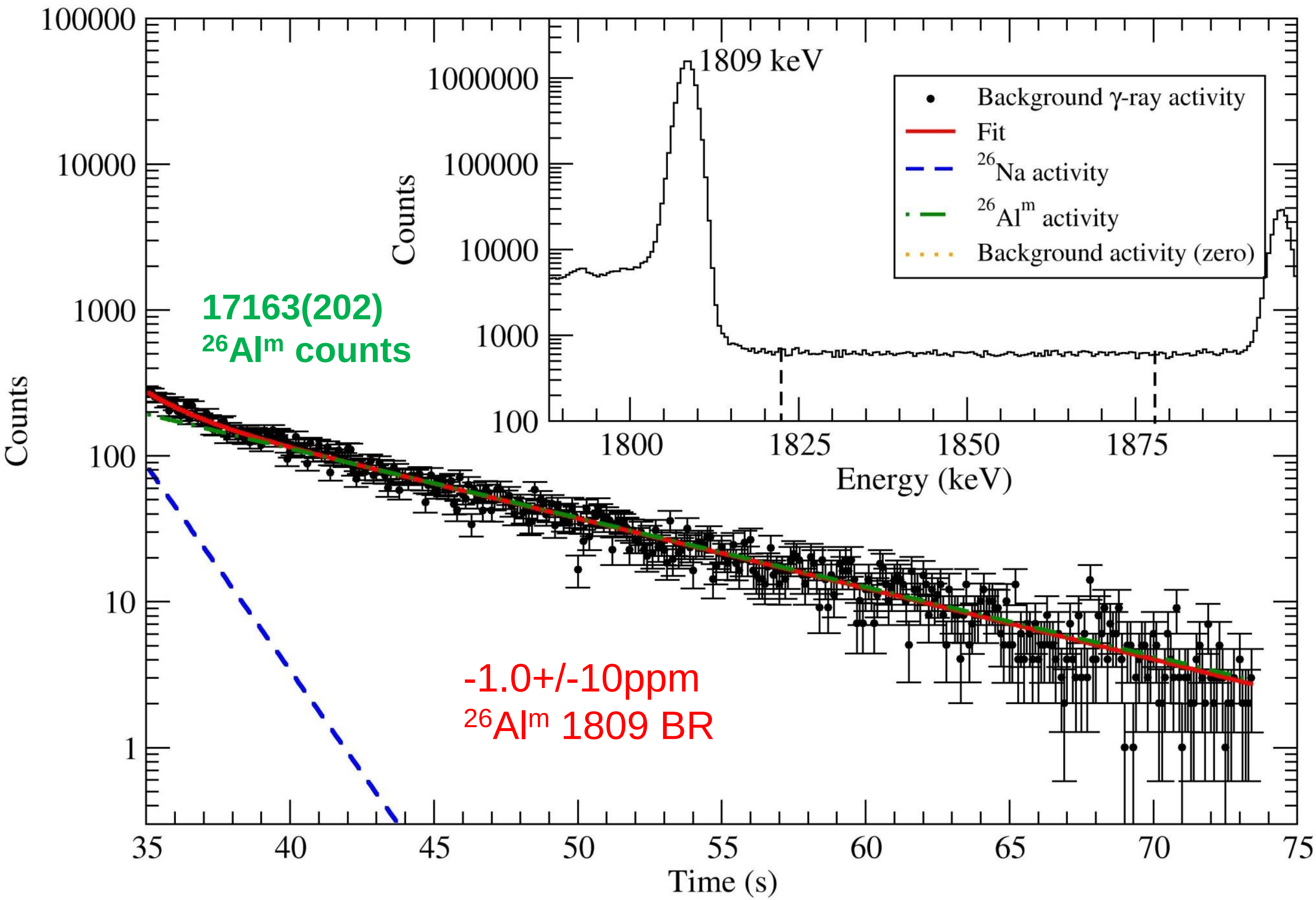
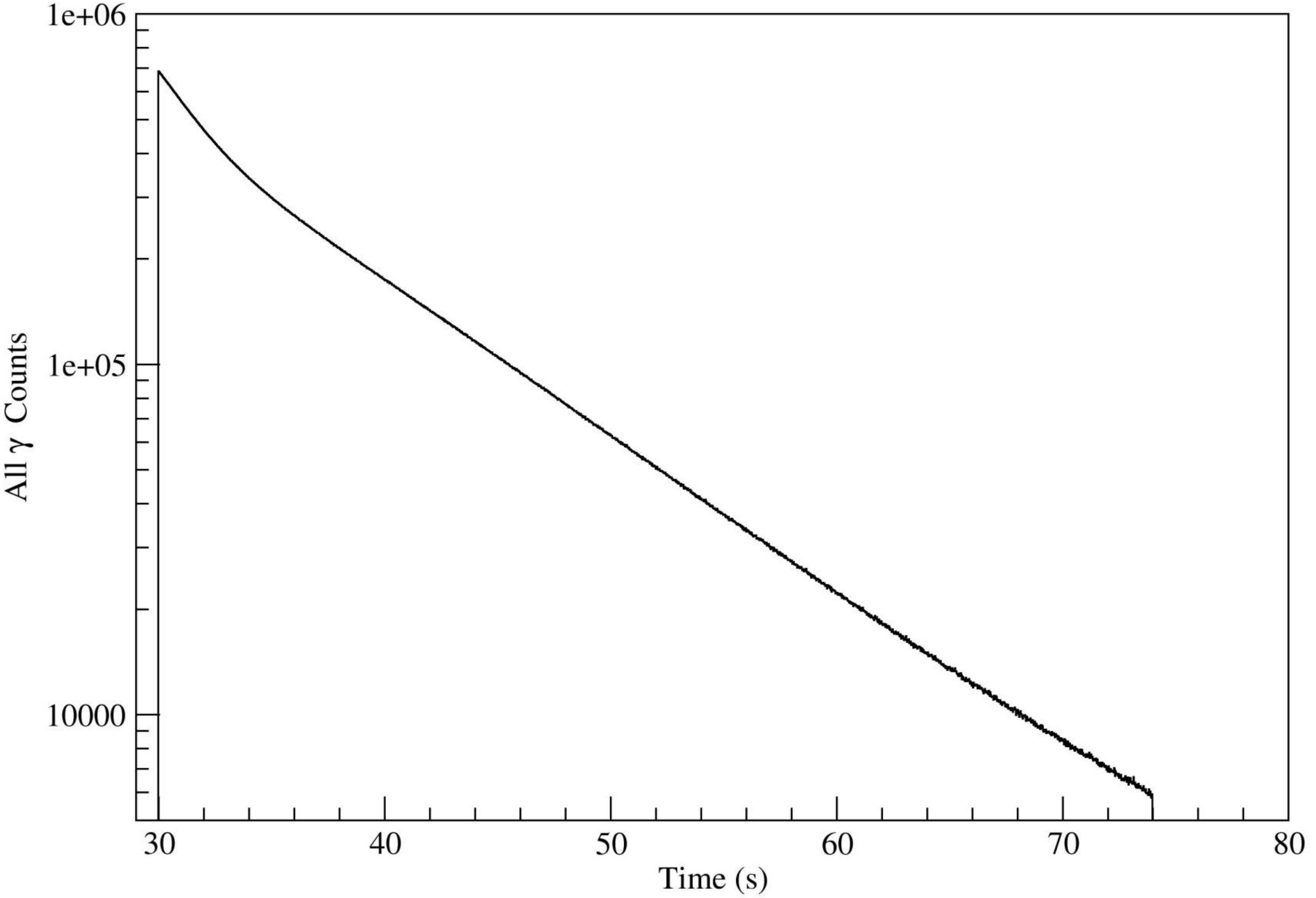
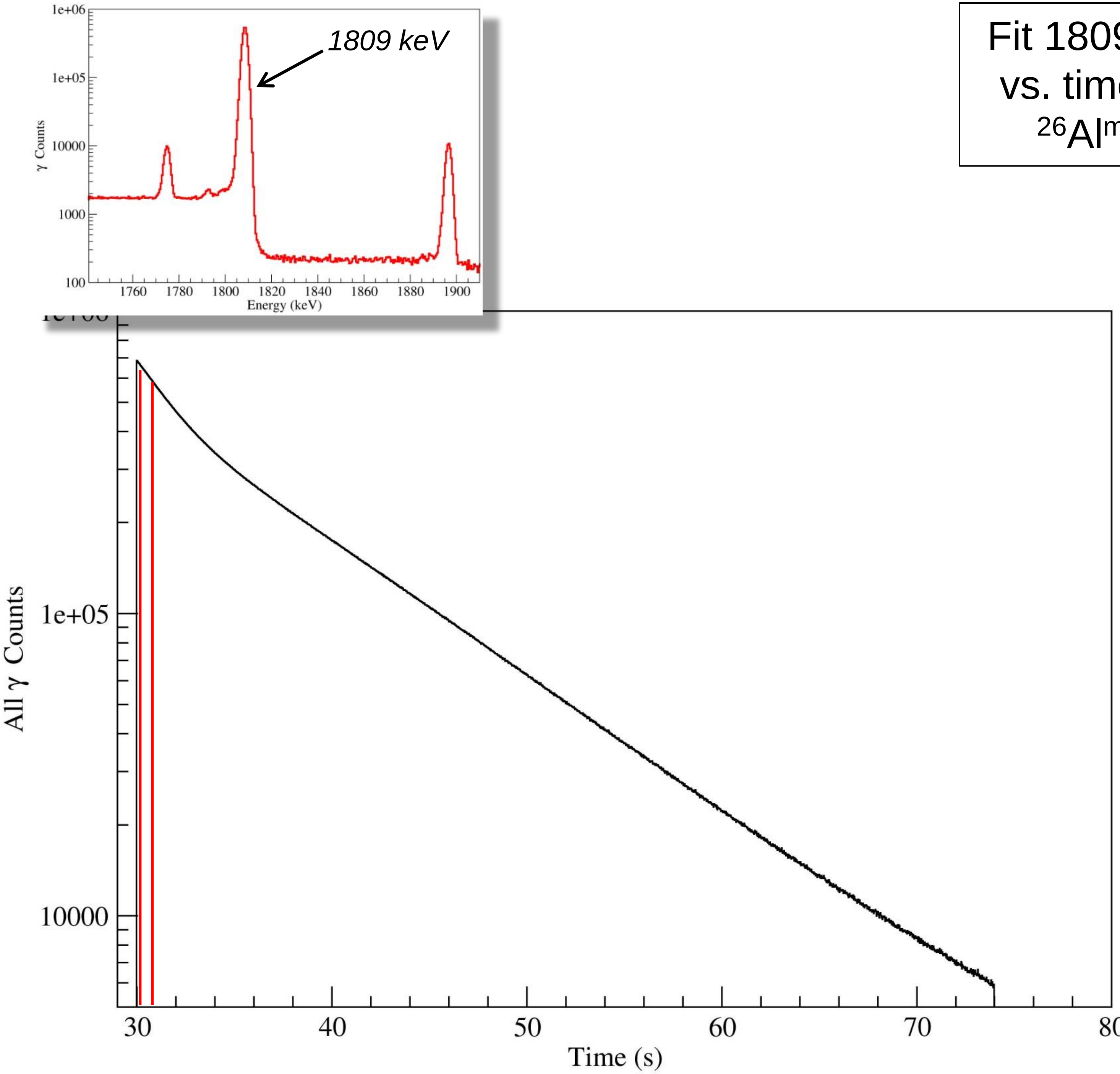


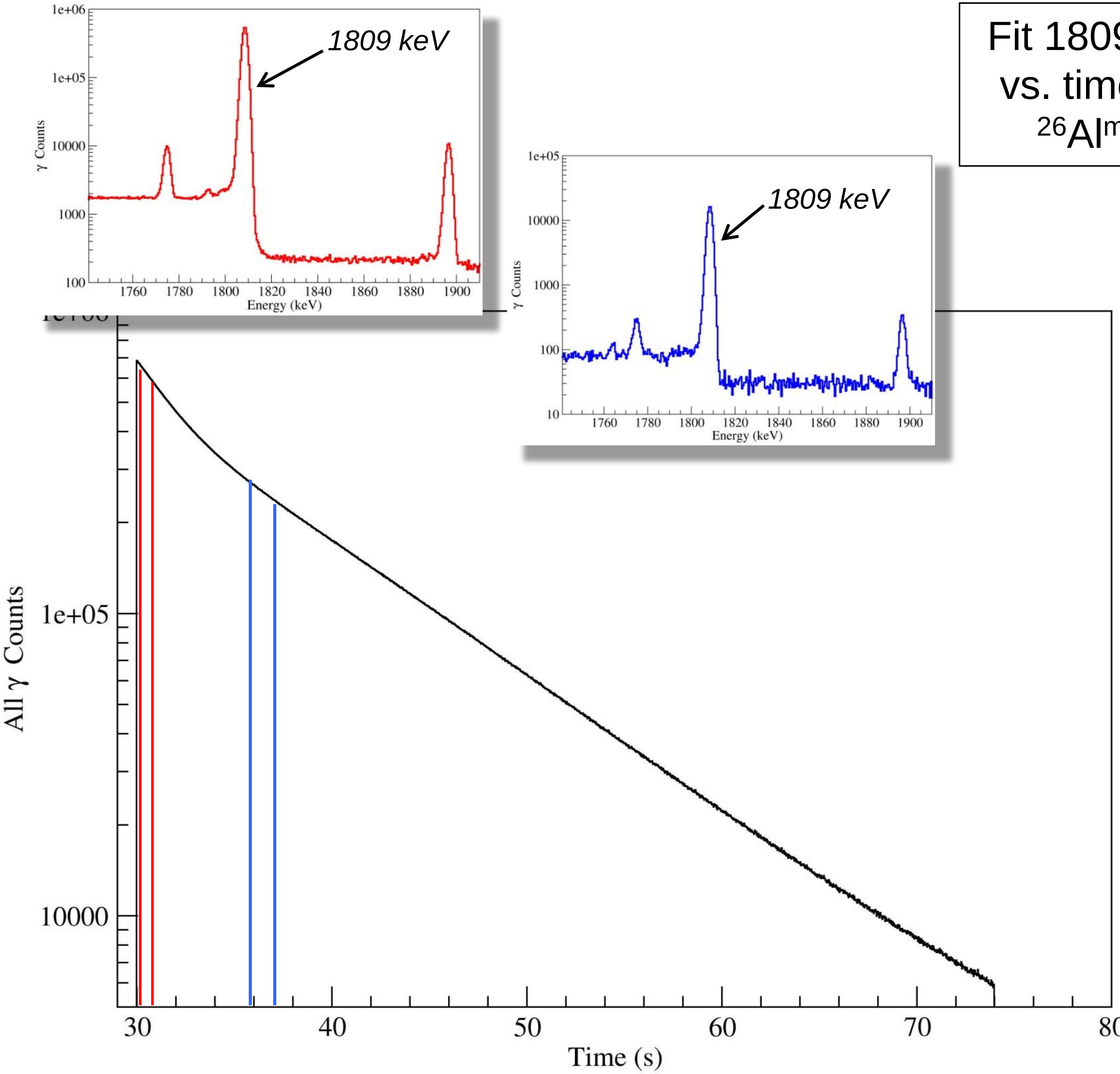
Fit 1809 keV peak area vs. time with ^{26}Na and $^{26}Al^m$ components



Fit 1809 keV peak area vs. time with ^{26}Na and ^{26}Al^{m} components



Fit 1809 keV peak area vs. time with ^{26}Na and $^{26}Al^{m}$ components



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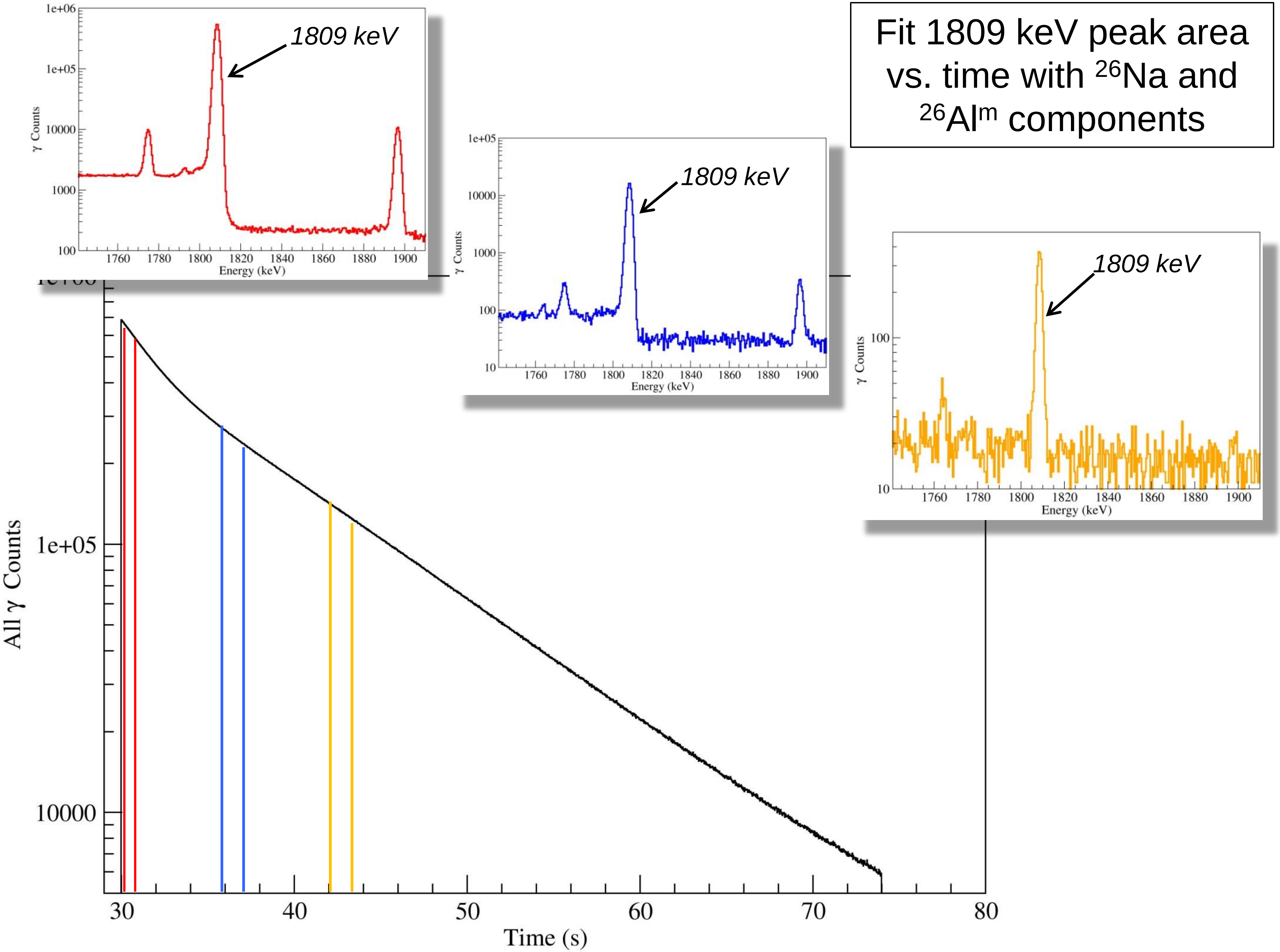

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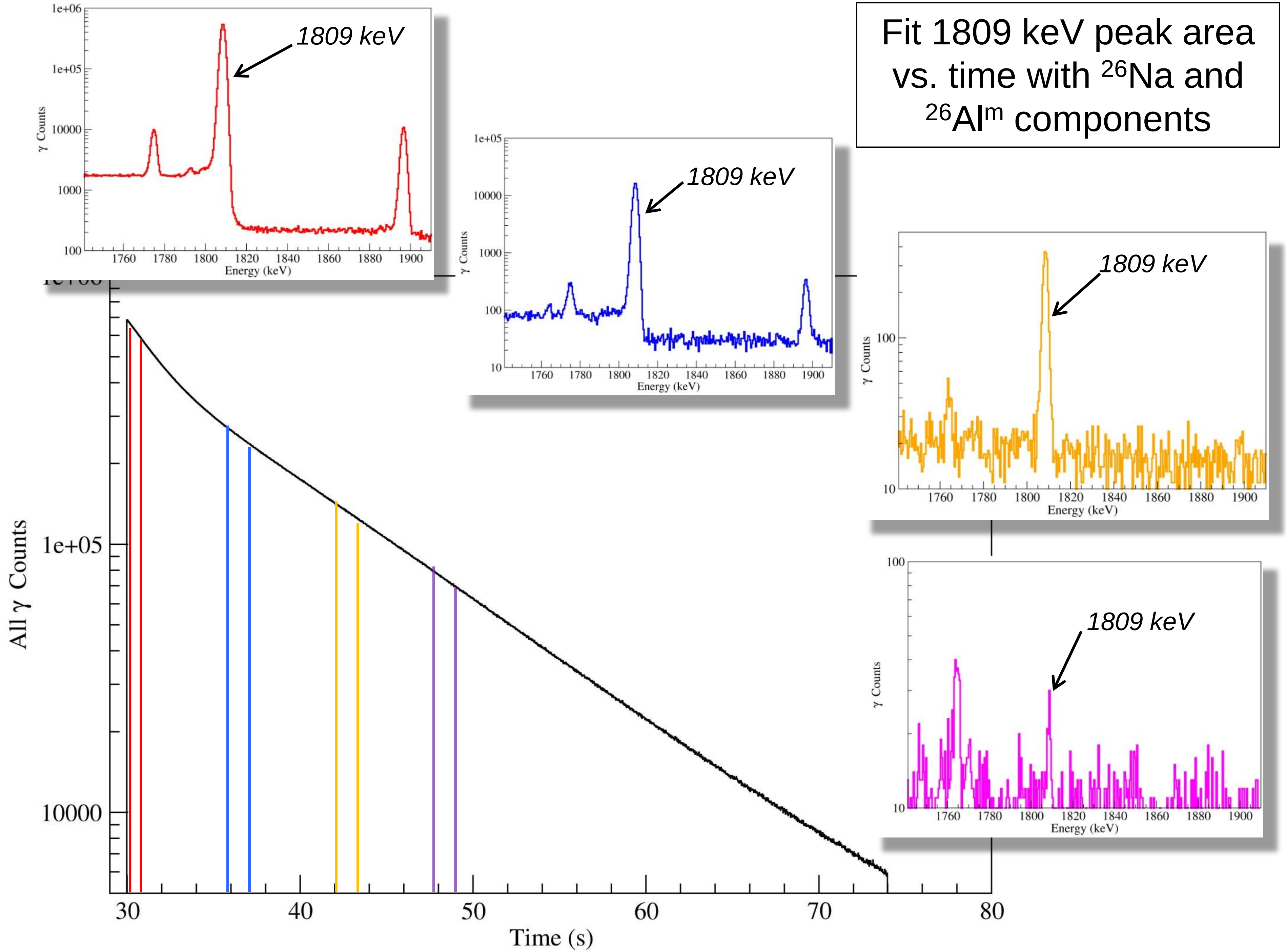
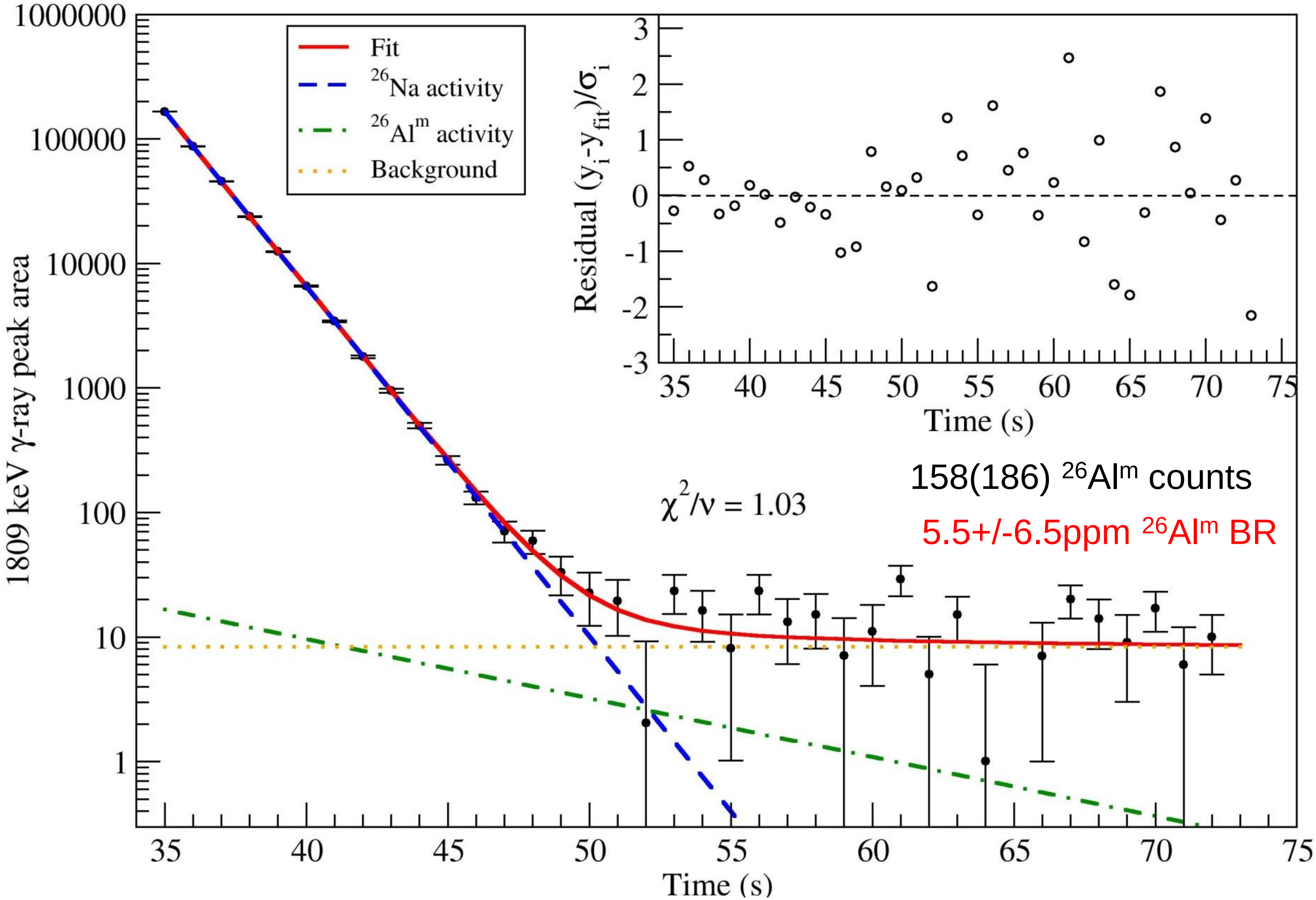


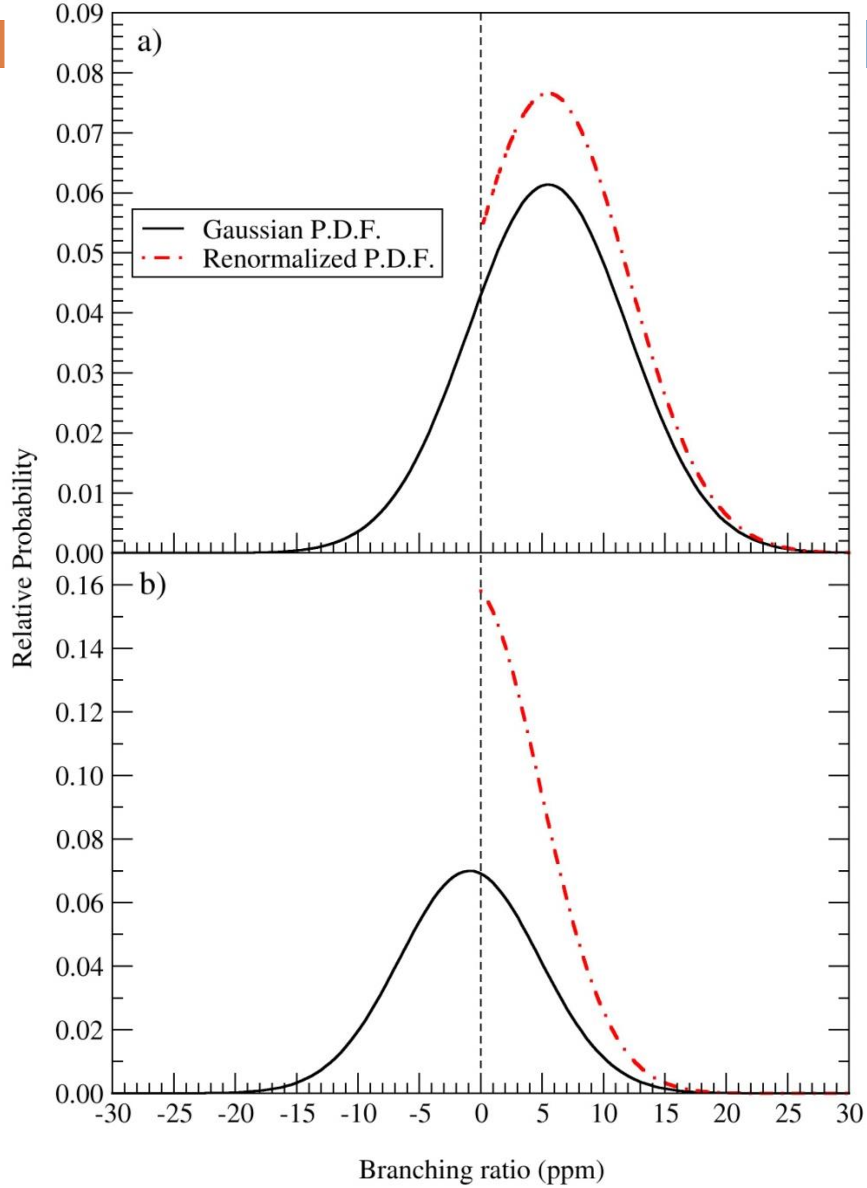
Peak Area vs. Time



158(186) ^{26}Al^{m} counts

5.5+/-6.5ppm ^{26}Al^{m} BR

$^{26}Al^{m}$ Non-Analog Branching Ratios



All measured BR consistent with zero

Total non-analogue decay:

5.5+/-6.5 ppm (peak area vs. time)

≤ 10 ppm @ 67% CL

≤ 15 ppm @ 90% CL

Direct feeding of 1809 keV:

-0.9+/-5.7 ppm (late time analysis)

≤ 5 ppm @ 67% CL

≤ 12 ppm @ 90% CL

$$100.0000 \pm^{0}_{0.0015} \%$$

P. Finlay *et al.*, Phys. Rev. C **85**, 055501 (2012)

$^{26}Al^{m}$ *ft* Value

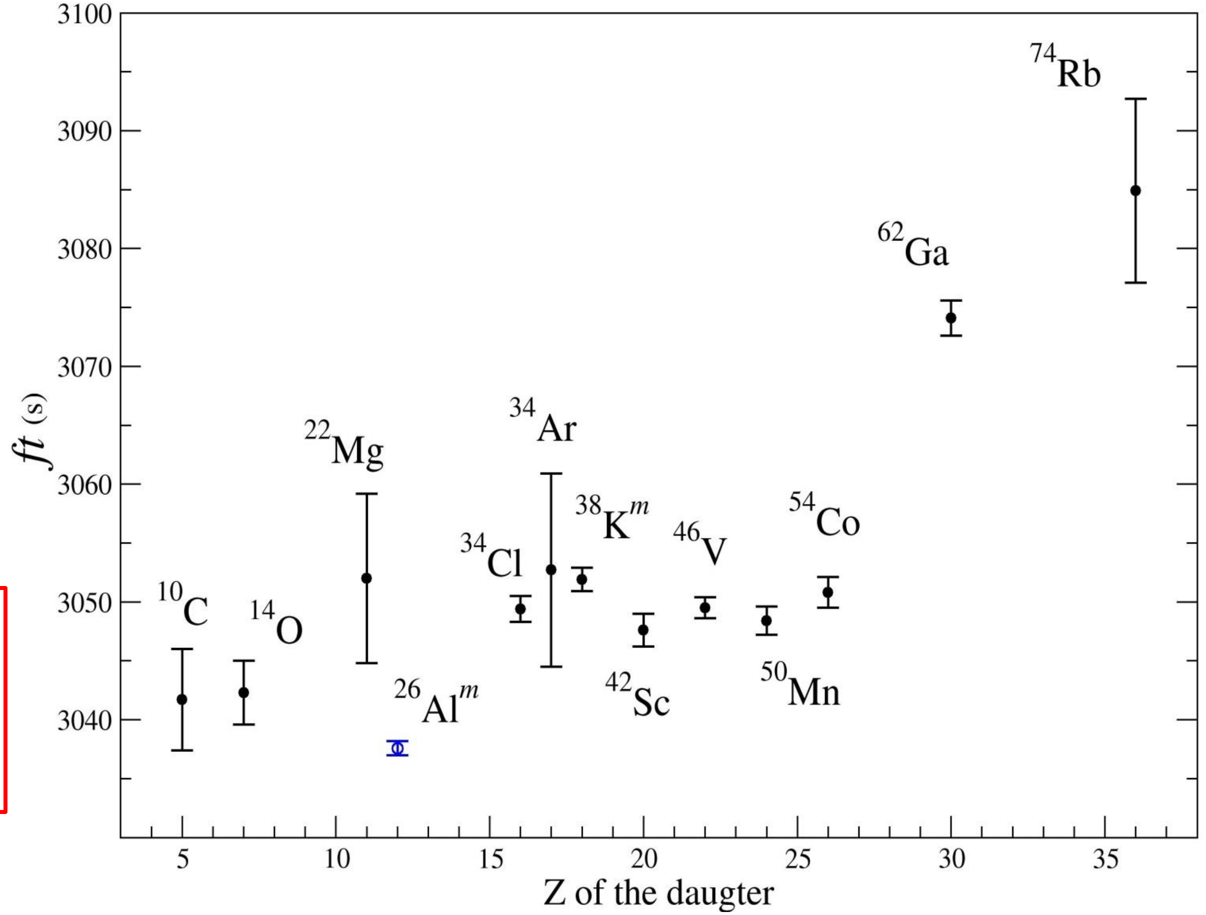
$$ft = \frac{ft_{1/2}(1+P_{EC})}{SBR}$$

$P_{EC} = 0.082$ %

$f = 478.237(80)$

$t_{1/2} = 6346.43(68)$ ms

$SBR = 100.0000^{+0}_{-0.0015}$ %



$ft = 3037.58(51)_{f}(32)_{T_{1/2}}(5)_{BR}$ s

Most precise *ft* for any superallowed emitter

$^{26}Al^m$ $\mathcal{F}t$ Value, Woods-Saxon δ_C

$\delta'_R = 1.478(20)$ %

$\delta_{NS} = 0.005(20)$ %

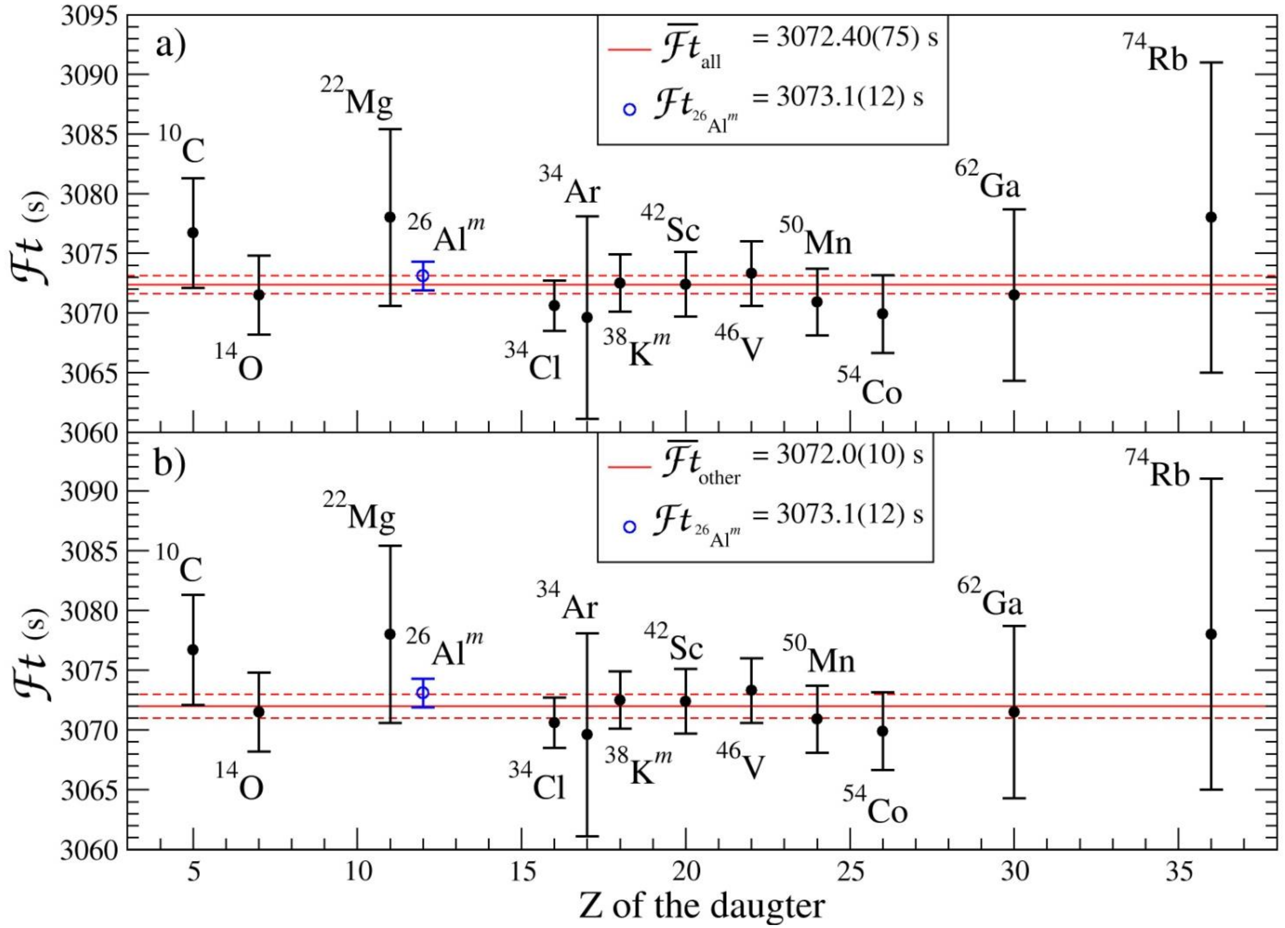
$\delta_C = 0.310(18)$ %

$\mathcal{F}t = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C)$

$= 3073.1(6)_{\delta_R'}(8)_{\delta_C - \delta_{NS}}(6)_{ft}$ s

$\mathcal{F}t_{^{26}Al^m} = 3073.1(12)$ s

$\mathcal{F}t_{other} = 3072.0(10)$ s



Based on J.C. Hardy and I.S. Towner, Physical Review C **79**, 055502 (2009)

$^{26}Al^m$ $\mathcal{F}t$ Value, Hartree-Fock δ_C

$\delta'_R = 1.478(20)$ %

$\delta_{NS} = 0.005(20)$ %

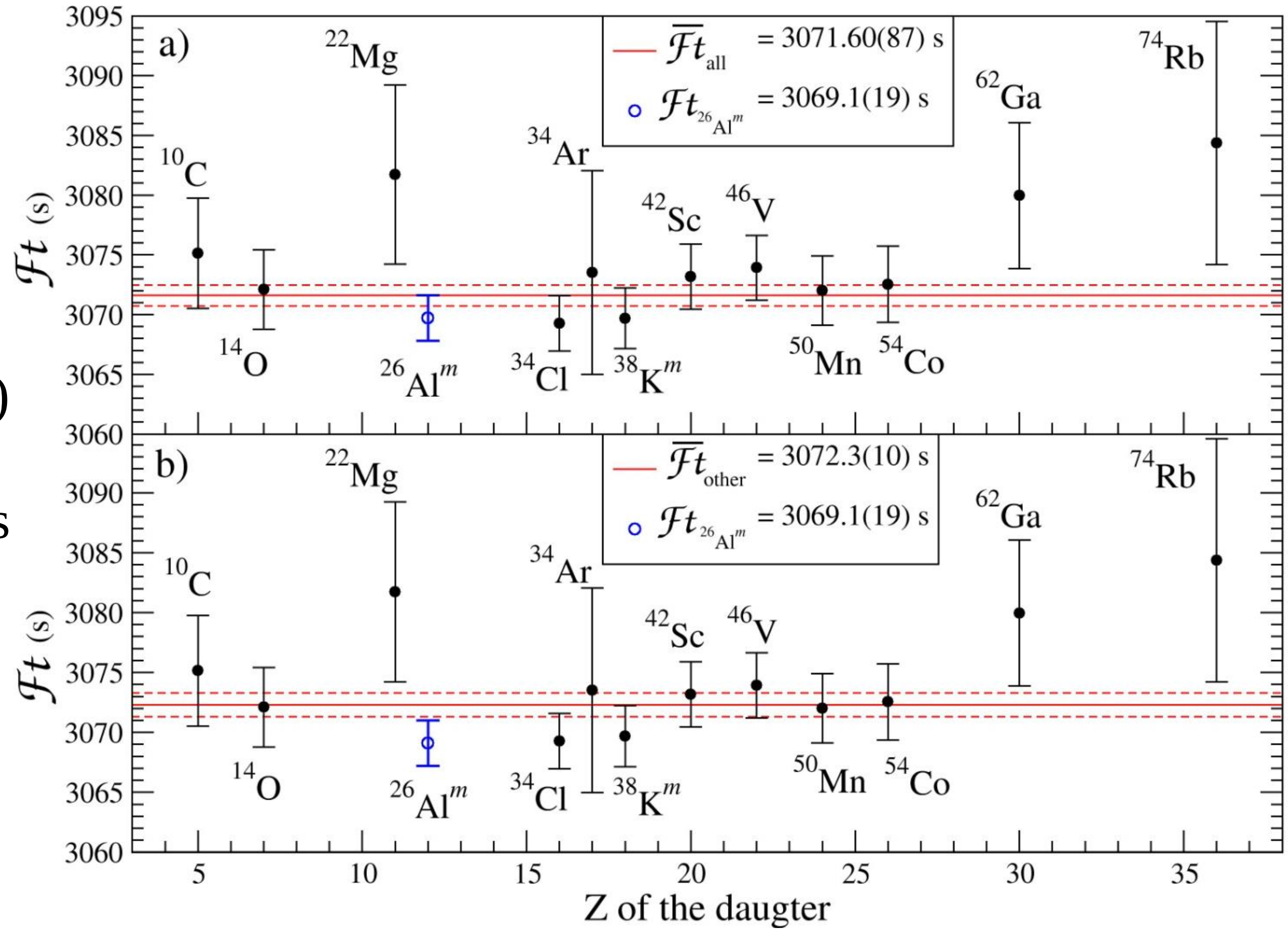
$\delta_C = 0.440(51)$ %

$\mathcal{F}t = ft(1+\delta'_R)(1+\delta_{NS}-\delta_C)$

$= 3069.1(6)_{\delta_R'}(17)_{\delta_C-\delta_{NS}}(6)_{ft}$ s

$\mathcal{F}t_{^{26}Al^m} = 3069.1(19)$ s

$\mathcal{F}t_{other} = 3072.3(10)$ s



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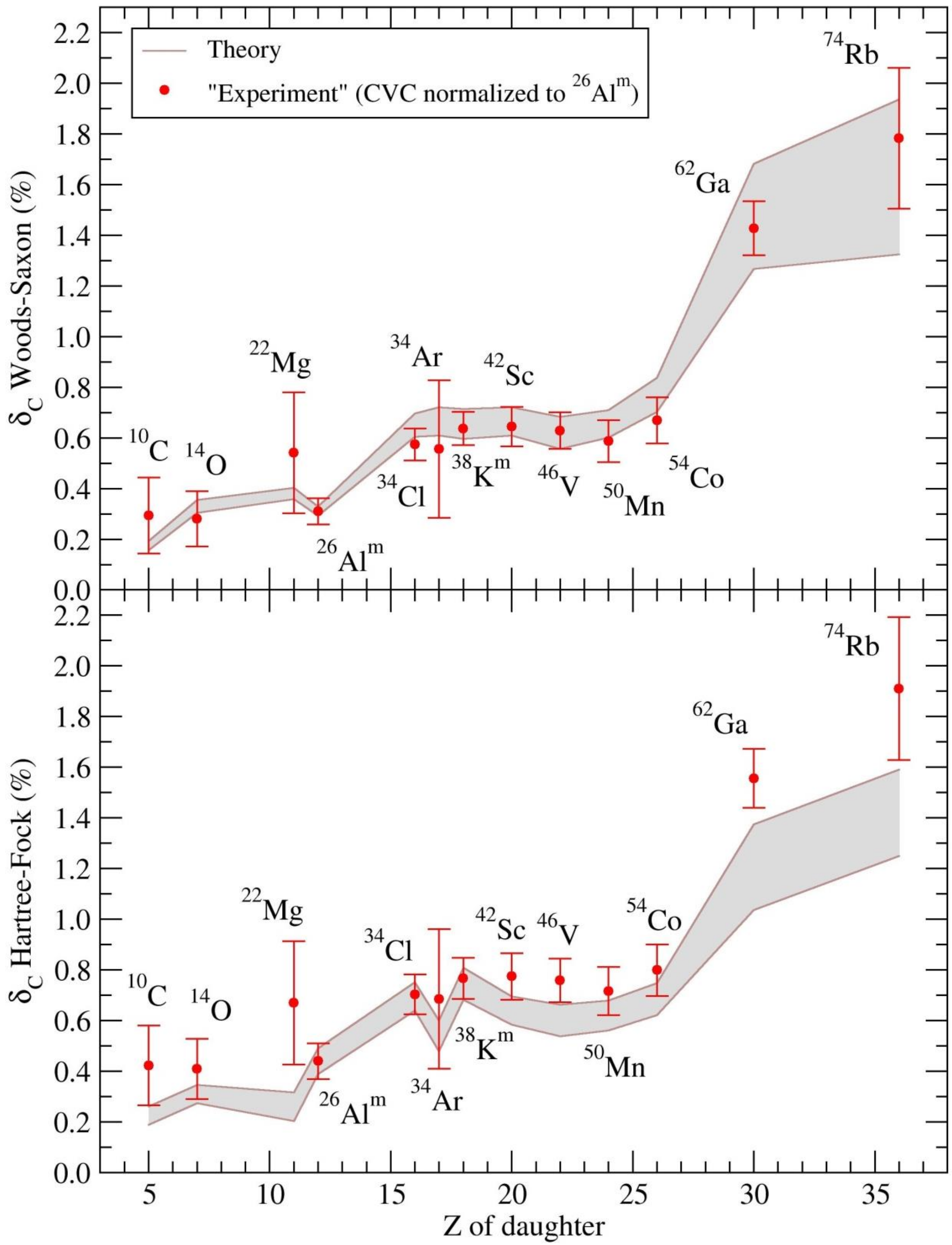


"Experimental" δ_C

$$\delta_C = 1 + \delta_{NS} - \frac{\mathcal{F}t\,(^{26}\mathrm{Al}^m)}{ft\,(1+\delta_R')}$$

-Woods-Saxon δ_C continue to form an impressively consistent set

-Hartree-Fock δ_C do not exhibit the same degree of conformity

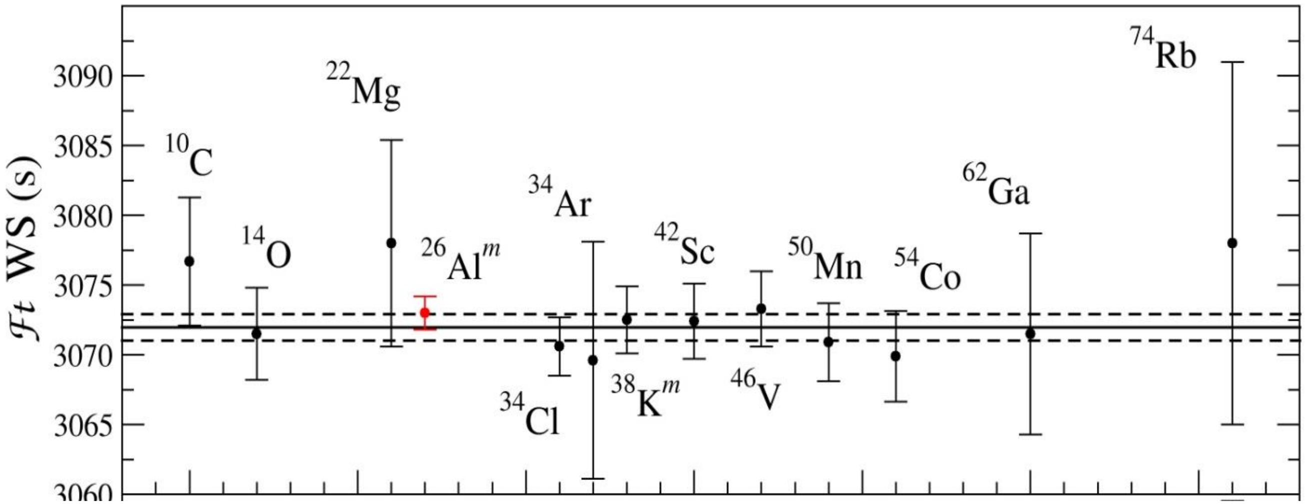
Hartree-Fock vs. Woods-Saxon and World-Averaged $\mathcal{F}t$

$\mathcal{F}t$ ($^{26}Al^{m}$)

WS: 3073.0(12) s

$\overline{\mathcal{F}t}$ (no $^{26}Al^{m}$)

WS: 3072.0(10) s



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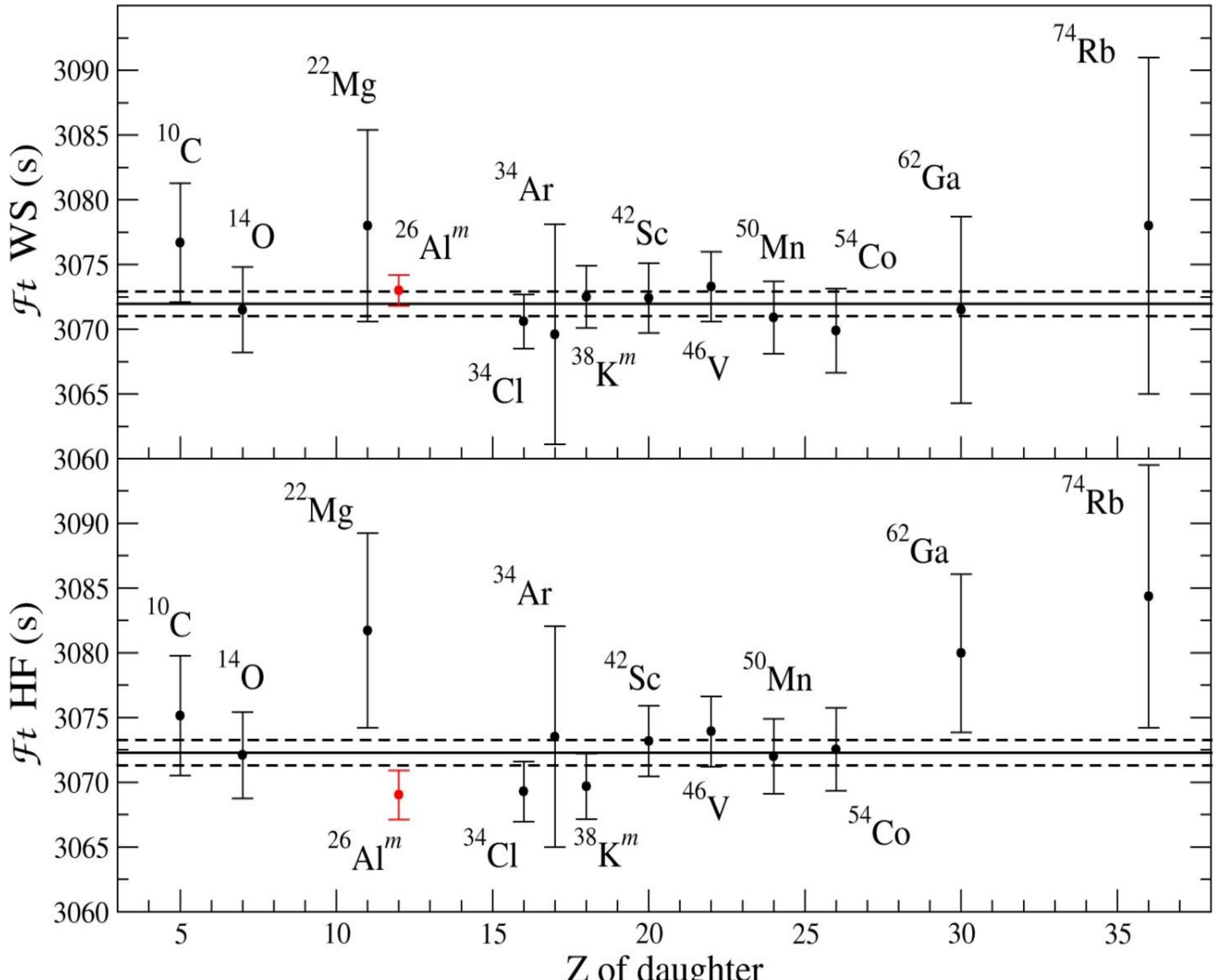


Hartree-Fock vs. Woods-Saxon and World-Averaged $\mathcal{F}t$

$\mathcal{F}t$ ($^{26}Al^{m}$)

WS: 3073.0(12) s
HF: 3069.0(19) s

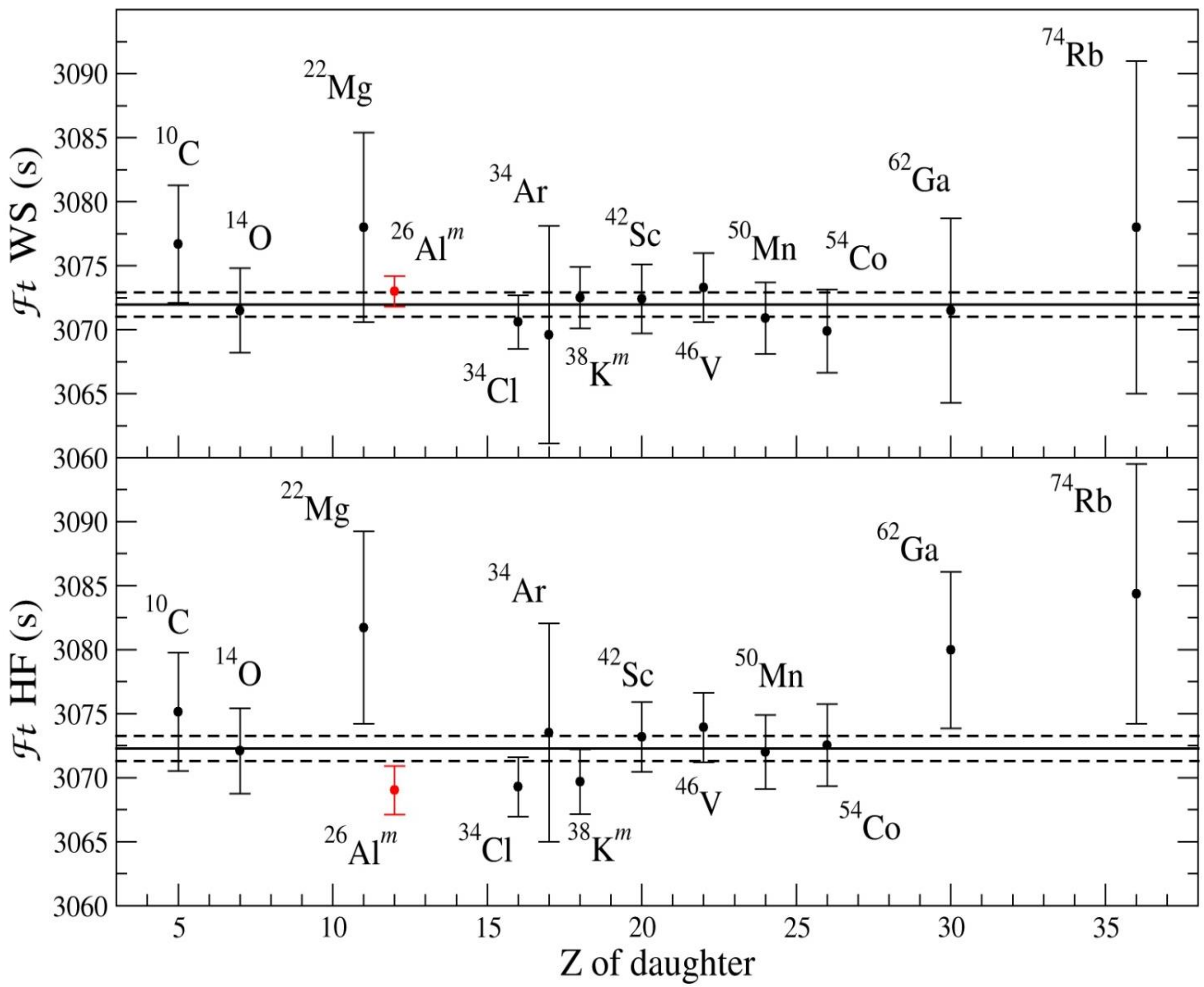
$\overline{\mathcal{F}t}$ (no $^{26}Al^{m}$)

WS: 3072.0(10) s
HF: 3072.3(10) s

$\overline{\mathcal{F}t}$ (with $^{26}Al^{m}$)

WS: 3072.38(75) s
HF: 3071.59(87) s

Systematic uncertainty = 0.79 s



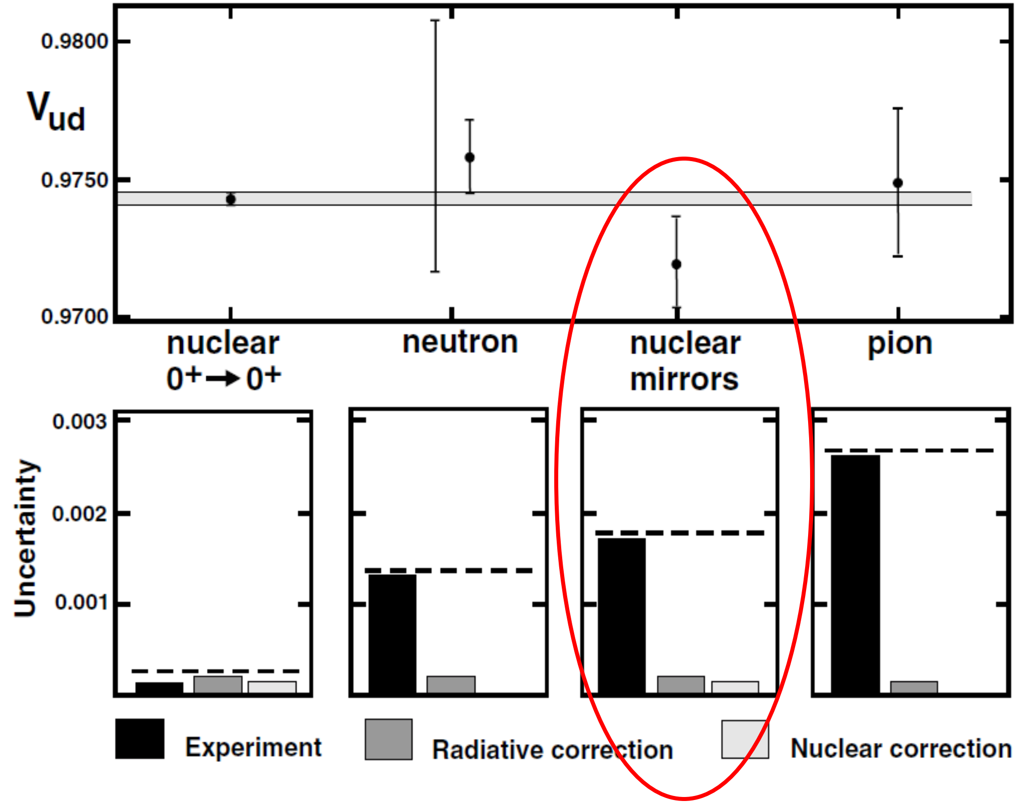
Further tests of ISB corrections??????

- Need to test superallowed corrections but independent of superallowed data!

- Want to avoid assuing CVC

T=1/2 Mirror Nuclei

Towner & Hardy, Rep. Prog. Phys. 73 (2010) 046301



- Dominated by experimental uncertainties.
- Also require δ_C corrections.
- Different nuclear structure than superallowed

$$A_{SM} = \frac{\mp\lambda_{J'J}\rho^2 - 2\delta_{J'J}\sqrt{\frac{J}{J+1}}\rho}{1+\rho^2}$$

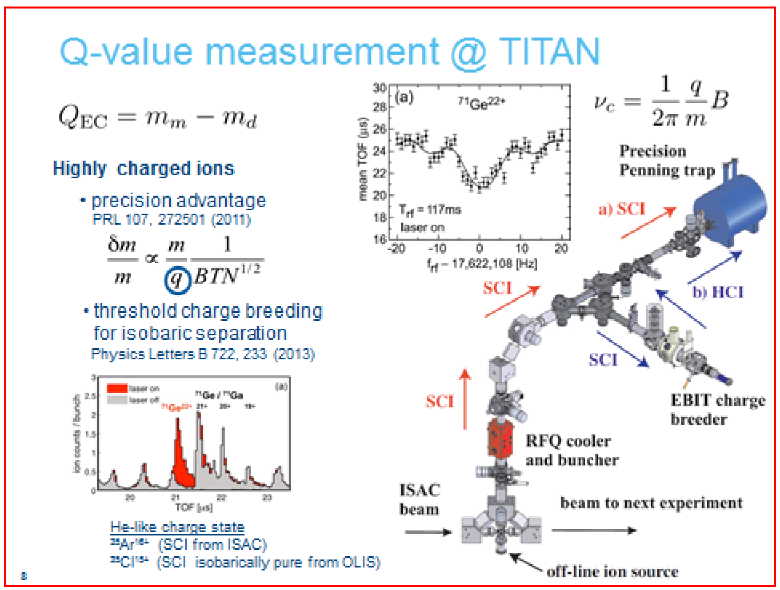
$$\rho = \frac{M_{GT}C_A}{M_F C_V}$$

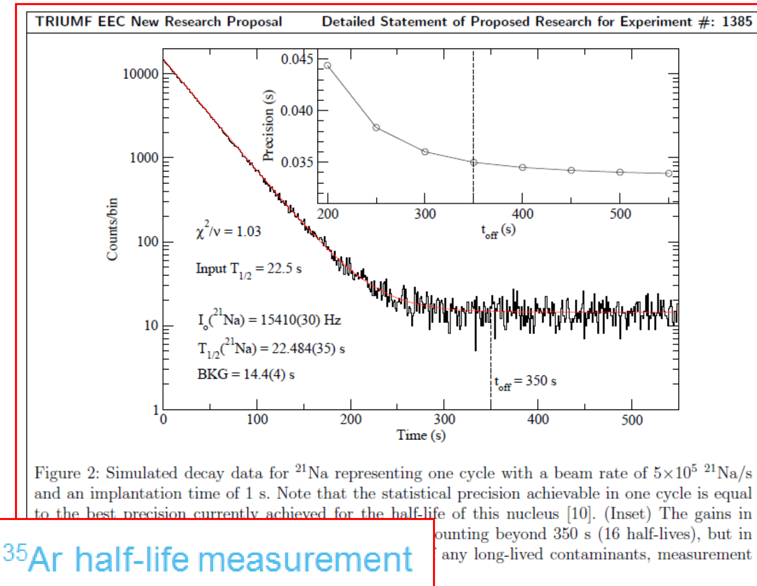
$$Ft^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = 2Ft^{0^+\to 0^+} = \frac{K}{G_F^2\ V_{ud}^2\ (1+\Delta_R^V)}$$

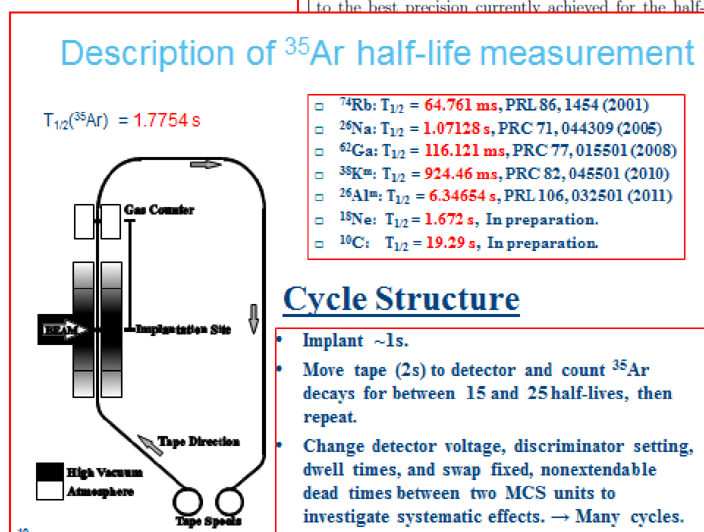
Mirror *ft* values at TRIUMF

Approved Experiments:

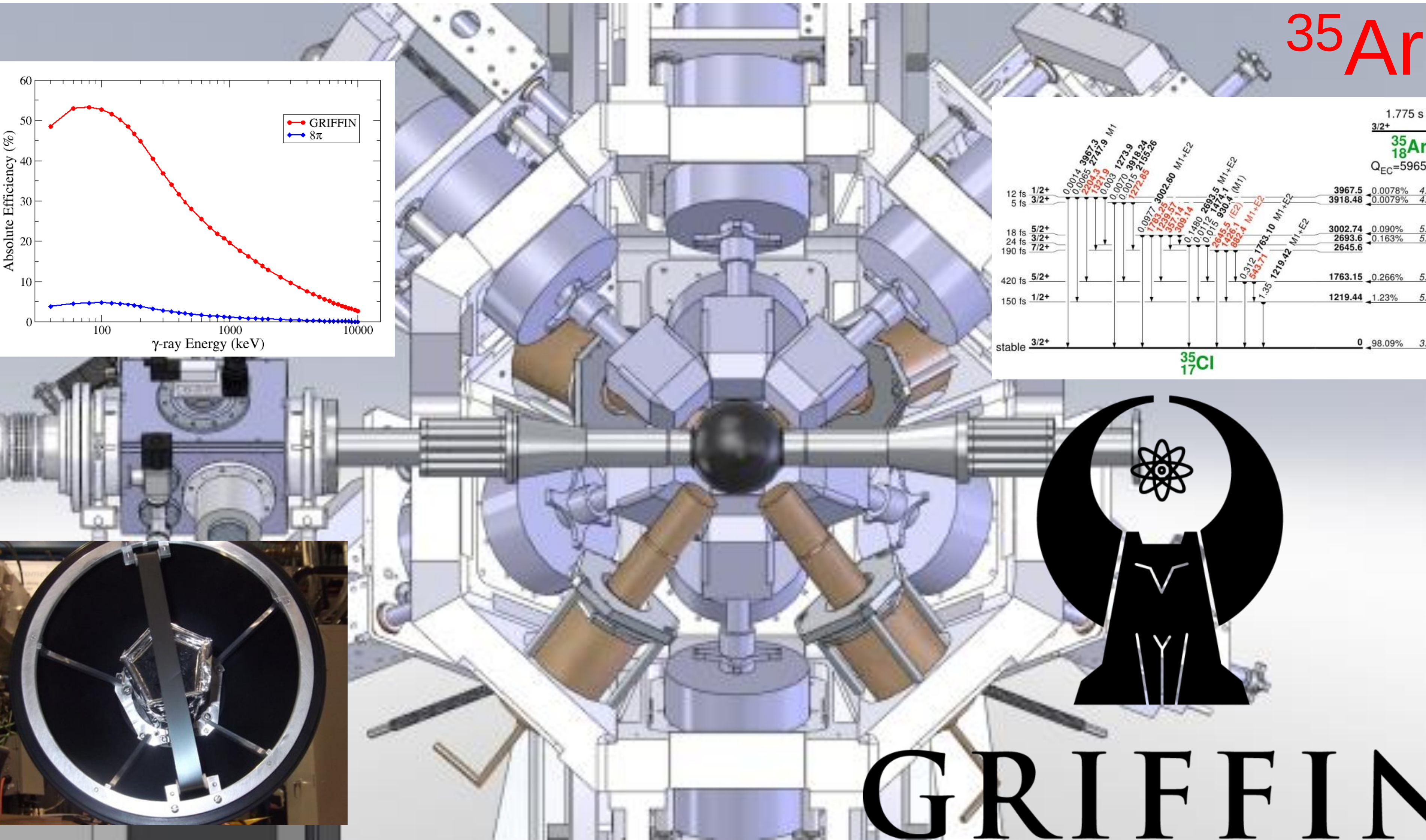
S1192 – Half-life and BR, ^{19}Ne
S1385 – Half-life for ^{21}Na
S1517 – Half-life and Q-value for ^{35}Ar







Mirror *ft* values at TRIUMF



Summary and Conclusions

- High-precision half-life and branching-ratio measurements for $^{26}Al^{m}$, carried out at TRIUMF, have resulted in the most precise superallowed ft and $\mathcal{F}t$ values for any superallowed emitter to date.

- This unrivaled precision for the $^{26}Al^{m}$ ft and $\mathcal{F}t$ values yields one of the most demanding consistency tests of leading isospin-symmetry-breaking corrections for these decays, required in order to extract V_{ud}, and currently a leading source of uncertainty.

- Going forward, ft-value measurements for the isospin T=1/2 mirror nuclei offer an excellent opportunity to test and refine these calculations, with the goal of improving the uncertainty in Vud and further constraining physics beyond the Standard Model.

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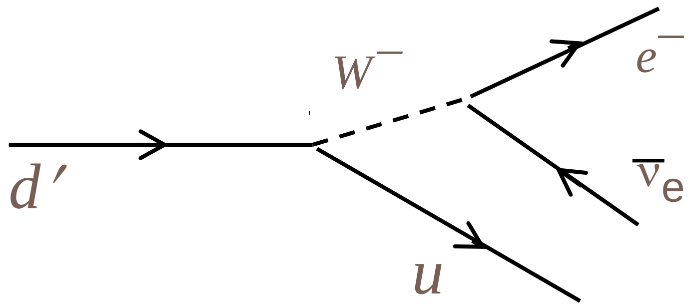
The Cabibbo-Kobayashi-Maskawa (CKM) matrix

The CKM matrix plays a central role in the Standard Model

➡ describes the mixing of different quark generations:
weak interaction eigenstates ≠ quark mass eigenstates



ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

u	c	t
d	s	b

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

$$|V_{ud}| = G_V / G_F$$

In the Standard Model the CKM matrix describes a unitary transformation.

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

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

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

V_{ud} from High-Precision Superallowed ft-values

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

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

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

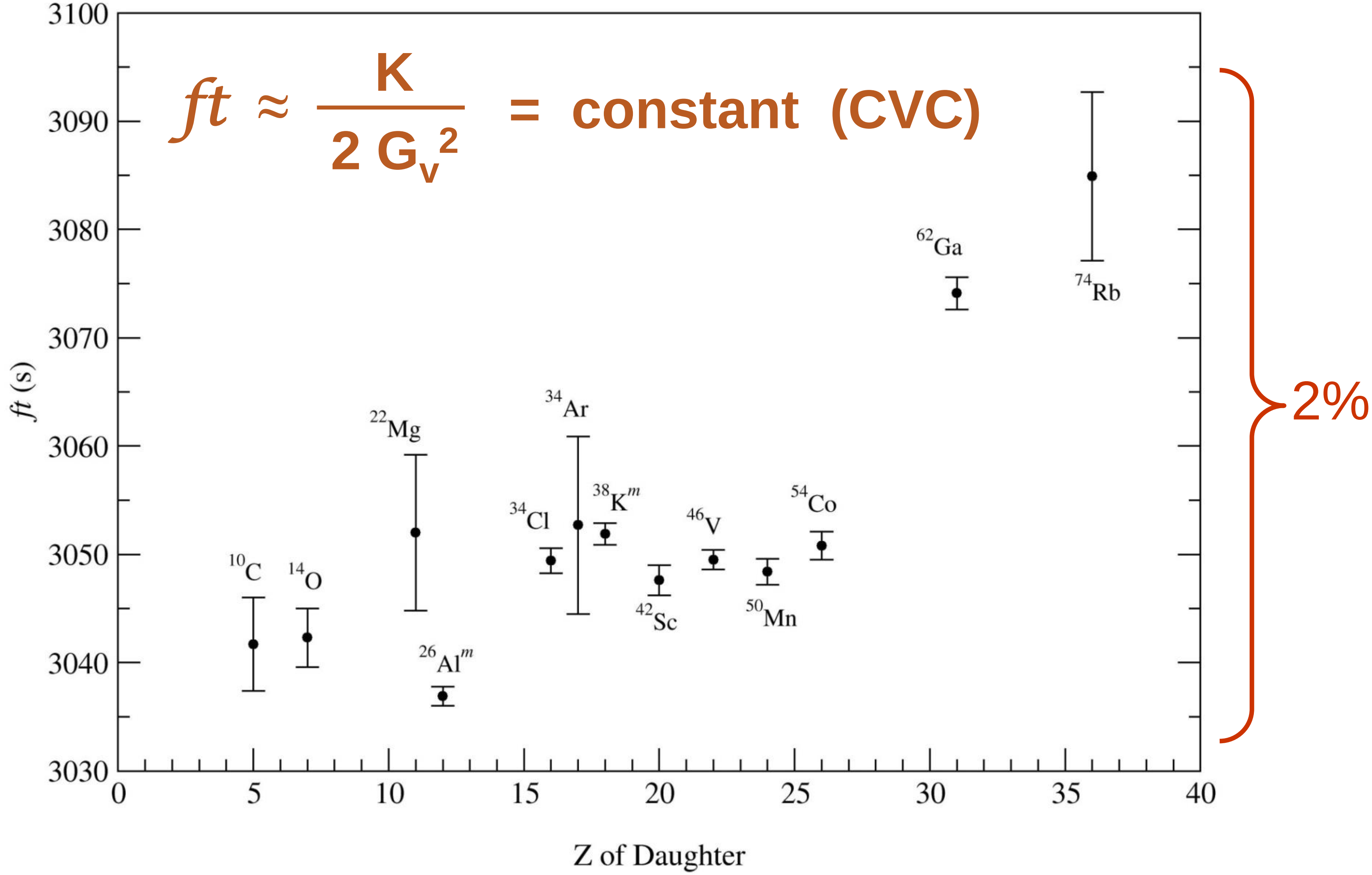
For the special case of $0^+ \rightarrow 0^+$ (pure Fermi) β decays between isobaric analogue states (superallowed) the matrix element is that of an isospin ladder operator:

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

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

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

Superallowed ft-values

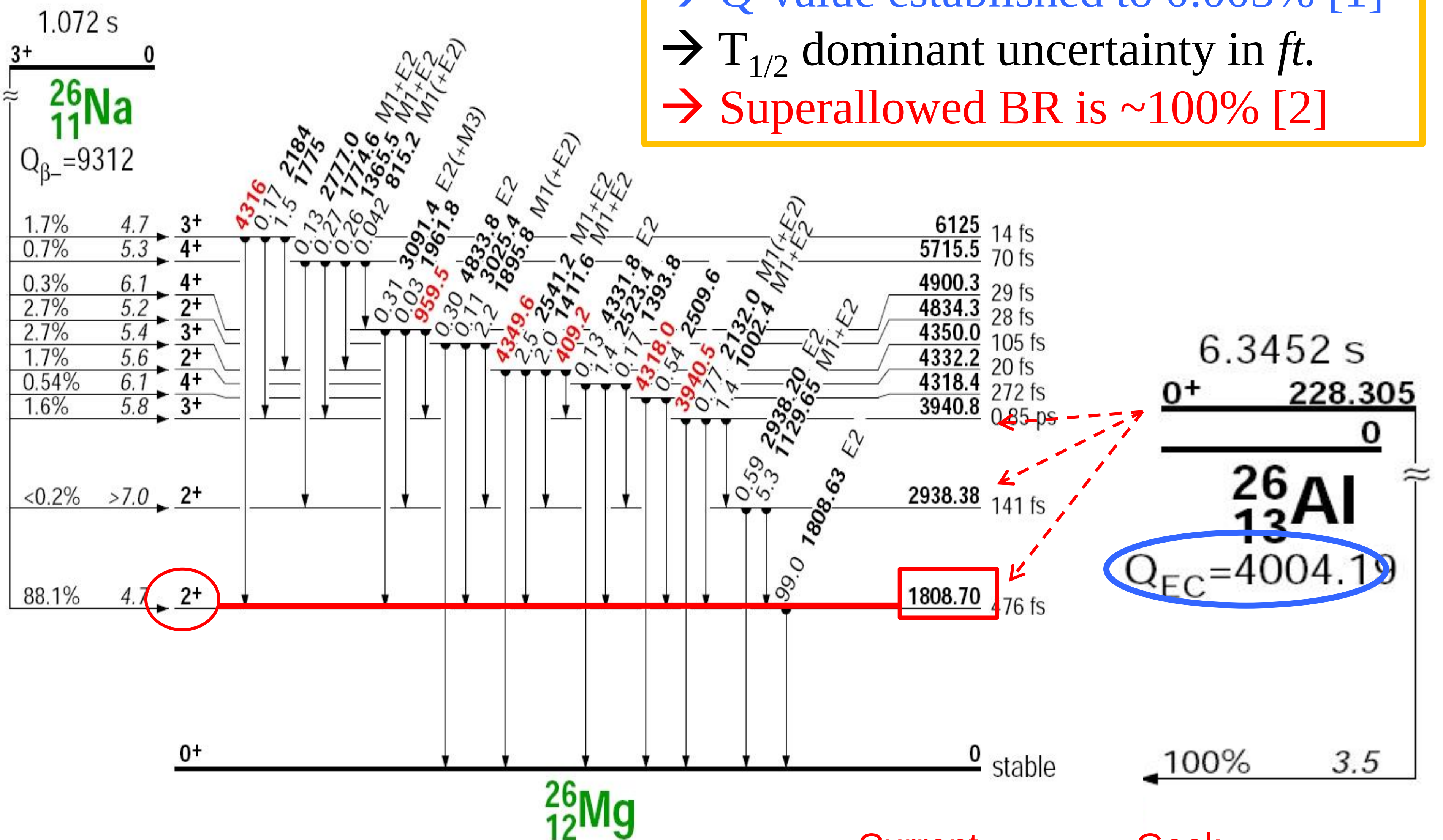


J.C. Hardy and I.S. Towner, Physical Review C **79**, 055502 (2009)

→ Q-value established to 0.003% [1]

→ $T_{1/2}$ dominant uncertainty in *ft*.

→ Superallowed BR is ~100% [2]



Current experimental upper limit is $7x10^{-5}$ [2]

Goal: reduce by order of magnitude

[1] T. Eronen *et al.*, Phys Rev Lett **97**, 232501 (2006)

[2] S.W. Kikstra *et al.*, Nuc Phys **A529** 39 (1991)

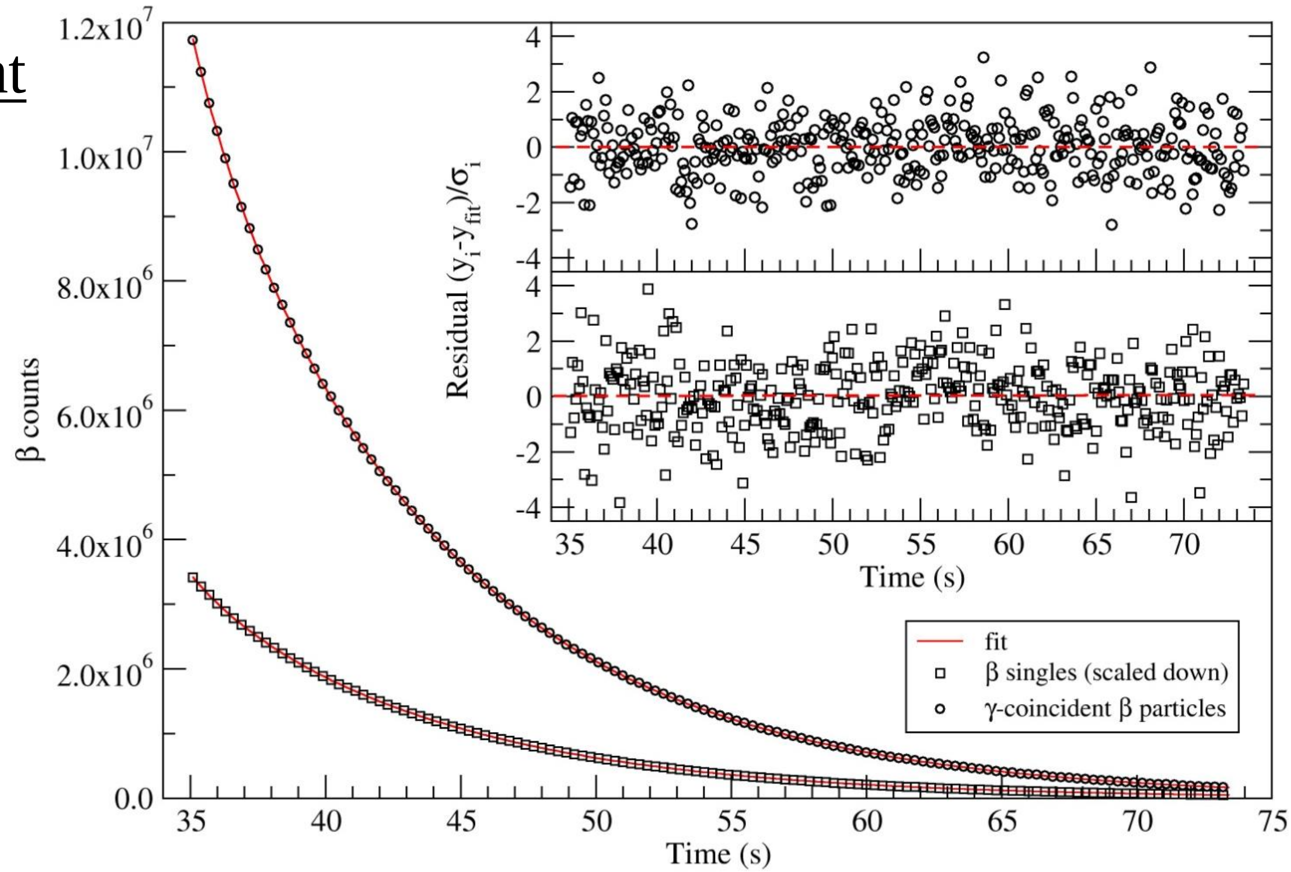
Counting the number of β particles

Read out event by event

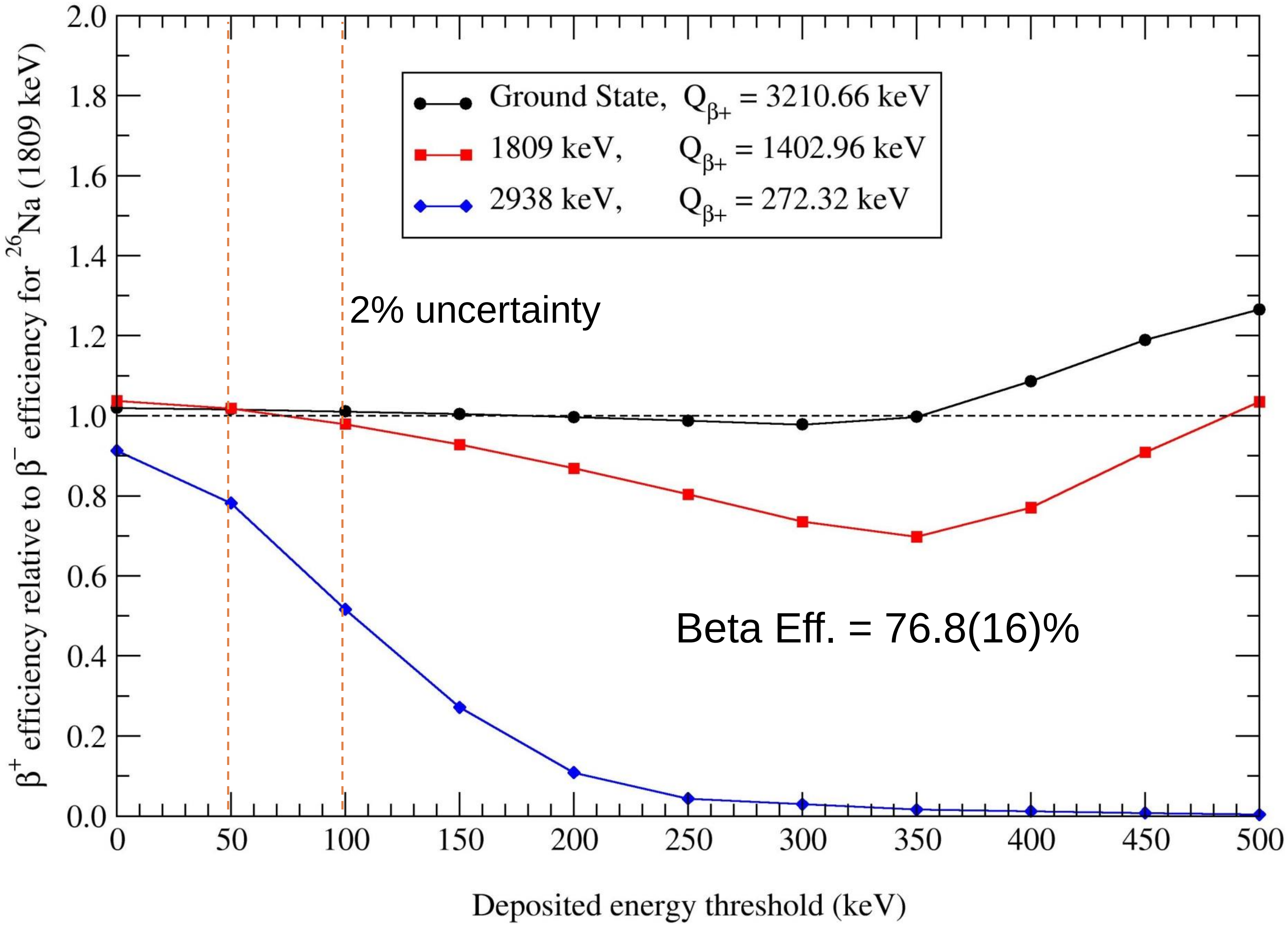
Energies → Low-energy cut

Times → Gate on good events

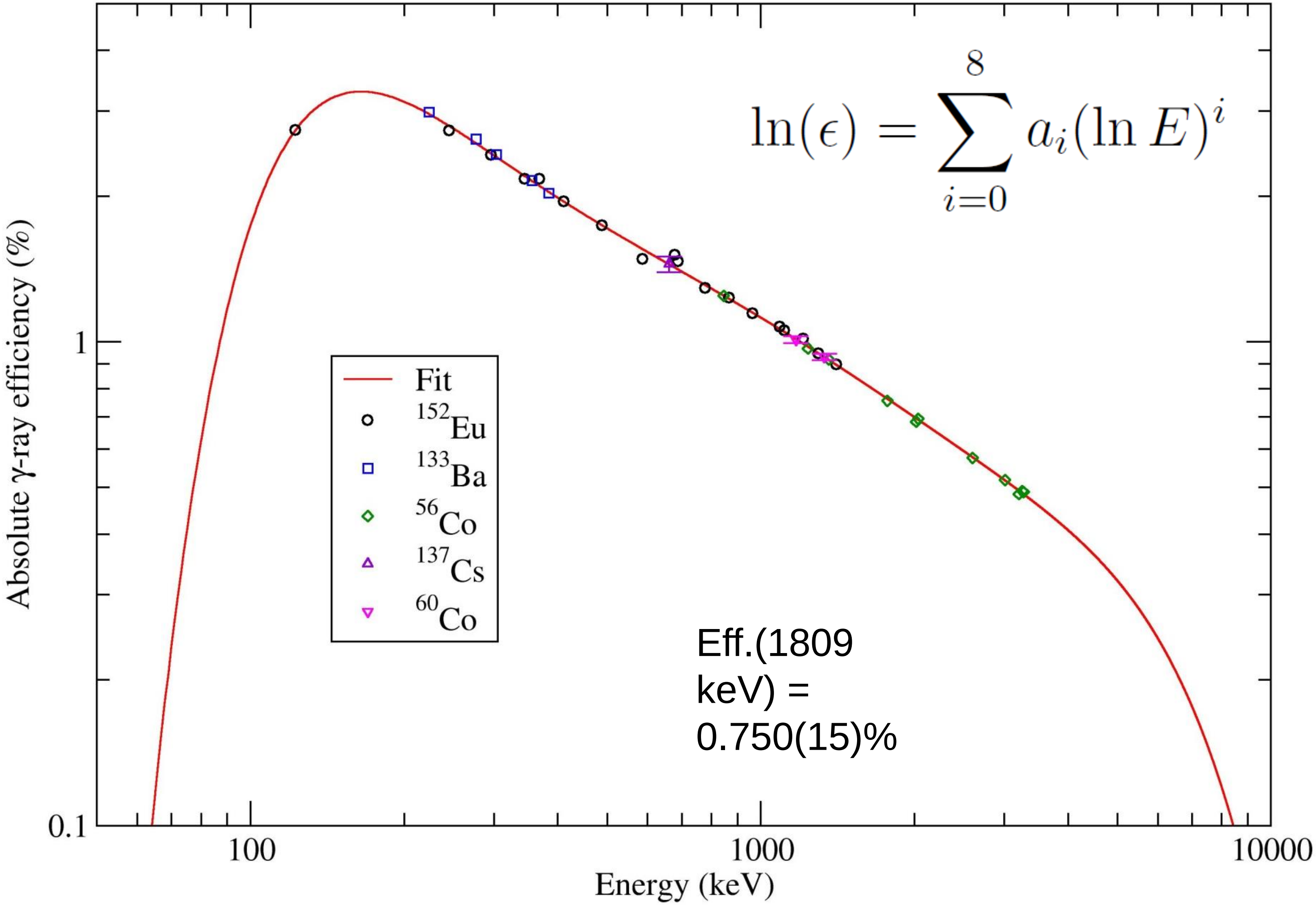
Distinguish β and βγ triggers → Scale down β singles



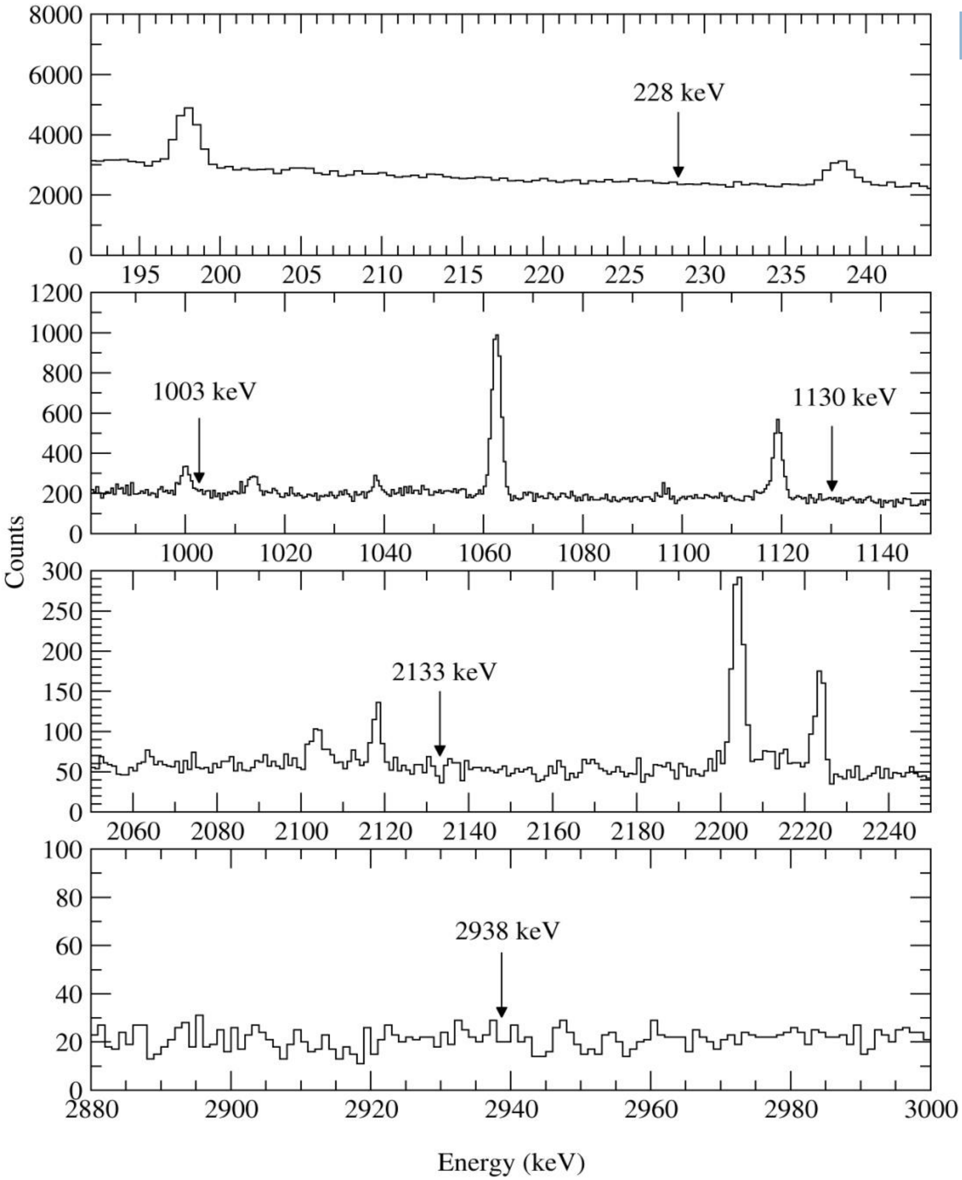
SCEPTAR Efficiency



8π Efficiency



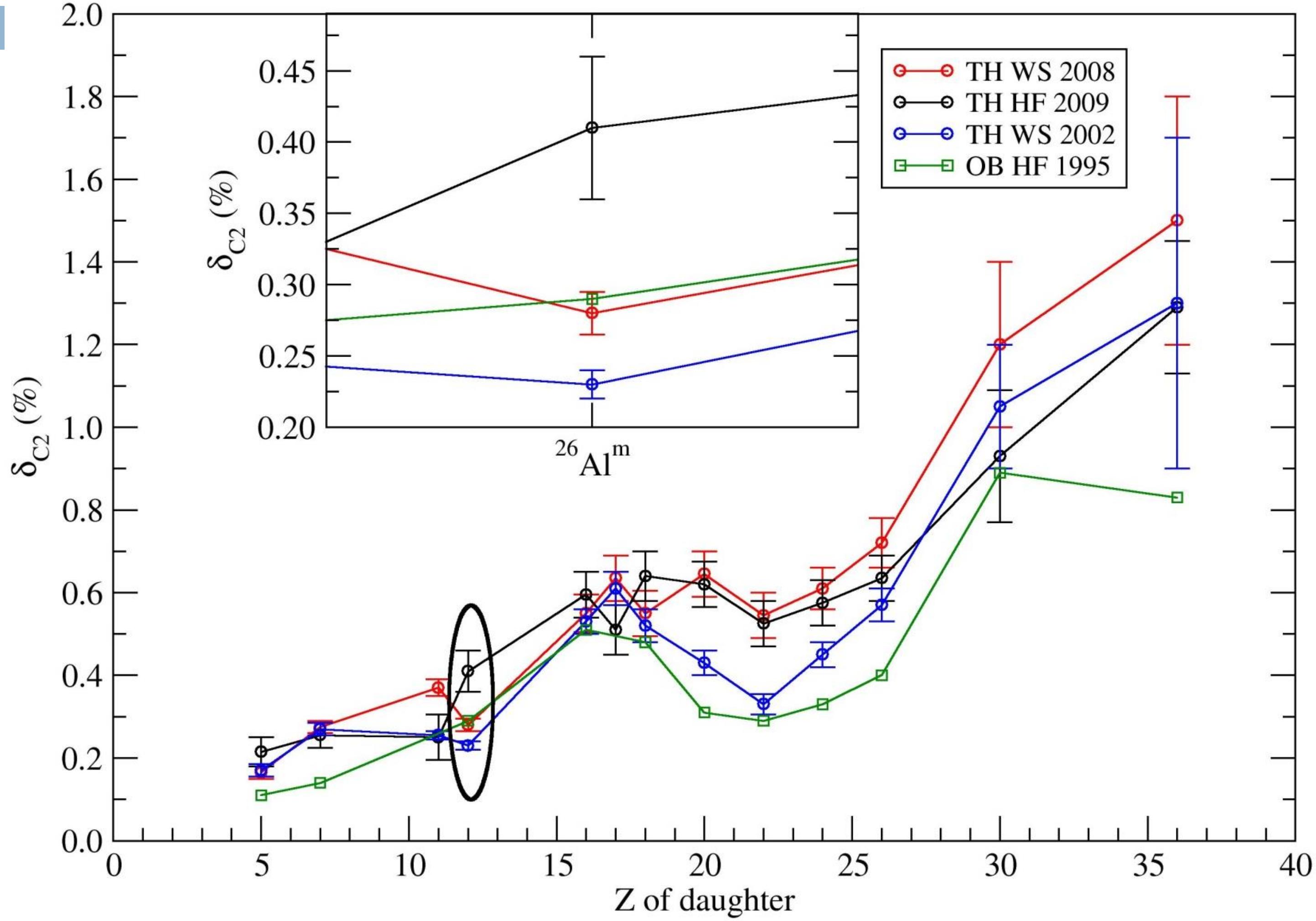
Other Potential $^{26}Al^{m}$ Branches



Transitions to other excited states dominated by EC, so beta-anti-coincidence gamma-ray data used in this analysis at late times in the cycle.

Level (J^π, E)	γ ray (keV)	Peak area (ppm)
3_1^+, 3942 keV	1003	11(12)
	2133	-10(6)
0_1^+, 3589 keV	1780	-12(25)
2_2^+, 2938 keV	1130	3(10)
	2938	4(6)
5^+, $^{26}Al^g$	228	3(15)

The Radial Overlap Correction: δ_{C2}



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I.S. Towner and J.C. Hardy, Physical Review C **66**, 035501 (2002)
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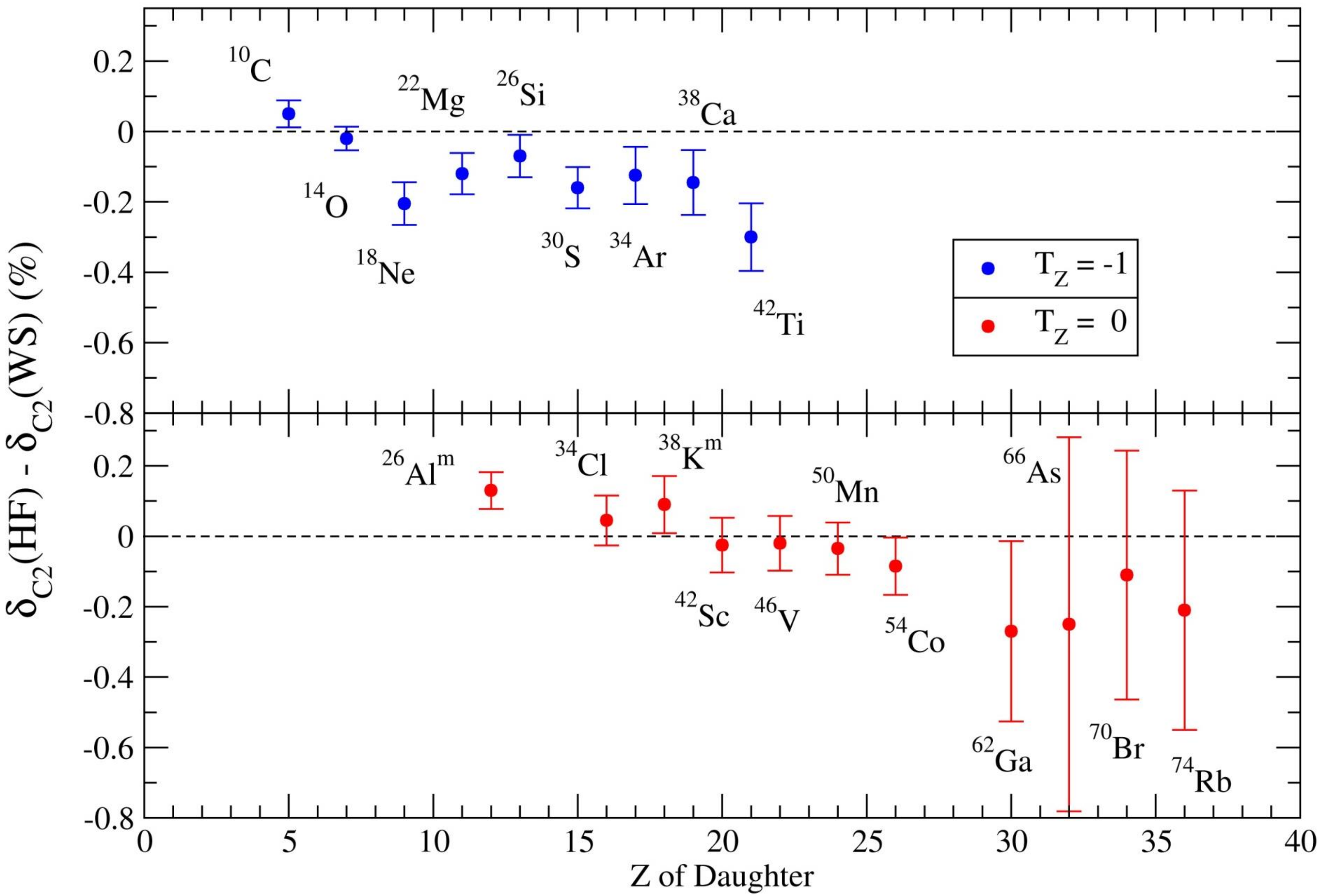
Z-dependence in Radial Overlap Correction



The Resulting Precision in G_V

Prior to this work: $G_V^2 = \dfrac{K}{2(1+\Delta_R^V)\overline{\mathcal{F}t}}$,

$$G_V^2/(\hbar c)^6 = 1.29126(33)_{\rm stat.}(11)_{\delta_C}(48)_{\Delta_R^V} \times 10^{-10}\ {\rm GeV}^{-4} ,$$

$$G_V/(\hbar c)^3 = 1.13633(15)_{\rm stat.}(5)_{\delta_C}(21)_{\Delta_R^V} \times 10^{-5}\ {\rm GeV}^{-2} ,$$

$$= 1.13633(26) \times 10^{-5}\ {\rm GeV}^{-2} .$$

Following this work:

$$G_V^2/(\hbar c)^6 = 1.29118(32)_{\overline{\mathcal{F}t}_{\rm stat.}}(17)_{\overline{\mathcal{F}t}_{\rm syst.}}(48)_{\Delta_R^V} \times 10^{-10}\ {\rm GeV}^{-4}$$

$$G_V/(\hbar c)^3 = 1.13630(14)_{\overline{\mathcal{F}t}_{\rm stat}}(8)_{\overline{\mathcal{F}t}_{\rm syst}}(21)_{\Delta_R^V} \times 10^{-5}\ {\rm GeV}^{-2} ,$$

$$= 1.13630(27) \times 10^{-5}\ {\rm GeV}^{-2}$$