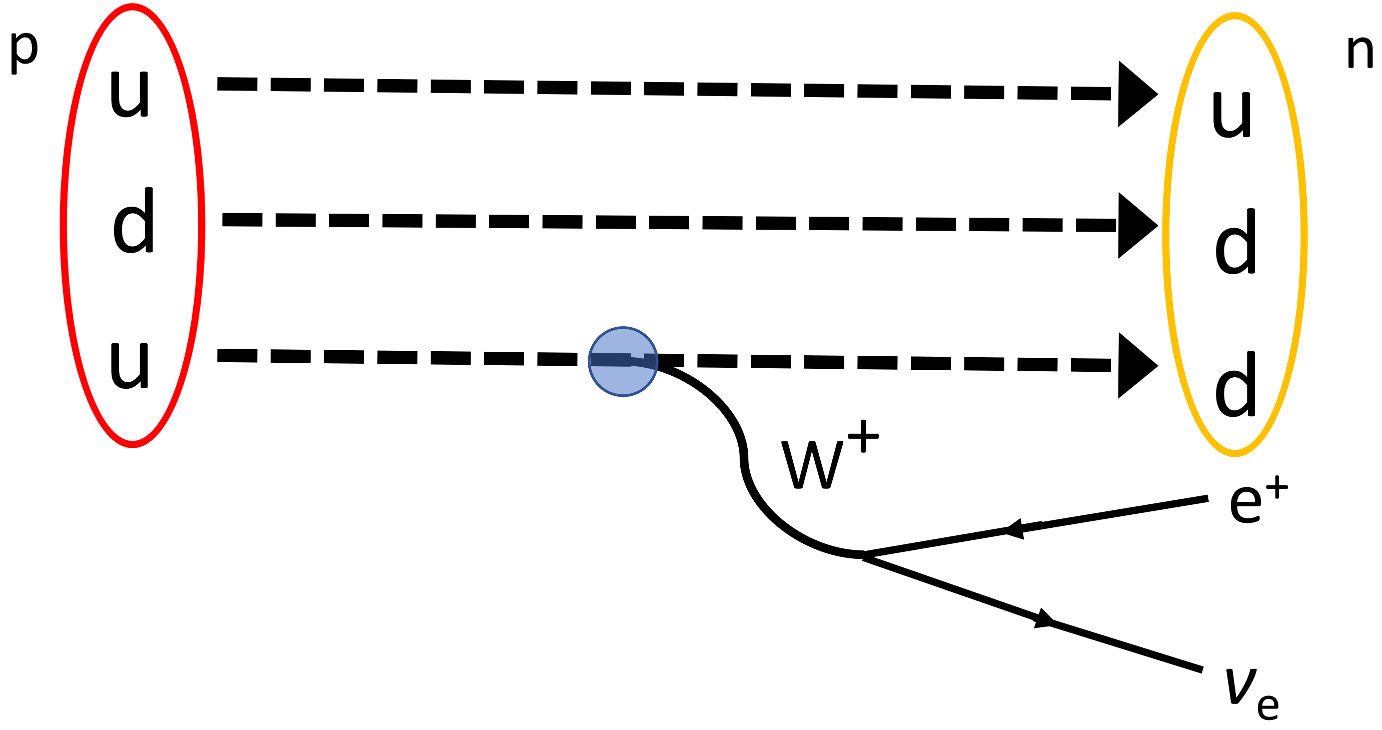
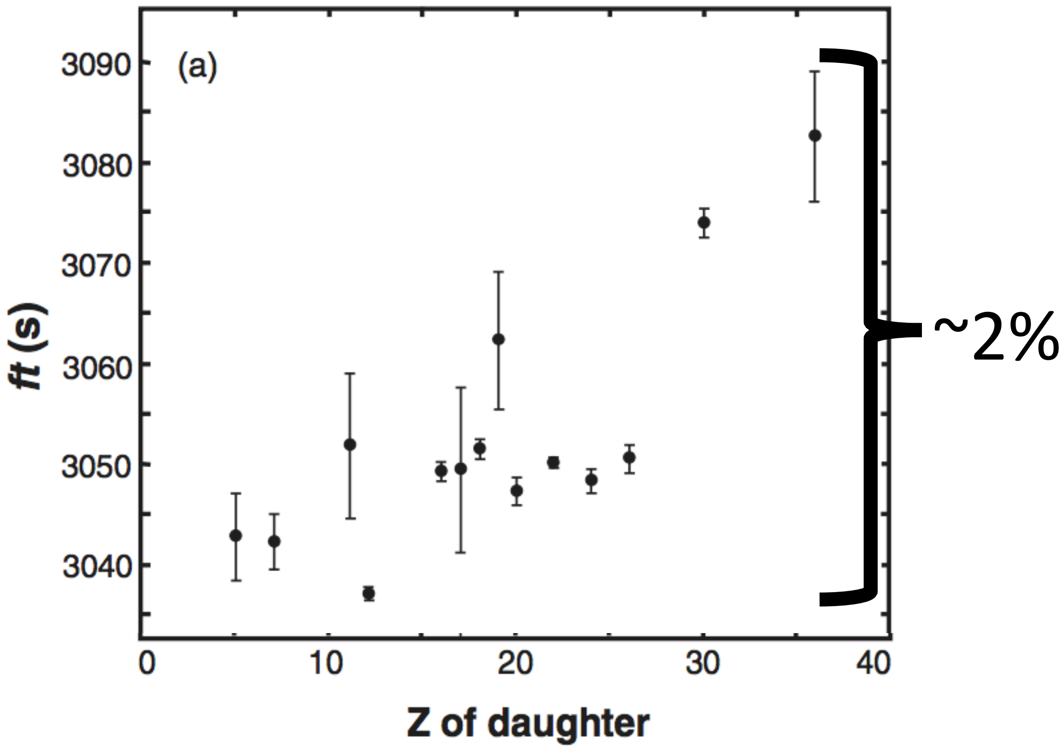
High-Precision Measurement of the Superallowed Fermi Beta Decay of ^{62}Ga

Andrew MacLean
University of Guelph
February 16, 2020

Beta Decay and ft Values





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

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

In the special case of pure Fermi transitions between isobaric analogue states.

$$ft = \frac{K}{2G_V^2} = \text{constant}$$

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

Superallowed Fermi Beta Decay

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

- δ'_R & δ_{NS} transition-dependent radiative correction.
  - Dependent on hadronic structure, positron interacting with Coulomb field.
- Δ_R^V transition-independent radiative correction.
  - Universal and independent of nucleus involved, higher energy physics.
- δ_C isospin symmetry breaking correction.
  - Configuration mixing between 0^+ states and imperfect overlap of proton and neutron radial wavefunctions.

Superallowed Fermi Beta Decay

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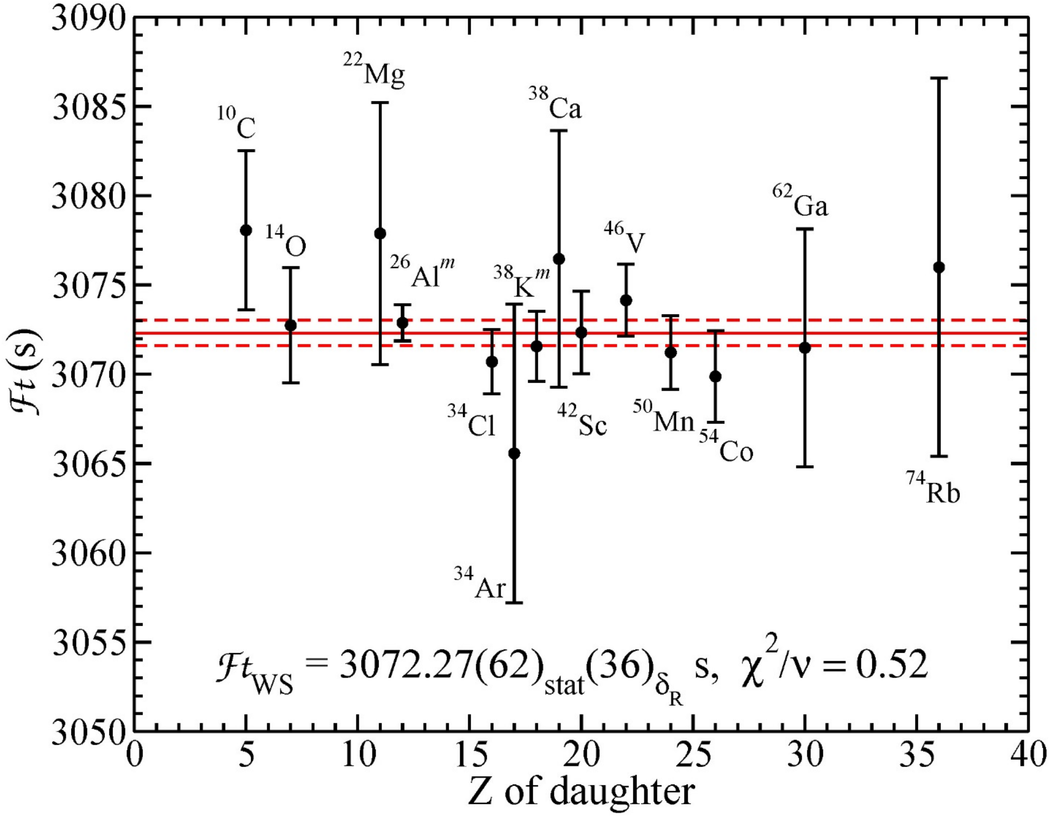

CKM Matrix

$$|V_{ud}| = \frac{G_V}{G_F} \qquad \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

As of 2015, good agreement with unity.

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(5)$$

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Superallowed Fermi Beta Decay

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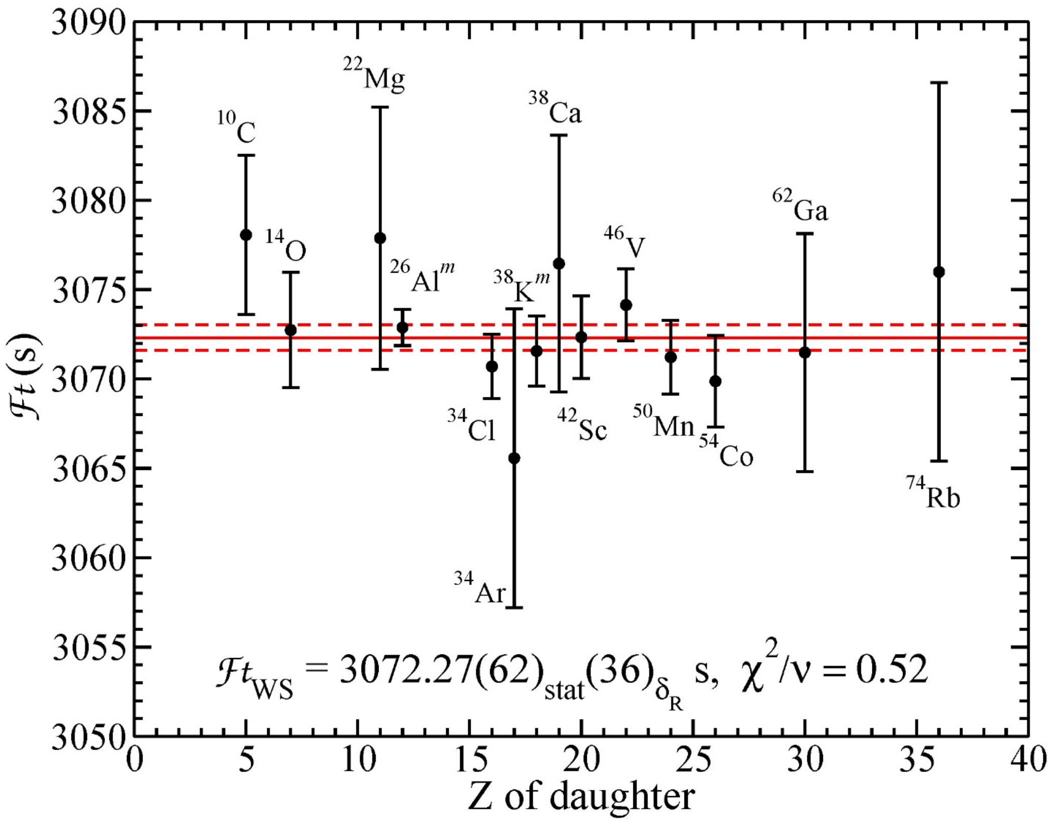
NEW as of 2019



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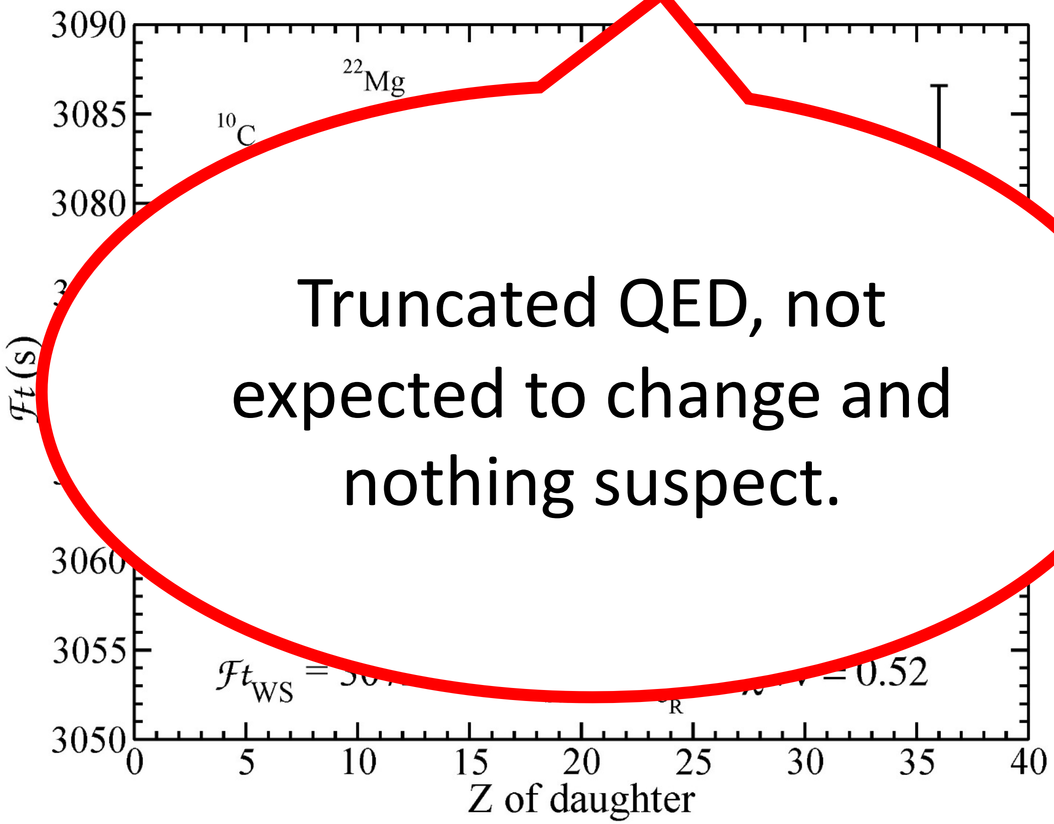
C.-Y. Seng et. al., Phys. Rev. Lett. **100**, 013001 (2019)

Superallowed Fermi Beta Decay

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



Truncated QED, not expected to change and nothing suspect.

CKM Matrix

$$|V_{ud}| = \frac{G_V}{G_F} \qquad \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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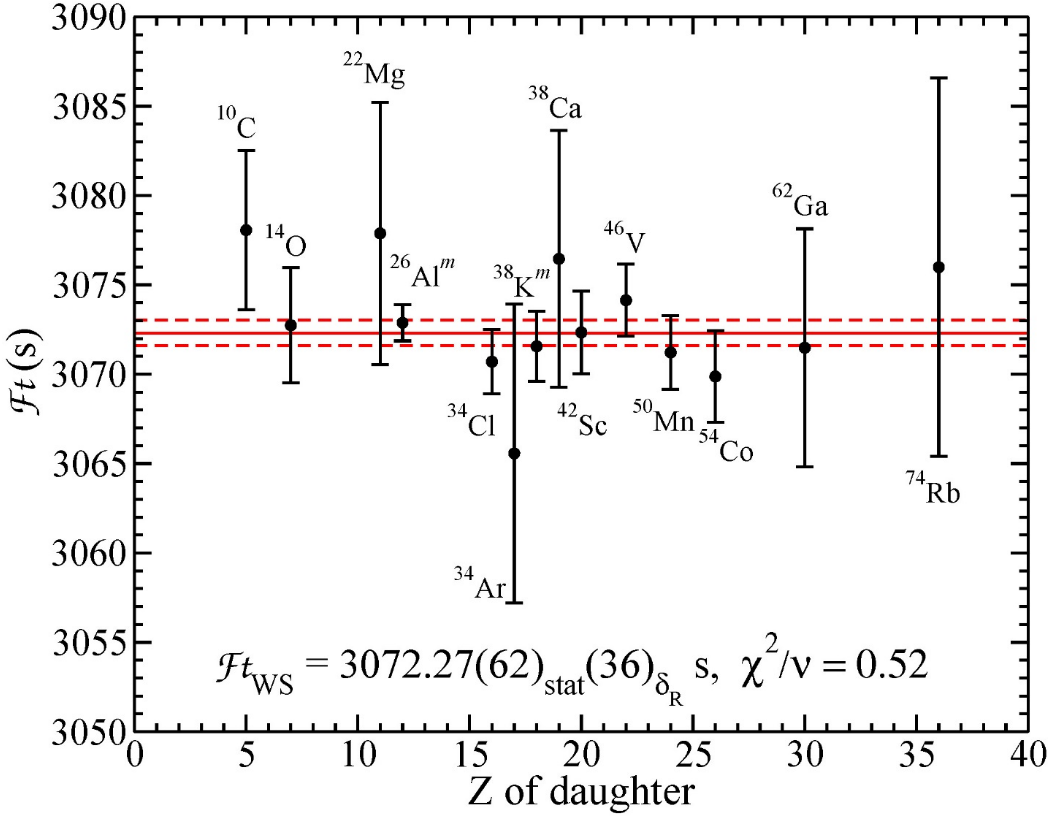

Involve detailed nuclear structure and can be difficult to calculate.

trix

V_{ub}

V_{cb}

V_{tb}

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

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Superallowed Fermi Beta Decay

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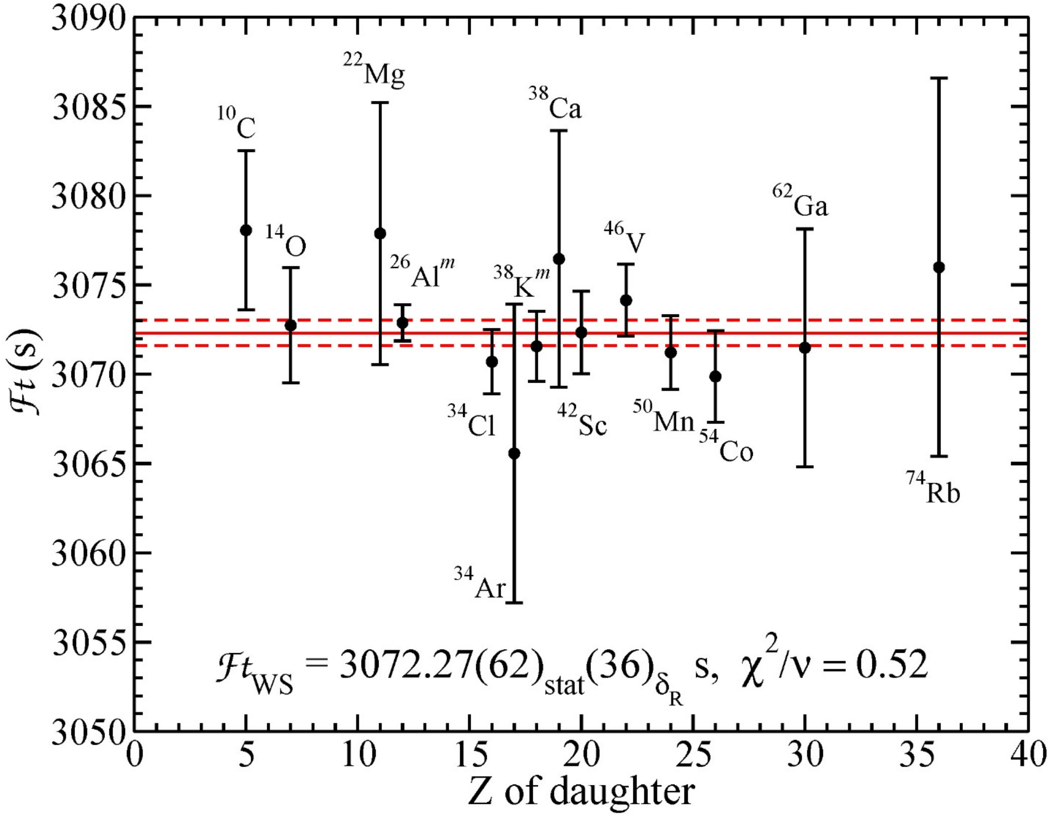

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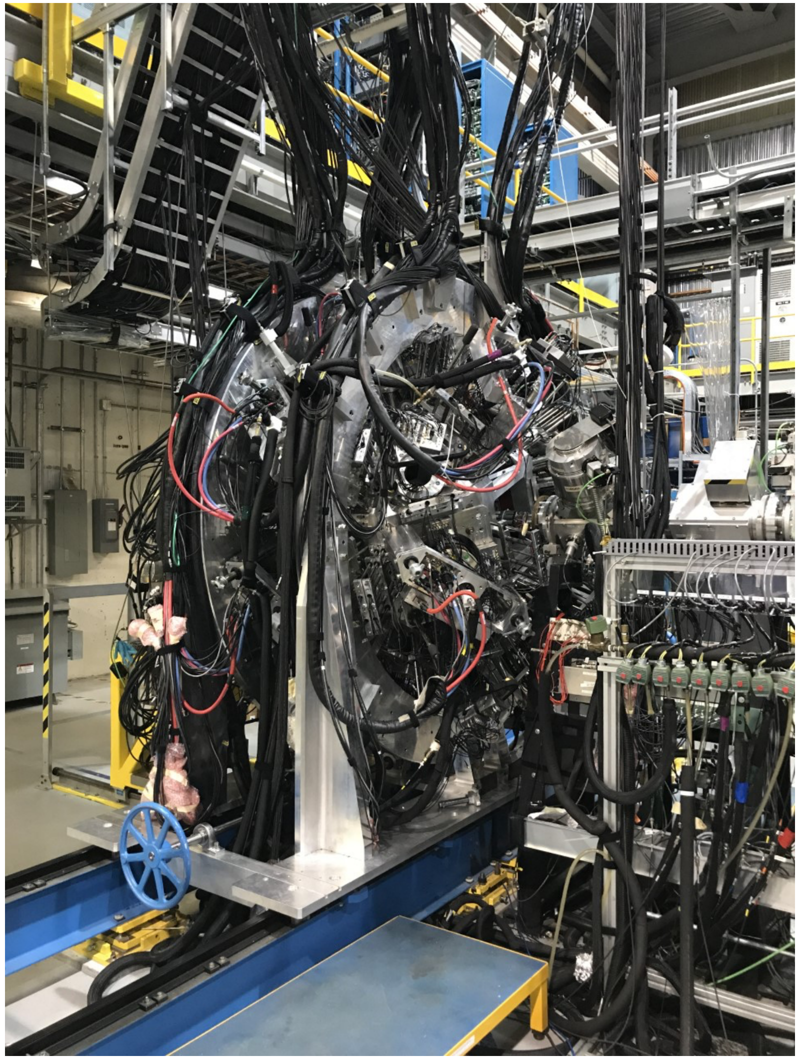
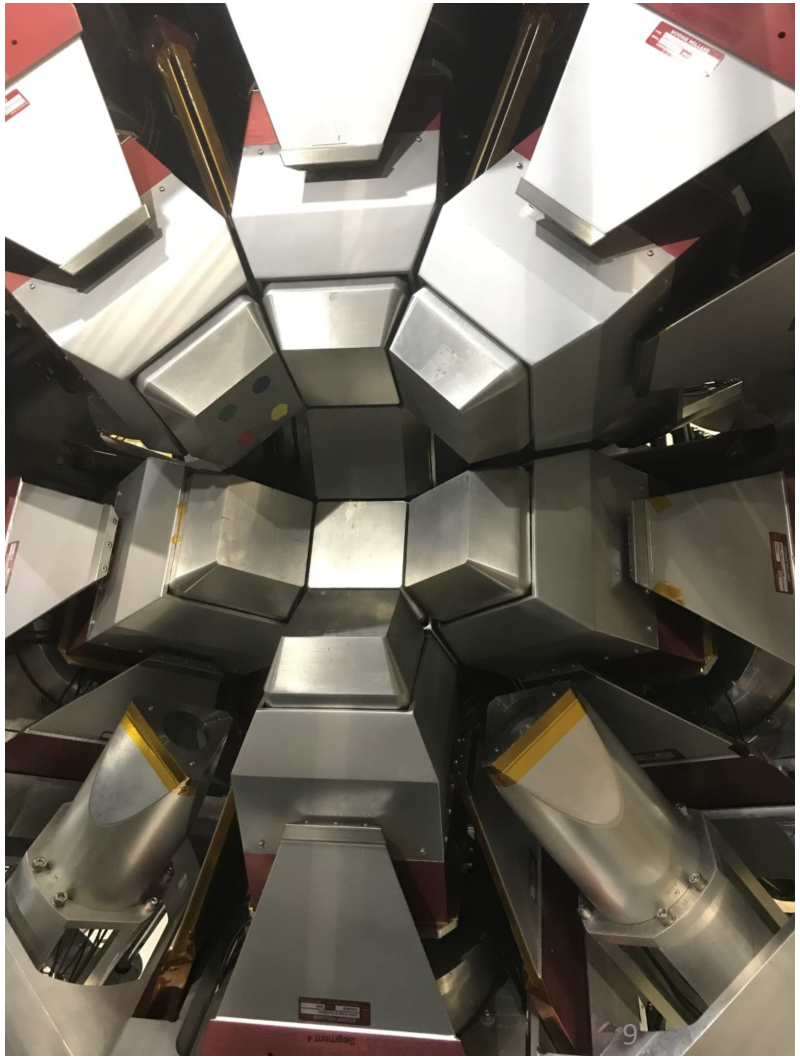
C.-Y. Seng et. al., Phys. Rev. Lett. **100**, 013001 (2019)

GRIFFIN



- High efficiency gamma-ray spectrometer.
- 16 large volume HPGe clover type detectors.
- Large assortment of ancillary detectors.
- For this work SCEPTAR was used to detect beta particles.

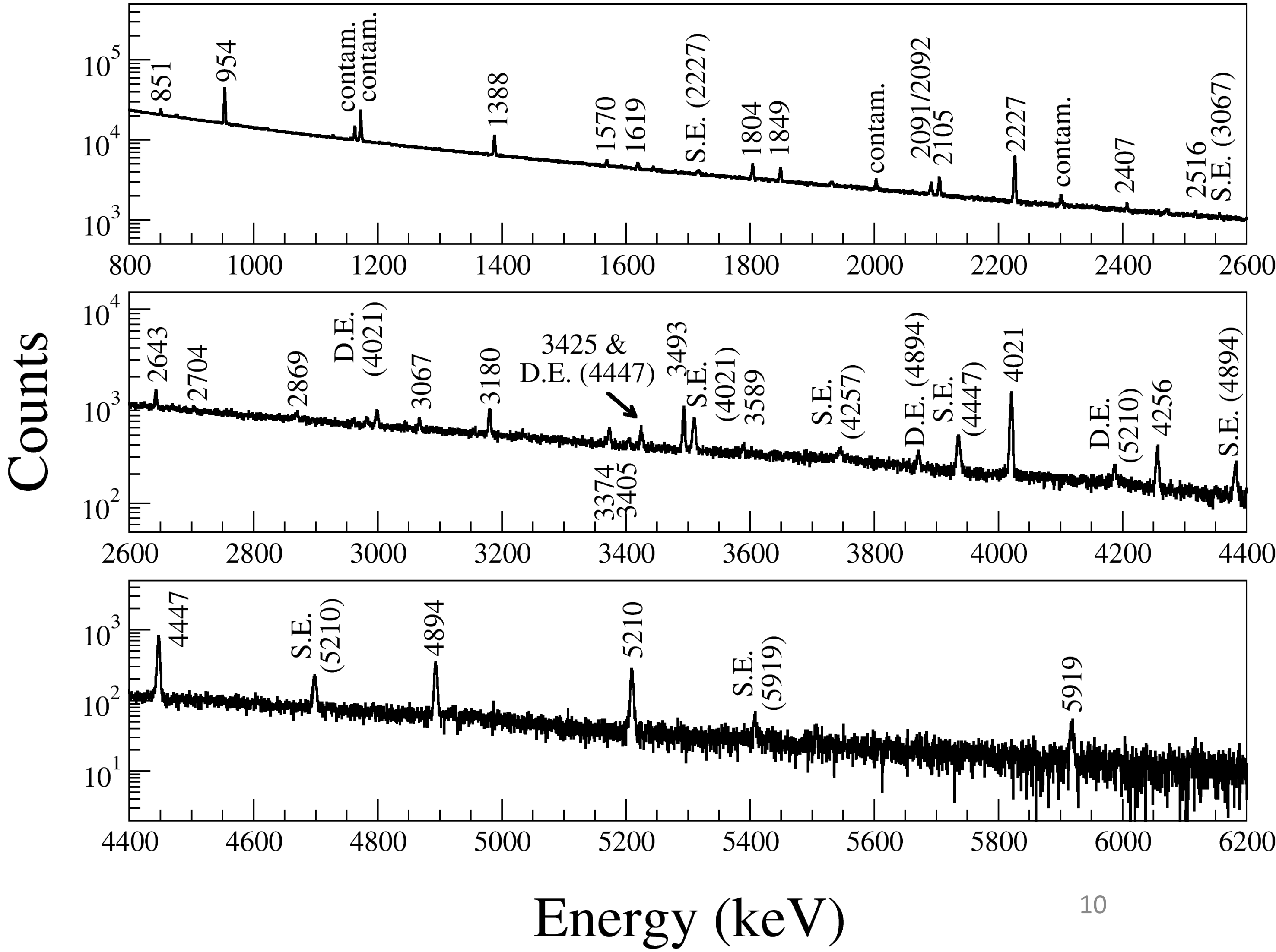


^{62}Ga Experiment

Singles spectra from the GRIFFIN spectrometer after 6 days of collecting data at ~8000 ions/s.

Able to vastly expand knowledge on the structure of the daughter, ^{62}Zn.

With available statistics, performed γ-γ angular correlations.

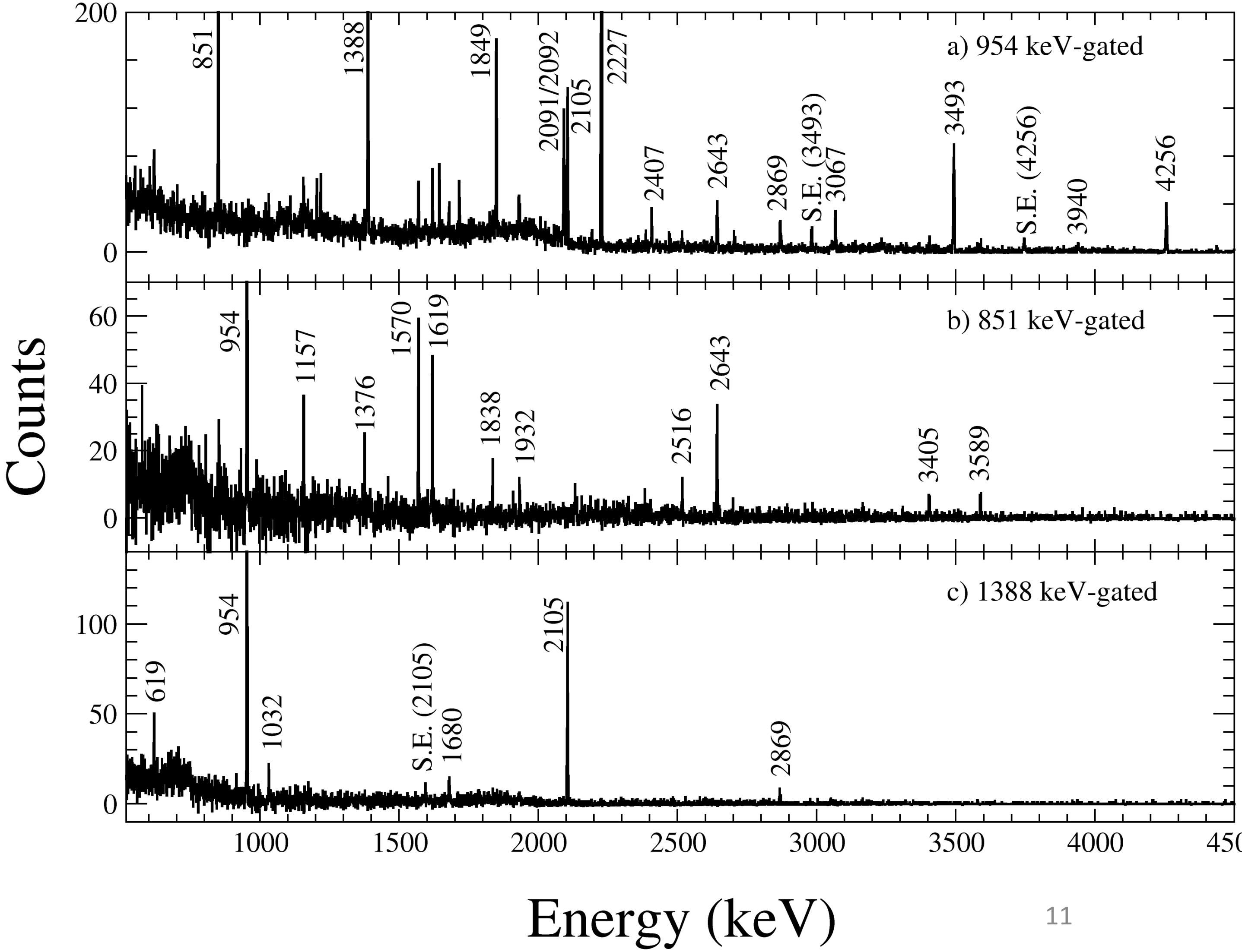


^{62}Ga Experiment

Excellent statistics to perform coincidence analysis.

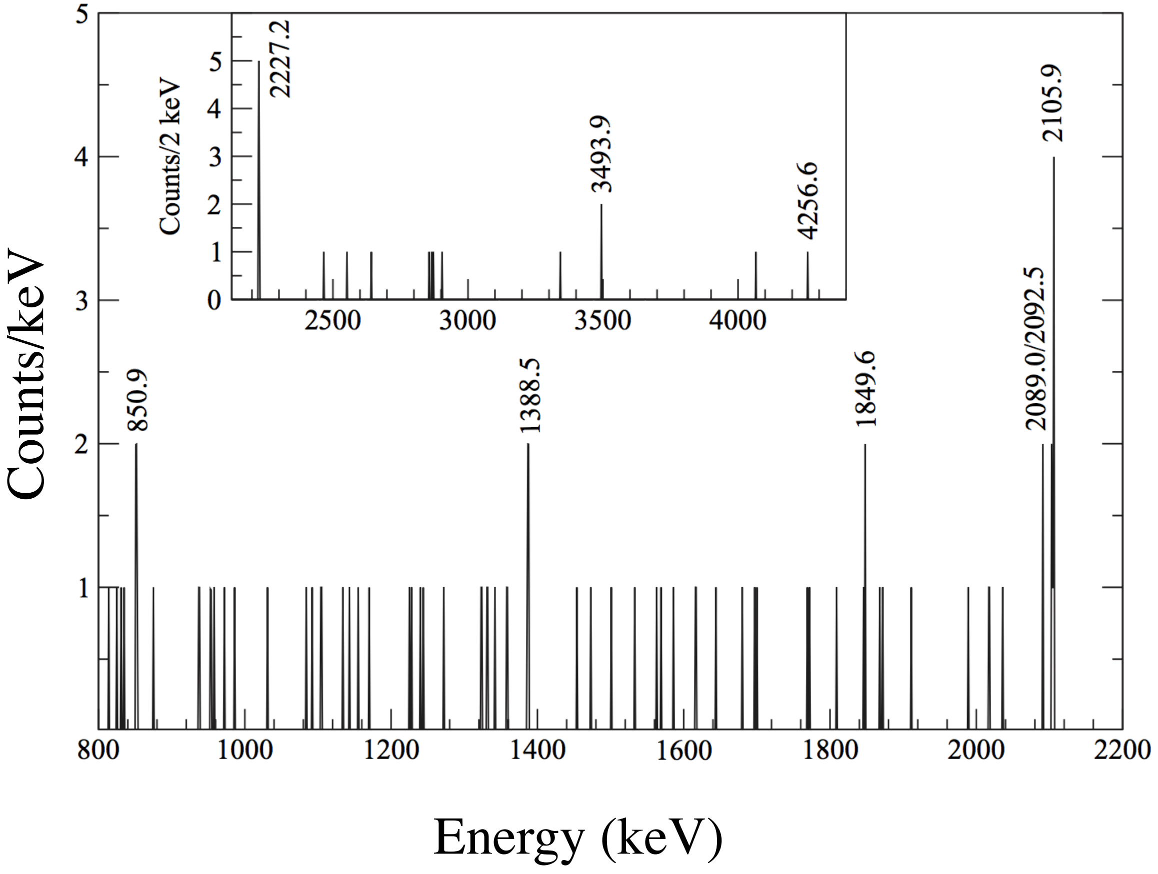
High confidence in placement of transitions in level scheme.

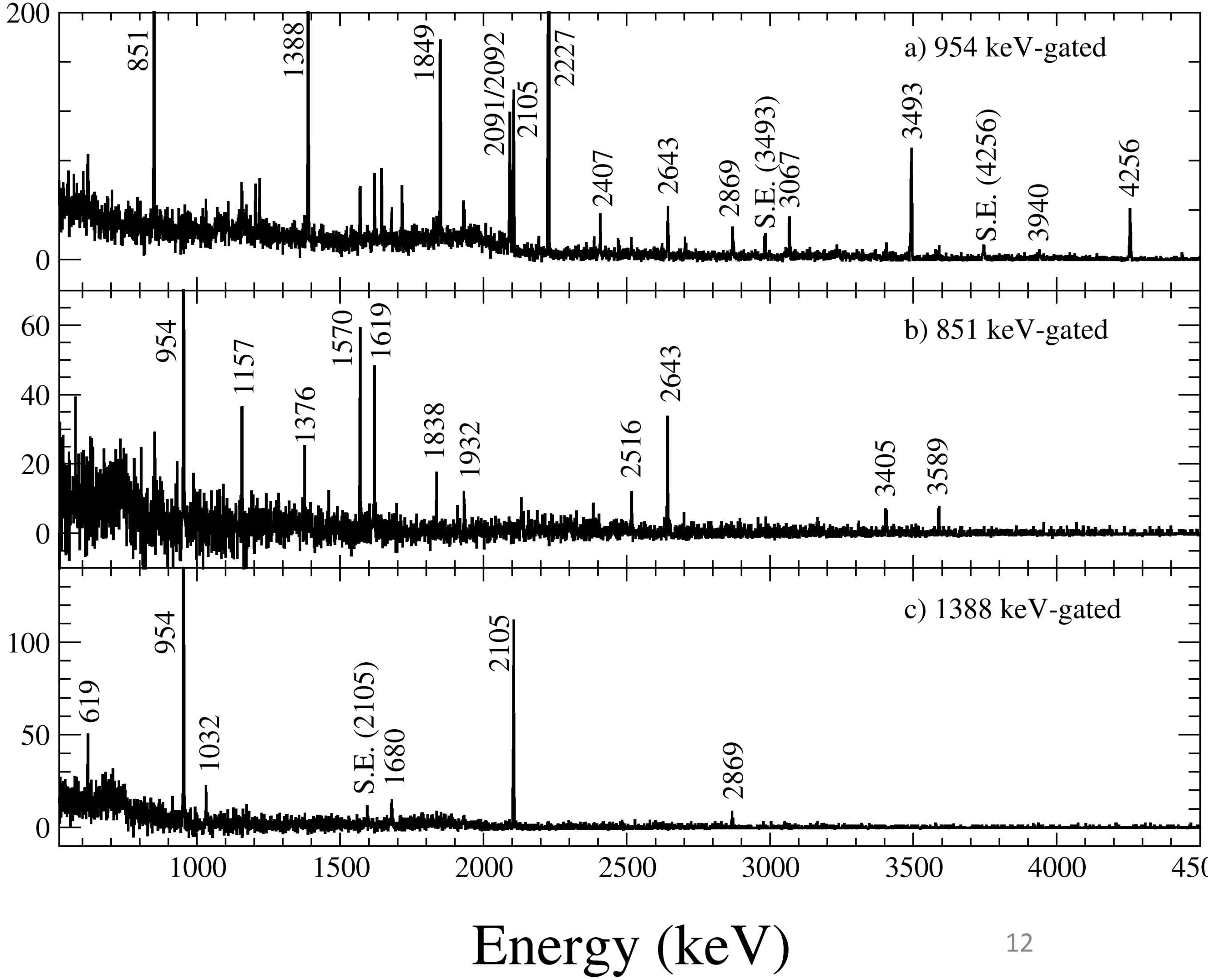
Allowed several doublets to be properly identified and given proper intensities.



^{62}Ga Experiment

Previous measurement



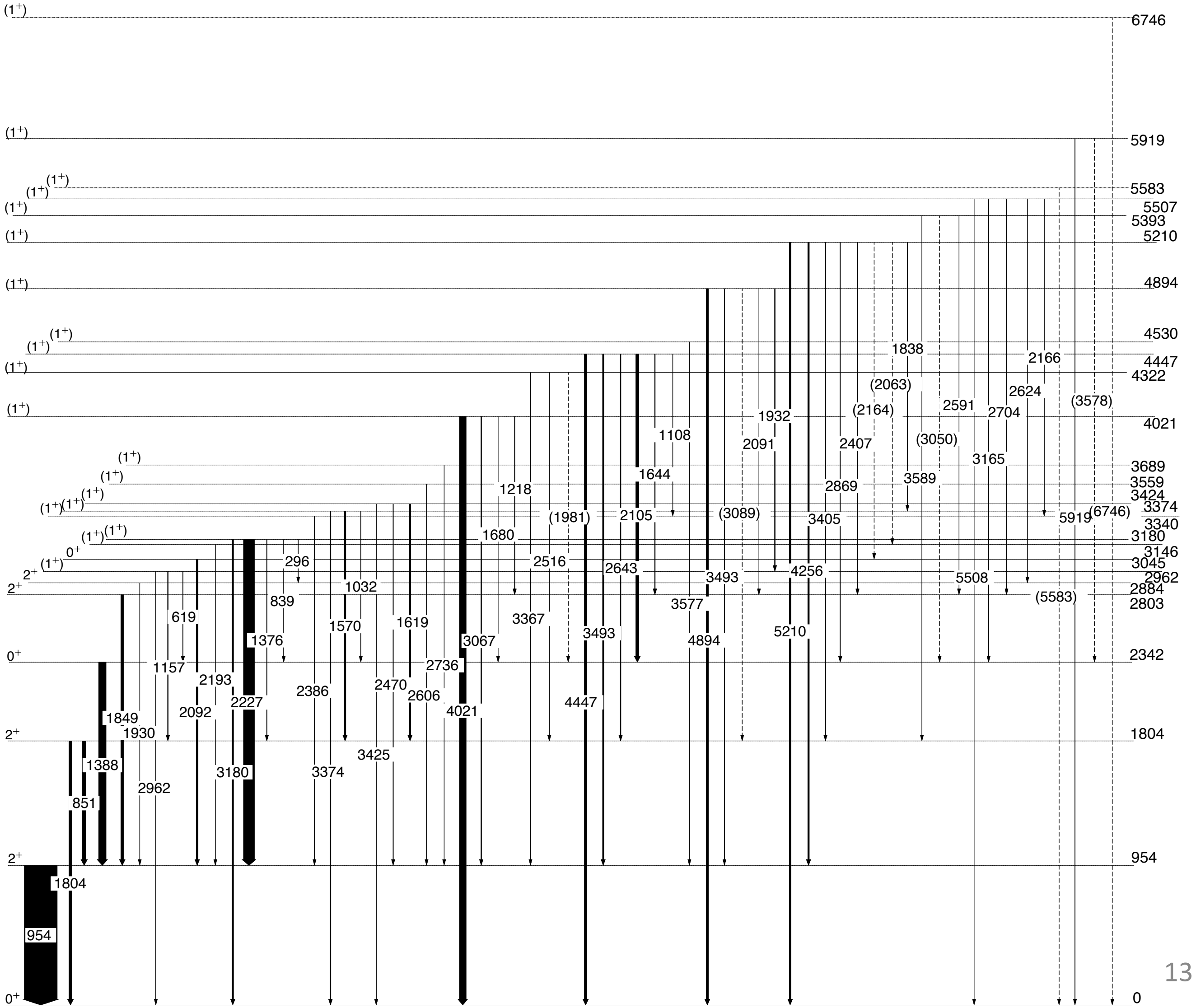


Finlay et. al., Phys. Rev. C.78, 025502 (2008).

^{62}Ga Experiment

Observed 64 γ-rays belonging to 25 excited states.

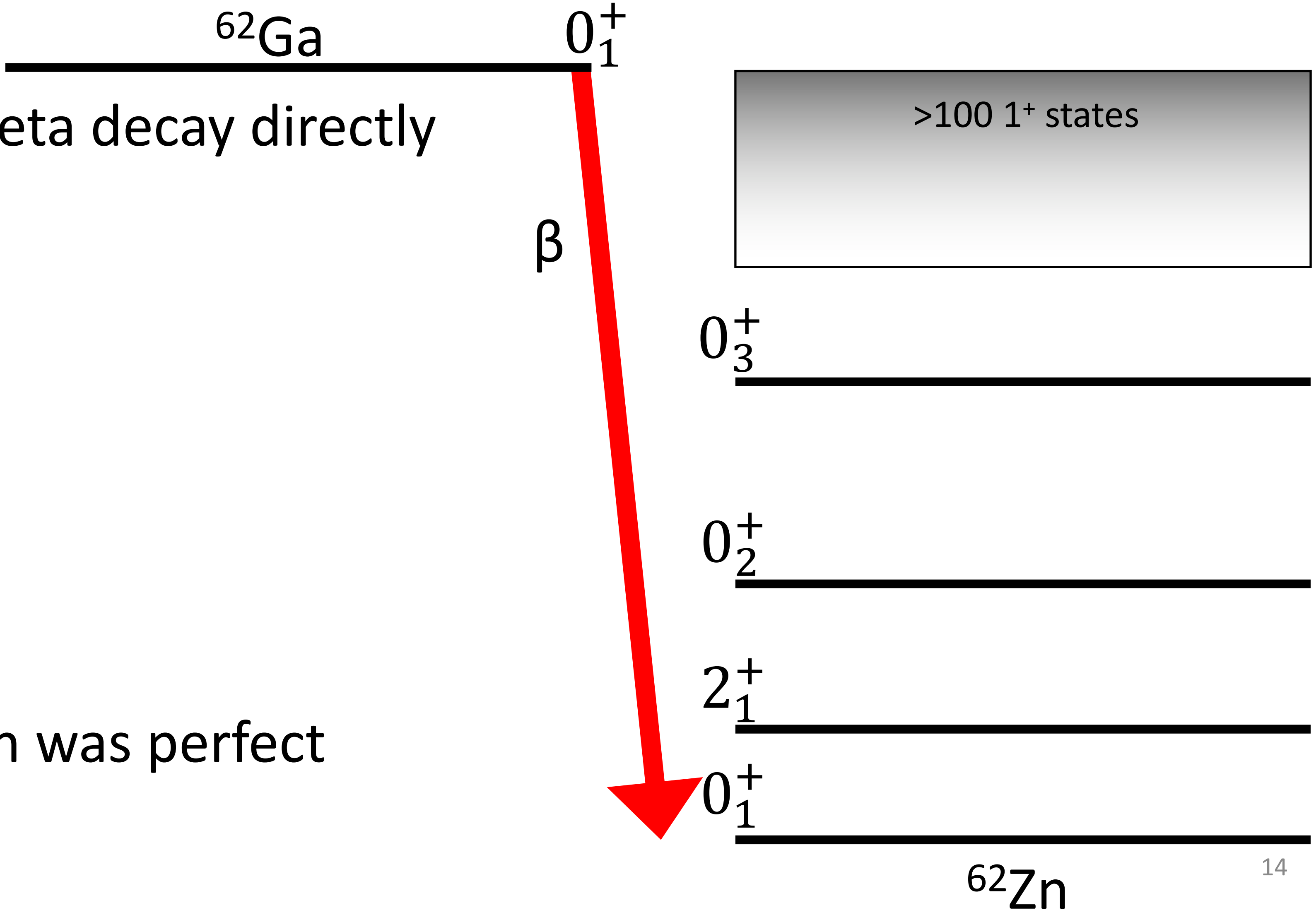
34 new transitions recorded with intensities being as low as one part per million.



Superallowed Branching Ratio

How frequently do you beta decay directly to the ground state?

Would be 100% if isospin was perfect symmetry.



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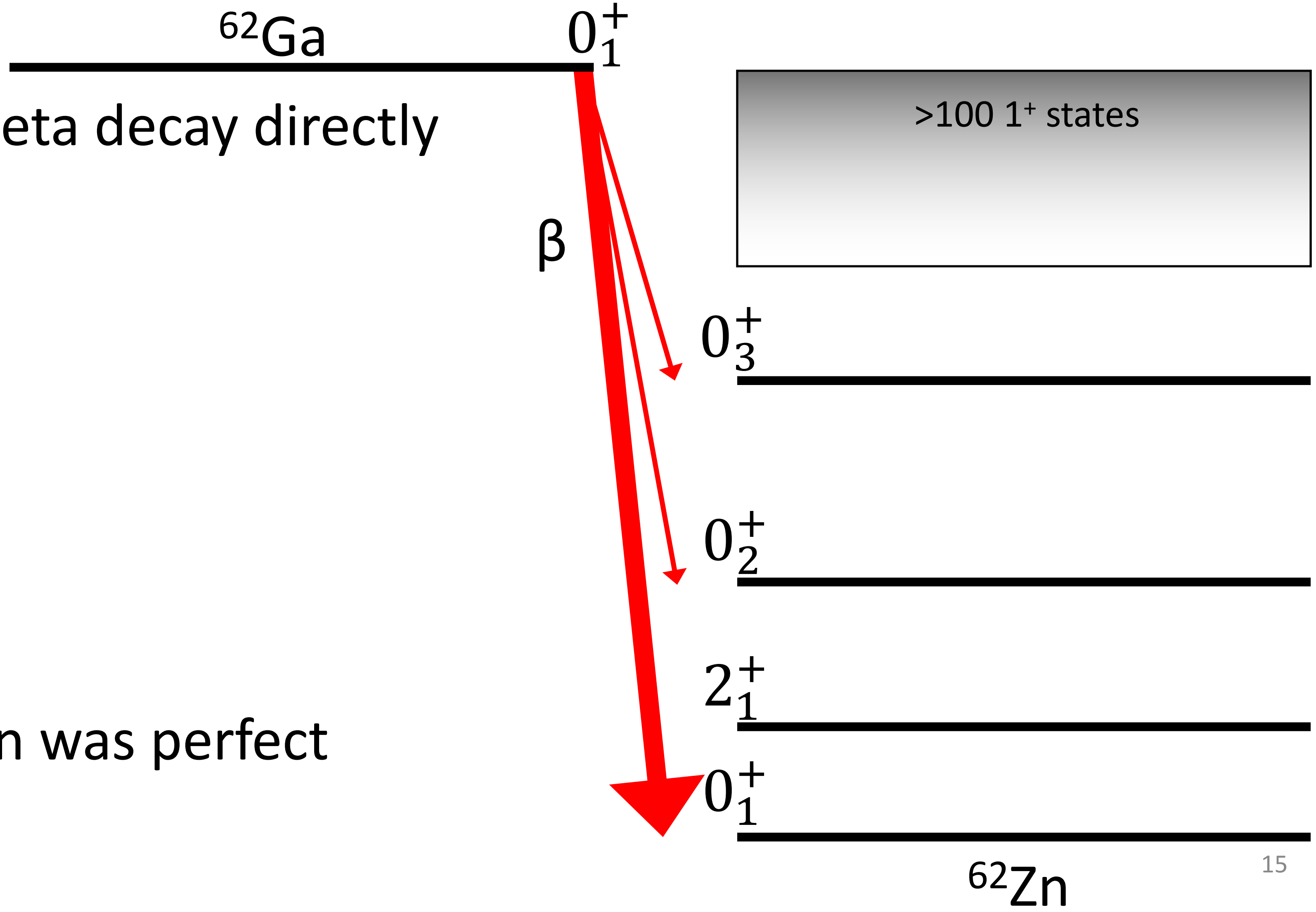
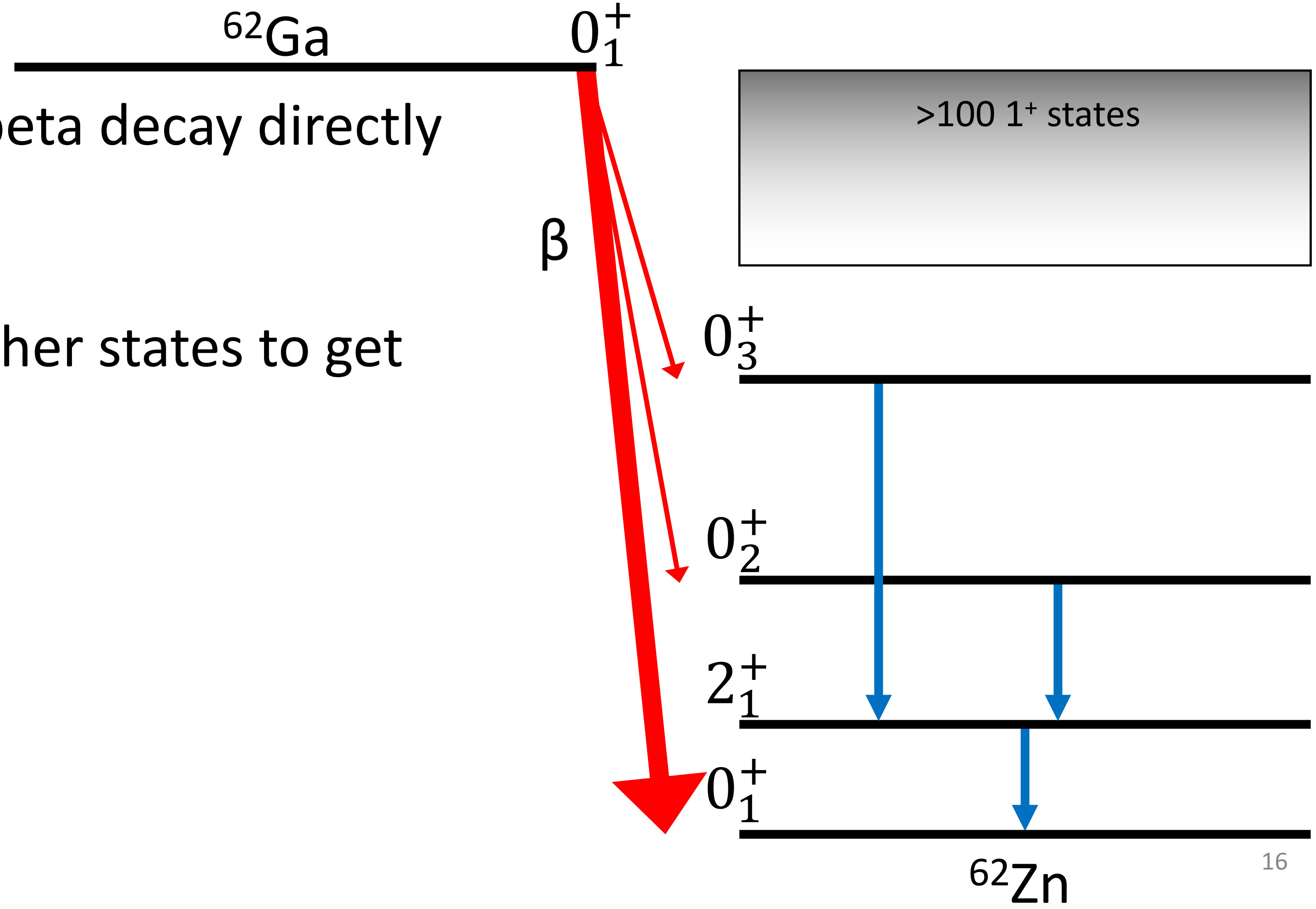


Would be 100% if isospin was perfect symmetry but it's not.

Superallowed Branching Ratio

How frequently do you beta decay directly to the ground state?

Use gamma-rays from other states to get the beta feeding.

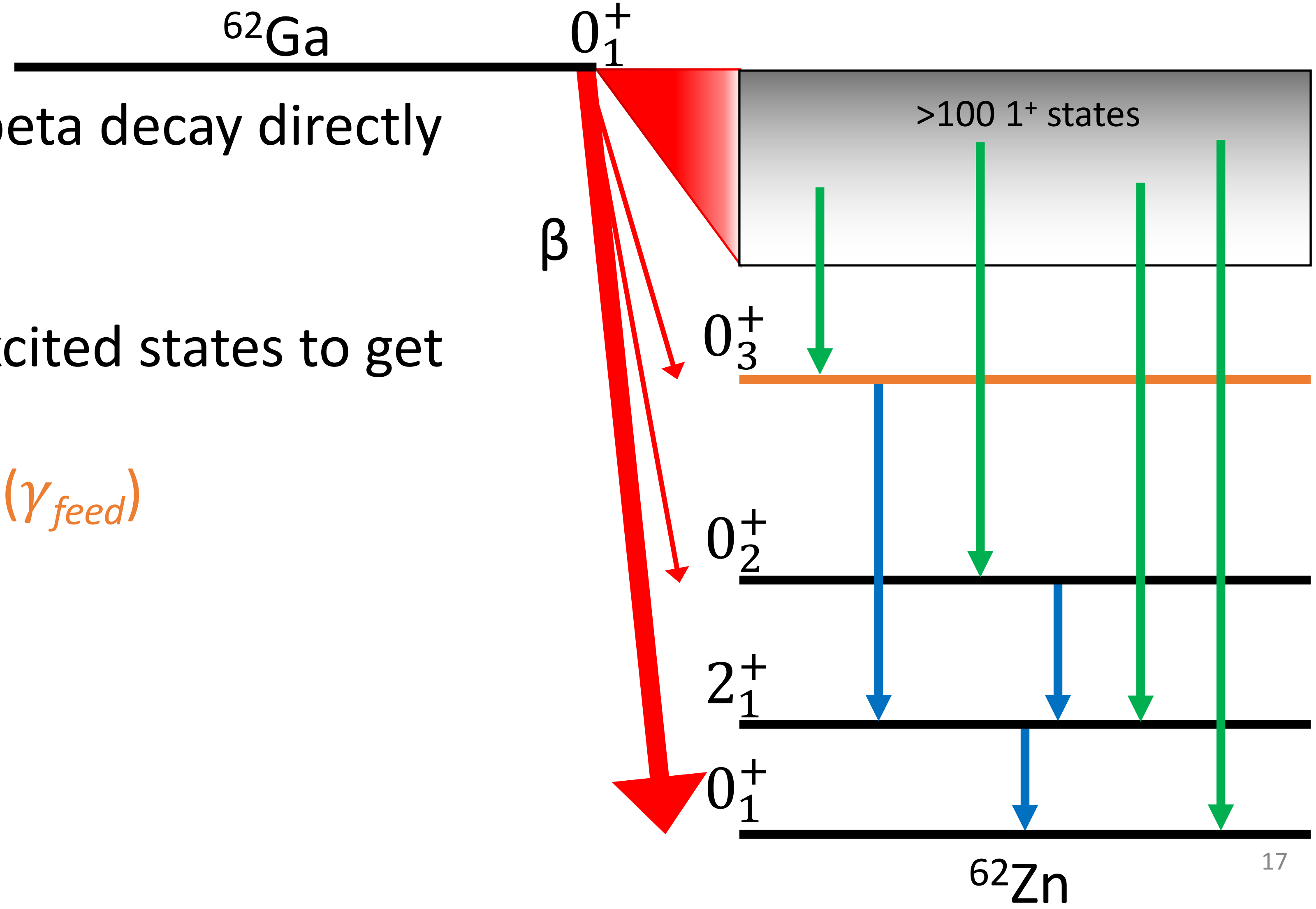


Superallowed Branching Ratio

How frequently do you beta decay directly to the ground state?

Use gamma-rays from excited states to get the beta feeding.

- $I(\beta_{feed}) = I(\gamma_{drain}) - I(\gamma_{feed})$



Superallowed Branching Ratio

How frequently do you beta decay directly to the ground state?

Use gamma-rays from excited states to get the beta feeding.

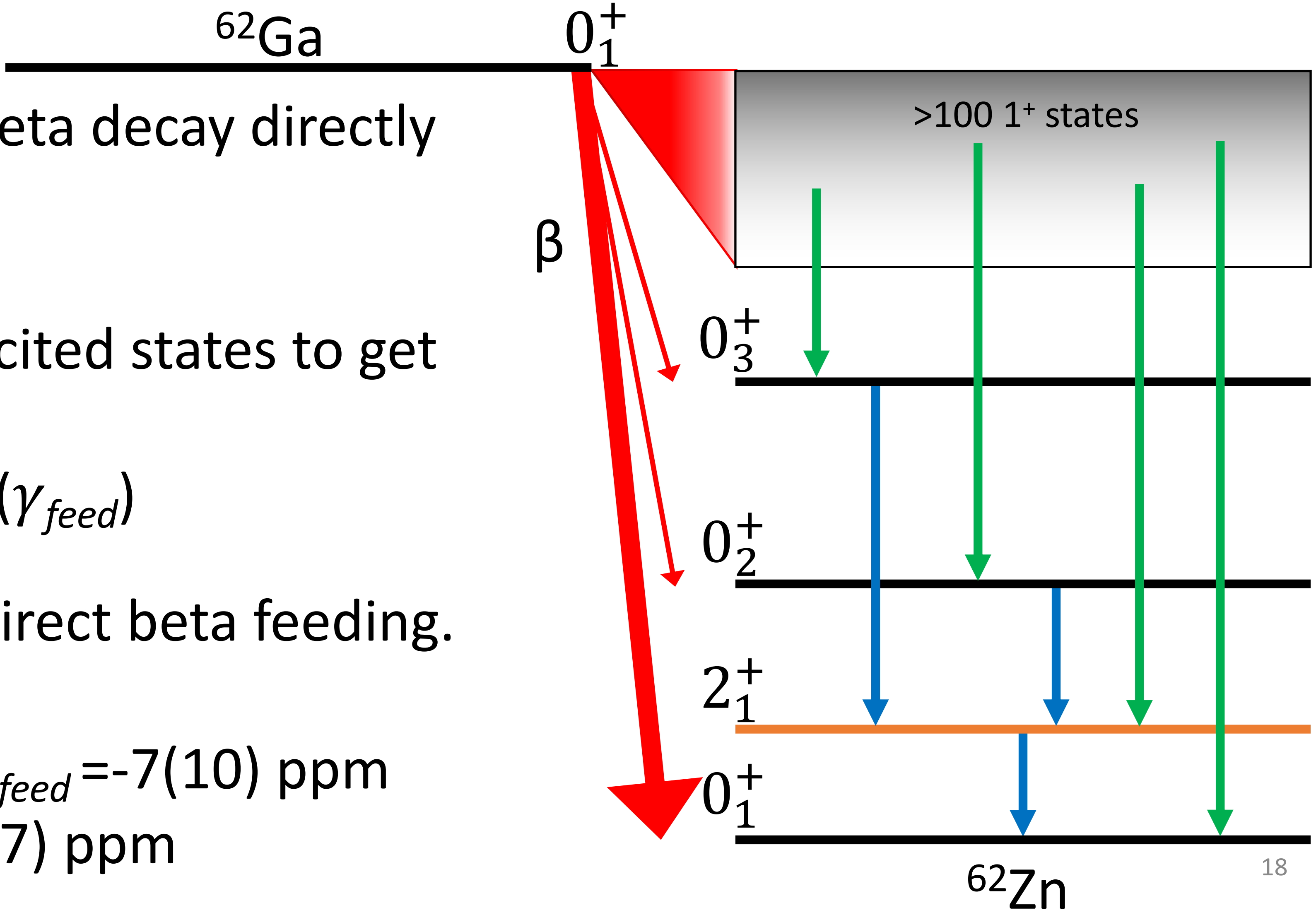
- $I(\beta_{feed}) = I(\gamma_{drain}) - I(\gamma_{feed})$

2+ levels should see no direct beta feeding.

- $I(\gamma_{feed}) = I(\gamma_{drain})$

The 954 keV level γ_{drain}-γ_{feed} =-7(10) ppm

Previous work was 122(27) ppm



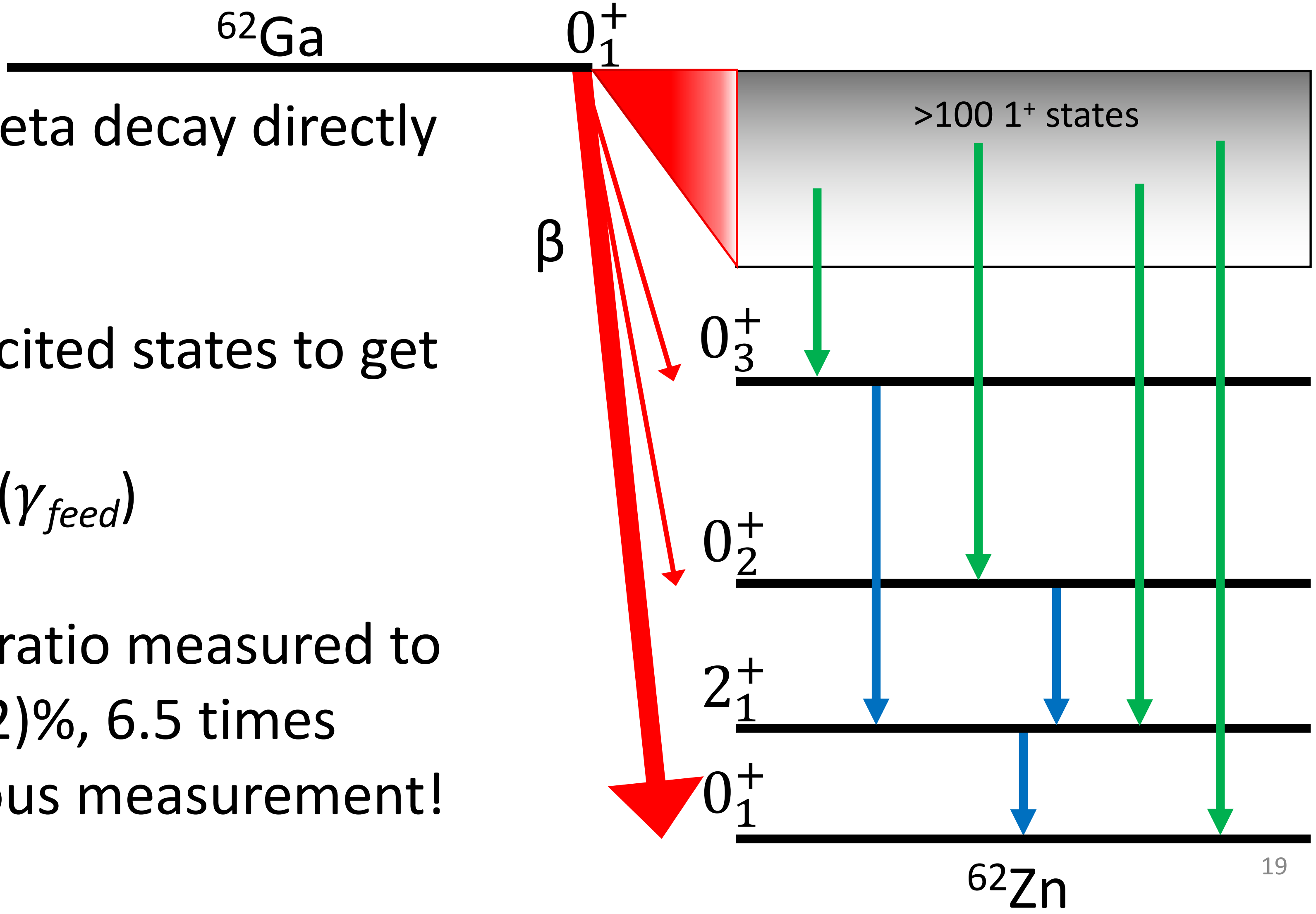
Superallowed Branching Ratio

How frequently do you beta decay directly to the ground state?

Use gamma-rays from excited states to get the beta feeding.

- $I(\beta_{feed}) = I(\gamma_{drain}) - I(\gamma_{feed})$

Superallowed branching ratio measured to a precision of 99.8647(12)%, 6.5 times more precise than previous measurement!

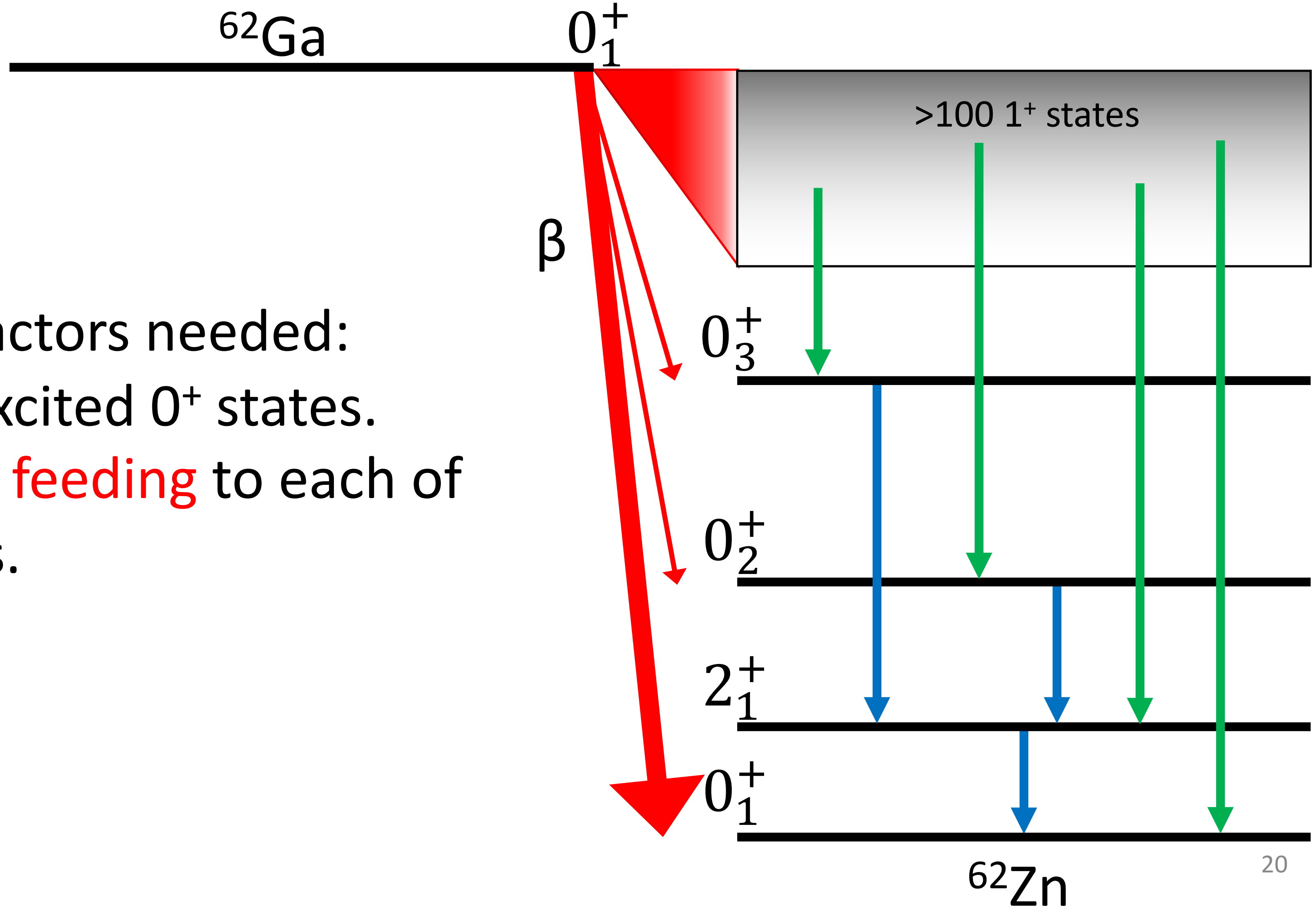


How do we test δ_C?

$$\delta_C = \delta_{C1} + \delta_{C2}$$

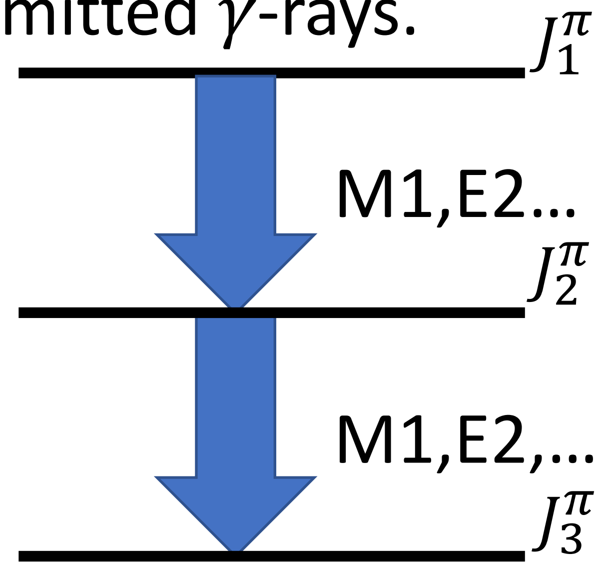
To determine δ_{C1} two factors needed:

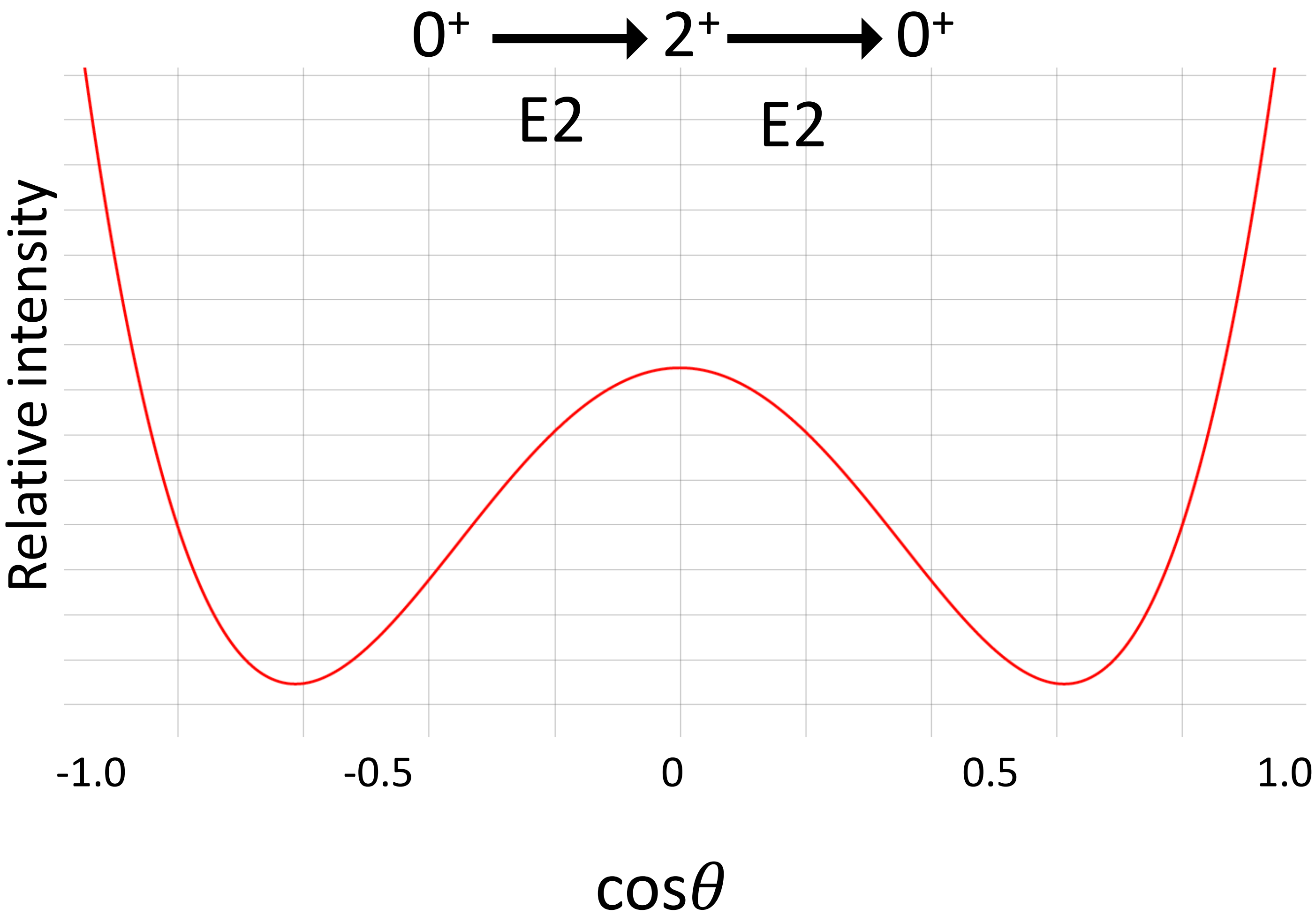
1. The energy of the excited 0^+ states.
2. The amount of beta feeding to each of the excited 0^+ states.
   - ➢ $I(\gamma_{drain})$- $I(\gamma_{feed})$.



Gamma-Gamma Angular Correlations

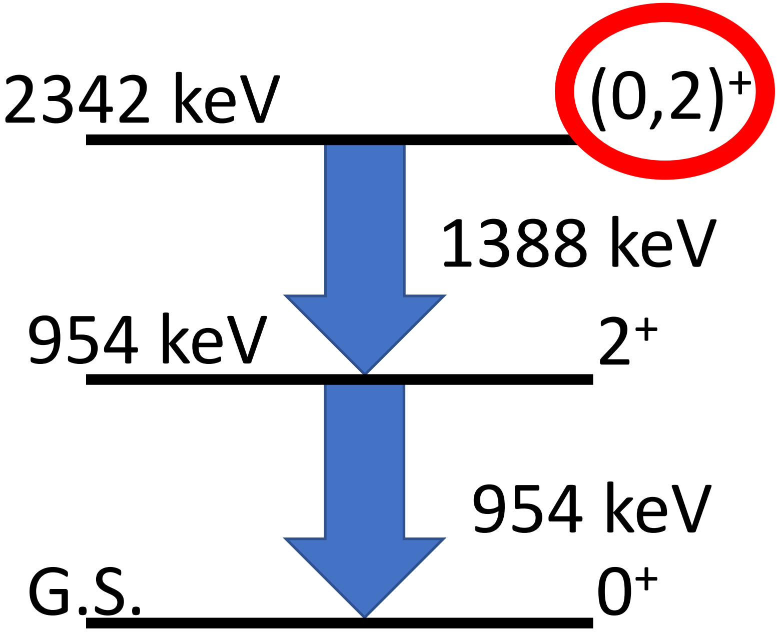
Coincident gamma-rays, in general, have a spatial correlation, dependent on the spins of the nuclear states and multipole character of the emitted γ-rays.

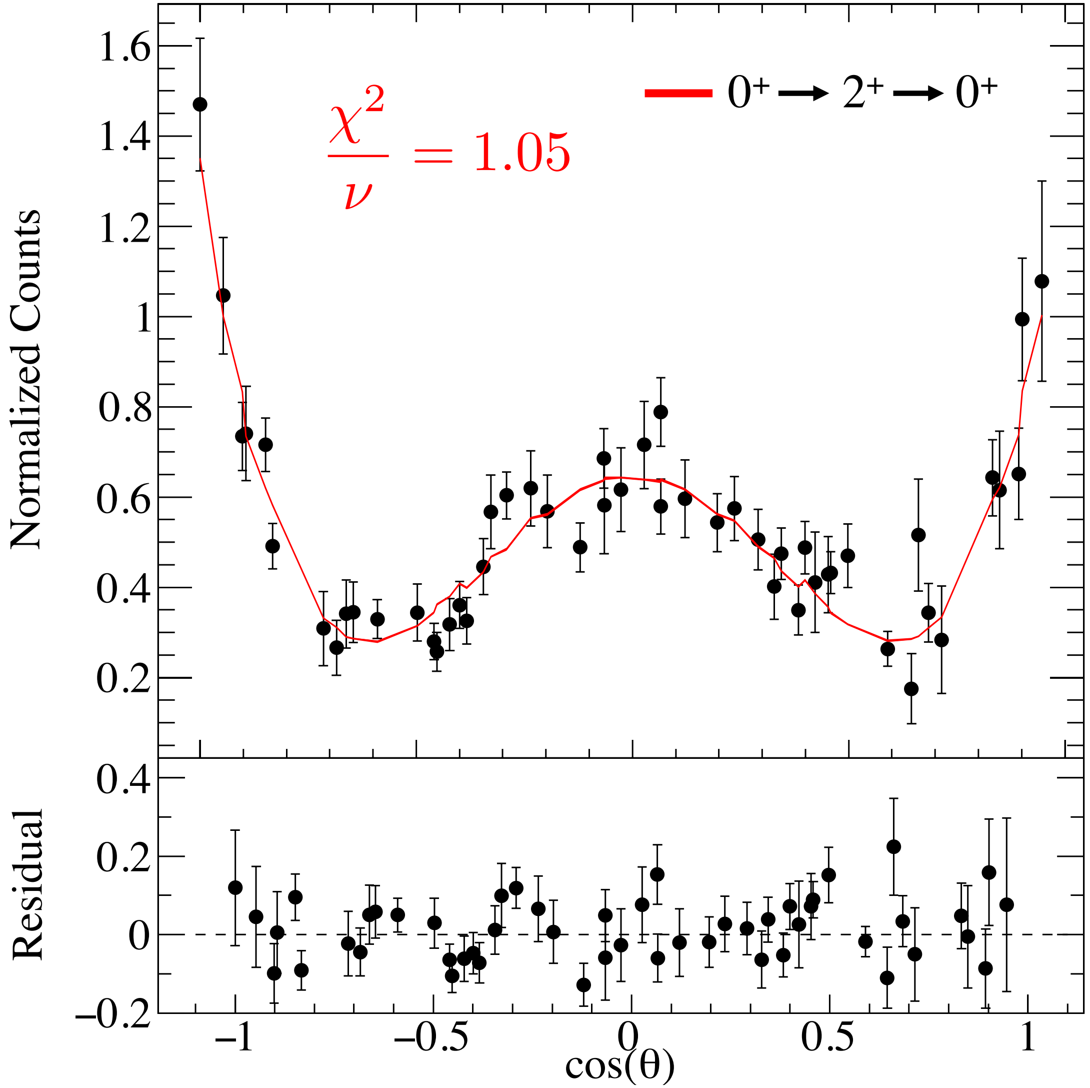




Gamma-Gamma Angular Correlations

Angular correlation measurement of the 1388-954 keV cascade in daughter nucleus, ^{62}Zn, compared to Geant4 simulation.





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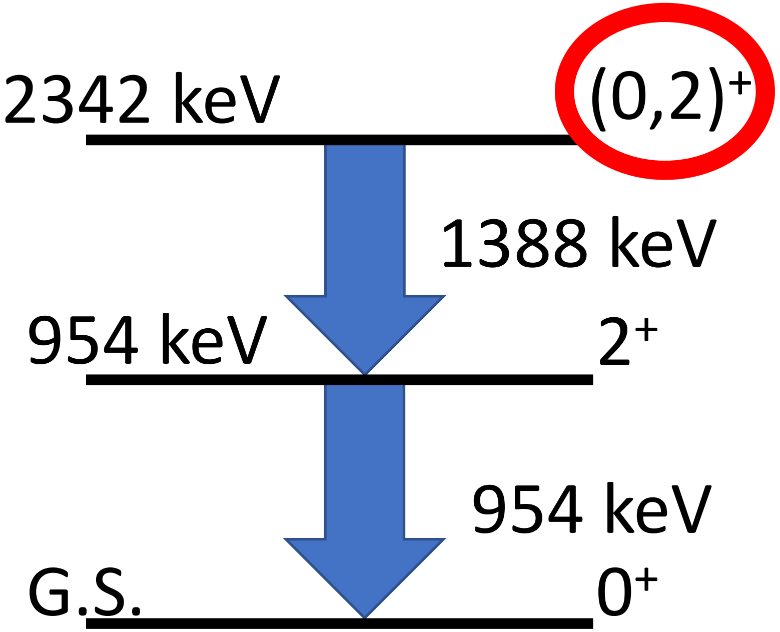
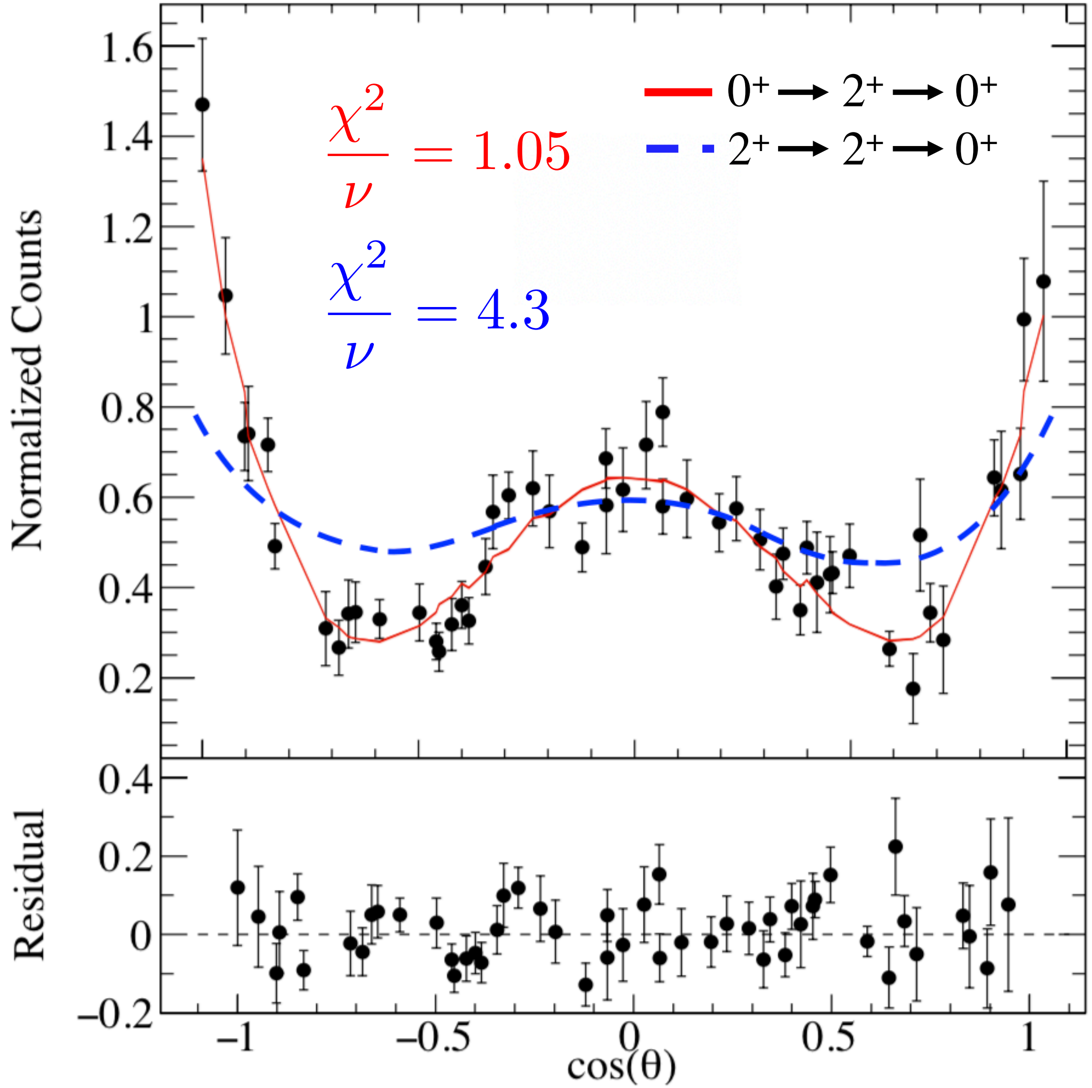
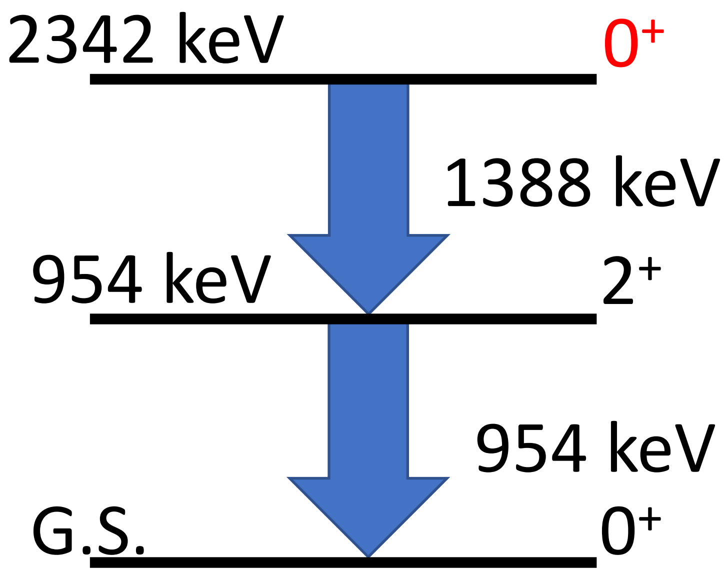
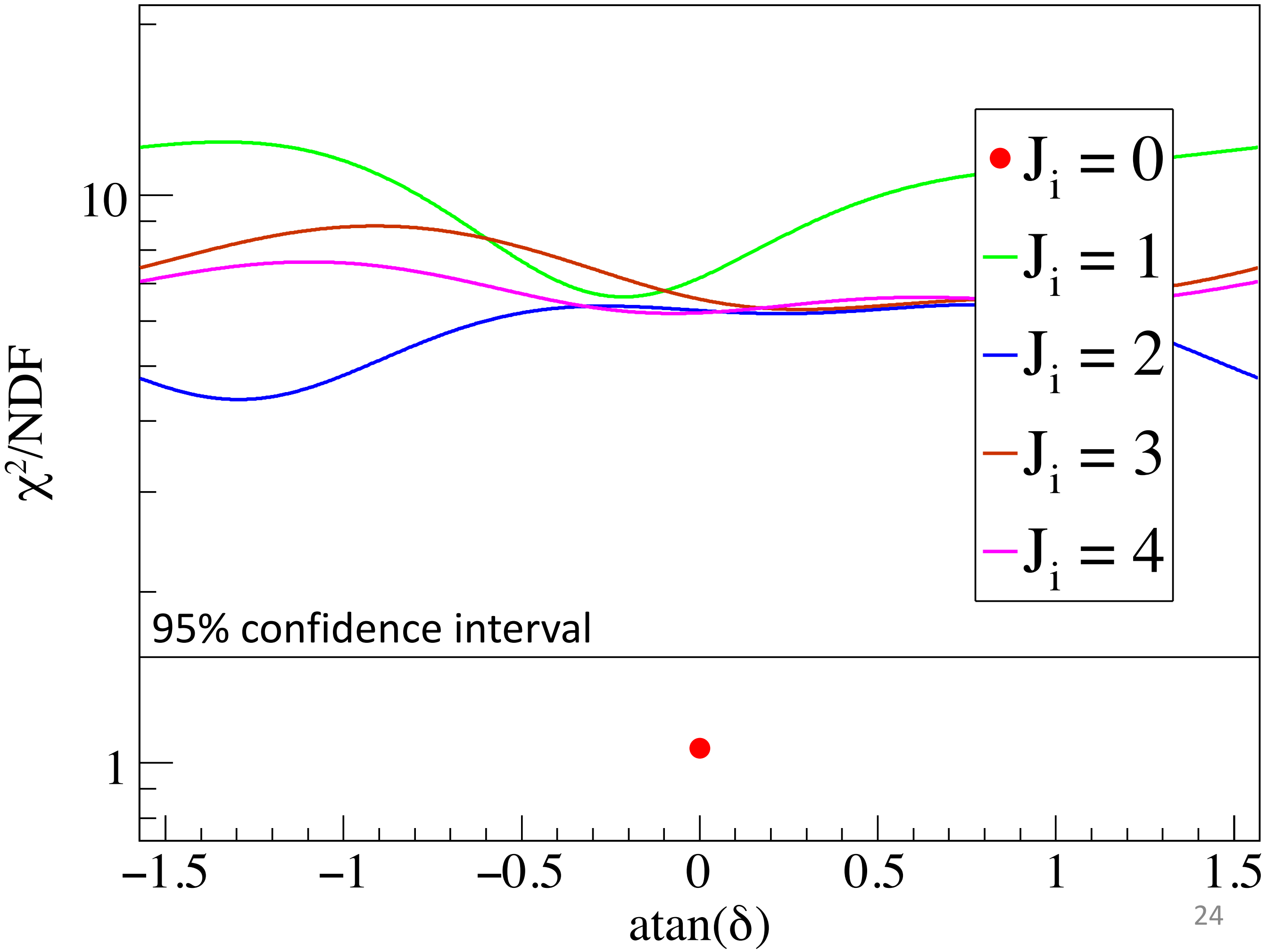




Gamma-Gamma Angular Correlations

Allowing spin of 2342 keV state to vary can clearly identify the spin as an excited 0^+ state.





Isospin Symmetry Break Correction

E_{level} (keV)	n	$\delta^n_{C1\,exp}$(%)	$\delta^n_{C1\,theo}$(%)	Ratio (theo/exp)
2342	1	0.032(3)	0.083(20)	2.59(25)
3045	2	0.038(4)	0.203(20)	5.34(77)

- Over estimation from theory.
- Factor of 2.6 for the first excited 0^+ state and over a factor of 5 for the second excited 0^+ state.
- Third, fourth and fifth excited 0^+ states, only limits were set on the isospin symmetry breaking correction from this experiment.

Thank you!

UNIVERSITY of GUELPH

TRIUMF

Special thanks to the GRIFFIN collaboration, funding agencies and you for your time!

Canada Foundation for Innovation
Fondation canadienne pour l'innovation

NSERC
CRSNG

Thank you!

UNIVERSITY of GUELPH

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Back-up Slides

Summary

- New calculations of Δ_R^V has changed V_{ud}, creating a significant disparity from unitarity in the top row of the CKM matrix.

- Leads to three possible explanations,
  1. The top row of the CKM matrix may need to be revisited.
  2. There may physics beyond the standard model.
  3. The theoretical corrections used to determine the $\mathcal{F}$t-values may need a larger model space.

- Experimentally we can measure the configuration mixing between 0^+ states, allowing for limits to be set on δ_{C1}.

- From observations in experiment, the mixing predicted by theory is significantly over estimated.

Implications of Recent Calculations

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

Recent calculations have reduced the uncertainty on Δ_R^V and additionally changed its central value.

Producing disagreement with unity in the CKM matrix.

Δ_{Rnew}^V = 2.467(22)%

$|V_{ud}|_{new} = 0.97370(21)_{\mathcal{F}t}(10)_{RC}$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984(4)$

Uncertainty dominated by $\mathcal{F}$t.

~4σ disagreement from unity!!

C.-Y. Seng and M. J. Gorchtein, M. Ramsey-Musolf, Phys. Rev. Lett. **100**, 013001 (2019)

Implications of Recent Calculations

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

Recent calculations have reduced the uncertainty on Δ_R^V and additionally changed its central value.

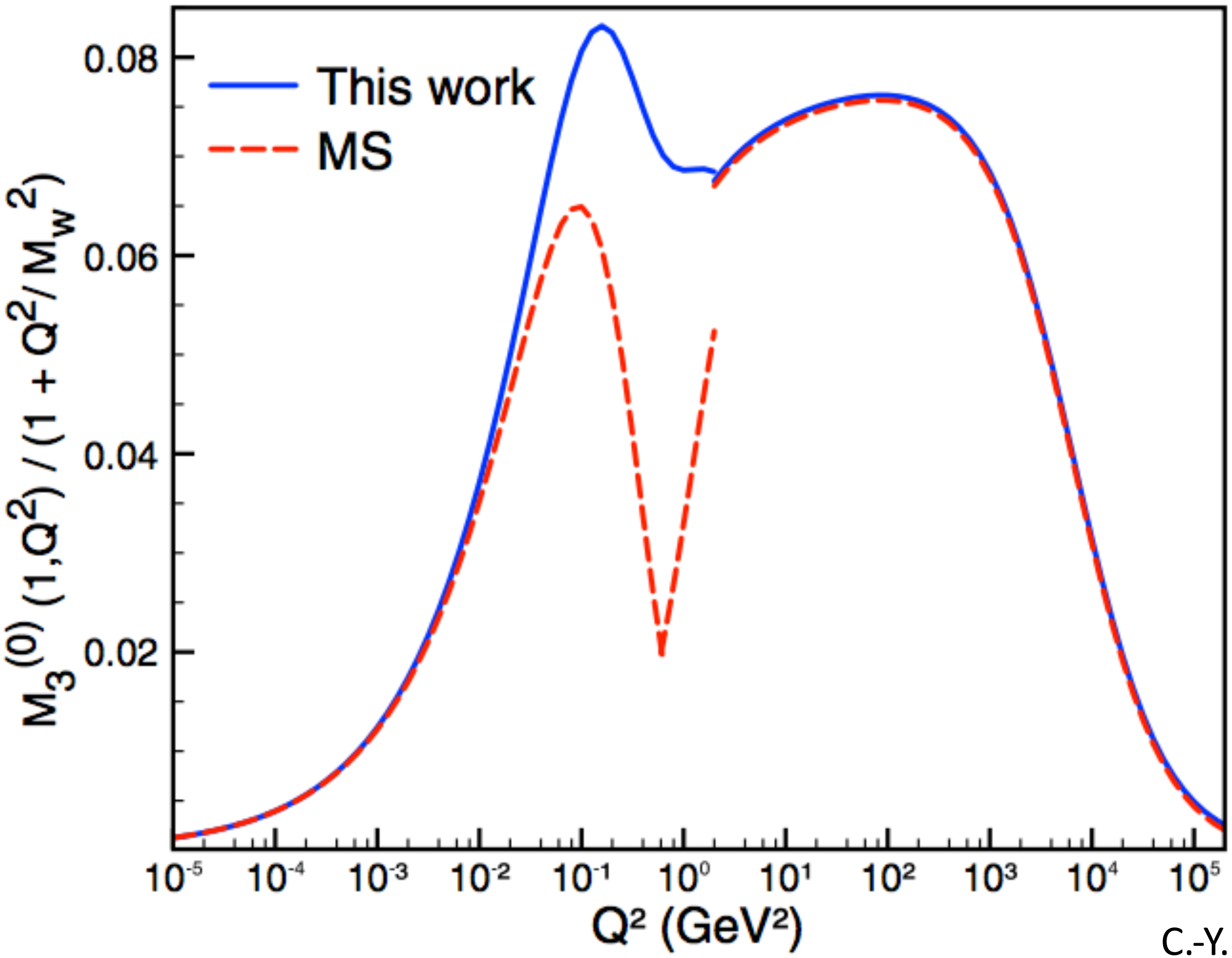
Δ_{Rold}^V = 2.361(38)%

$|V_{ud}|_{old} = 0.97420(10)_{\mathcal{F}t}(18)_{RC}$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(5)$

Good agreement from unity

New Δ_R^V Calculation

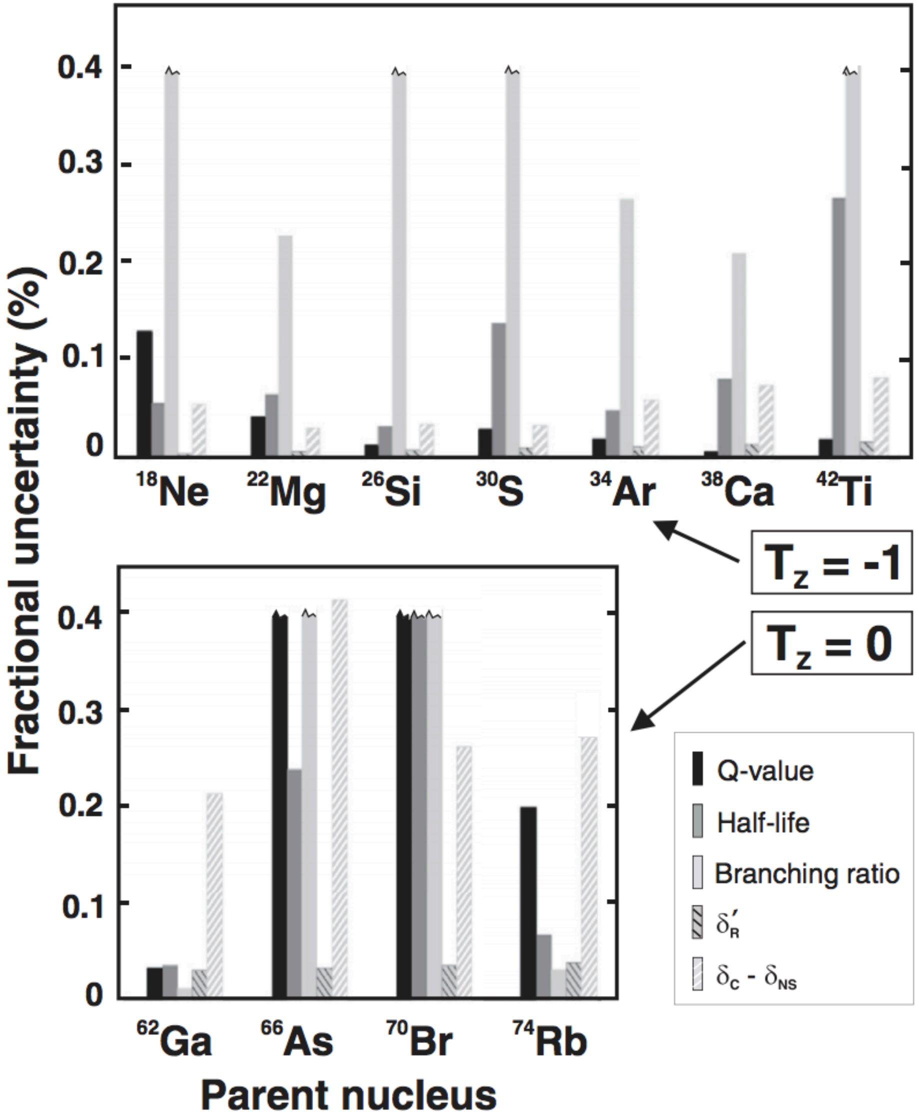


Integrate this to get new value, red is old function blue is new function.

1. Assume no physics other than Born at low Q.
2. Require function to vanish as Q^2 approaches 0.
3. Integral must match pQCD not the function itself.

C.-Y. Seng et. al., Phys. Rev. Lett. **100**, 013001 (2019)

Fractional Uncertainties

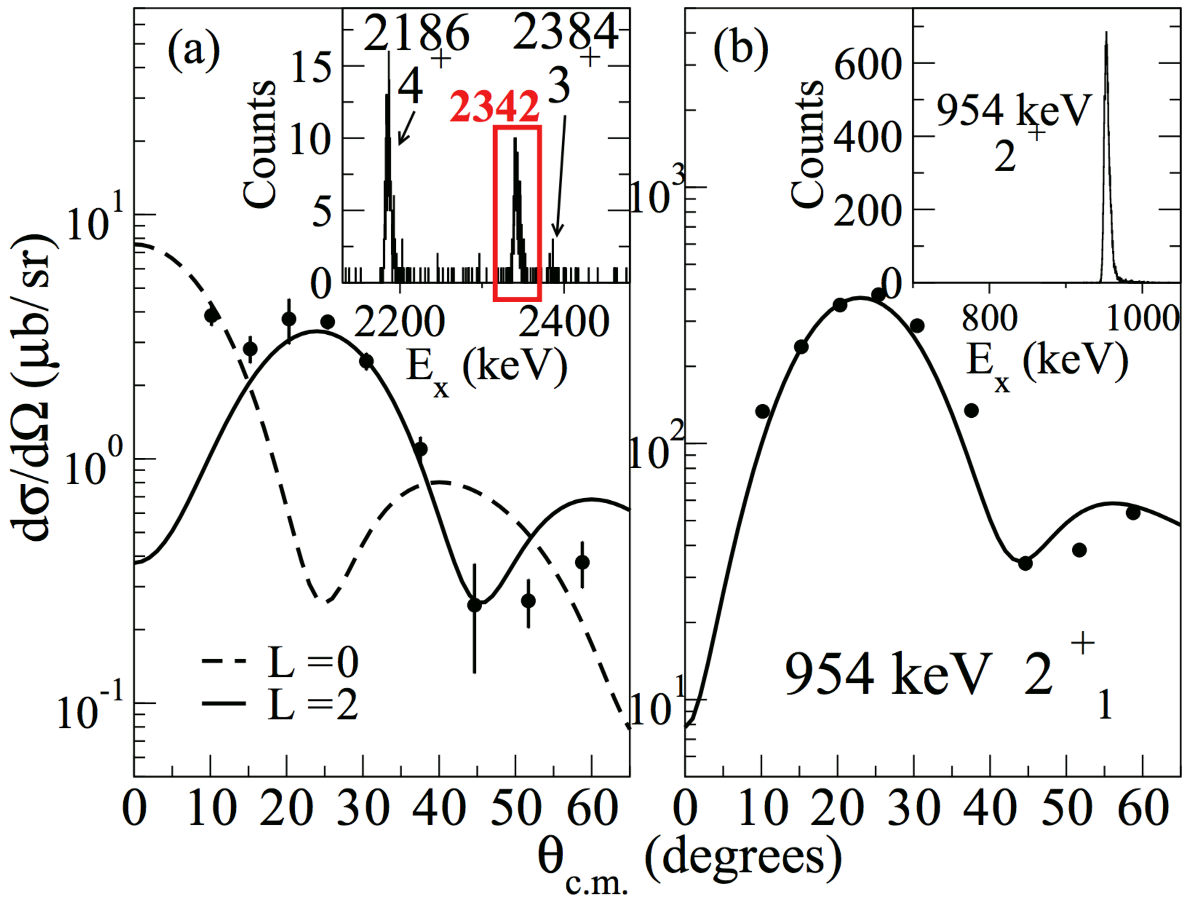


Fractional uncertainty in superallowed emitters, for the theoretical corrections in heavier nuclei δ_C is the dominant source of uncertainty.

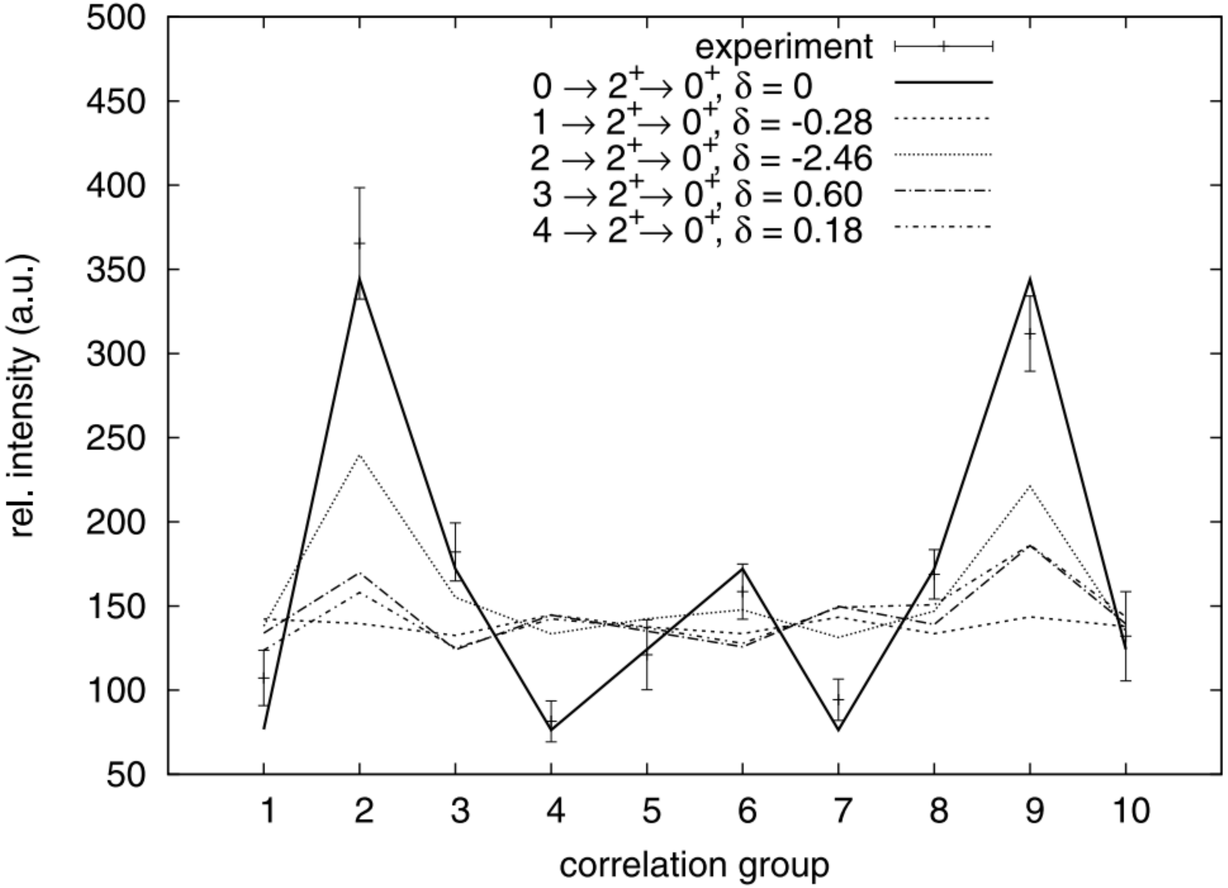
I. S. Towner and J. C. Hardy, Phys. Rev. C.77, 025501(2008).

Spin assignment of 2.34 MeV state

Two discrepant measurements assigning the spin of the 2.34 MeV state as 2+ and 0+.

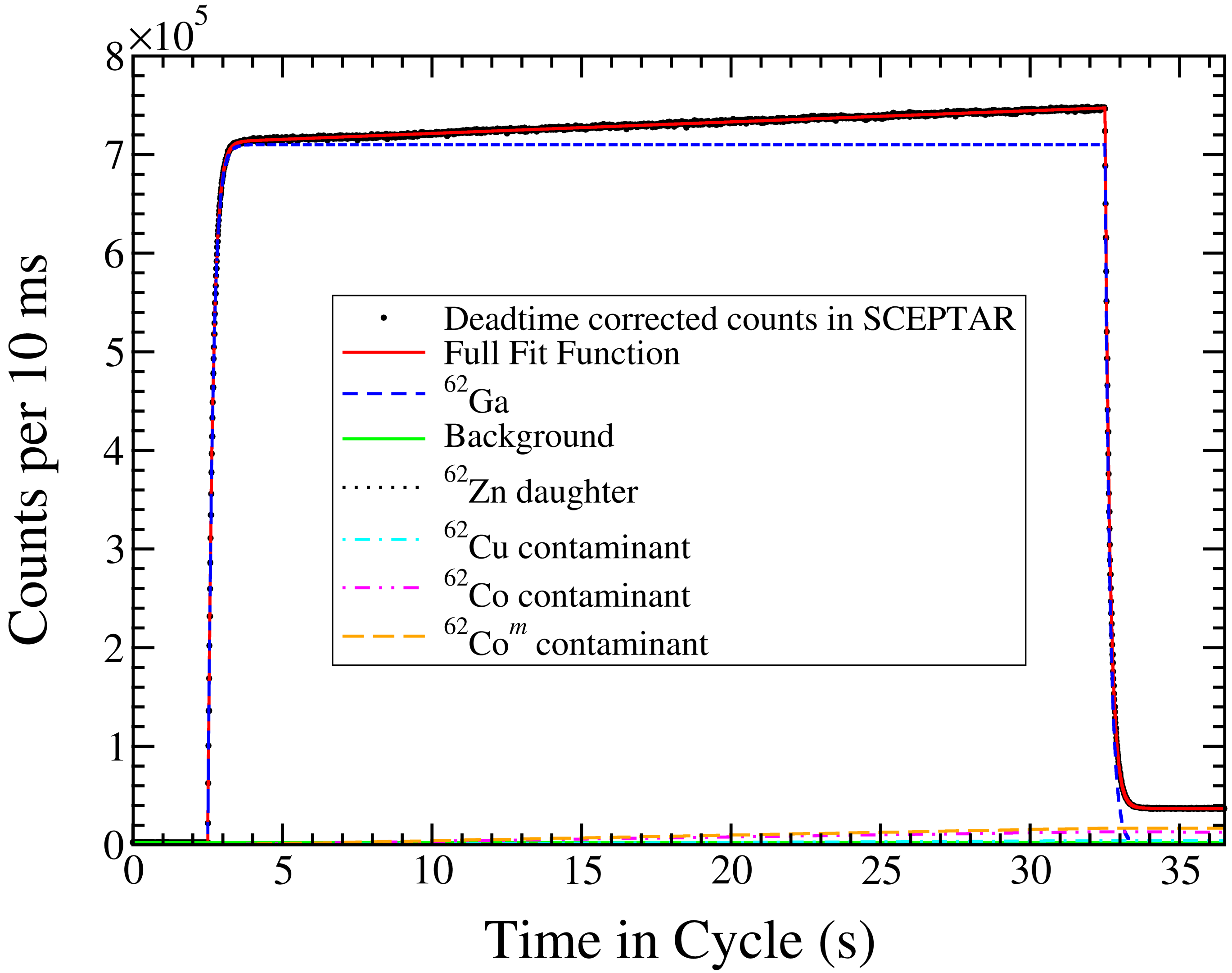


K. G. Leach, Phys. Rev. C. **88**, 031306 (2013)



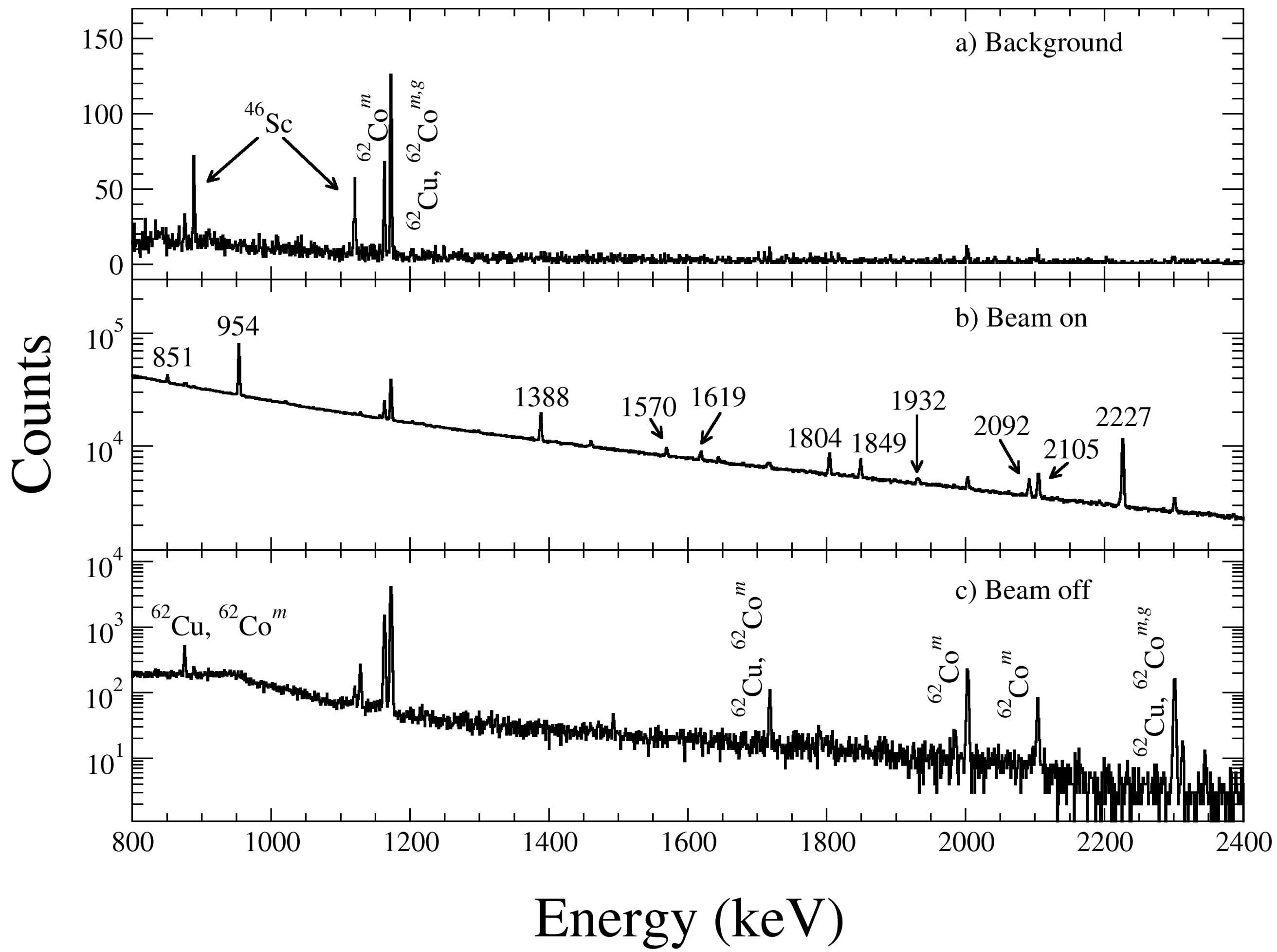
M. Albers, Nucl. Phys. A **847**, 180 (2010)

Beta Cycle Fit



Fit to the beta cycles, integrating gives the total number of beta decays observed from ^{62}Ga.

Contaminants

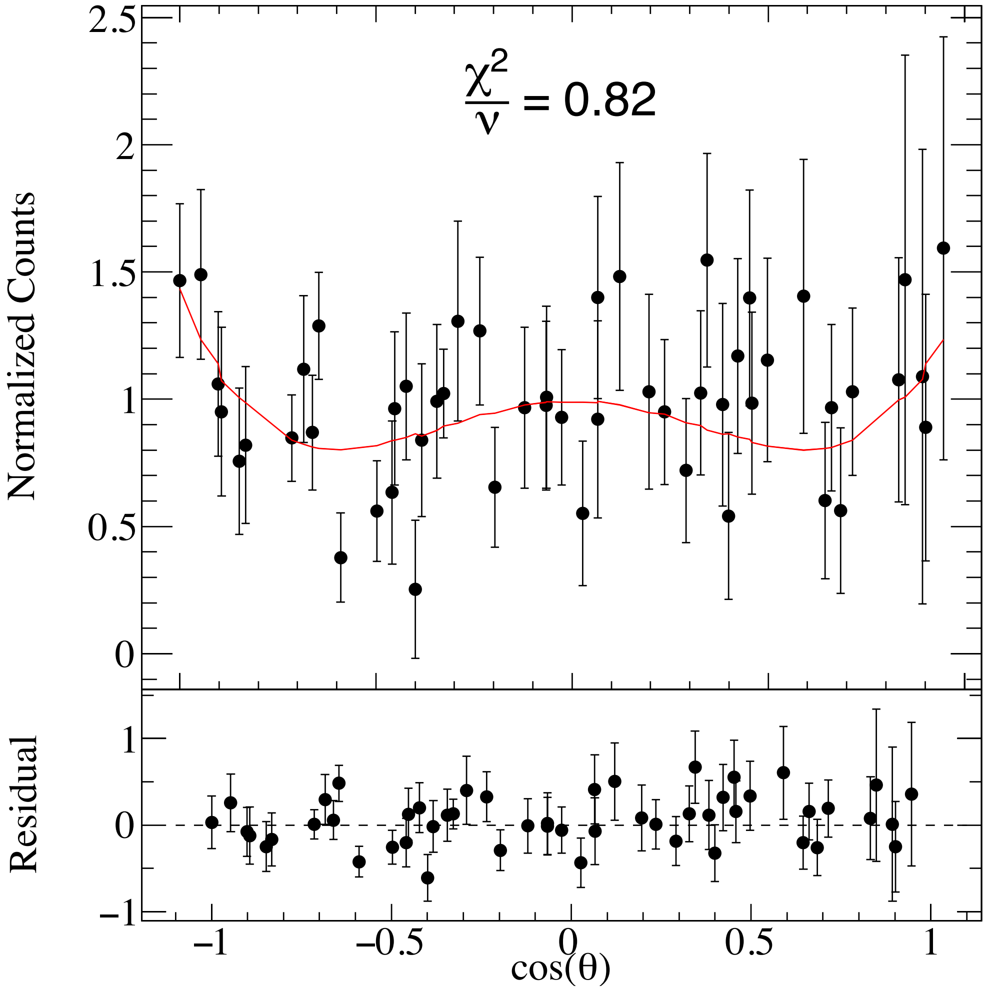


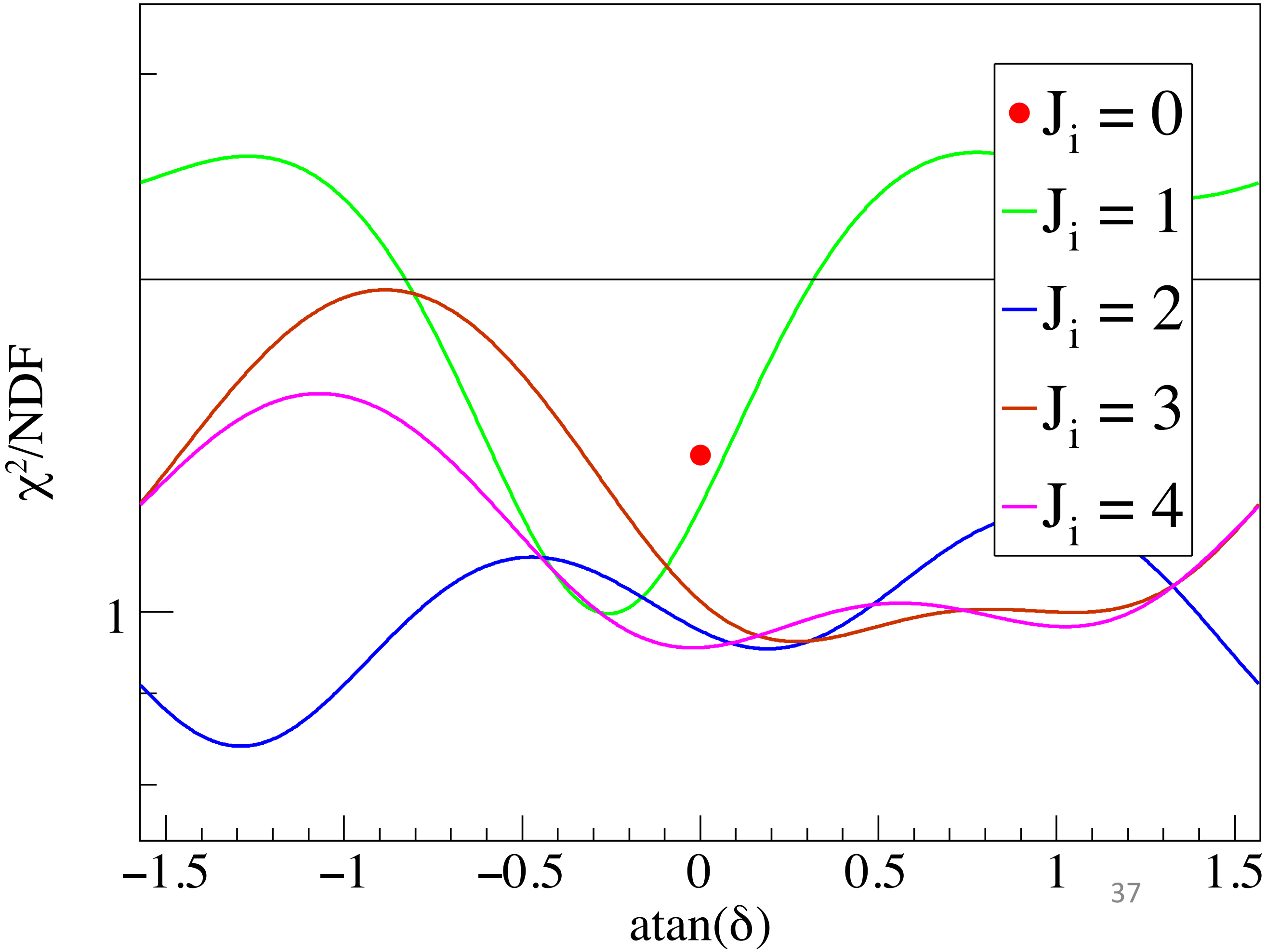
Gamma-ray spectrum gated at different points in the cycle to see contaminants.

^{62}Co, ^{62}Cu and ^{46}Sc being the primary contaminants.

Angular Correlations

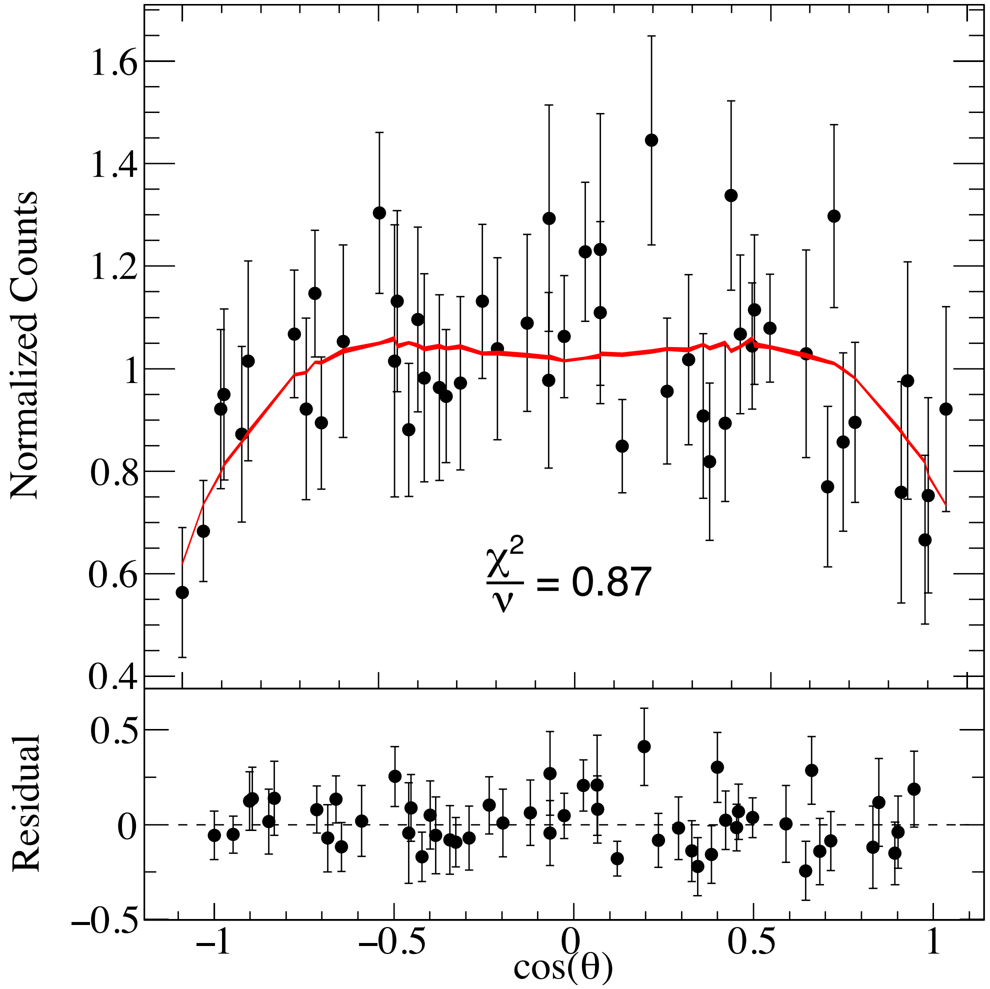
851-954 keV cascade, known $2^+ \rightarrow 2^+ \rightarrow 0^+$

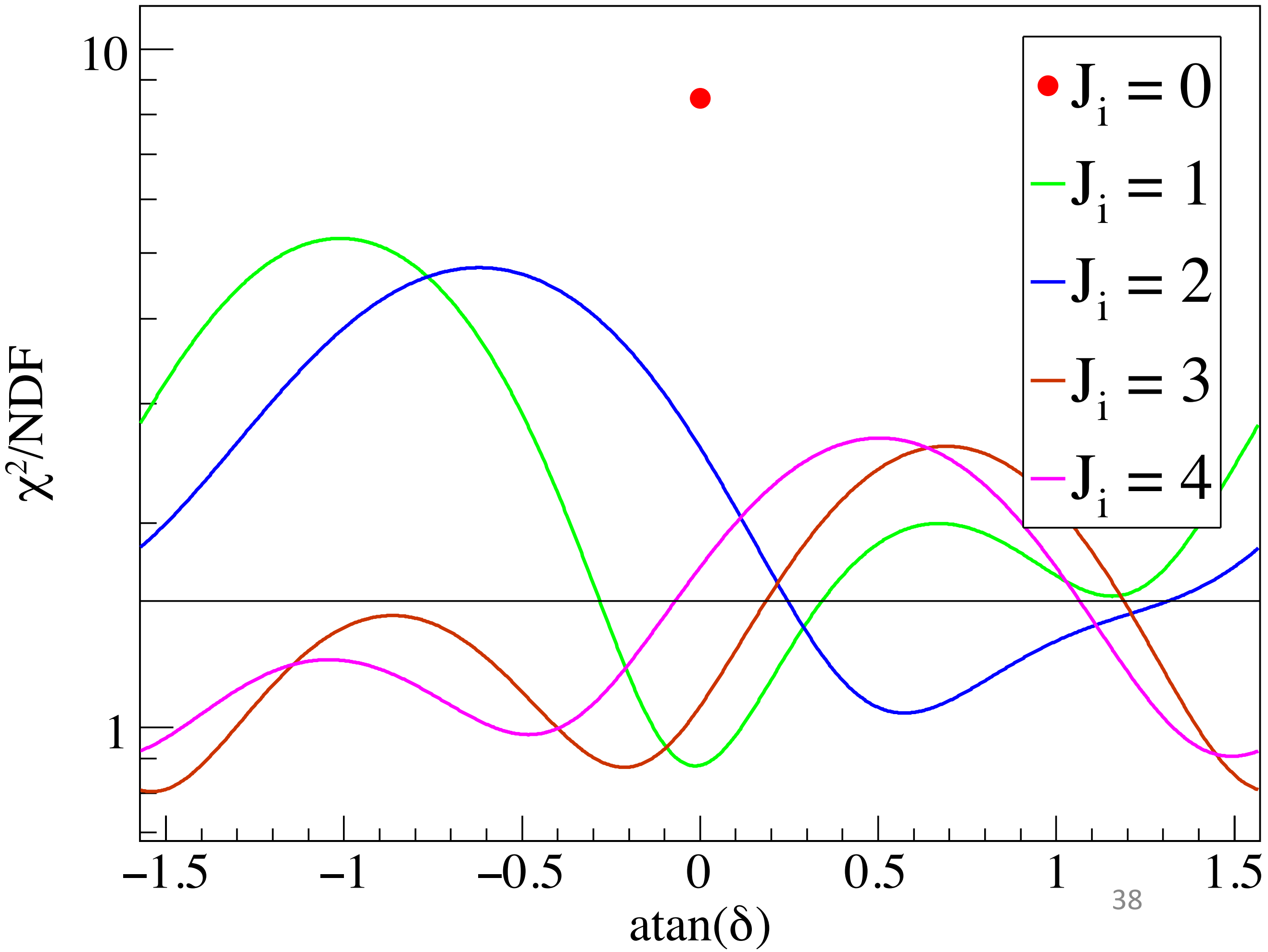




Angular Correlations

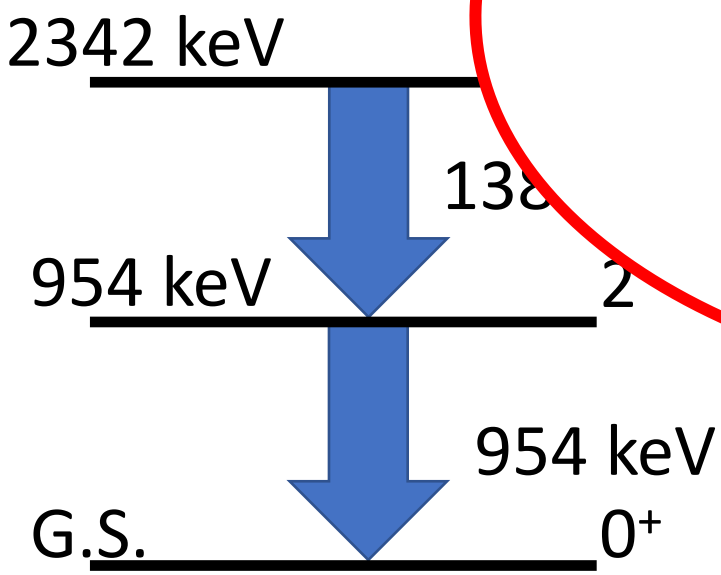
2226-954 keV cascade, known $1^+ \rightarrow 2^+ \rightarrow 0^+$



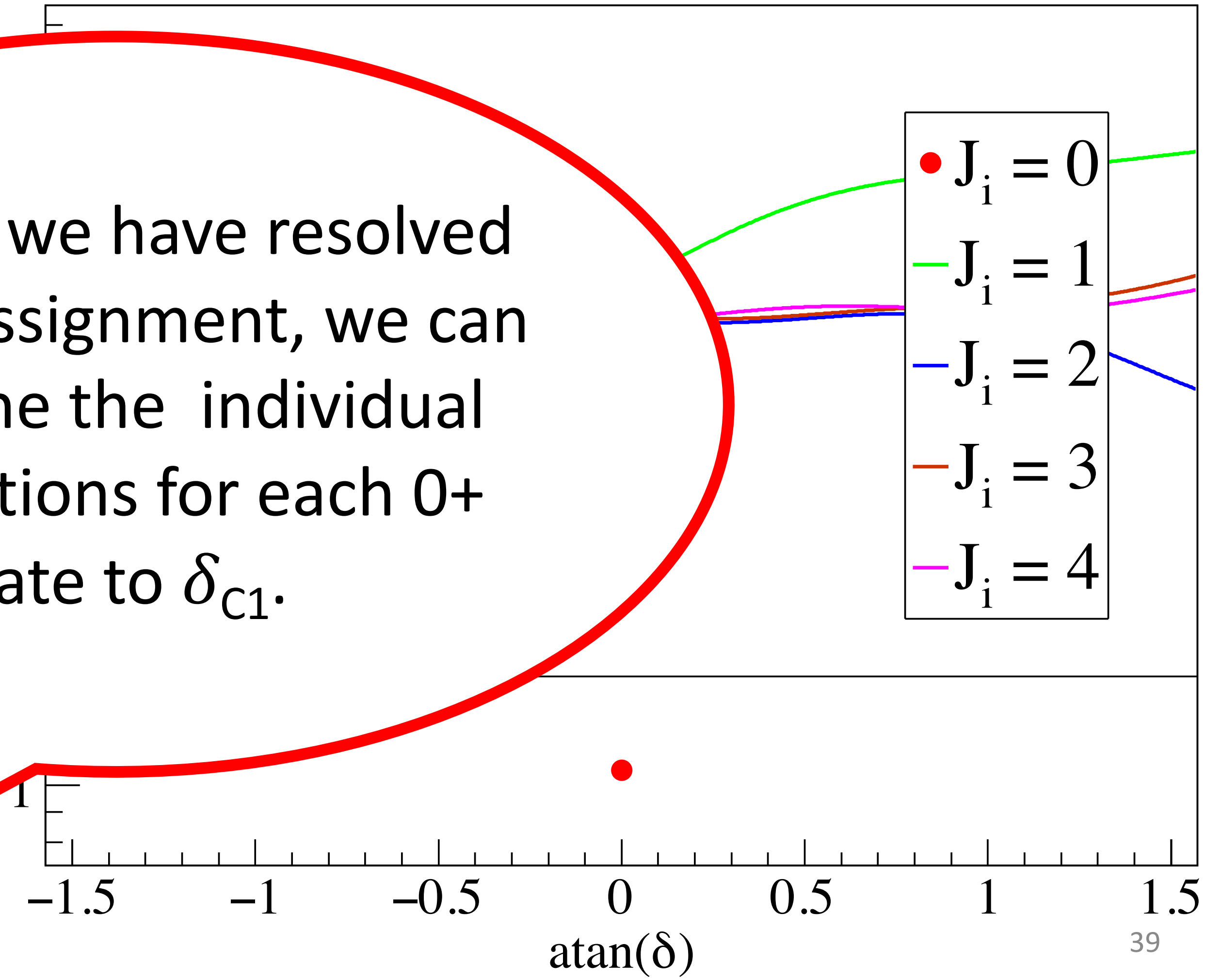


Gamma-Gamma Angular Correlations

Allowing spin of 2342 keV stat
to vary can clearly iden
spin as an excited 0



Now that we have resolved the spin assignment, we can determine the individual contributions for each 0+ state to δ_{C1}.

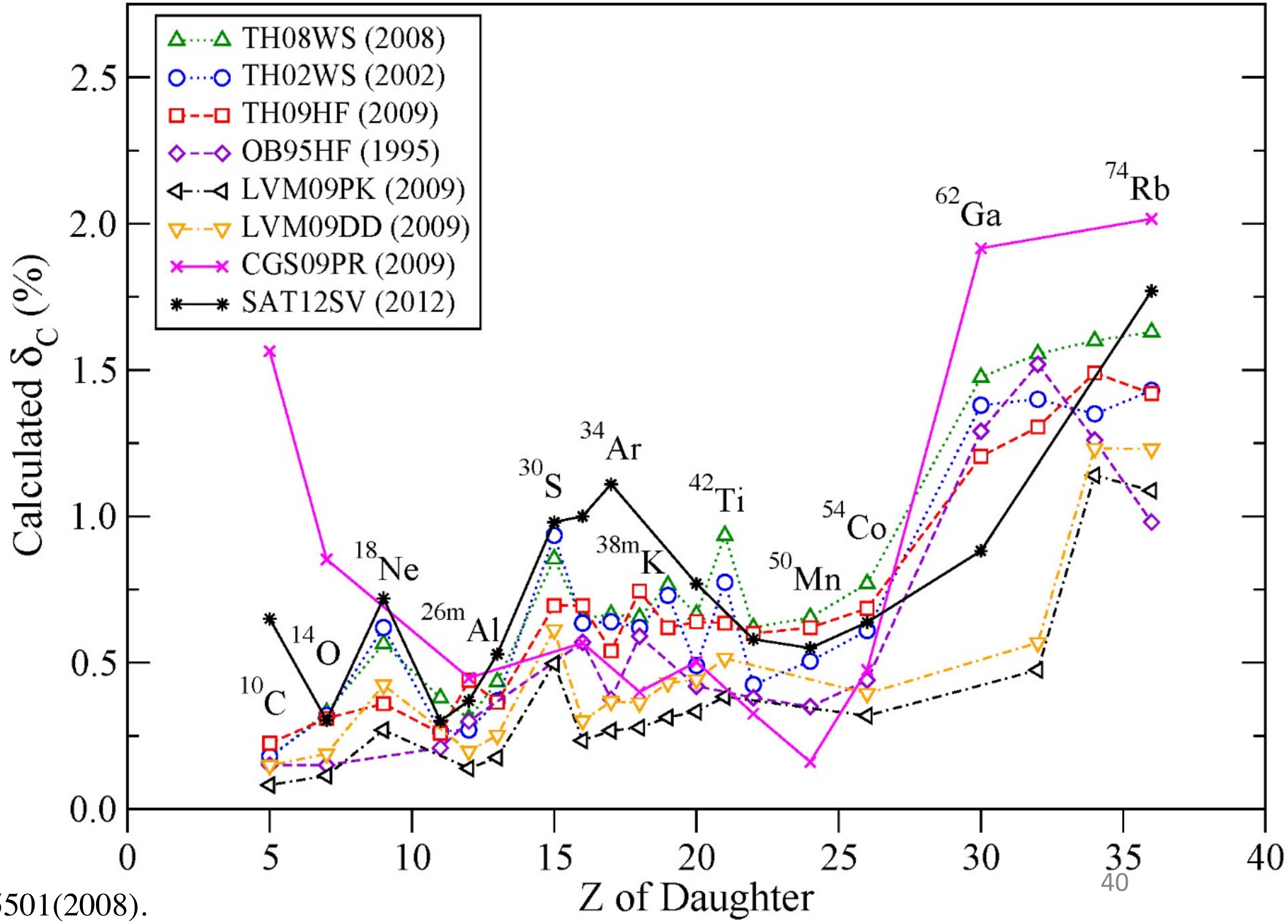


Constraining Theory

$\delta_C = \delta_{C1} + \delta_{C2}$

δ_{C1} – Configuration mixing of 0^+ states.

δ_{C2} – Imperfect overlap of proton and neutron radial wavefunctions.



I. S. Towner and J. C. Hardy, Phys. Rev. C.77, 025501(2008).

Possible Solutions

Possible sources of disagreement:

1. One of $|V_{ud}|$, $|V_{us}|$, or $|V_{ub}|$ may need to be re-evaluated.
2. There could be physics which exists beyond the Standard Model.
3. The applied corrections currently used for the $\mathcal{F}t$-values may need to be further scrutinized and include a larger model space.

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

Possible Solutions

Possible sources of disagreement:

1. One of $|V_{ud}|$, $|V_{us}|$, or $|V_{ub}|$ may no
2. There could be physics which exis
3. The applied corrections currently be further scrutinized and include

Dominant source of uncertainty (especially heavy nuclei).

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