A crack in nuclear mirror symmetry

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Mirror-symmetry violation in bound nuclear ground states

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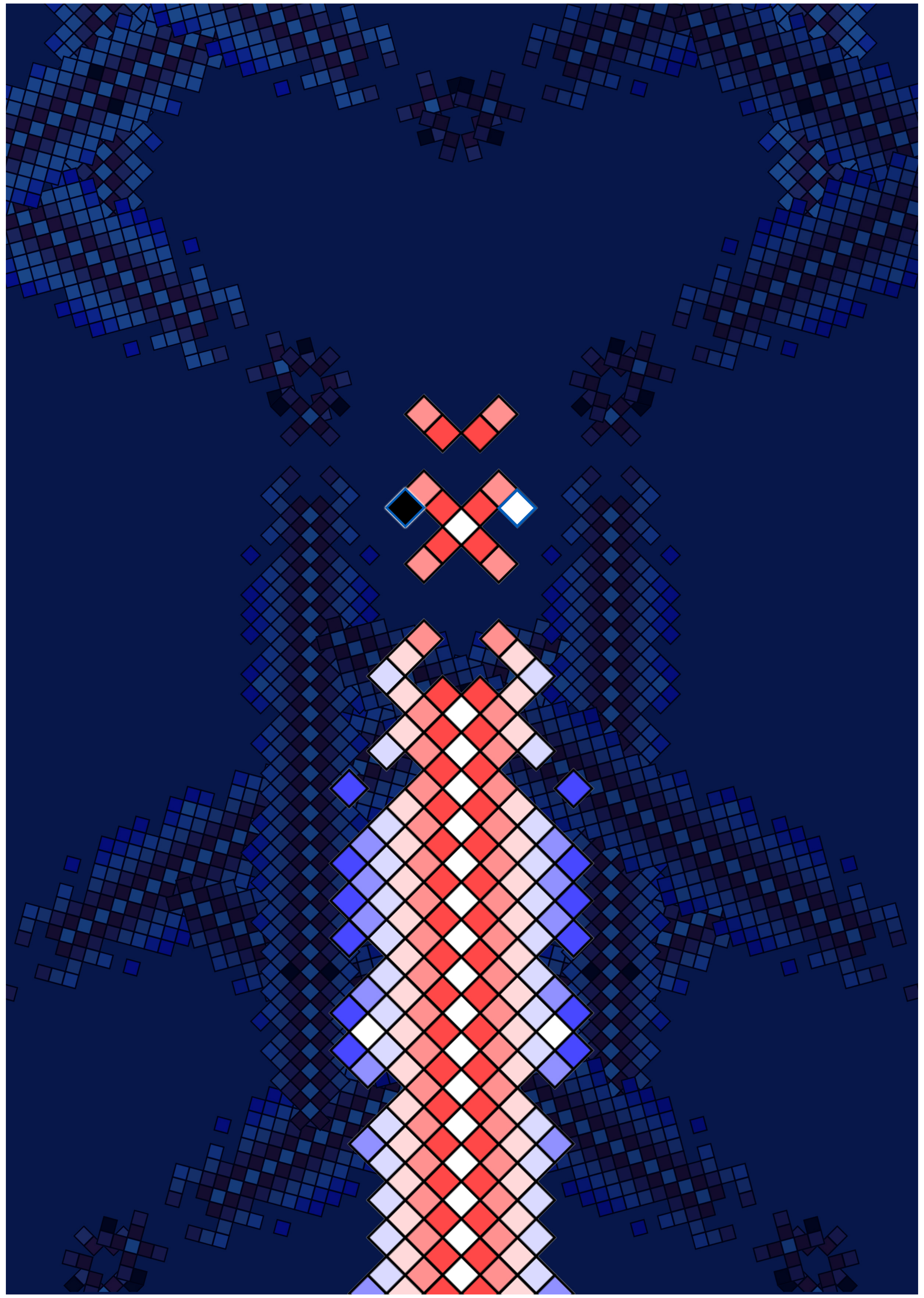
Learning with Purpose

Outline

- Symmetries in physics (*briefly*)
- Iso(baric)-spin symmetry
  - How does isospin manifest in nuclei?
- NSCL Experiment (^{73}Sr)
- Evidence for mirror-symmetry breaking in ^{73}Sr/^{73}Br
- Summary



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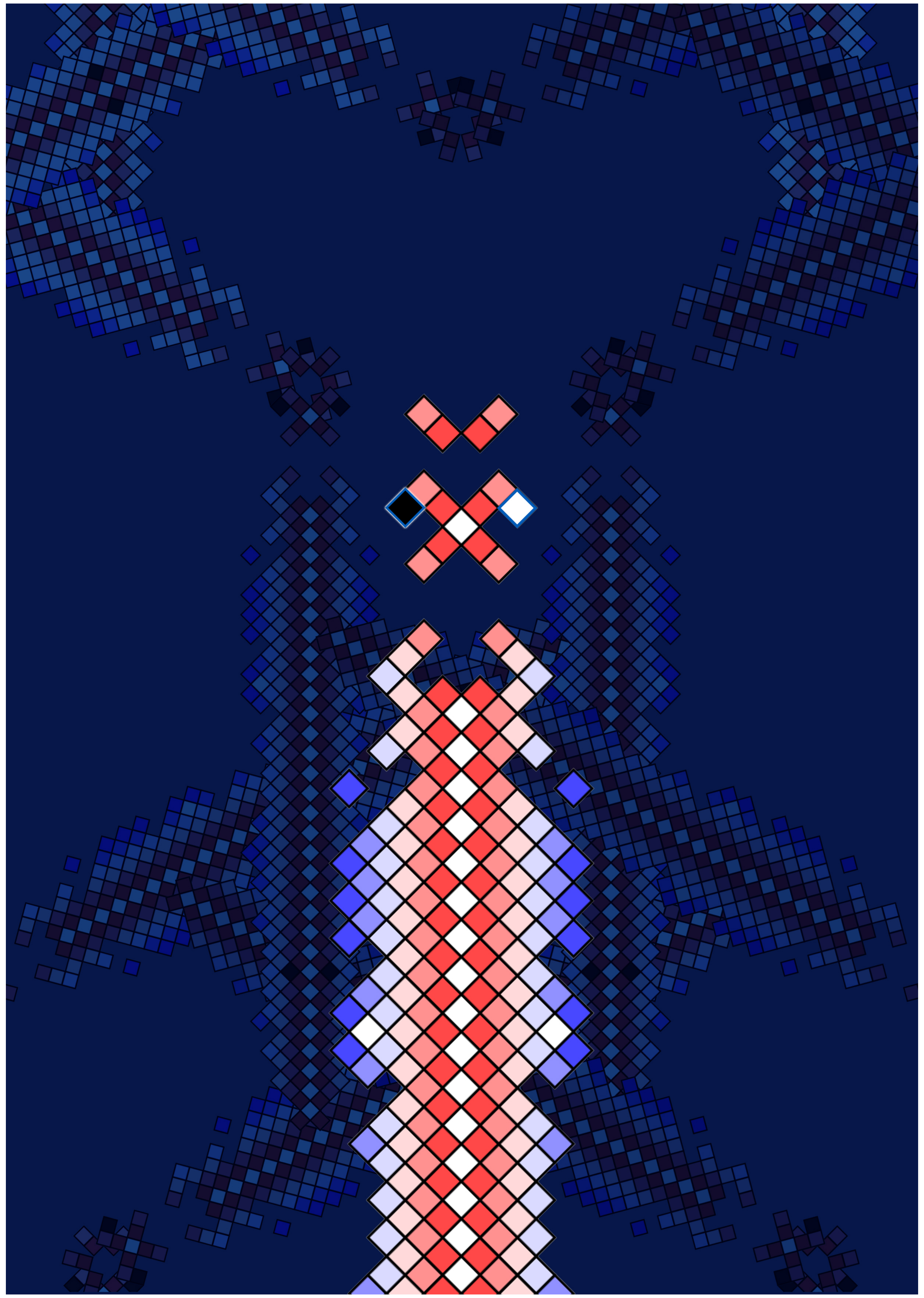

Symmetries in Physics

Amalie "Emmy" Noether

Noether's theorem (paraphrase):

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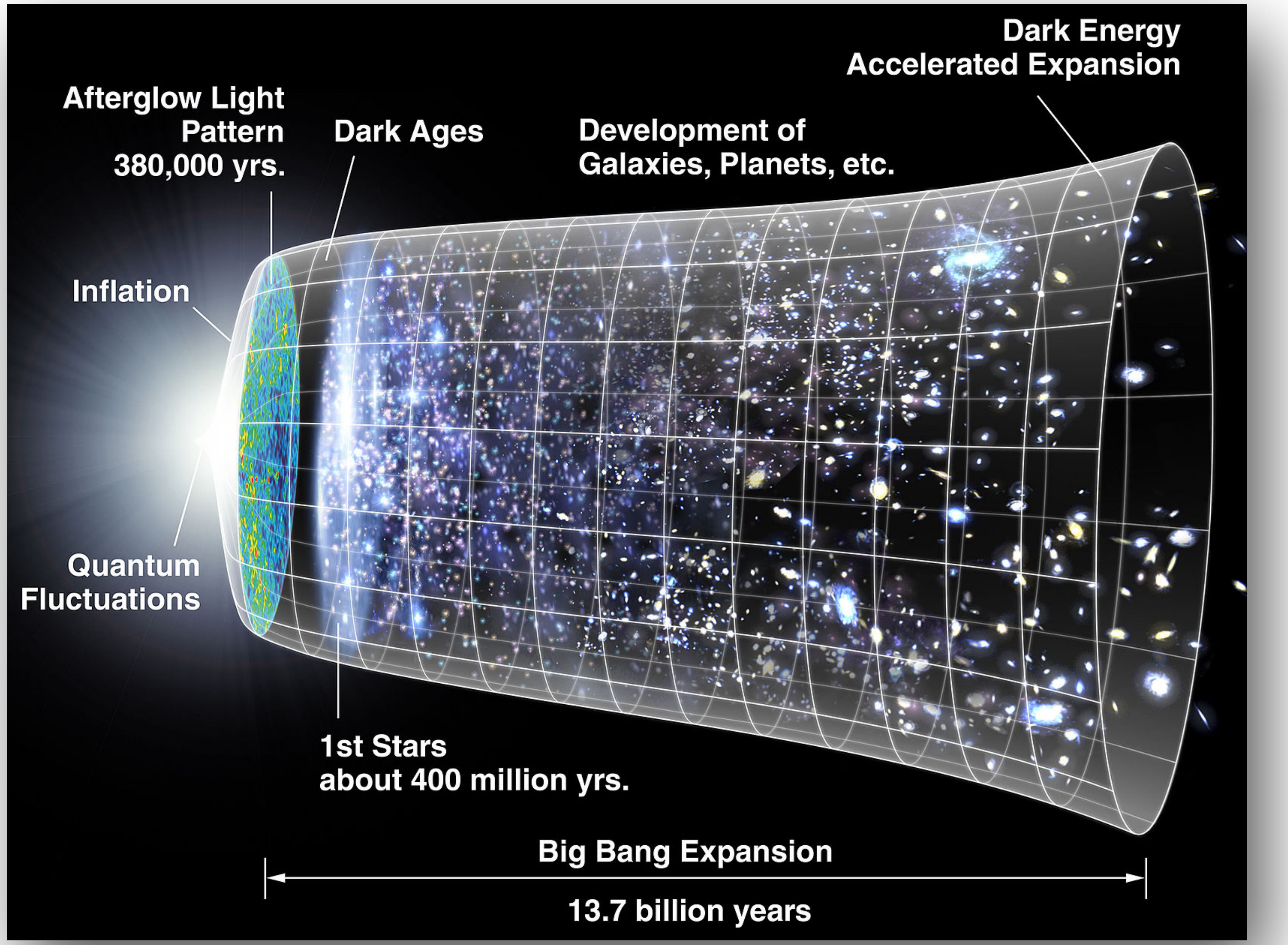
<u>Matter/Anti-matter asymmetry</u>



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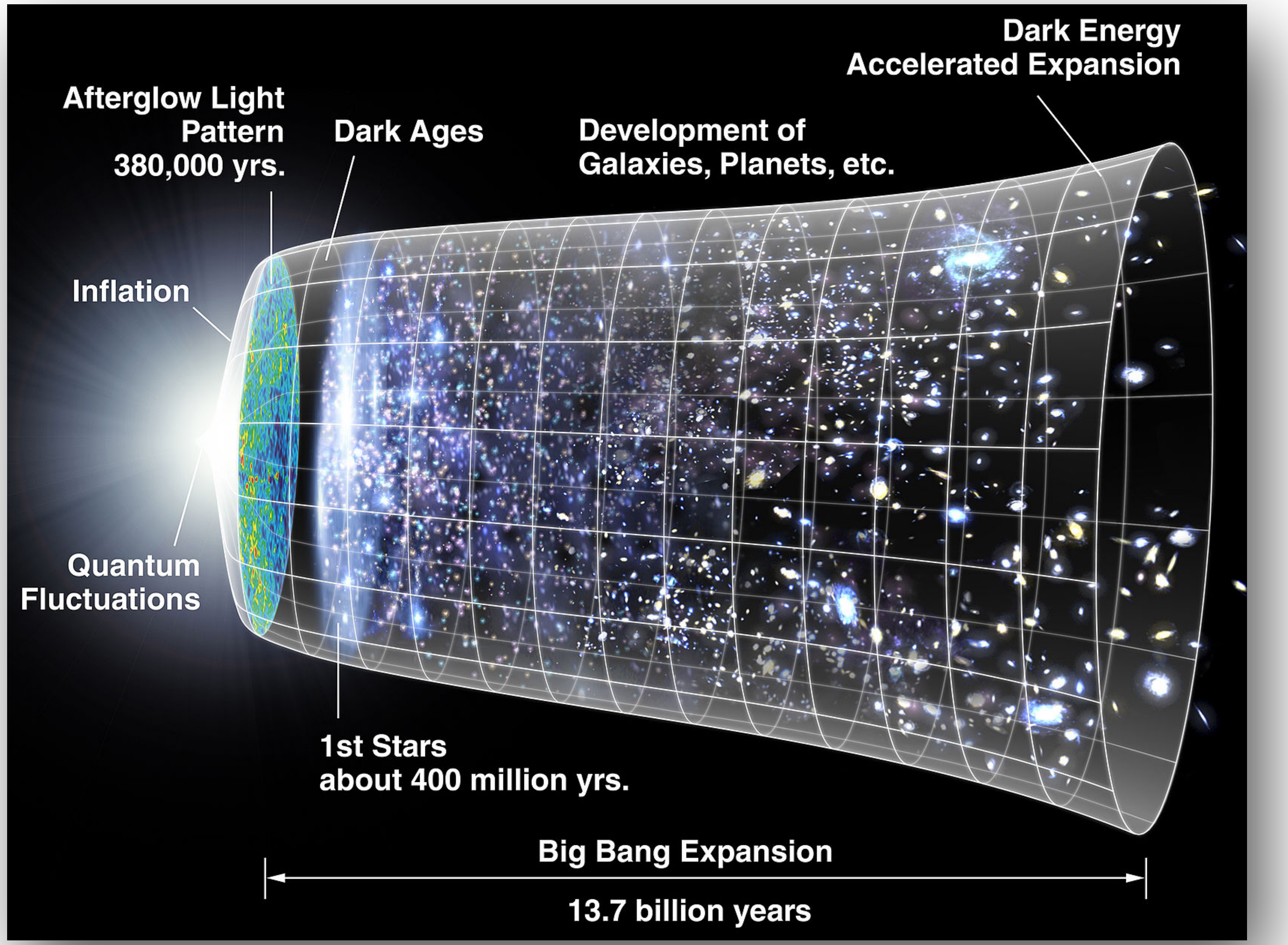
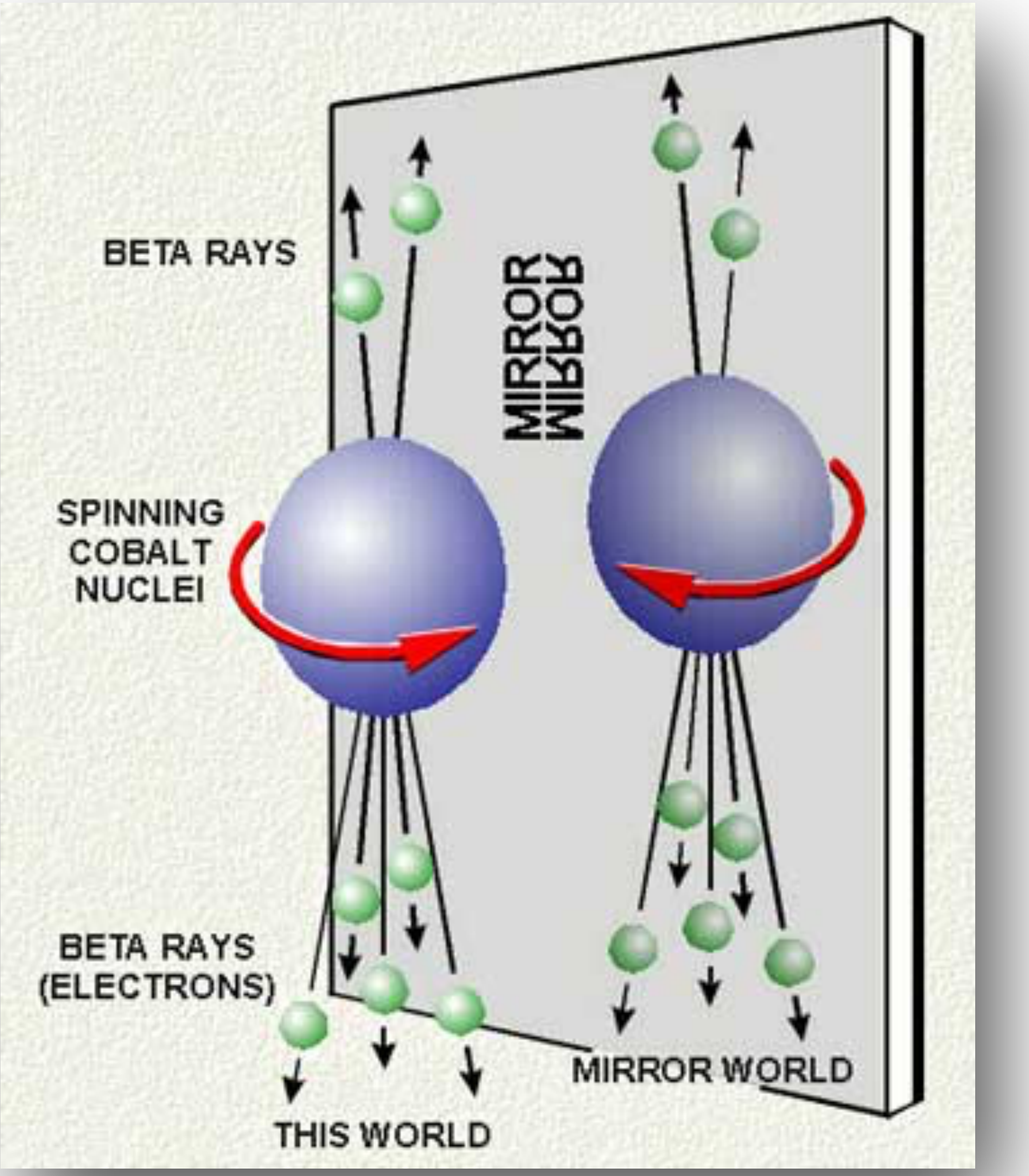


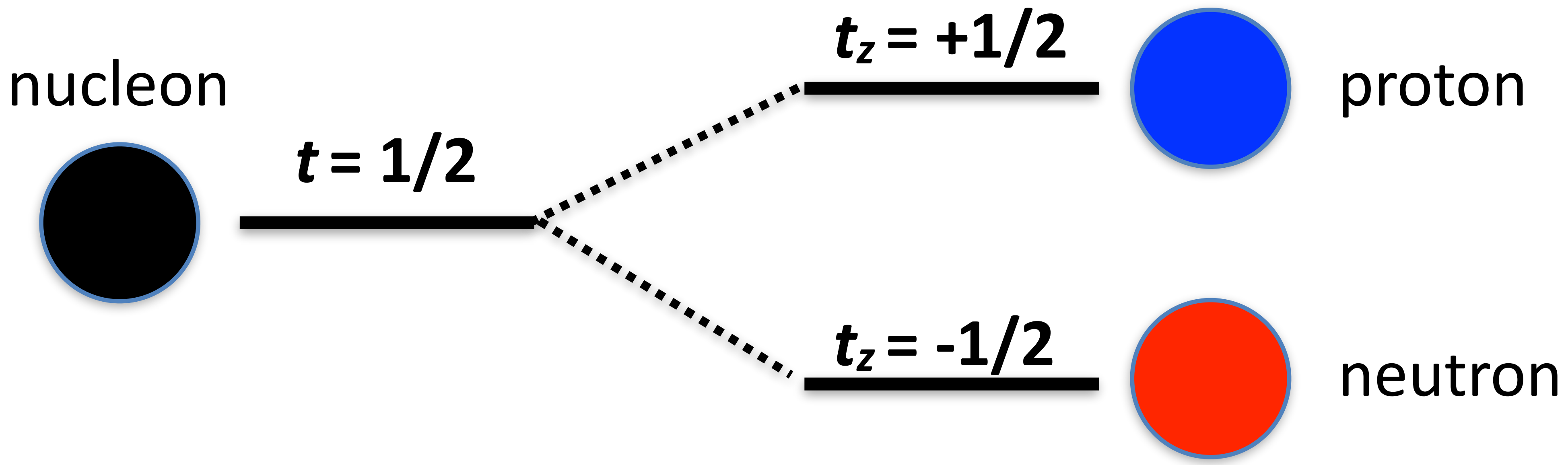
Parity violation



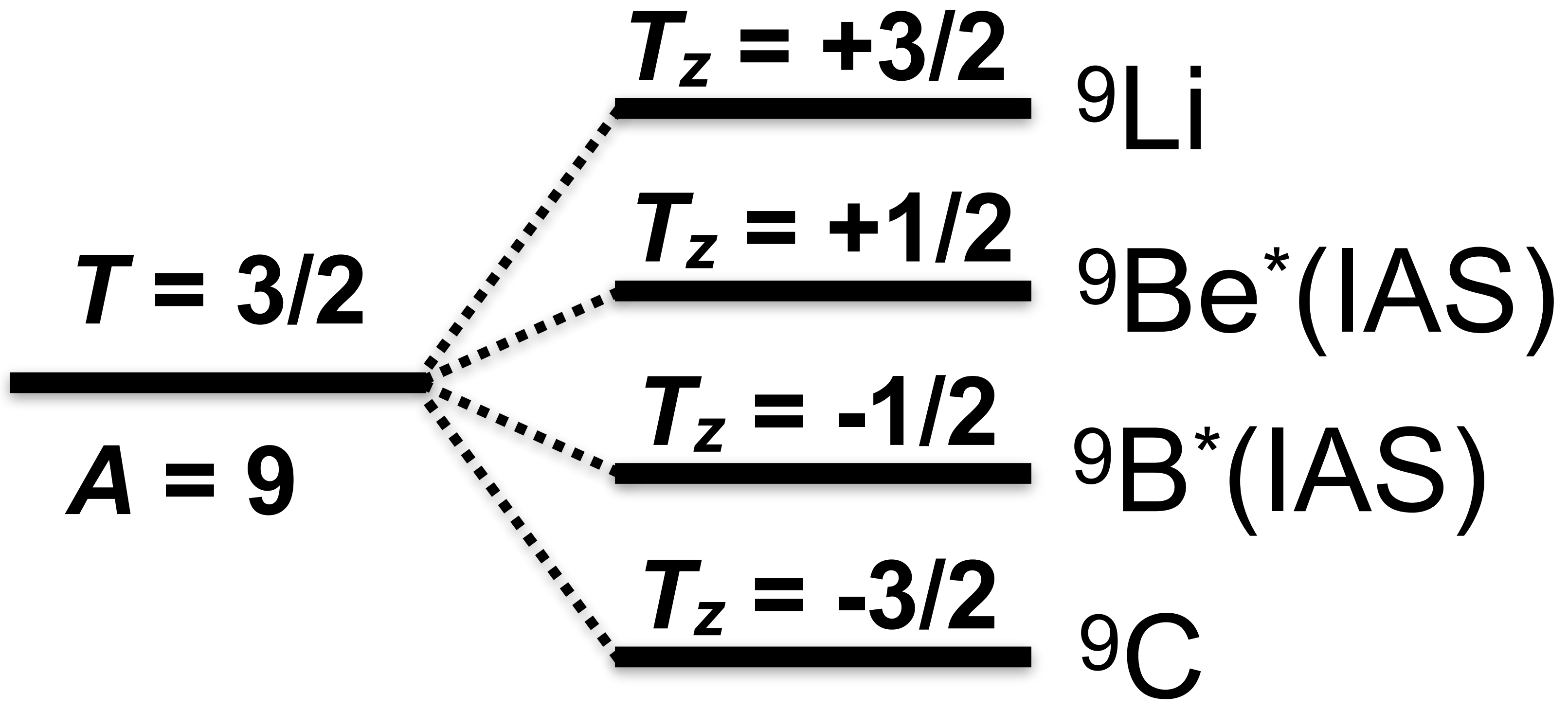
Iso(baric)spin in Nuclei

Heisenberg (1932)

Wigner (1937)



Can then define **TOTAL isospin, *T*,**



$$T_z = \frac{1}{2}(Z - N)$$

Nuclei with N and Z exchanged are called **mirror nuclei** and they should have a similar set of states.

Invariance in isobaric-spin space
$\Longrightarrow$ ***conservation of isospin***

…but it's broken

- Protons and neutrons *DO* have slightly difference masses. (0.14%)

- The interactions are not equal,

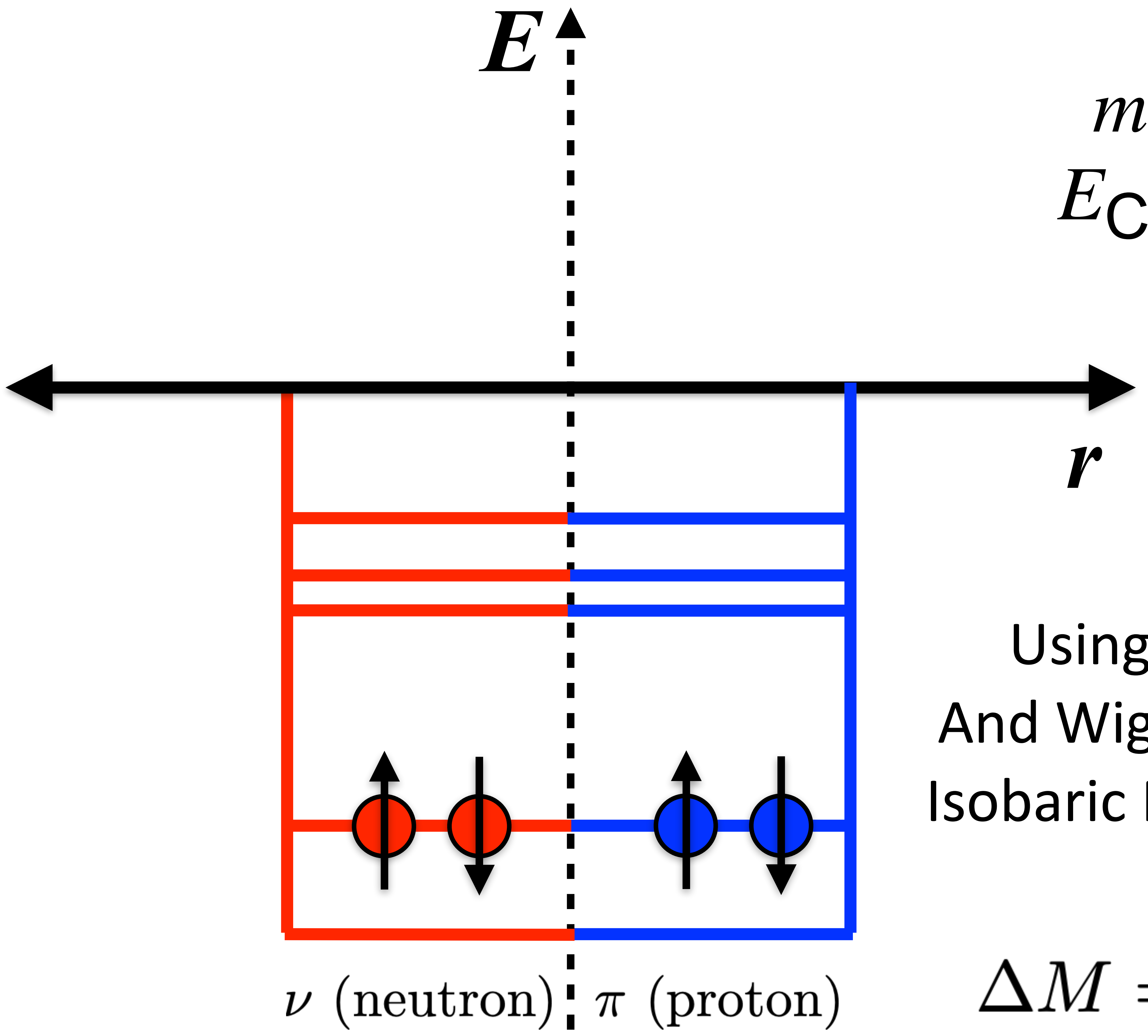
$$V_{nn} > V_{pp} \ (\sim 1\%) \qquad V_{np} > \frac{V_{nn} + V_{pp}}{2} \ (\sim 2.5\%)$$

- On top of that protons have charge, and so the Coulomb interaction is a major source of isospin symmetry breaking in nuclei.

> ✦ Isospin symmetry is broken.
> ✦ Early on it was thought that isospin symmetry would be of little use in heavy nuclei (large *Z*).
> ✦ It has remained a surprisingly robust symmetry.

Coulomb Energy in Nuclei

Protons with no charge



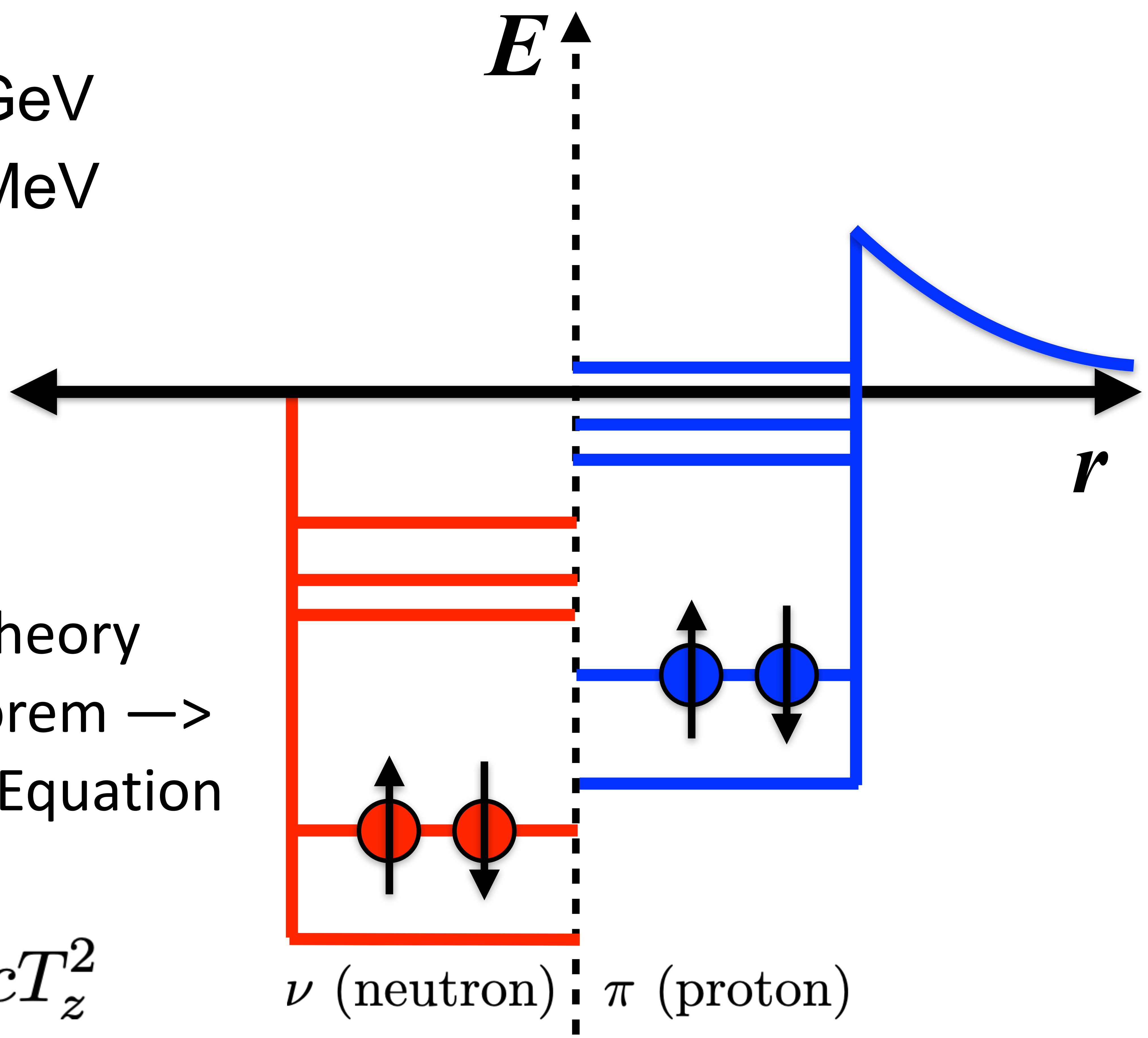
Consider the relative scale of the Coulomb energy:

$$m(^{73}\text{Br}) \approx 68 \text{ GeV}$$
$$E_\text{C}(^{73}\text{Br}) \approx 19 \text{ MeV}$$

Using Perturbation Theory
And Wigner-Eckart theorem —>
Isobaric Mass Multiplet Equation
(IMME)

$$\Delta M = a + bT_z + cT_z^2$$

Including proton charge



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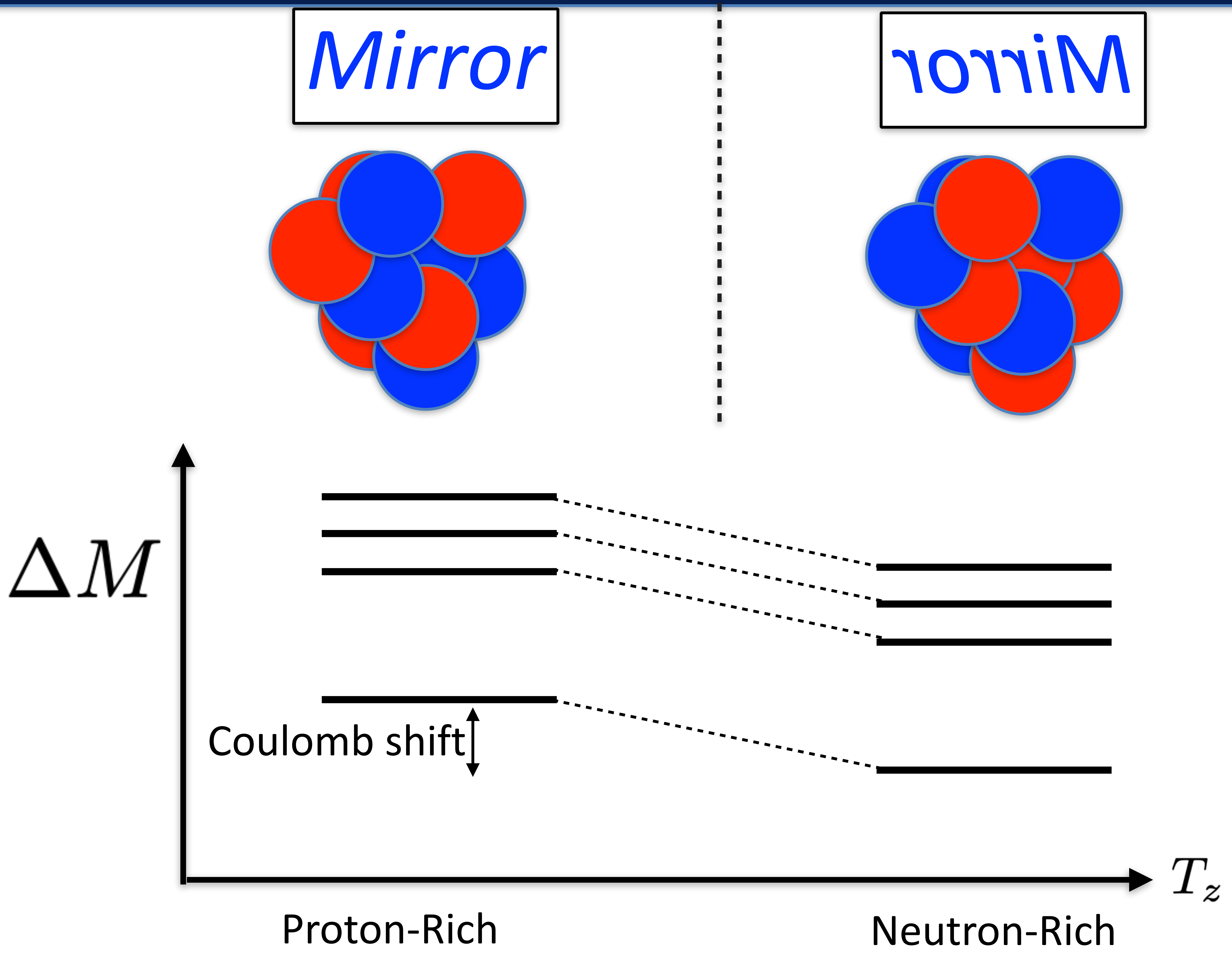
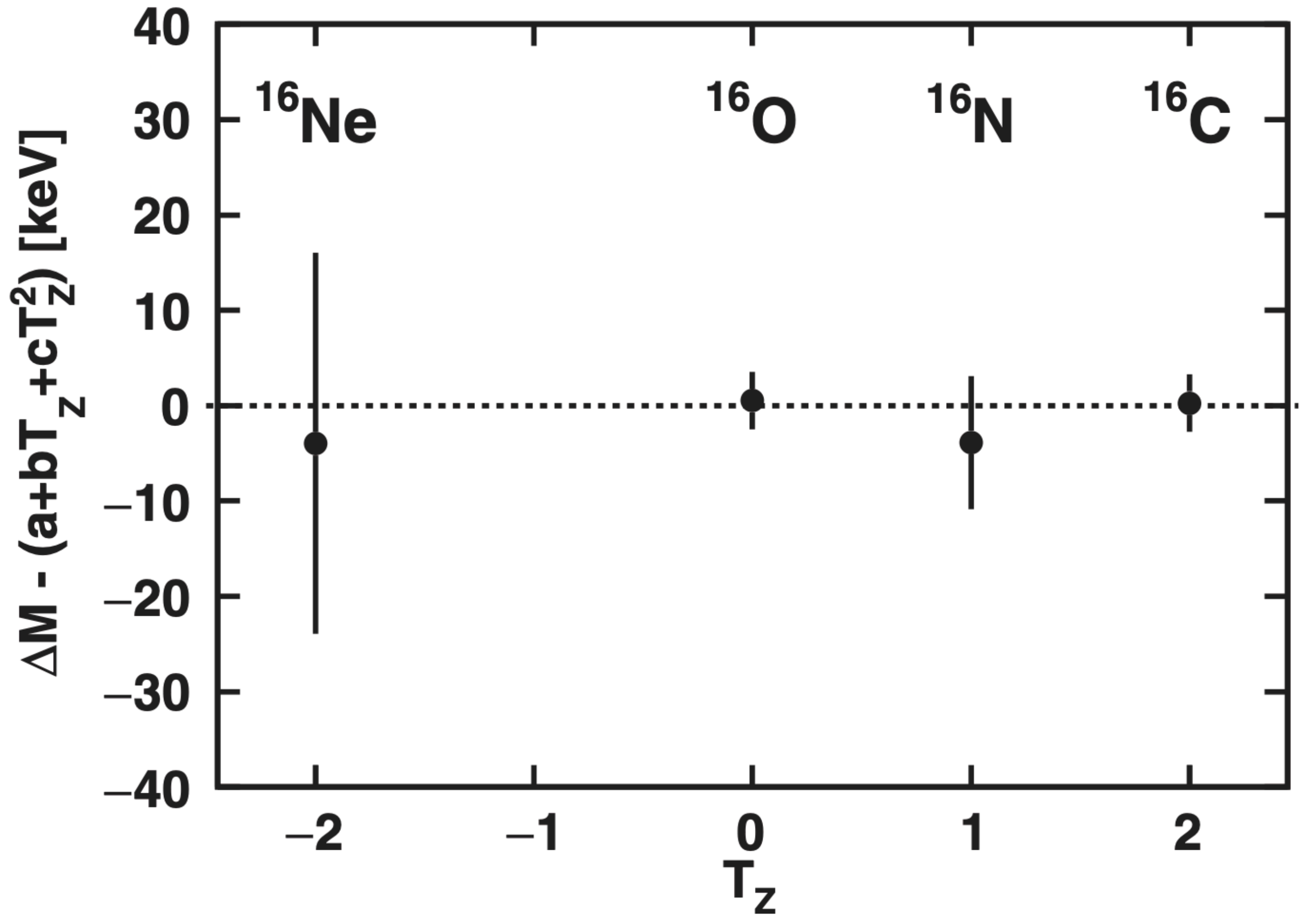


(IMME) $\Delta M = a + bT_z + cT_z^2$



Brown et al. *PRC 95 (044326)*

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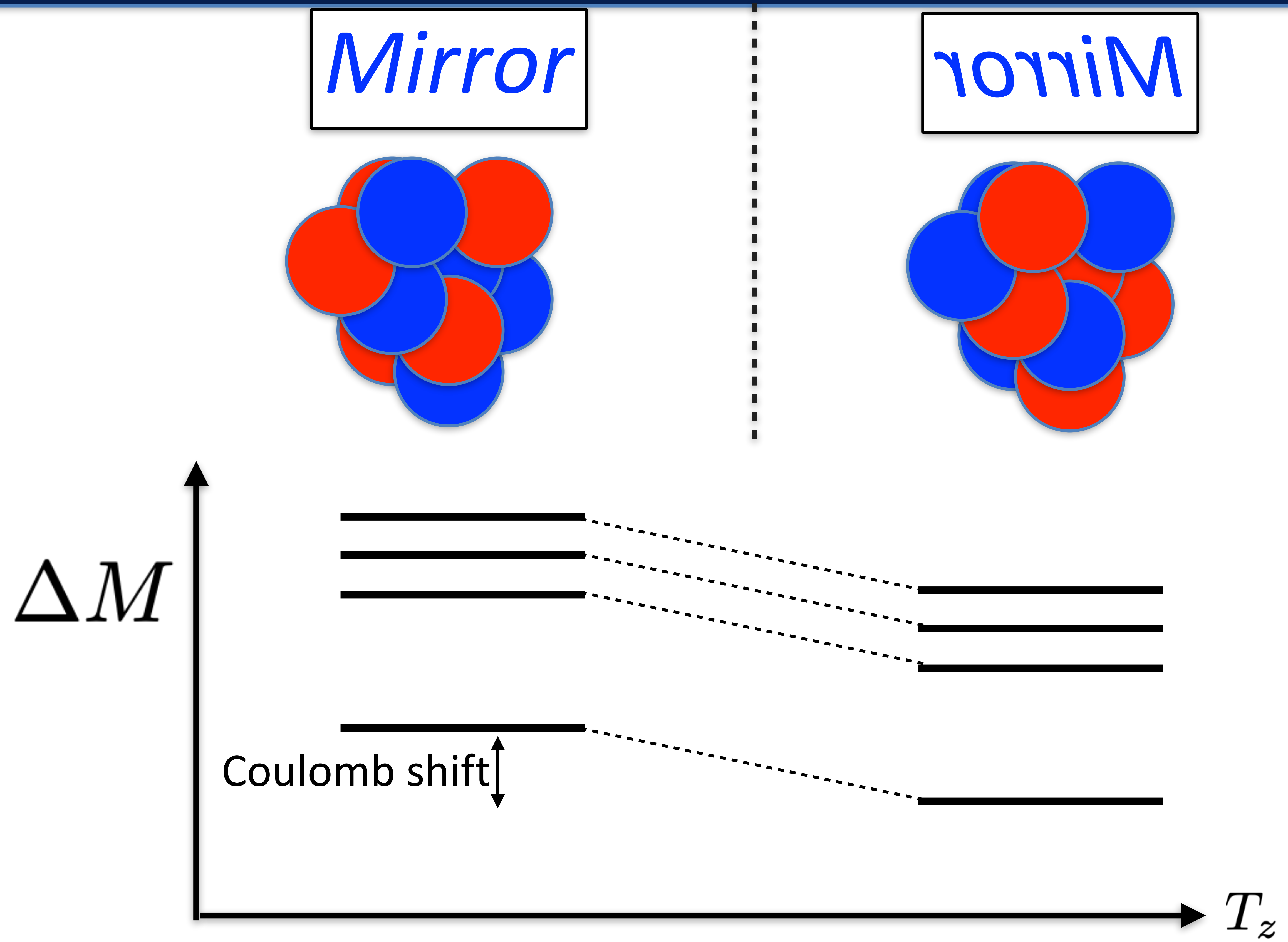

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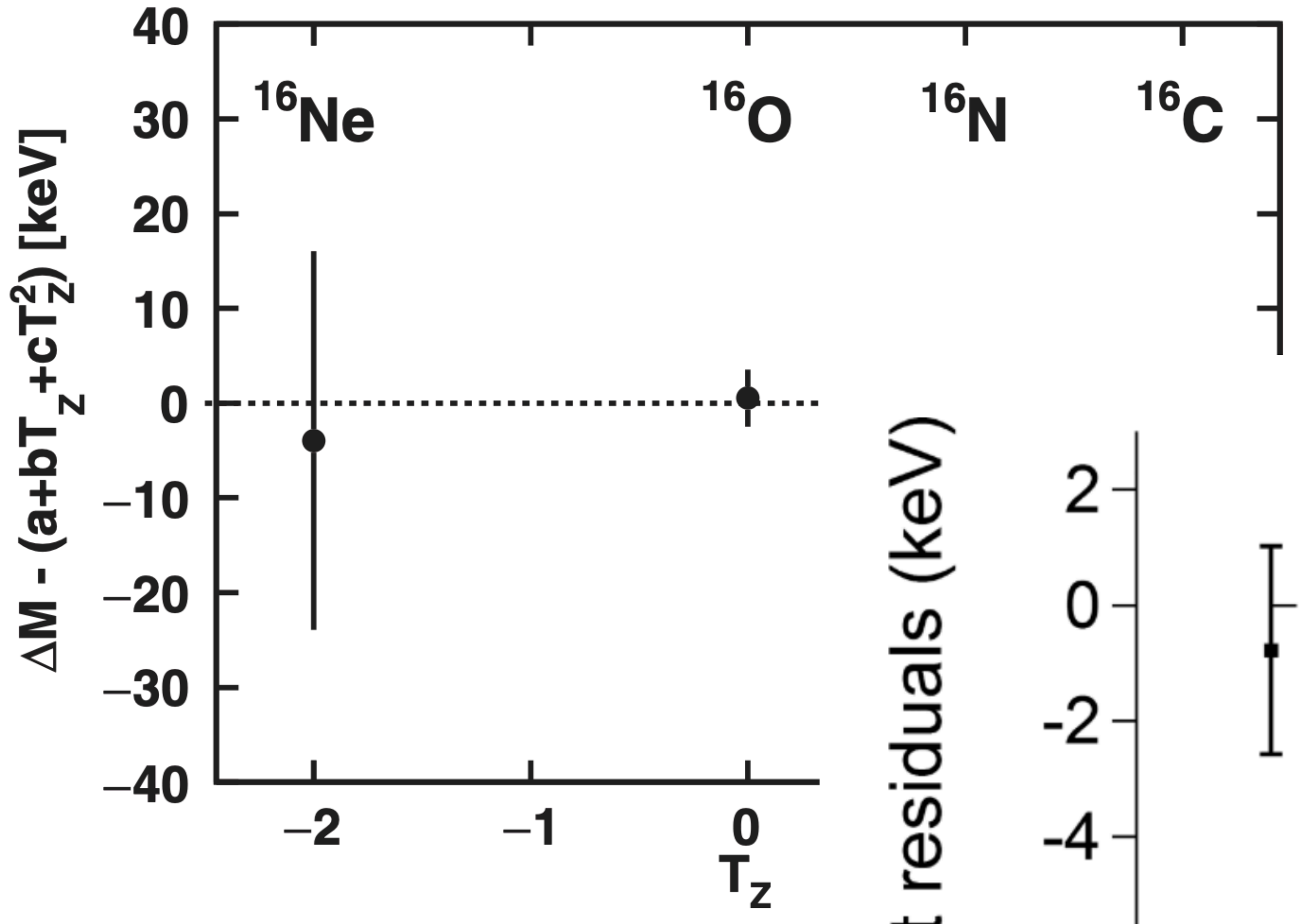

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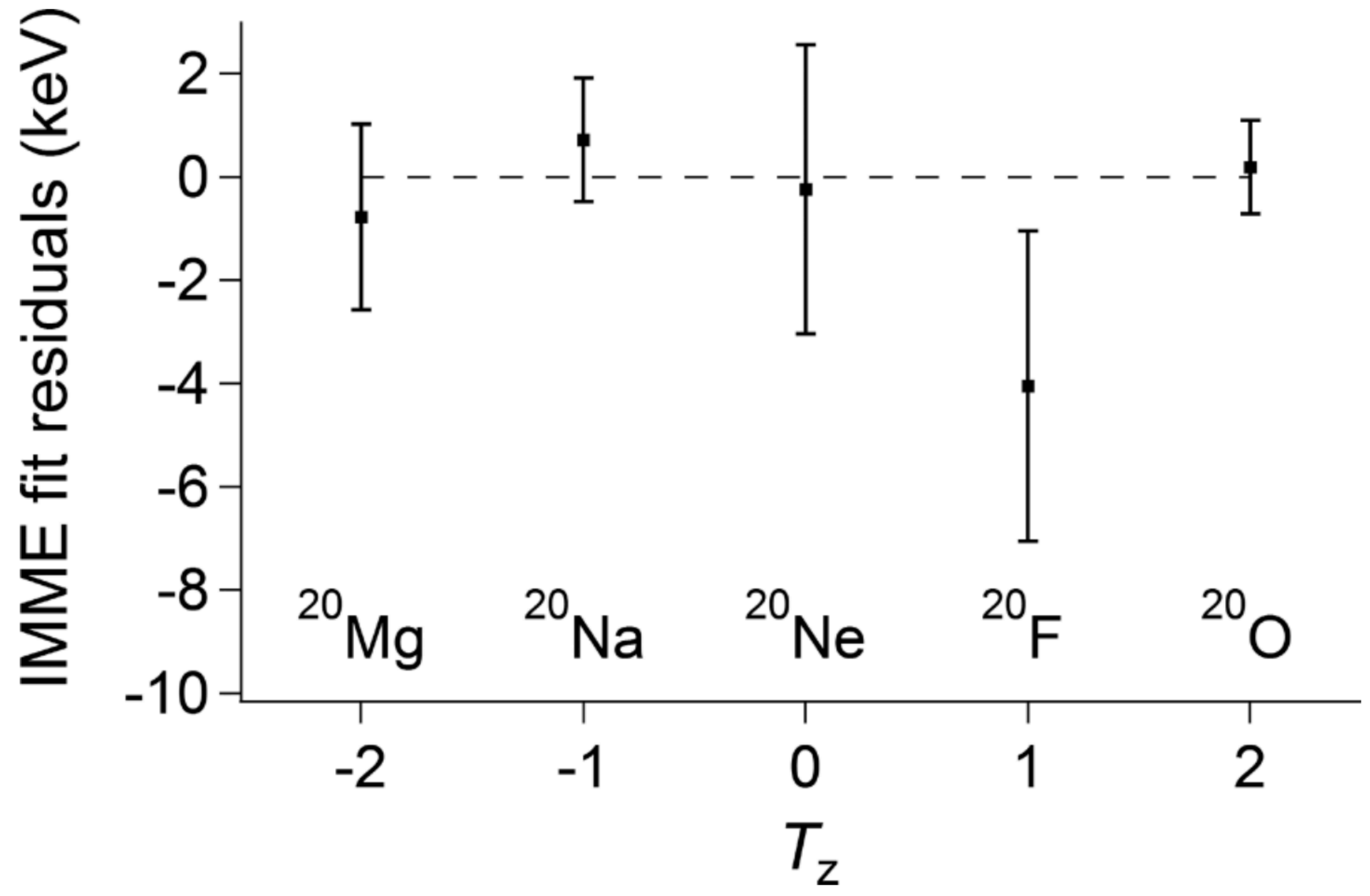

Glassman et al. *PRC 92 (042501)*

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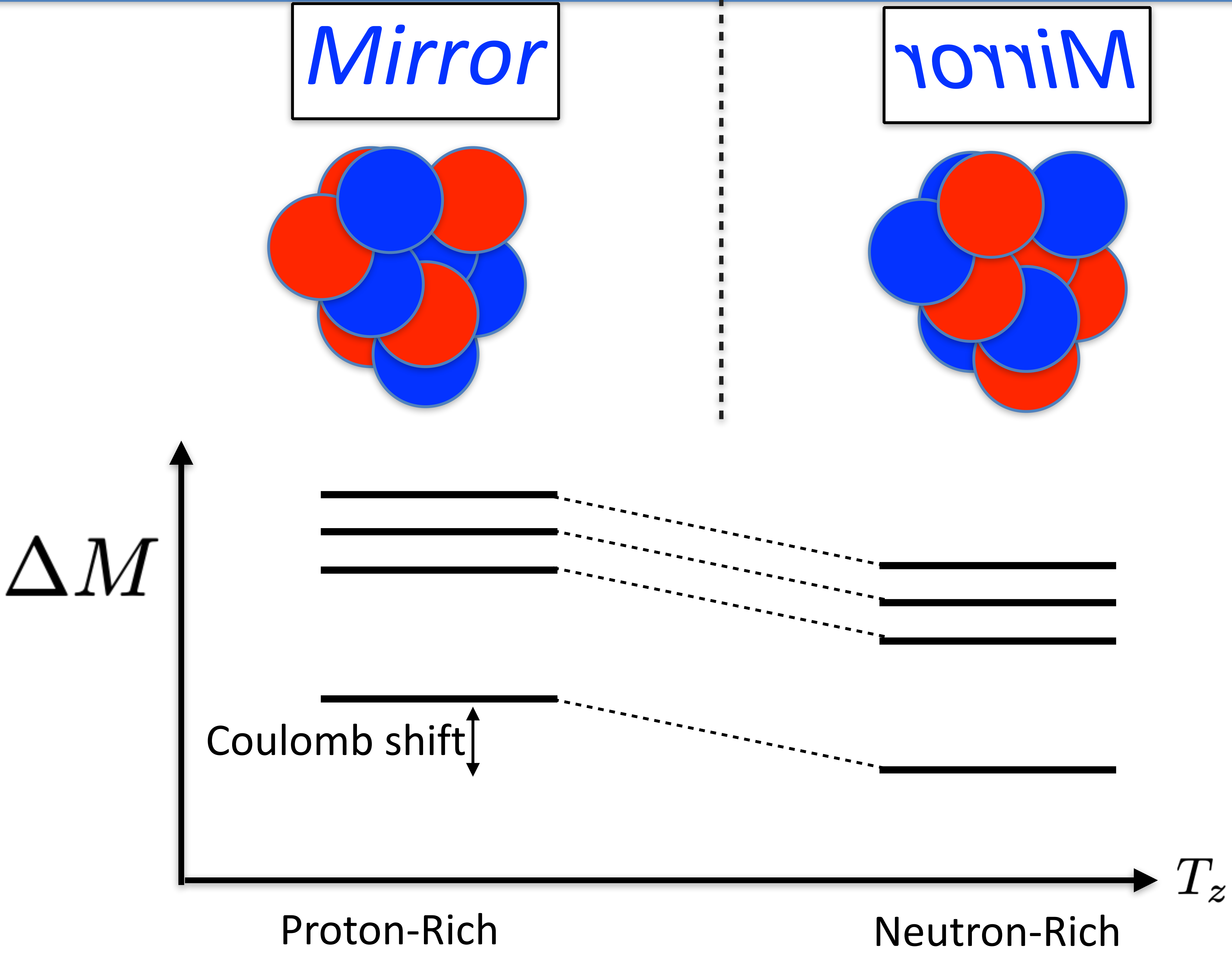
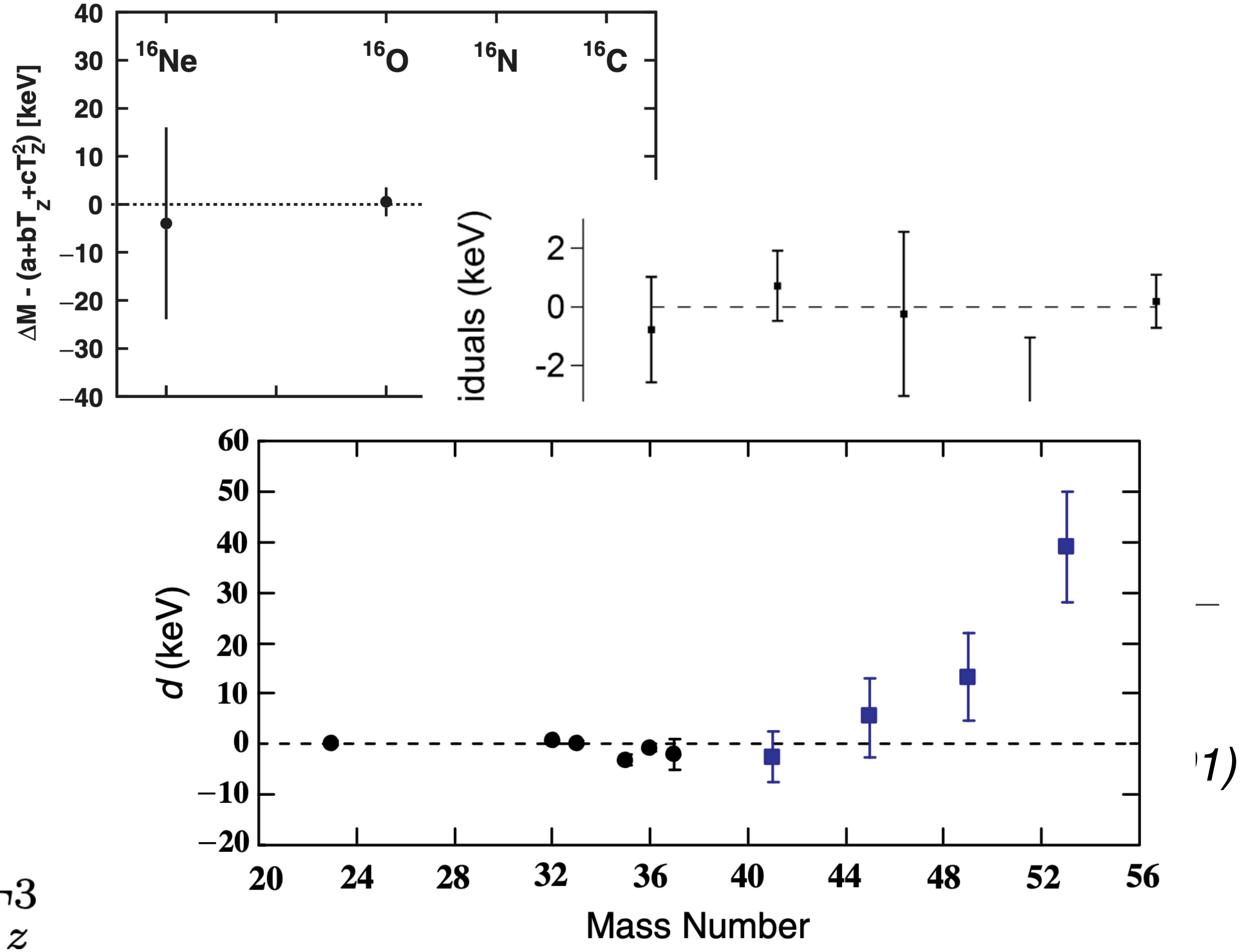


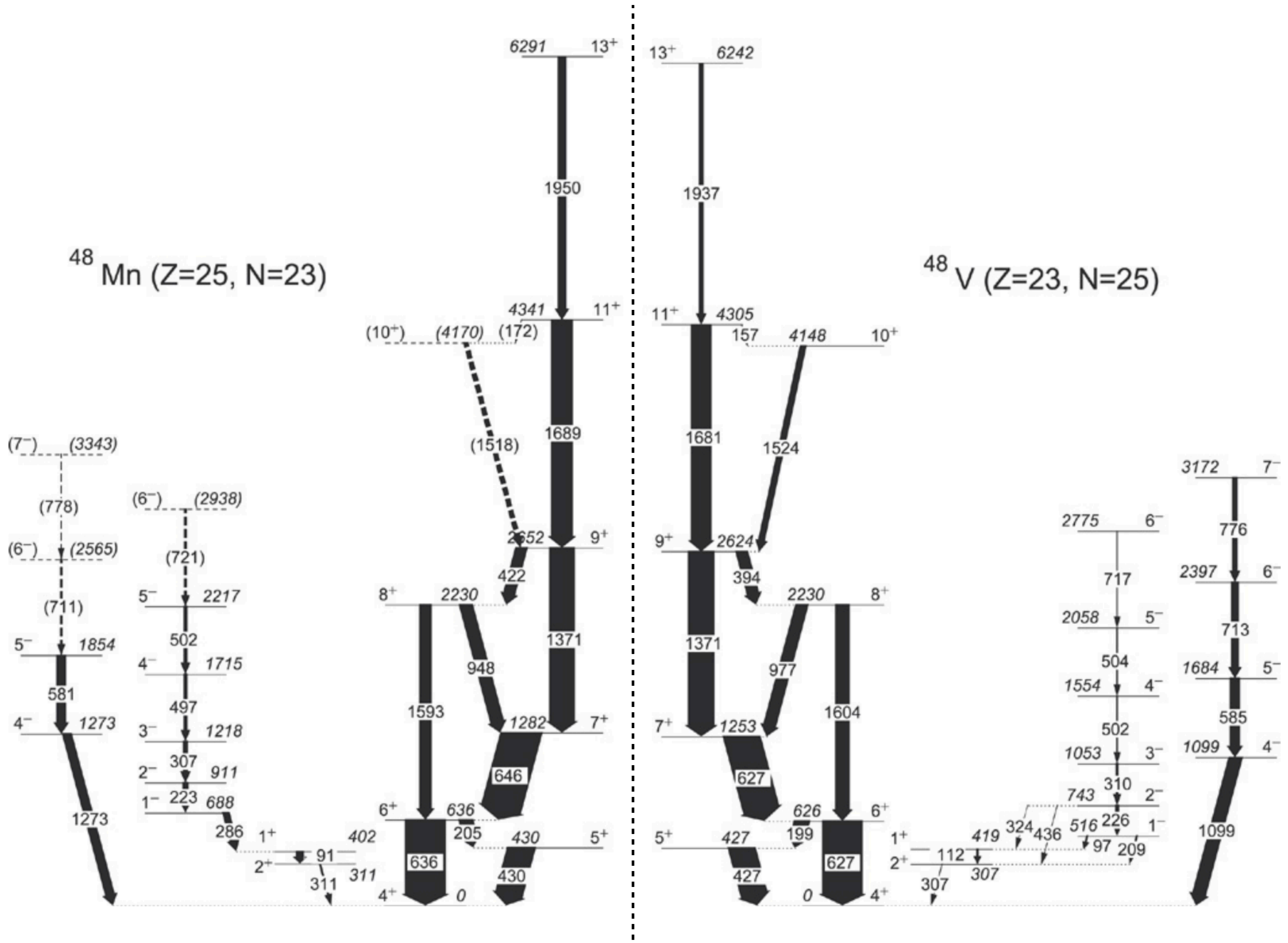
(IMME) $\Delta M = a + bT_z + cT_z^2 + dT_z^3$

IMME provides a test of charge-symmetry breaking in nuclei

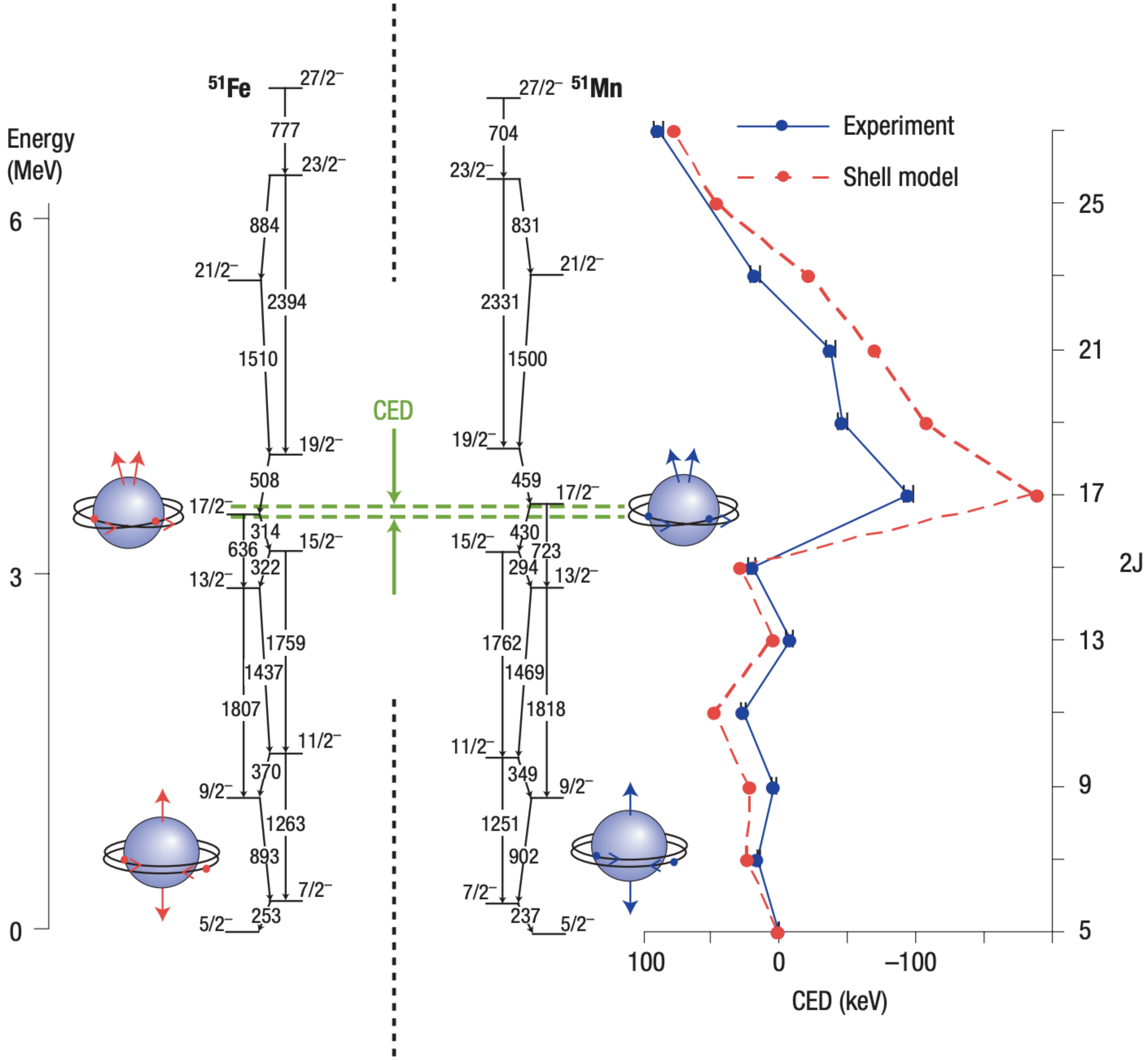


Zhang et al. *PRL 109 (102501)*

Holds for excited states of nuclei!

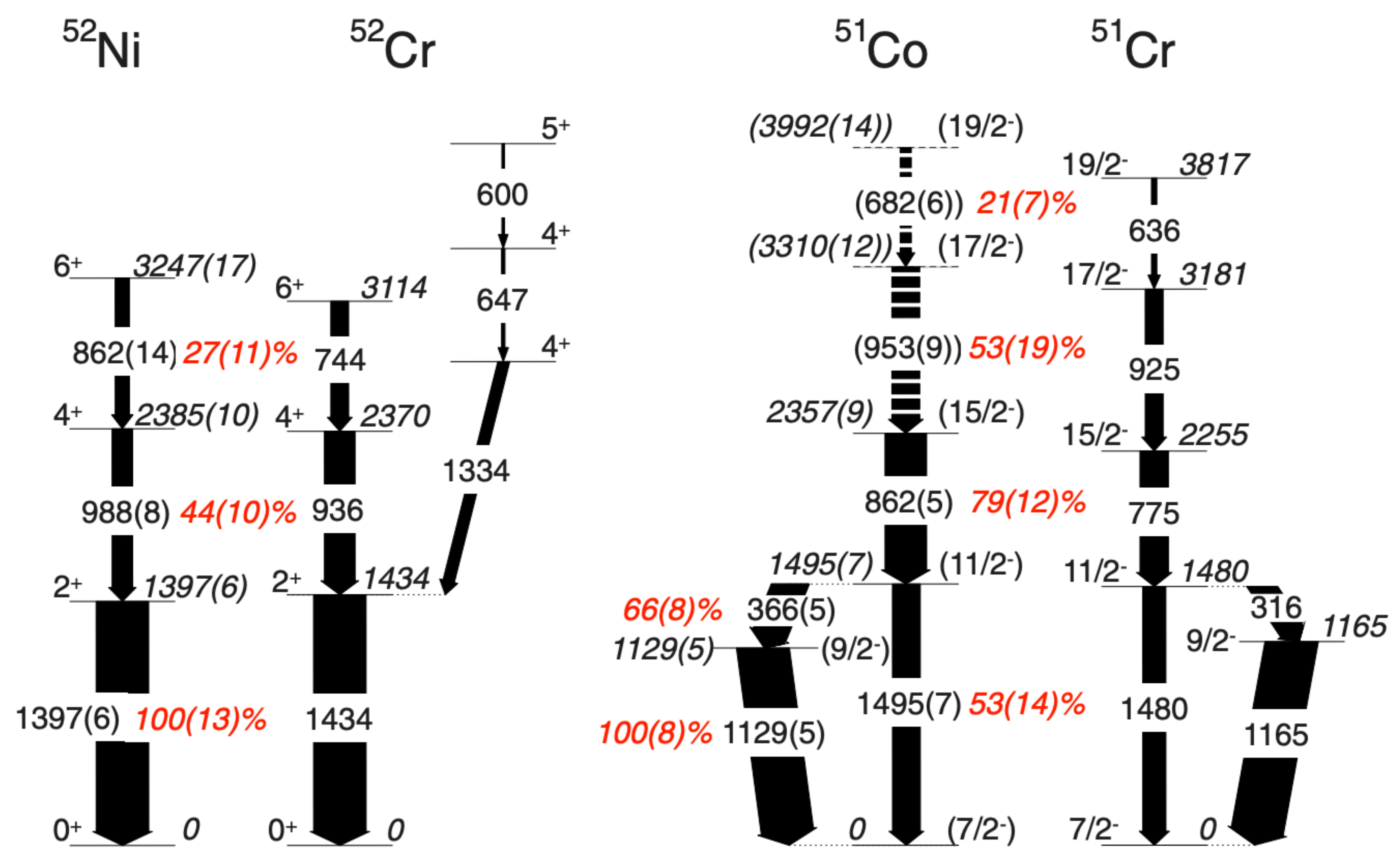


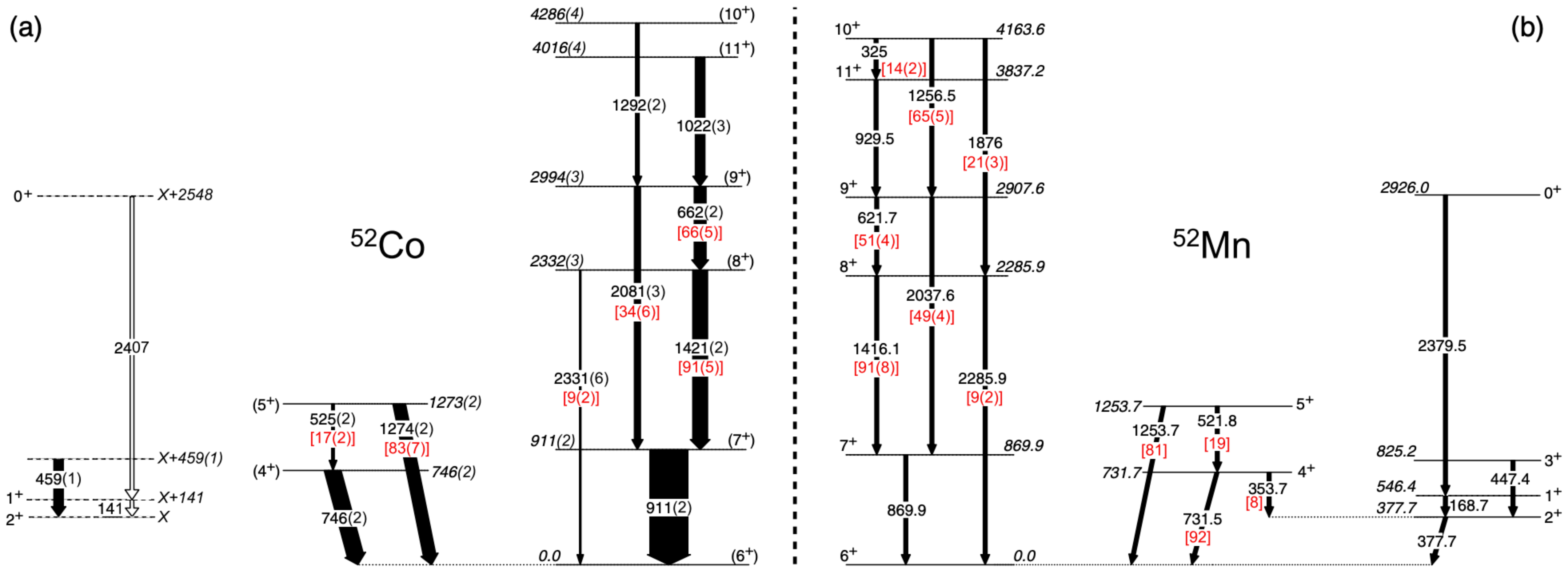
Bentley & Lenzi, Prog. in Part. and Nuc. Phys. 59(2), 497–561

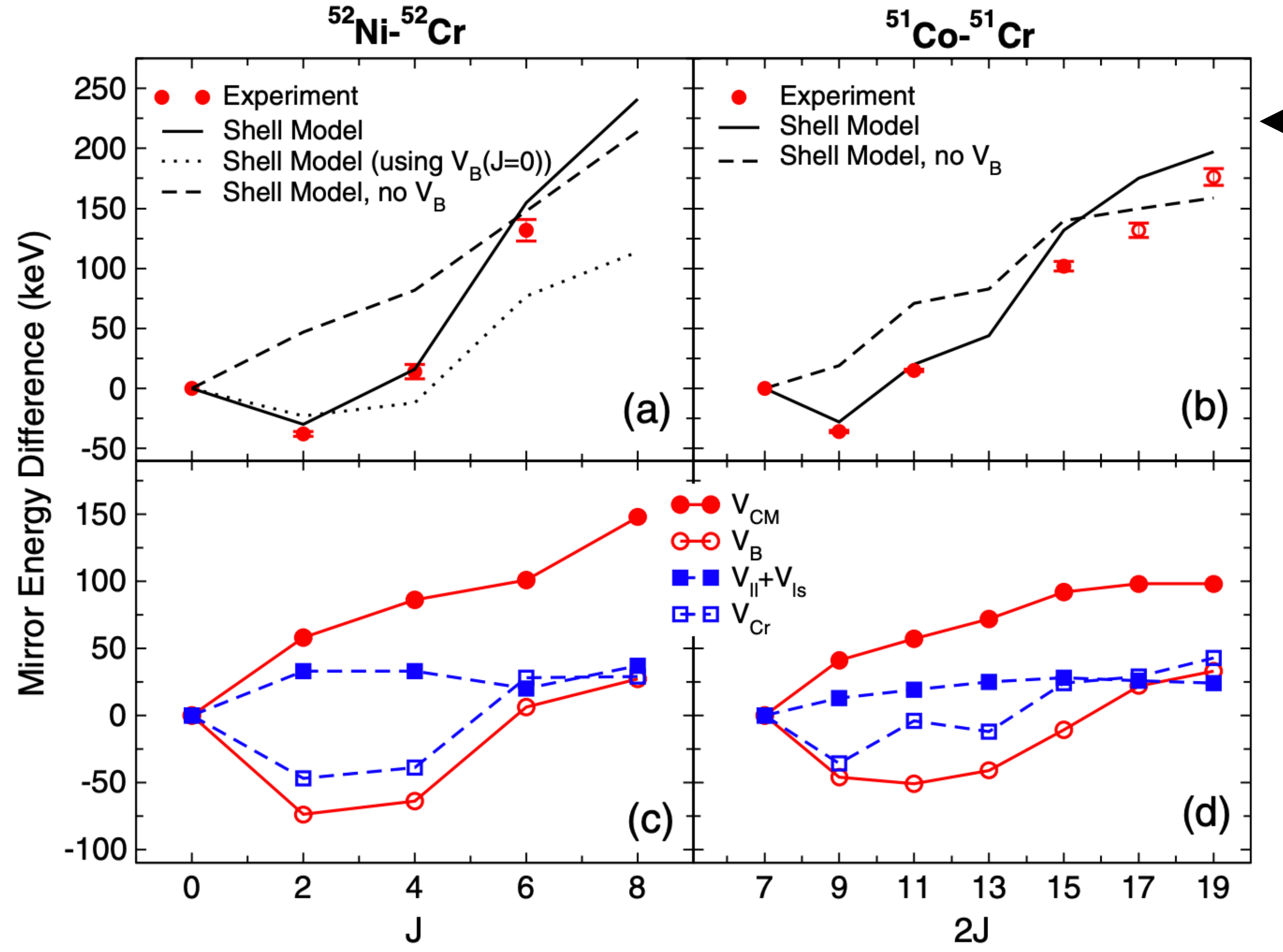


Warner, Bentley, & Isacker, Nat. Phys. 2(5), 311–318

MEDs and Isospin Symmetry Breaking



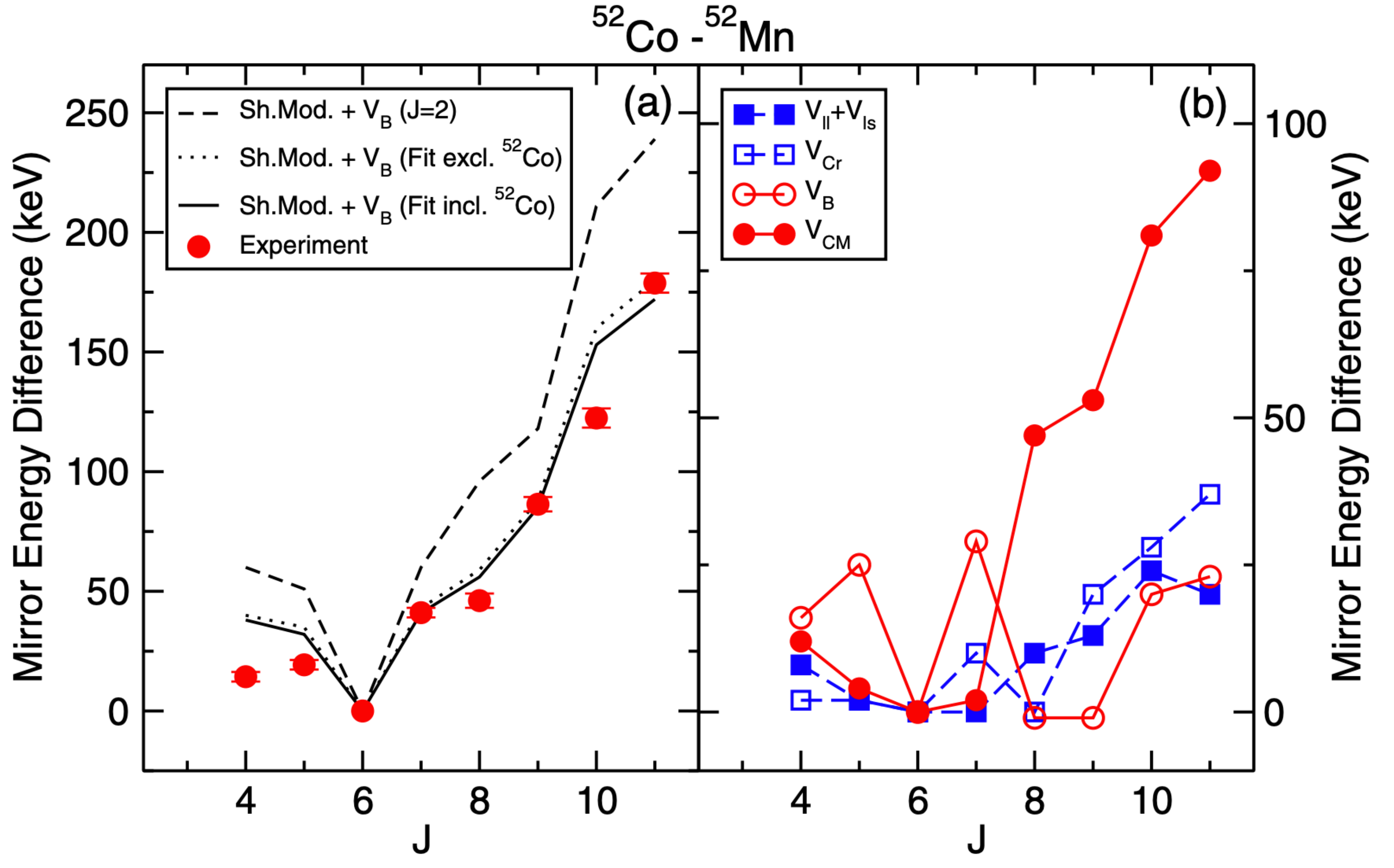




Included 100 keV spin-dependent ISB term

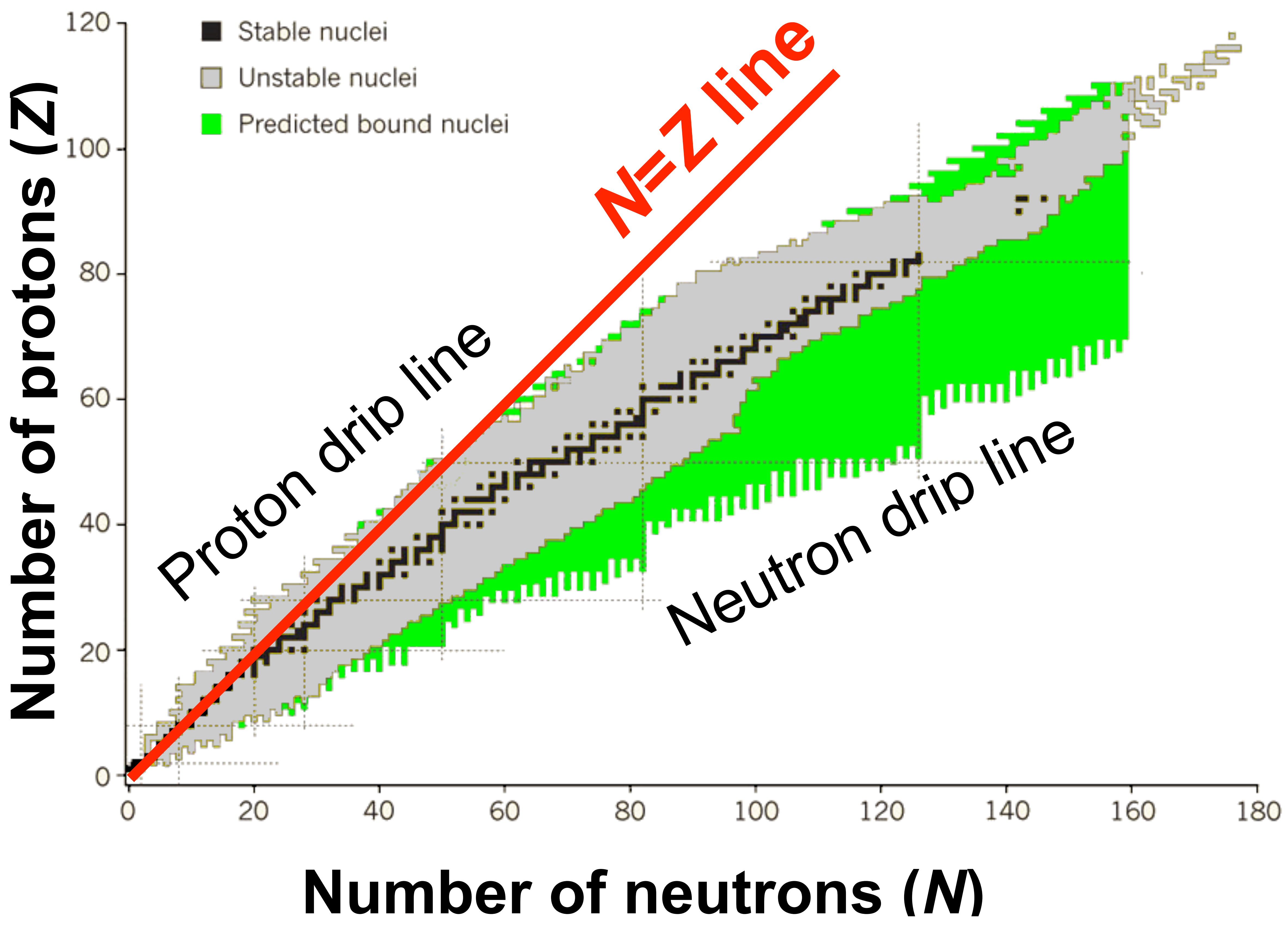
Included -72->+35 keV spin-dependent ISB terms

Davies et al., PRL 111, 072501 (2013)



Milne et al., PRL 117, 082502 (2016)

Mirror Chart of Nuclides



- Can only really test isospin symmetry in nuclei near *N*=*Z* line -> re-plot chart of nuclides

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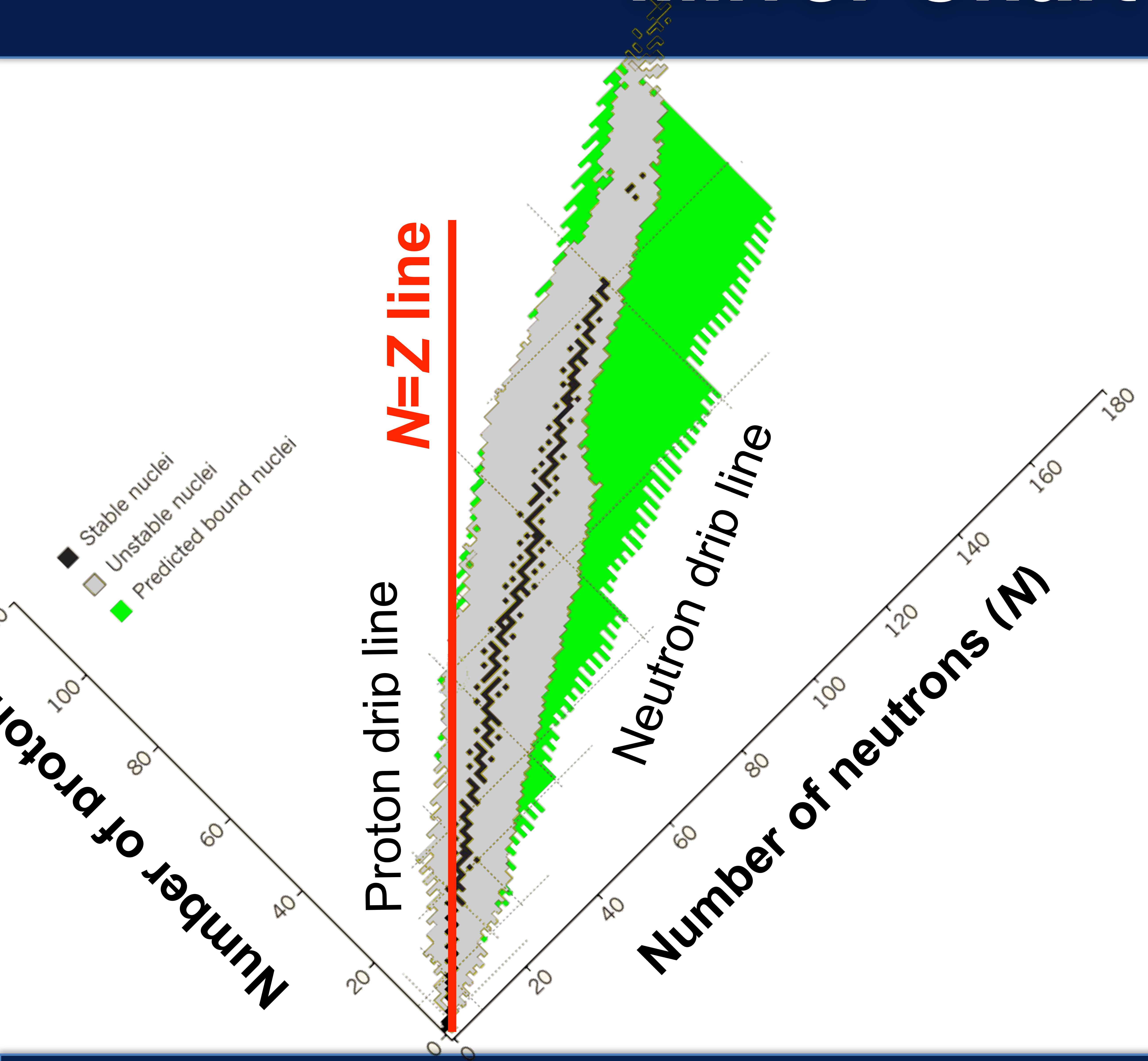

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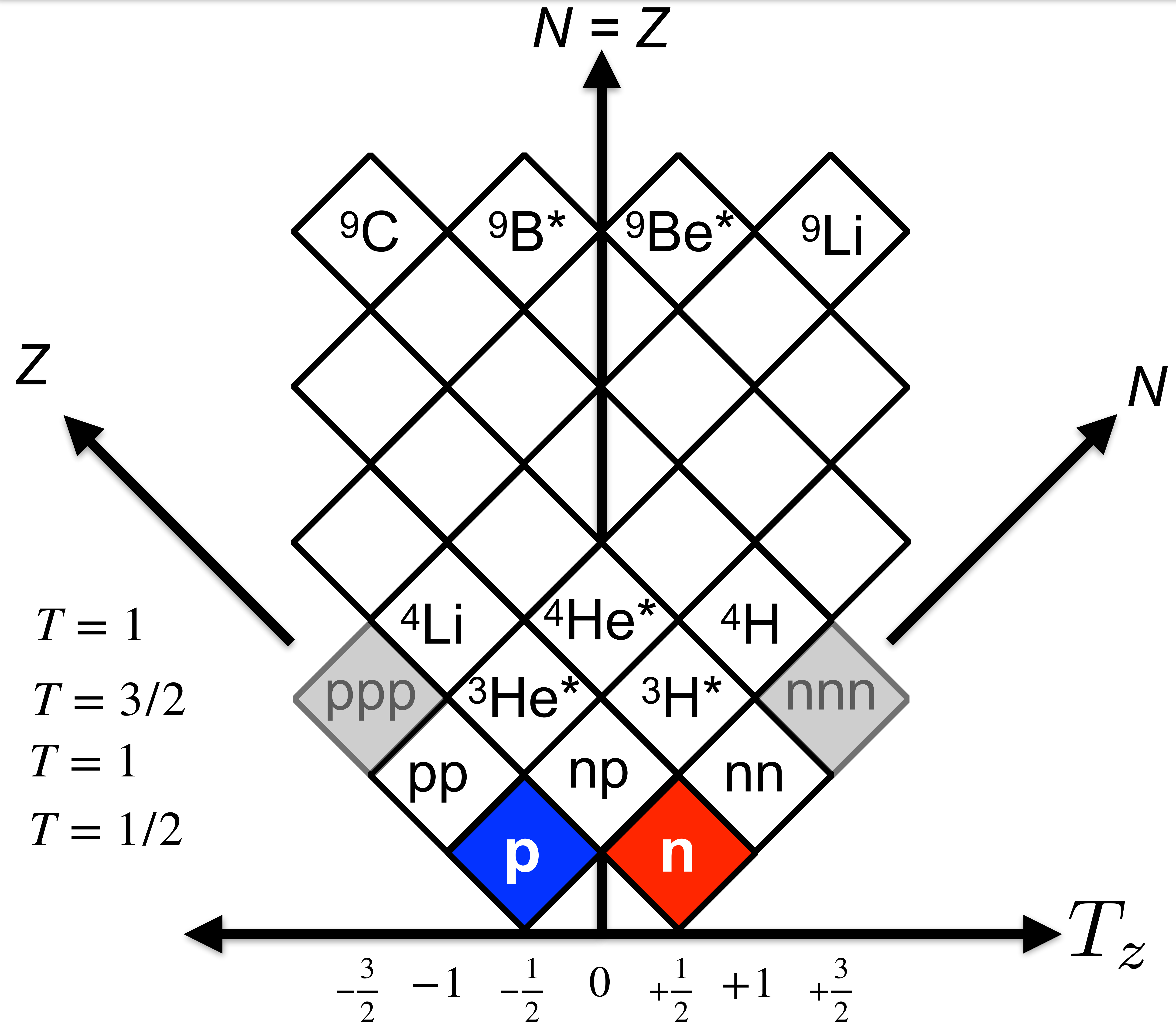

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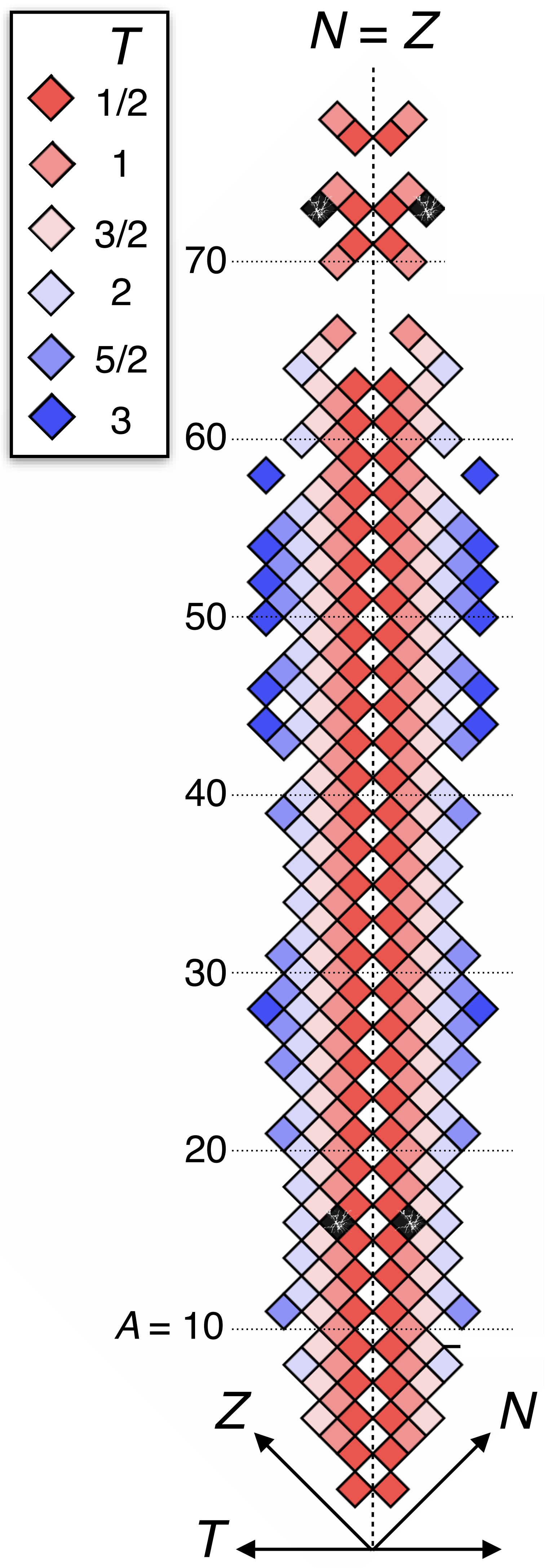

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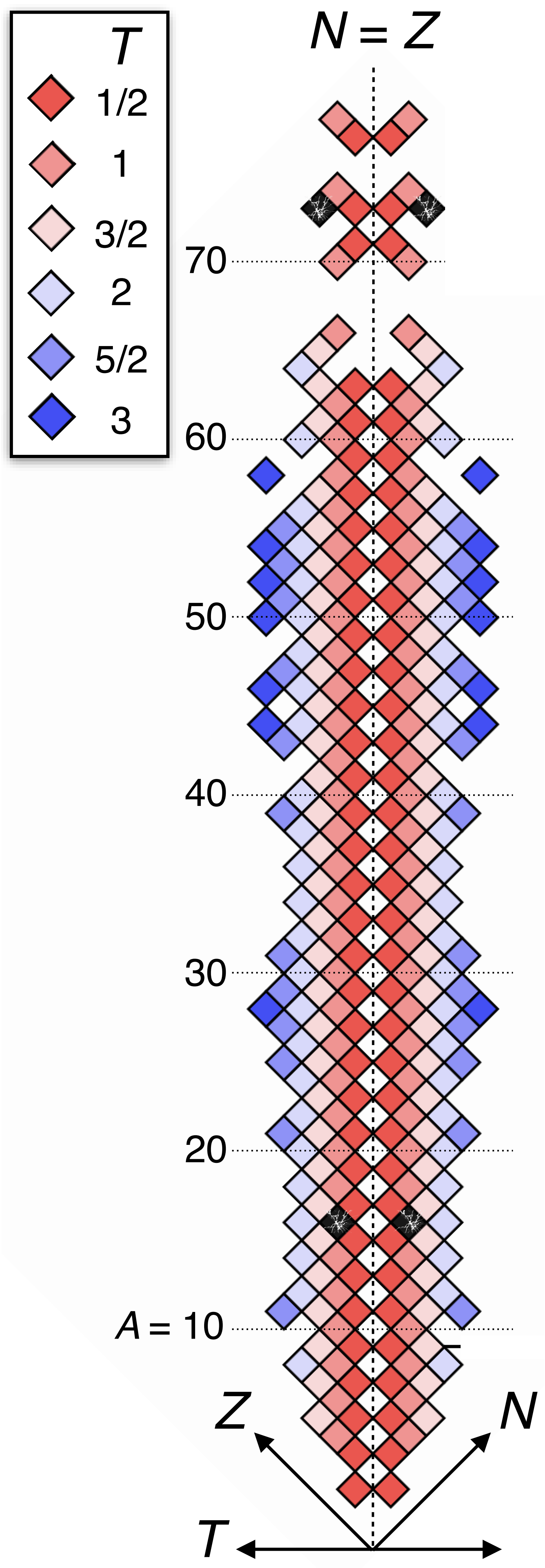

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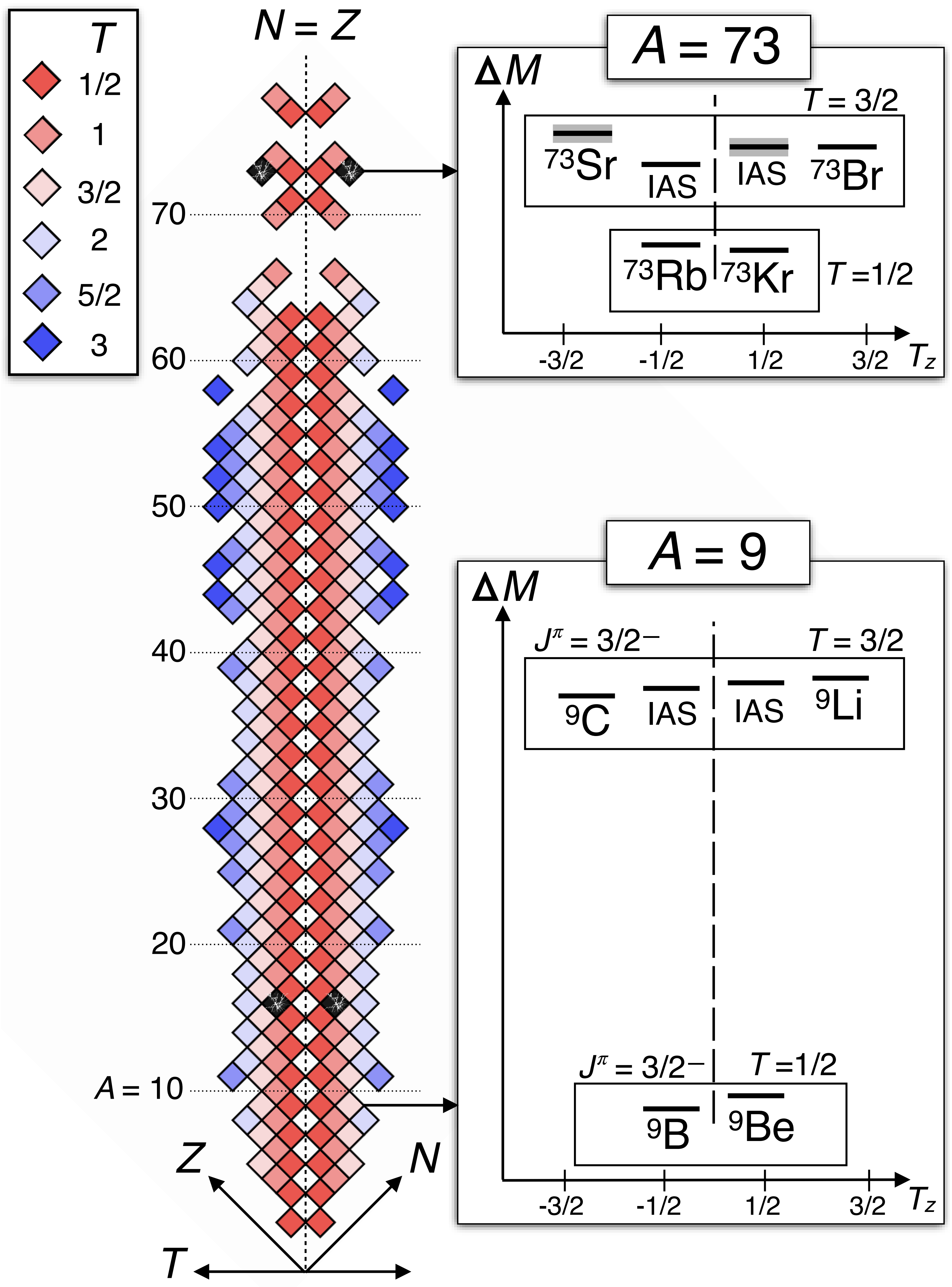

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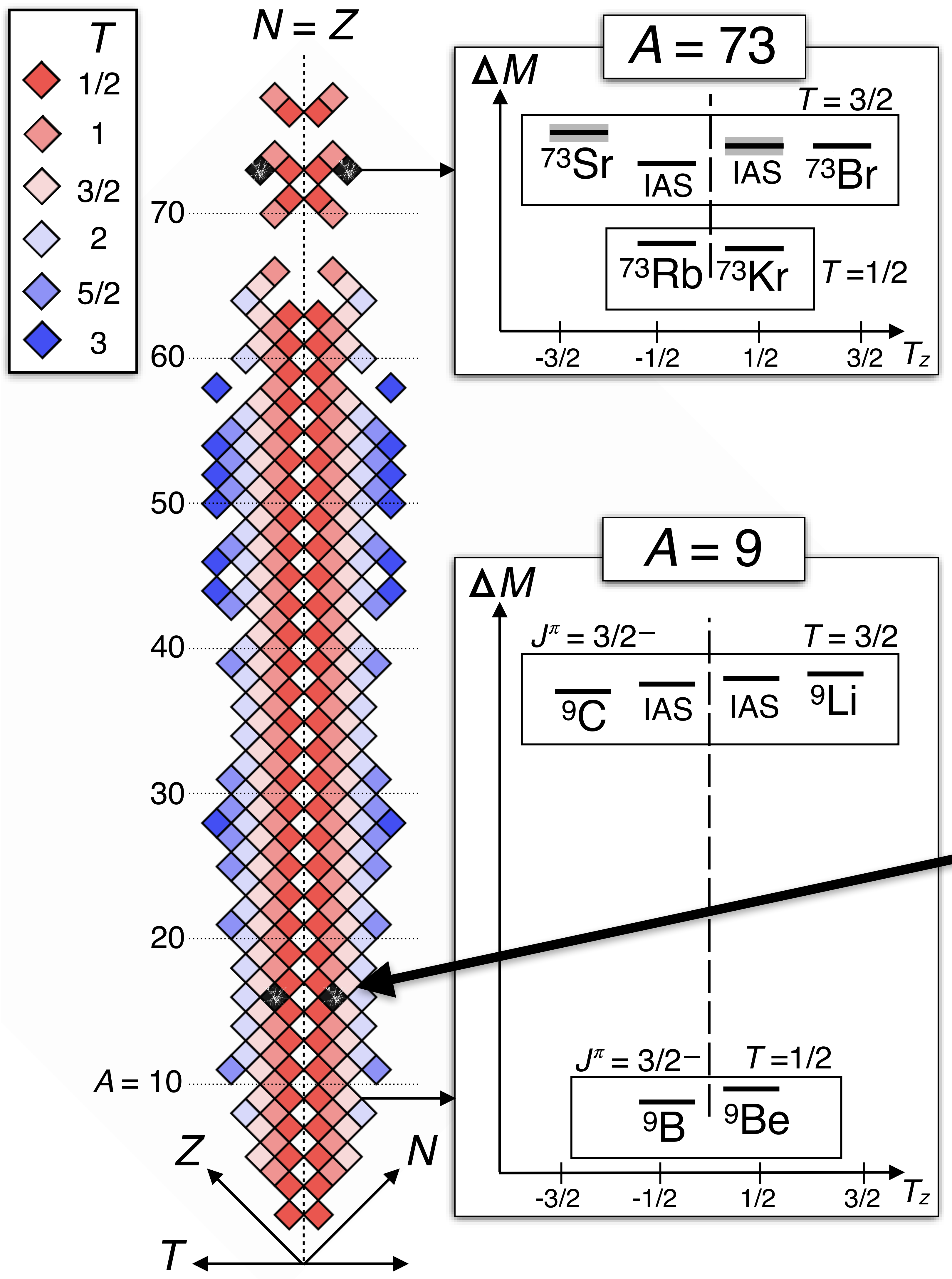

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What about these guys (^{16}F/^{16}N)?

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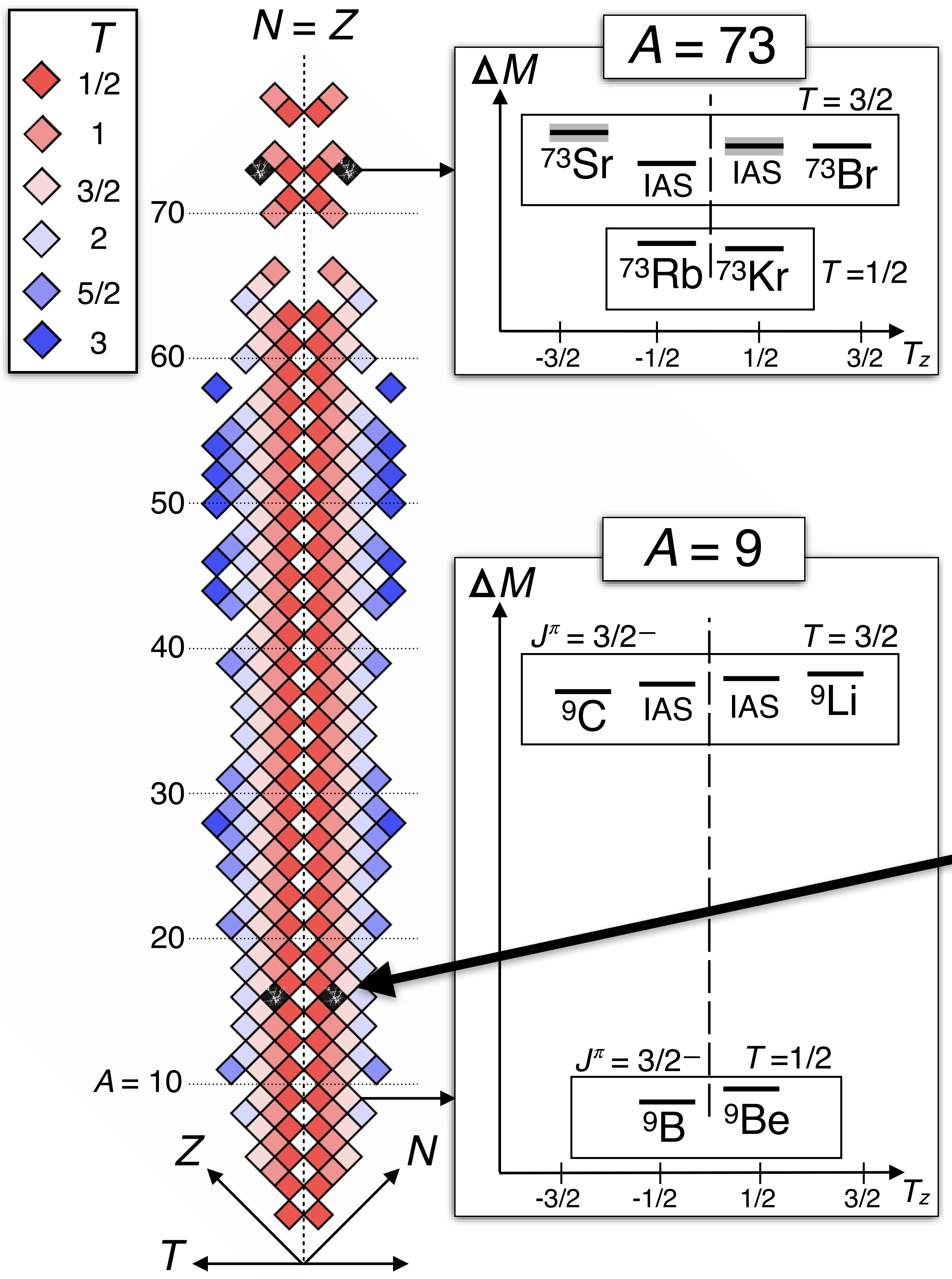

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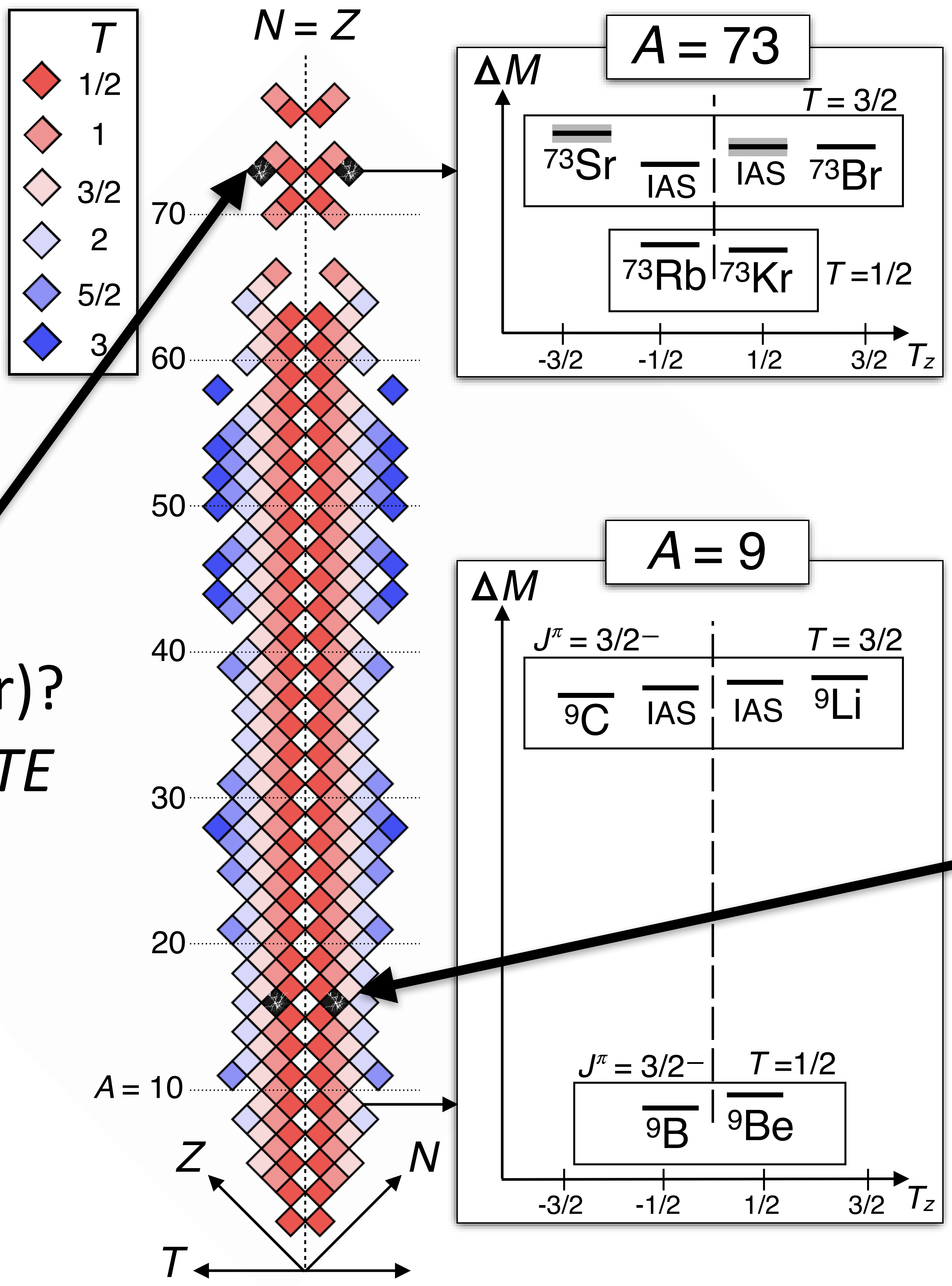

And here (^{73}Sr/^{73}Br)?
Can't be TE shift…

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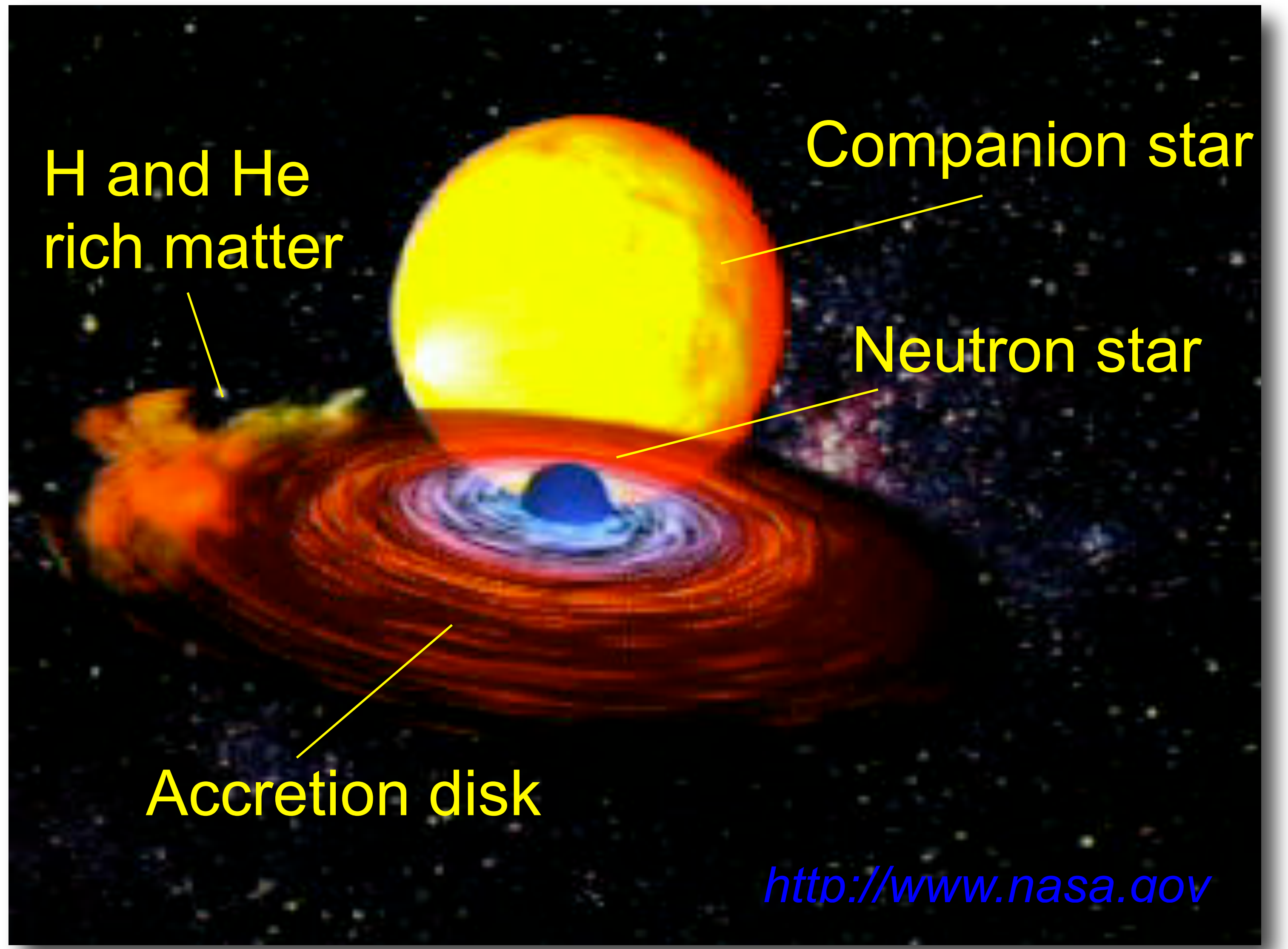
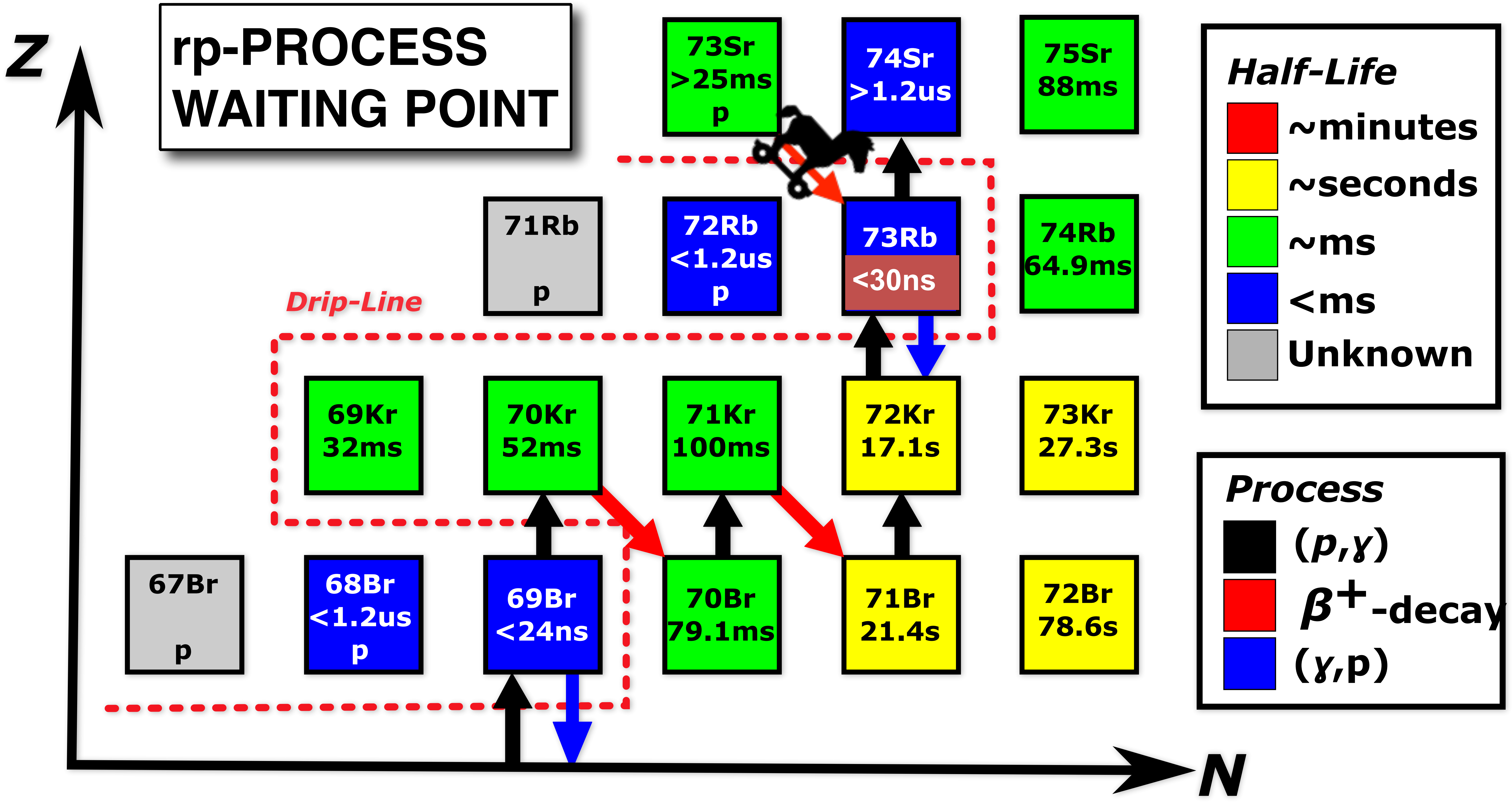
NSCL Experiment - Motivation

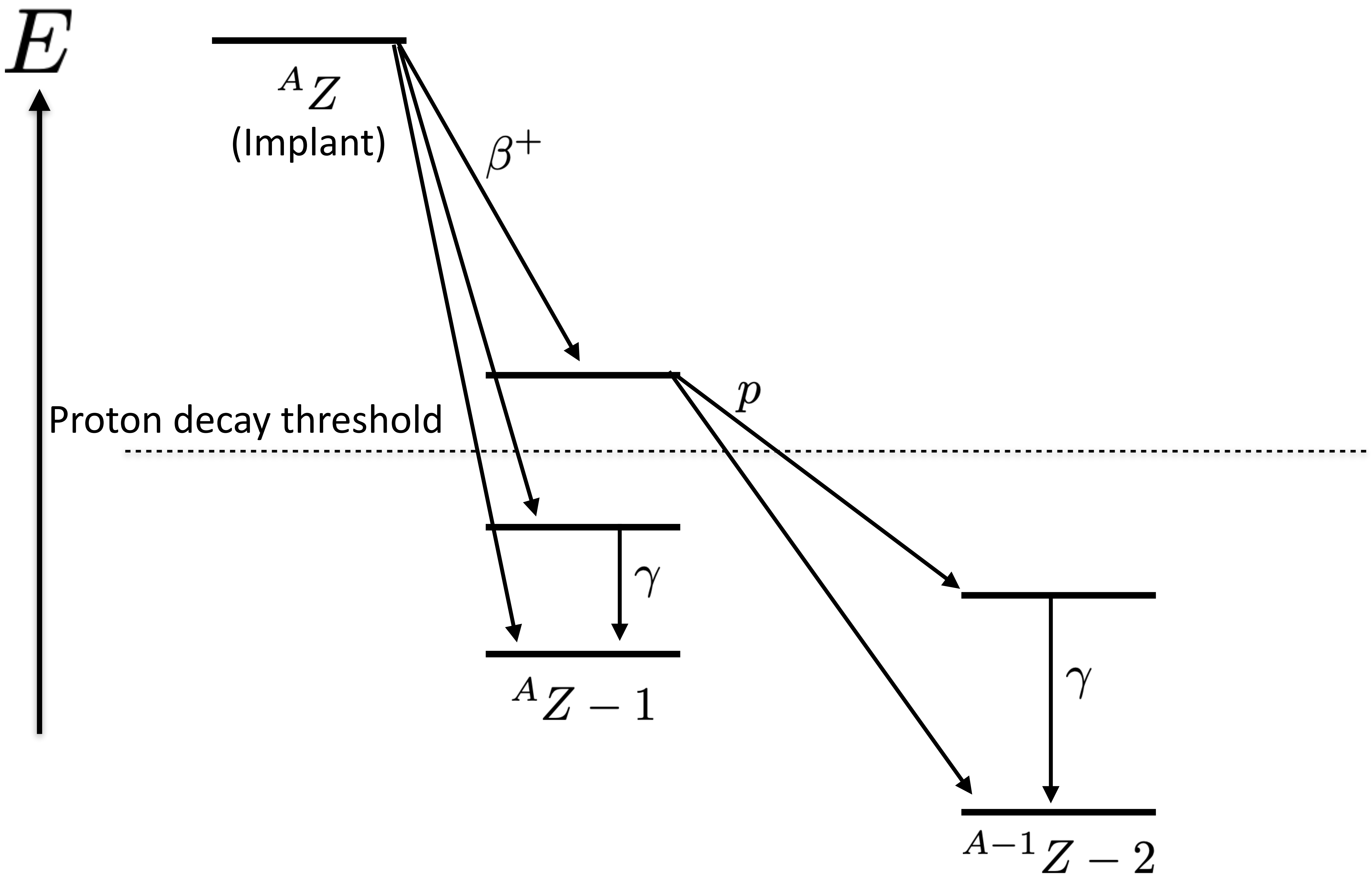
- Goal: Measure properties of ^{73}Rb through β-delayed proton emission of ^{73}Sr
- This has astrophysical implications in the rapid-proton capture process.





NSCL Experiment

- Implant ^{73}Sr into an active detector and watch for β-delayed proton emission
- Surrounded by high purity germanium array to look for γ-decays in coincidence



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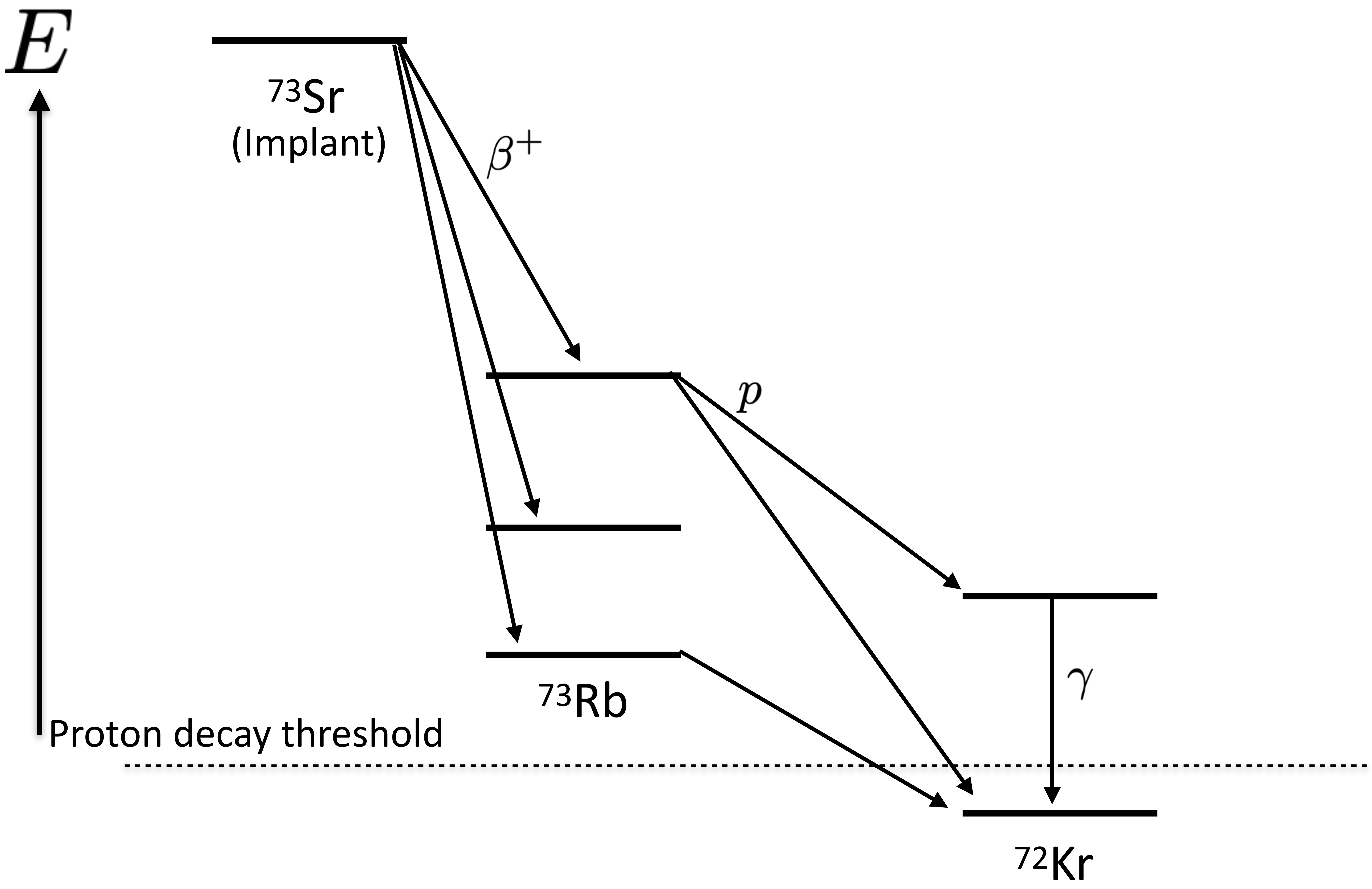

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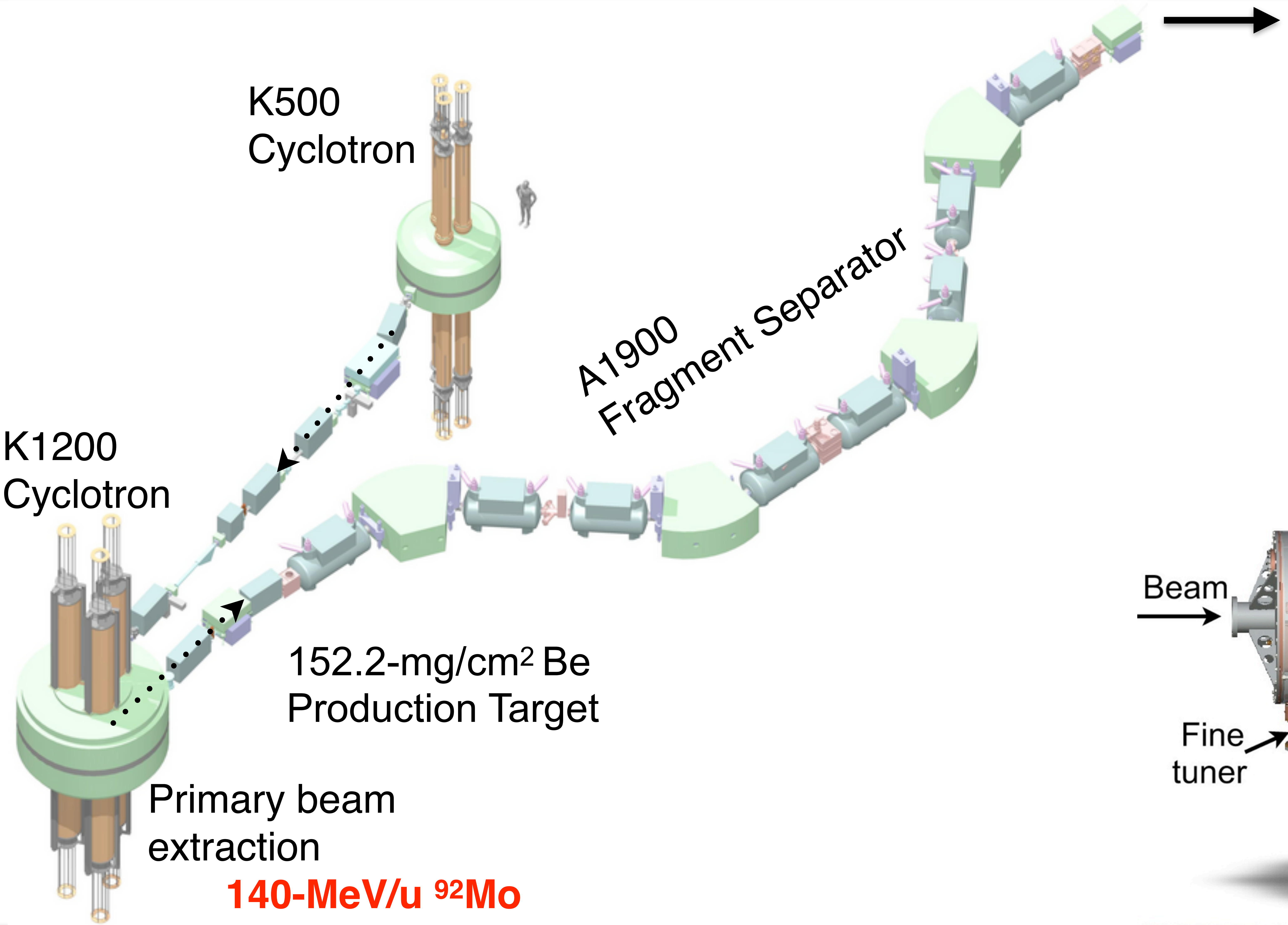
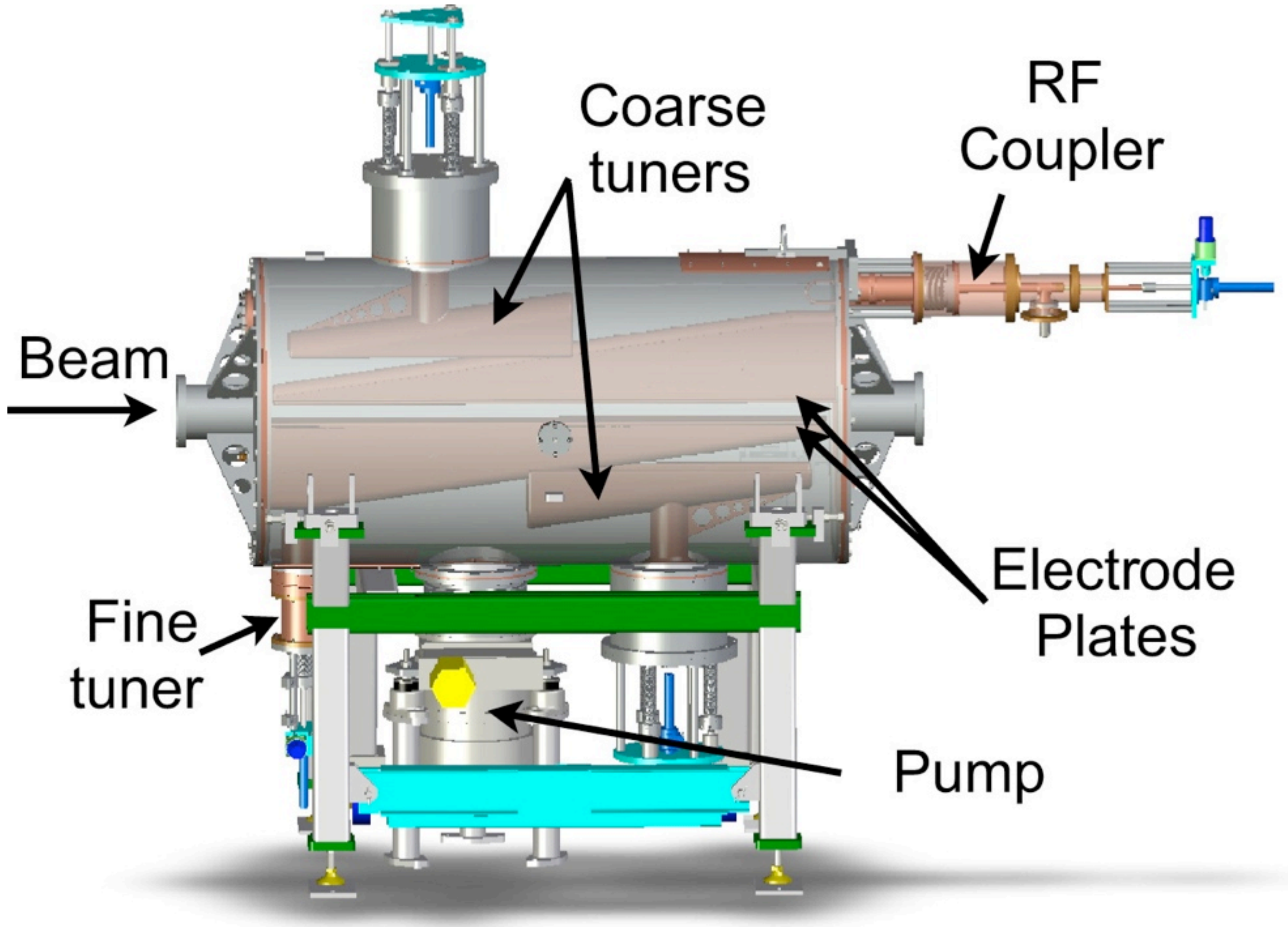
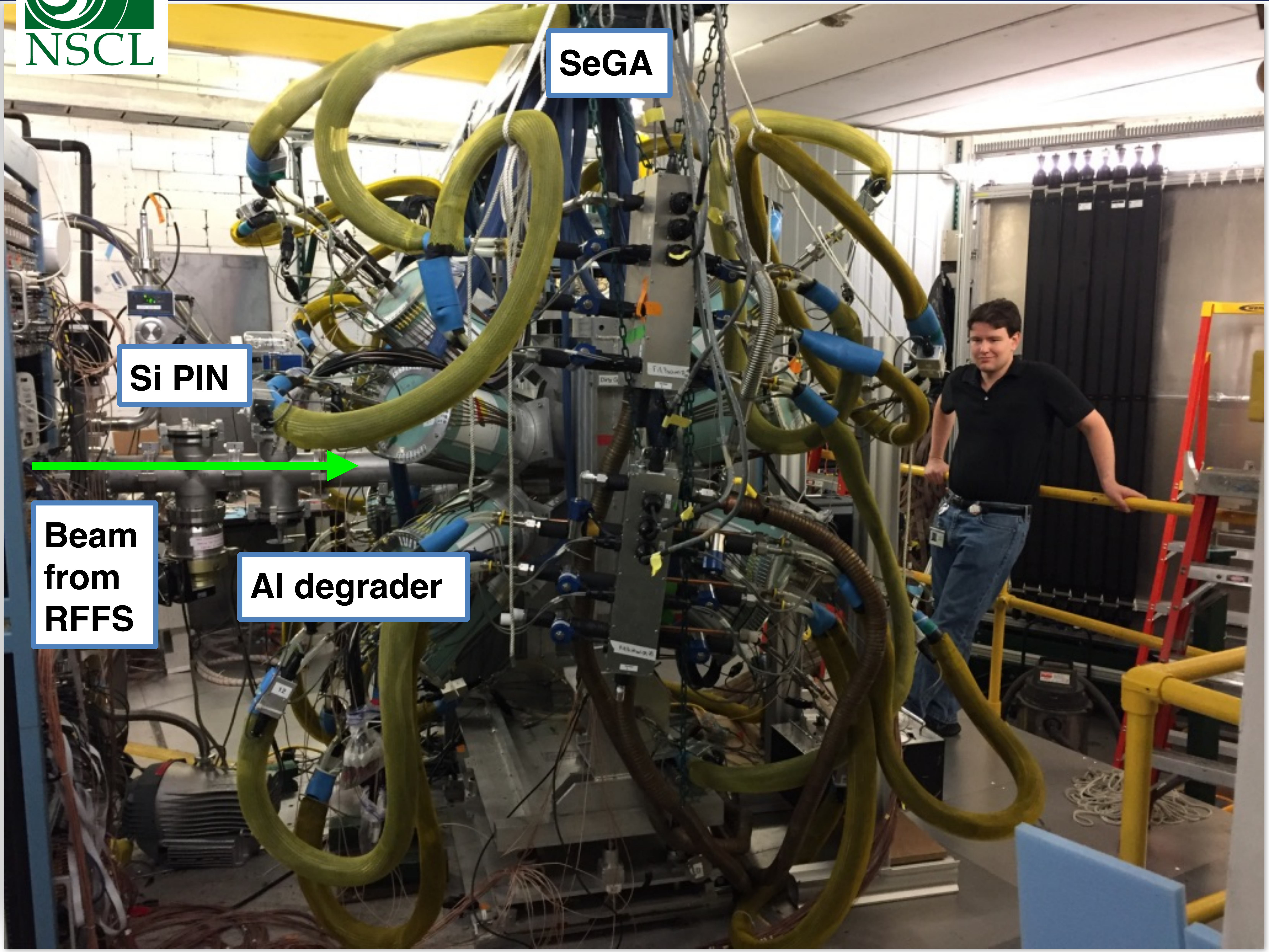


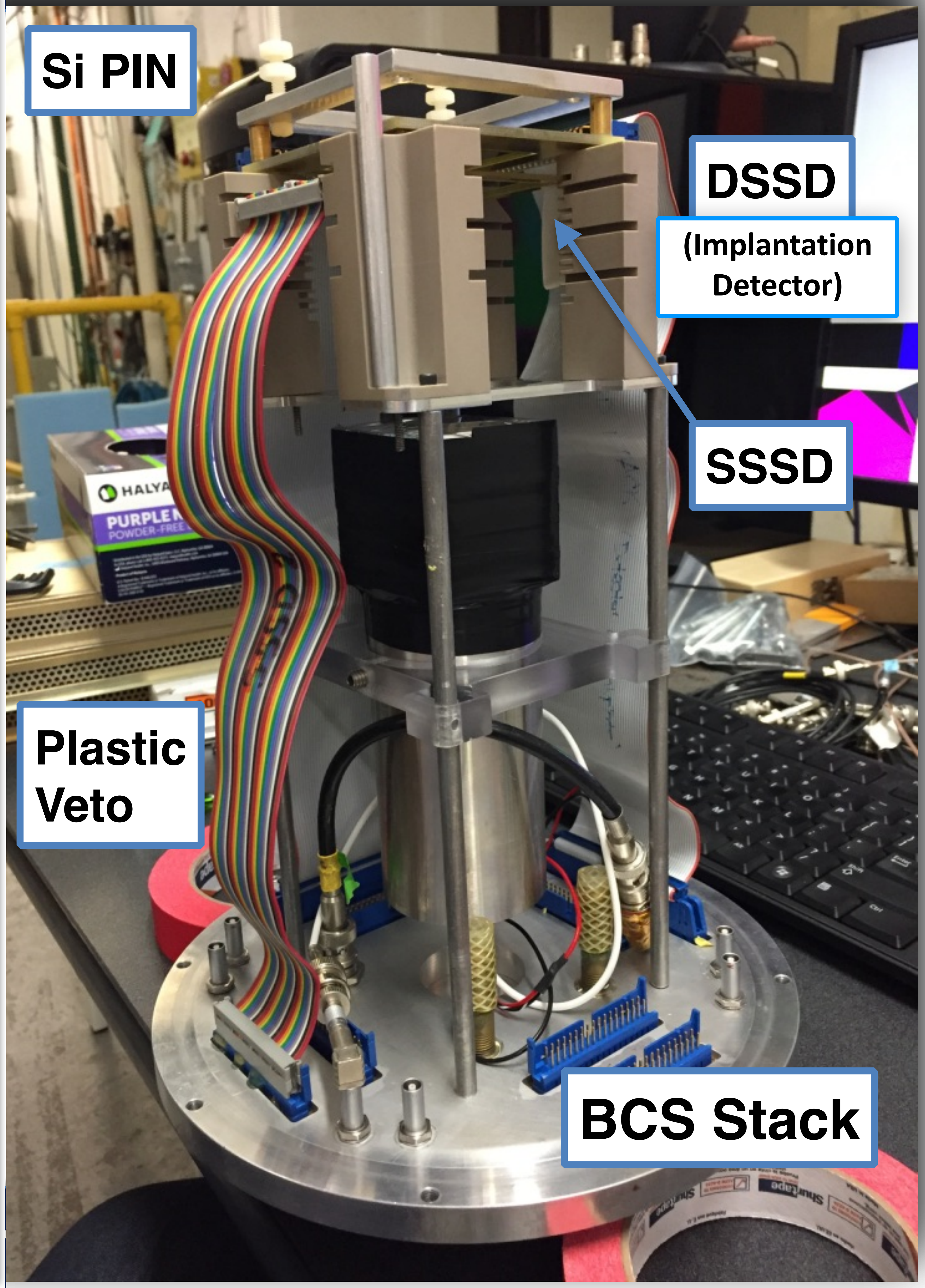
Secondary beam:
^{73}Sr cocktail

^{73}Sr beam was purified by a factor of 4500 after RFFS!



Experimental Setup: Decay Station





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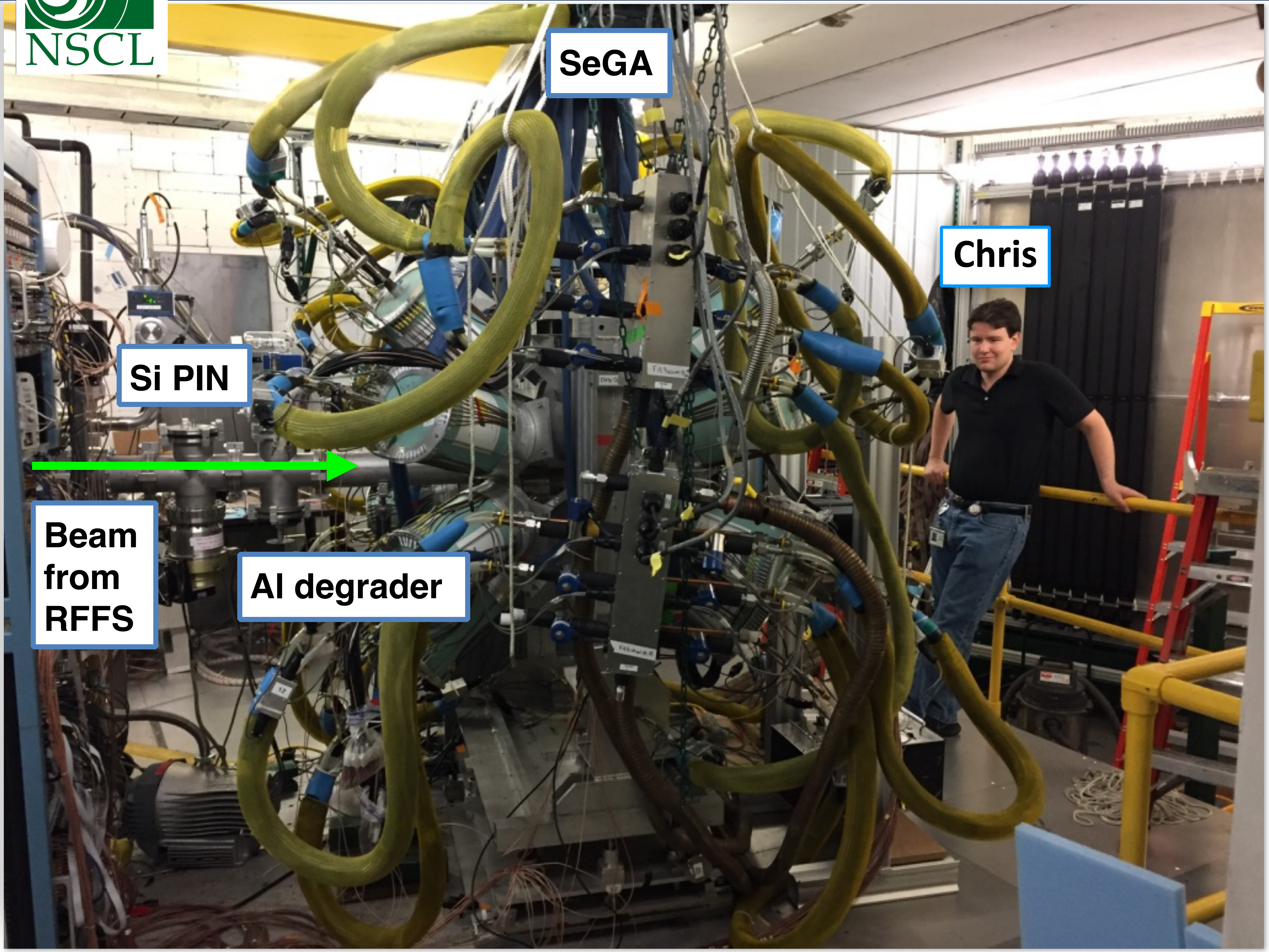
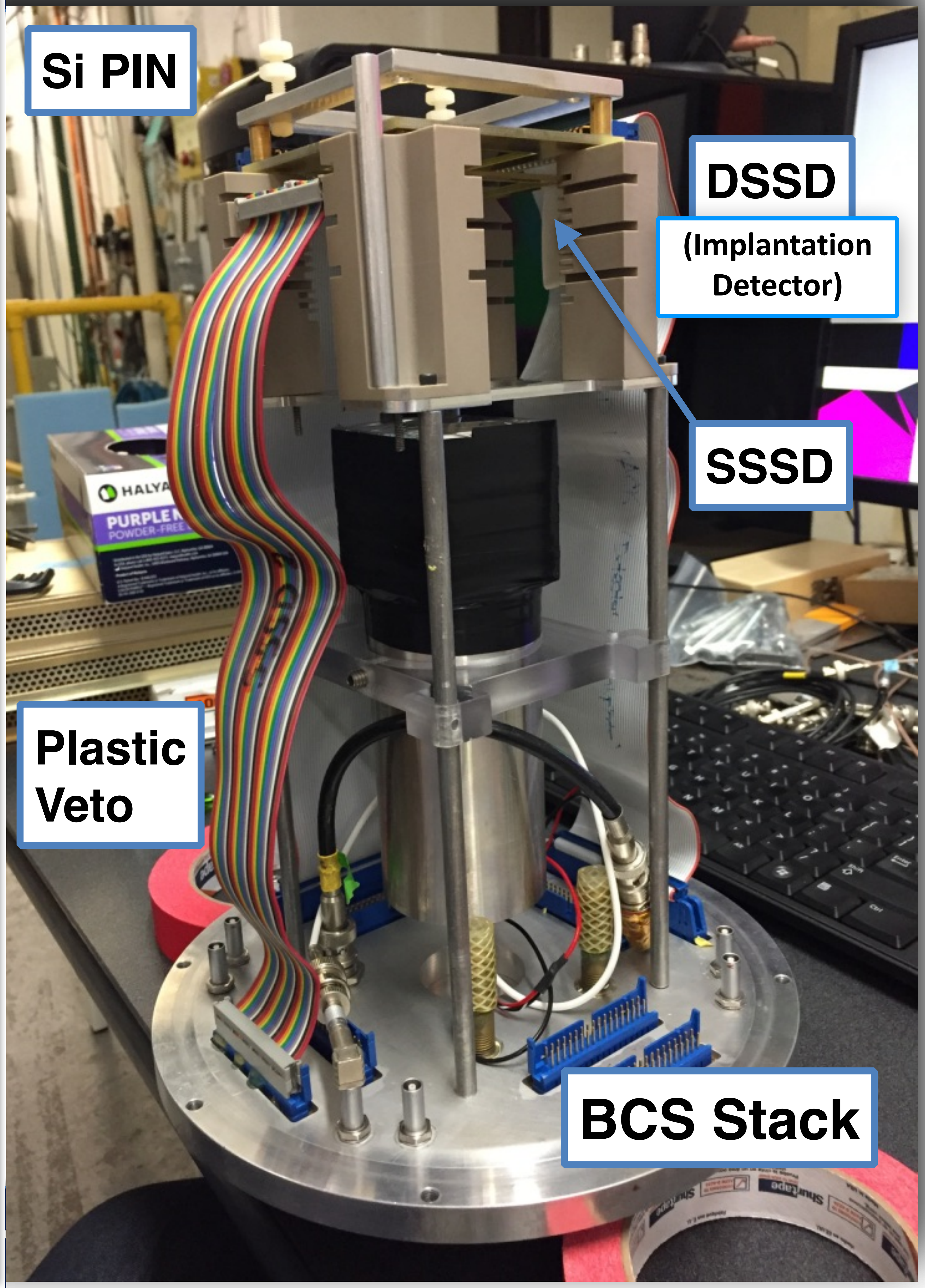
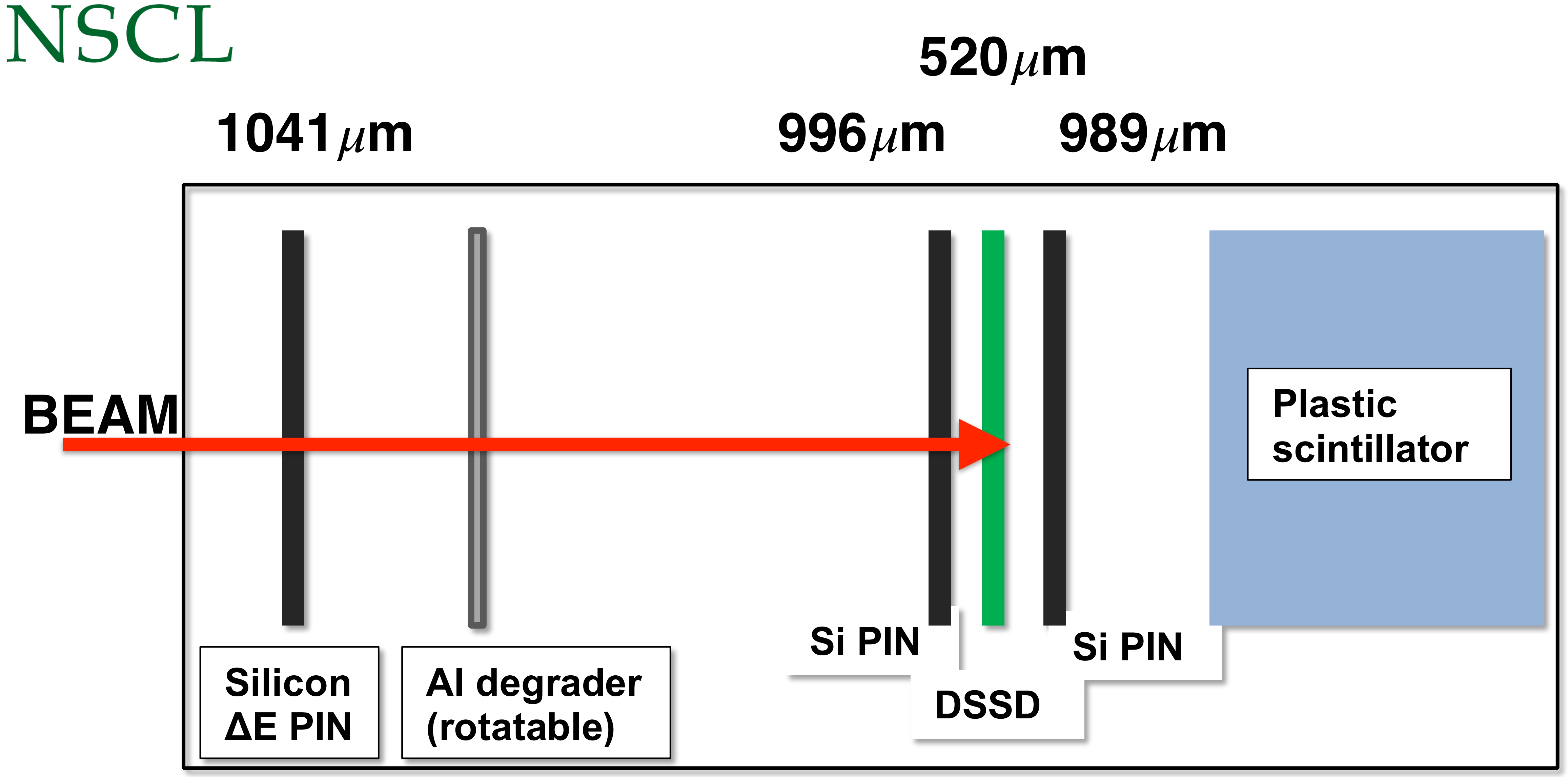
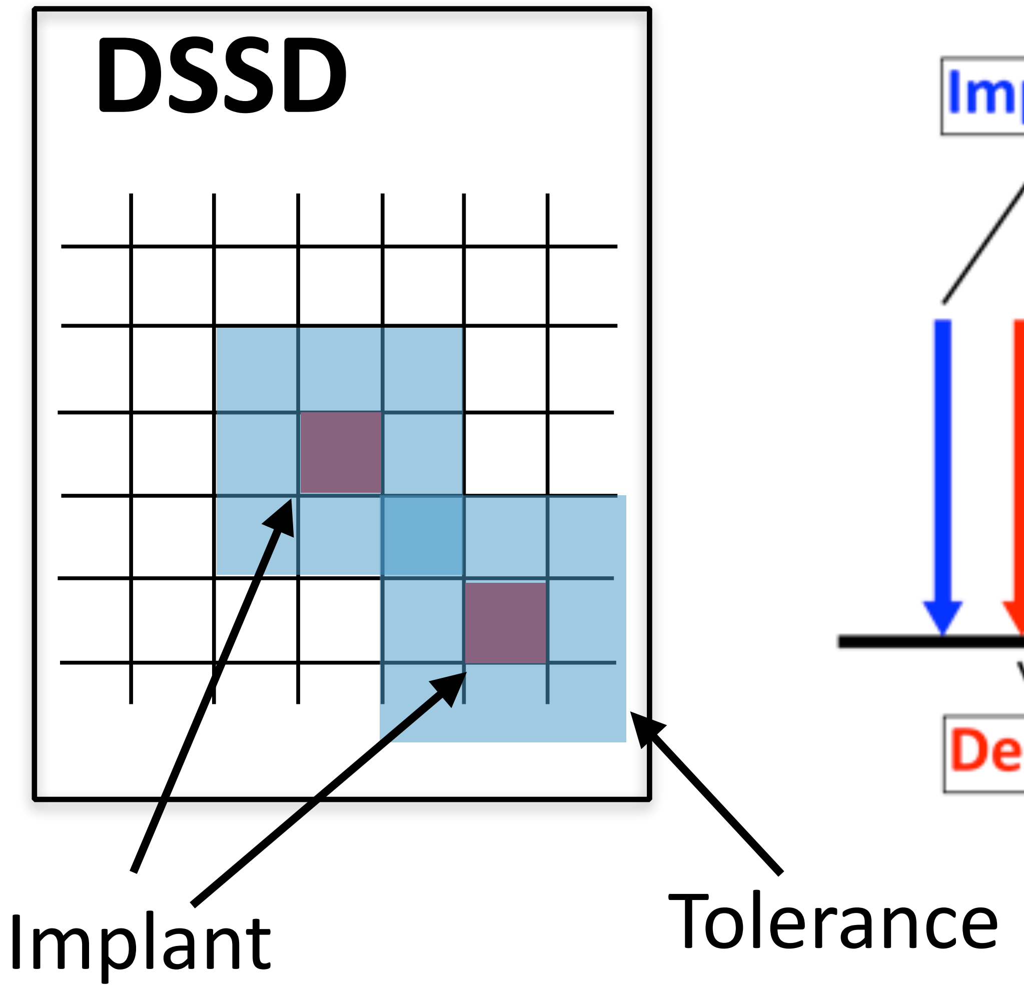
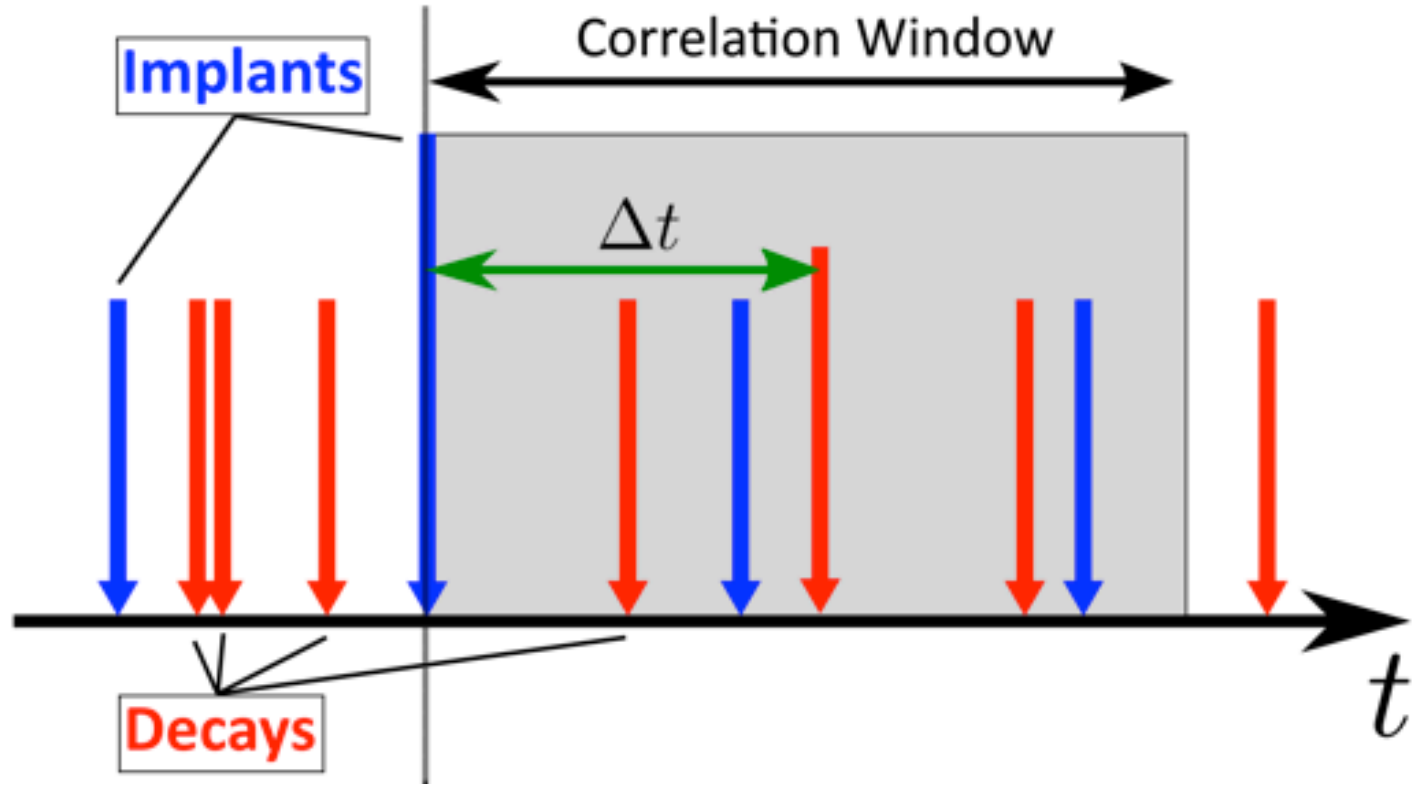


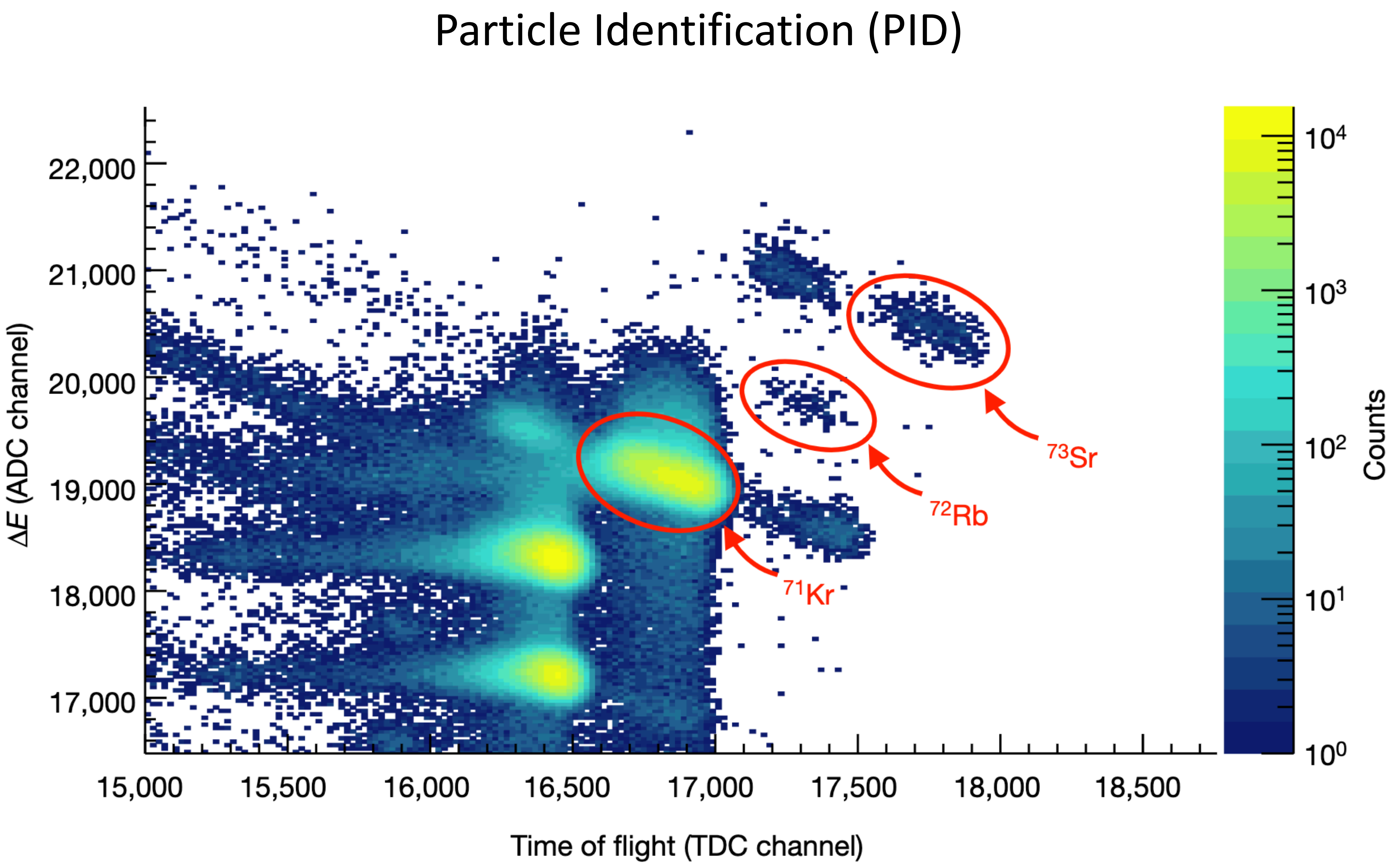


Experimental Results



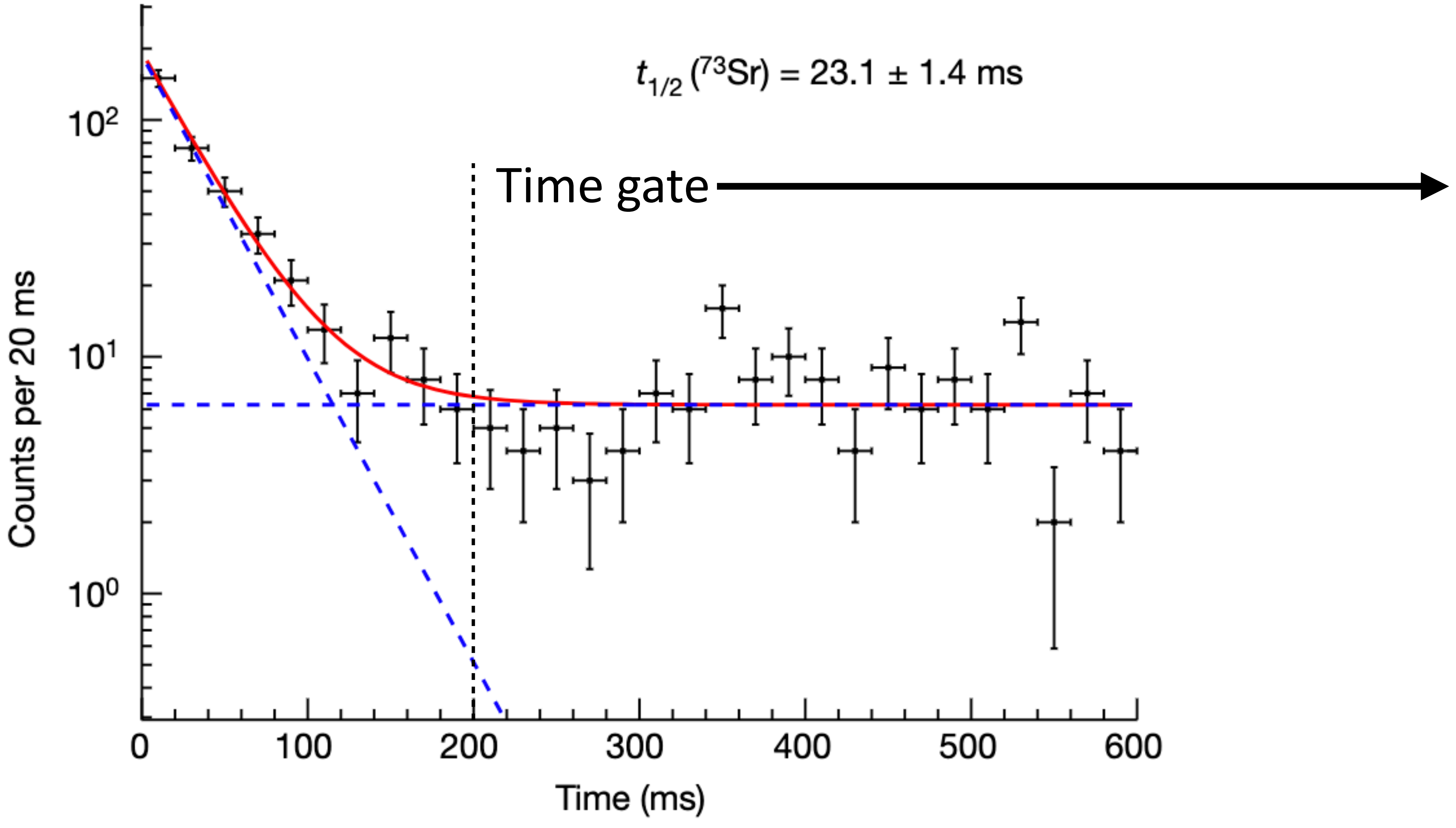




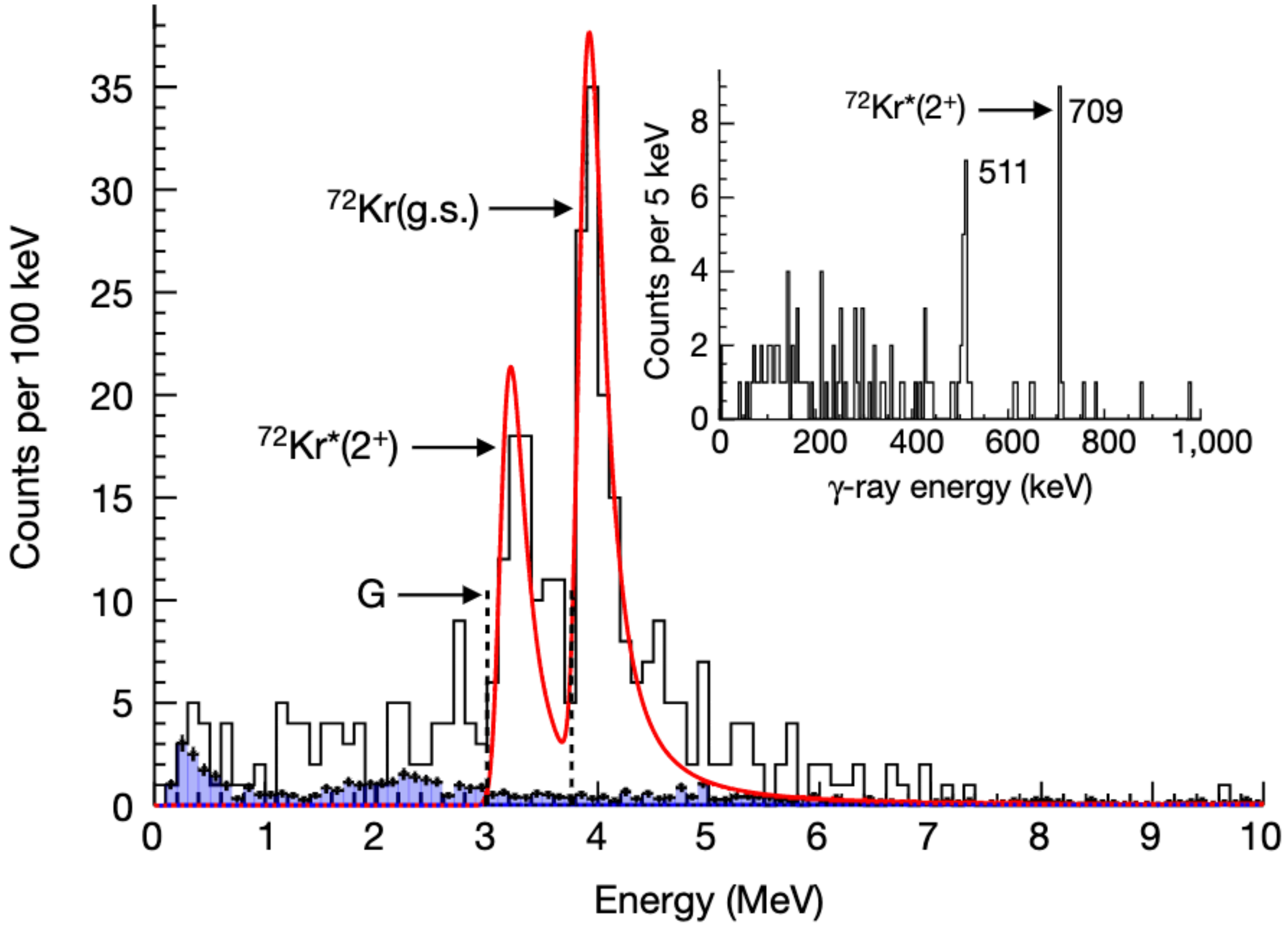


Experimental Results

Implant-decay Correlation time



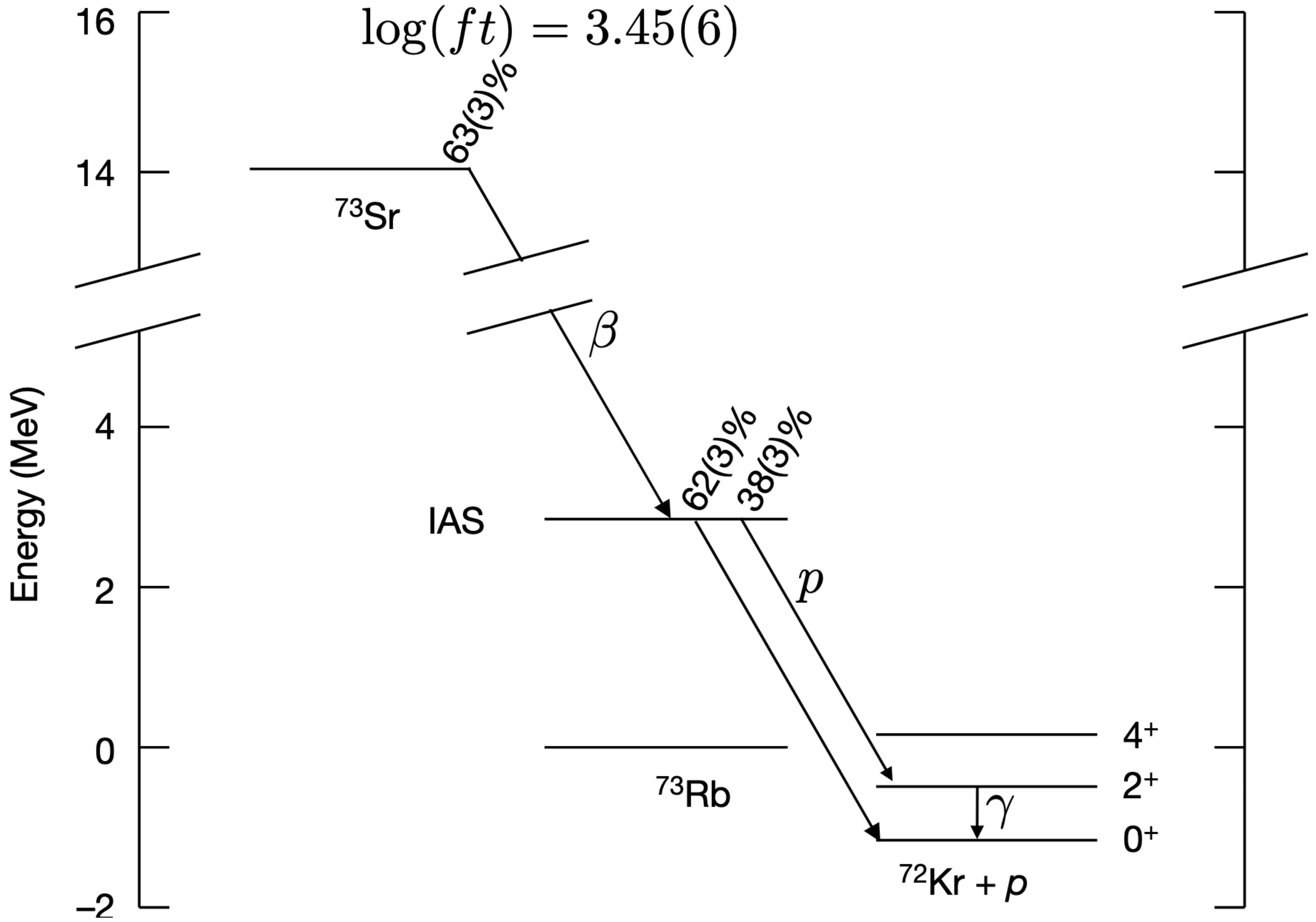
Charged-particle spectrum



- Evidence of only one species when gating on PID
  - Tell's us we are looking at ground state decays

Capture some of β^+ and all of proton, resulting in "β-summing"

Experimental Results



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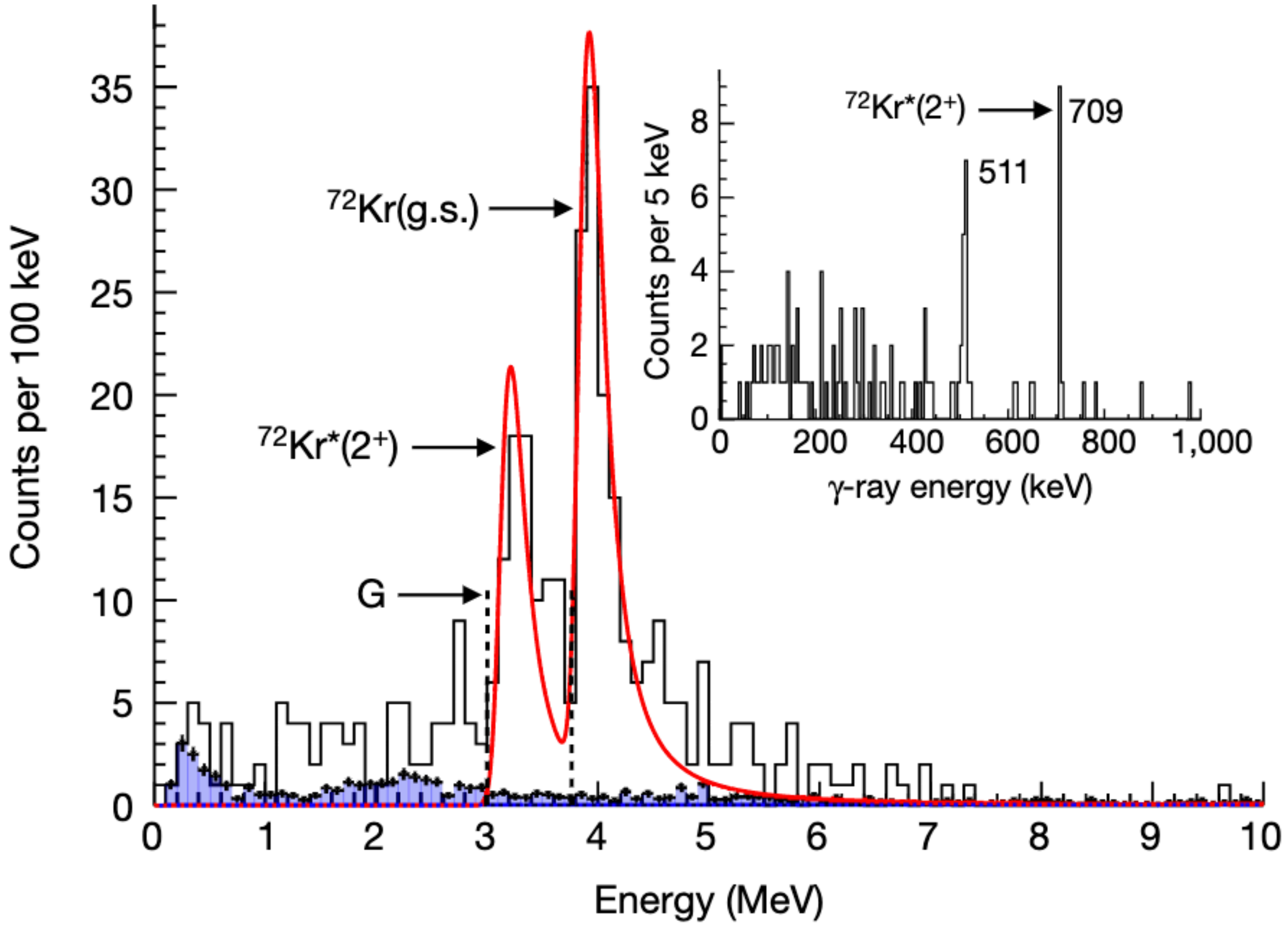

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When energetically available, β+ decay will primarily proceed through IAS (superallowed Fermi decay) —> conservation of isobaric spin

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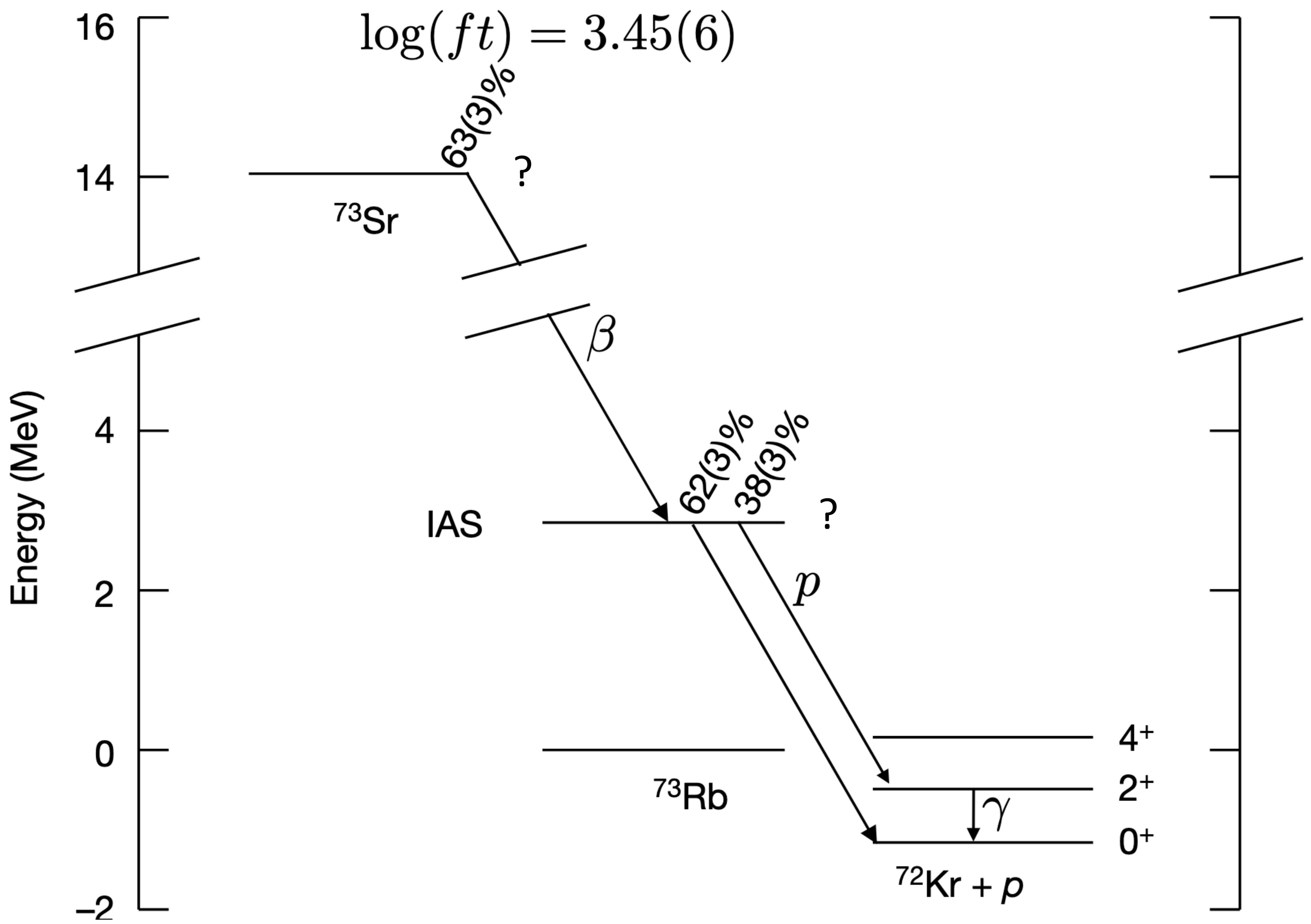

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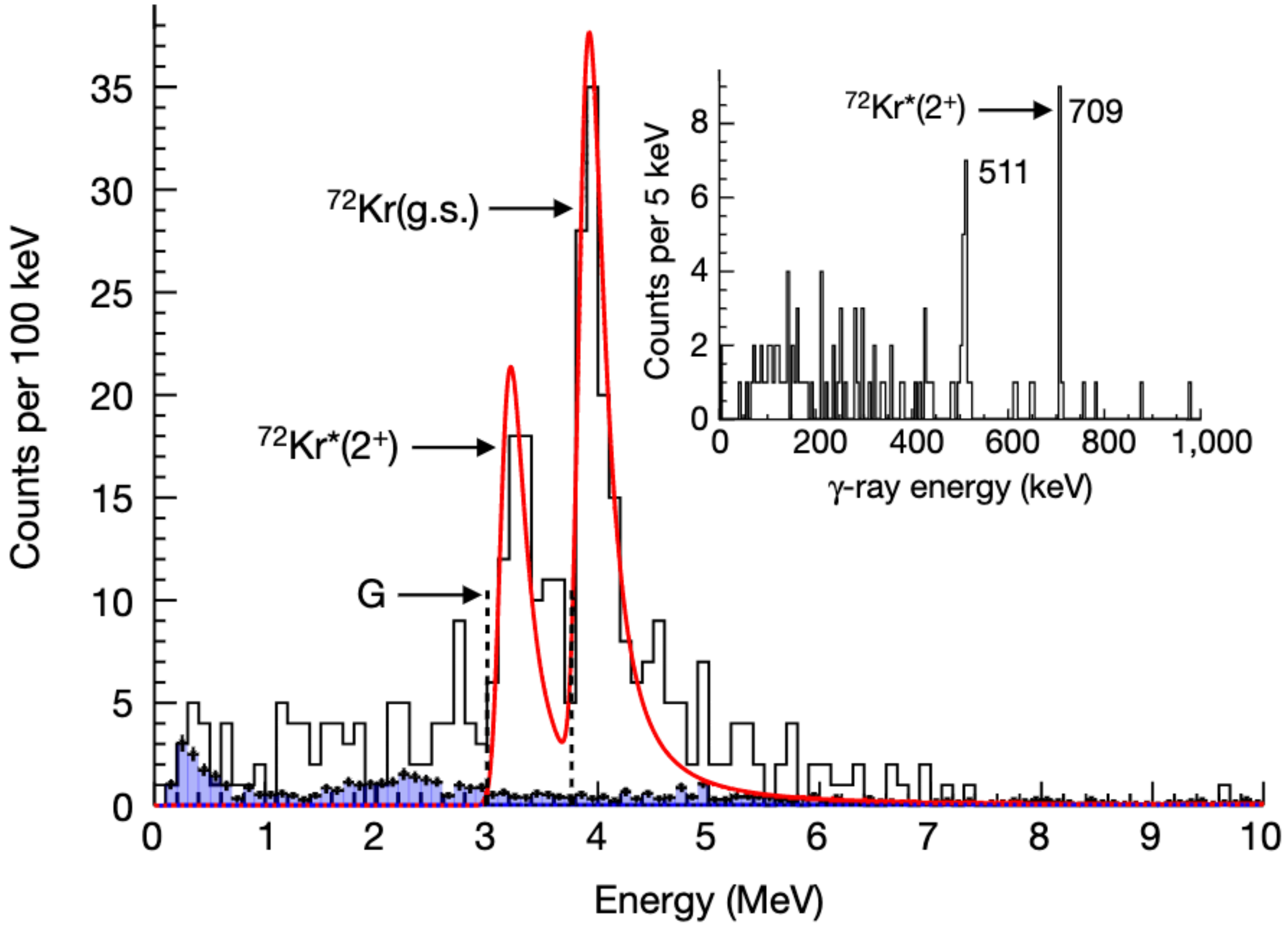

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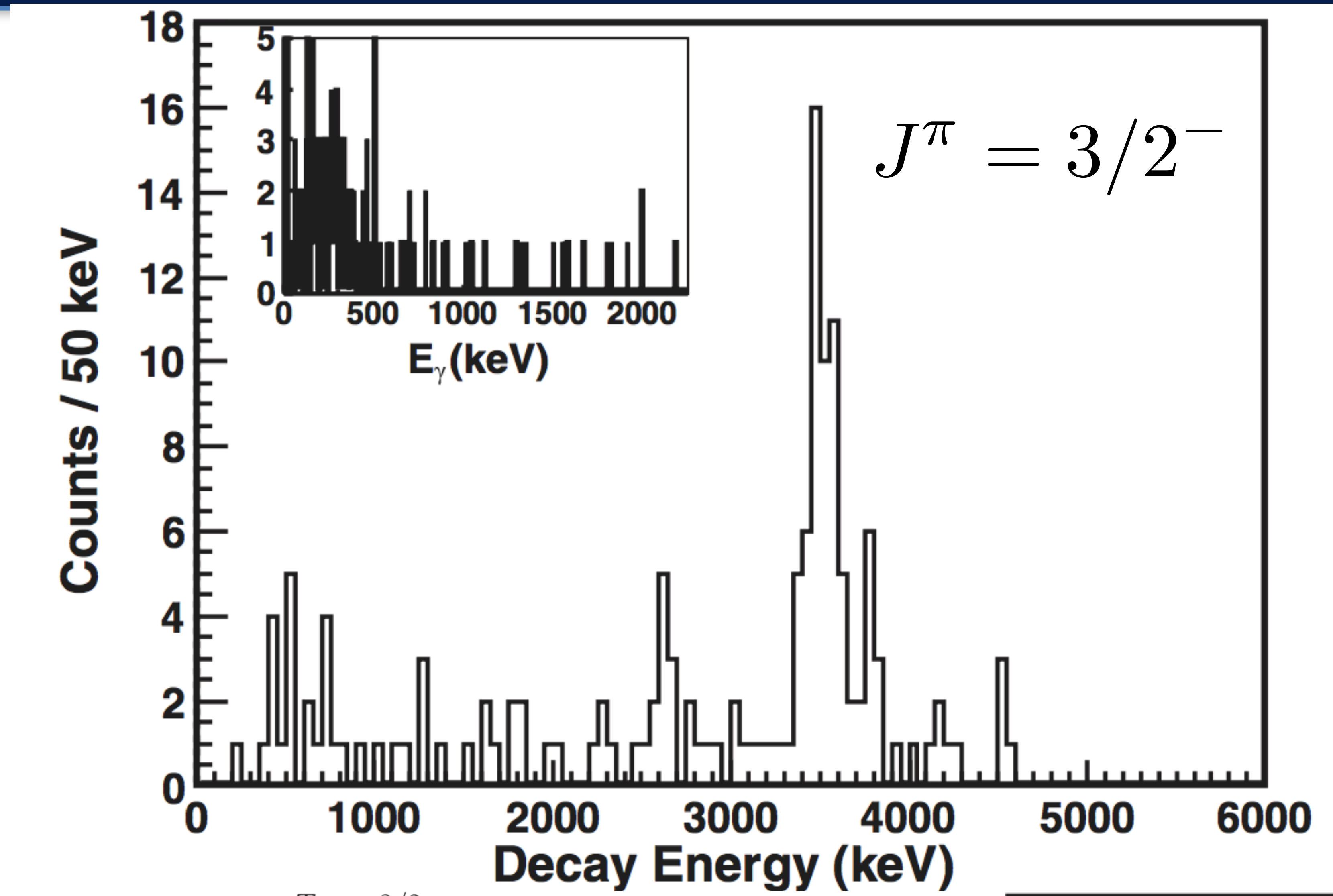
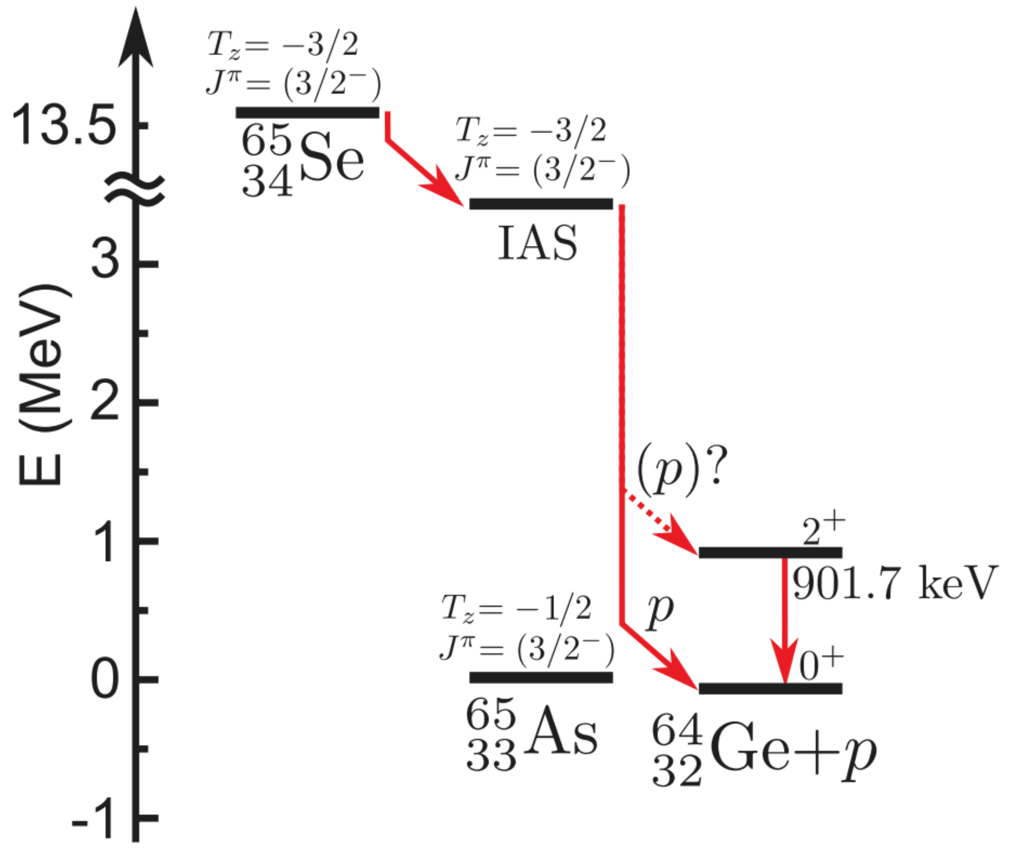
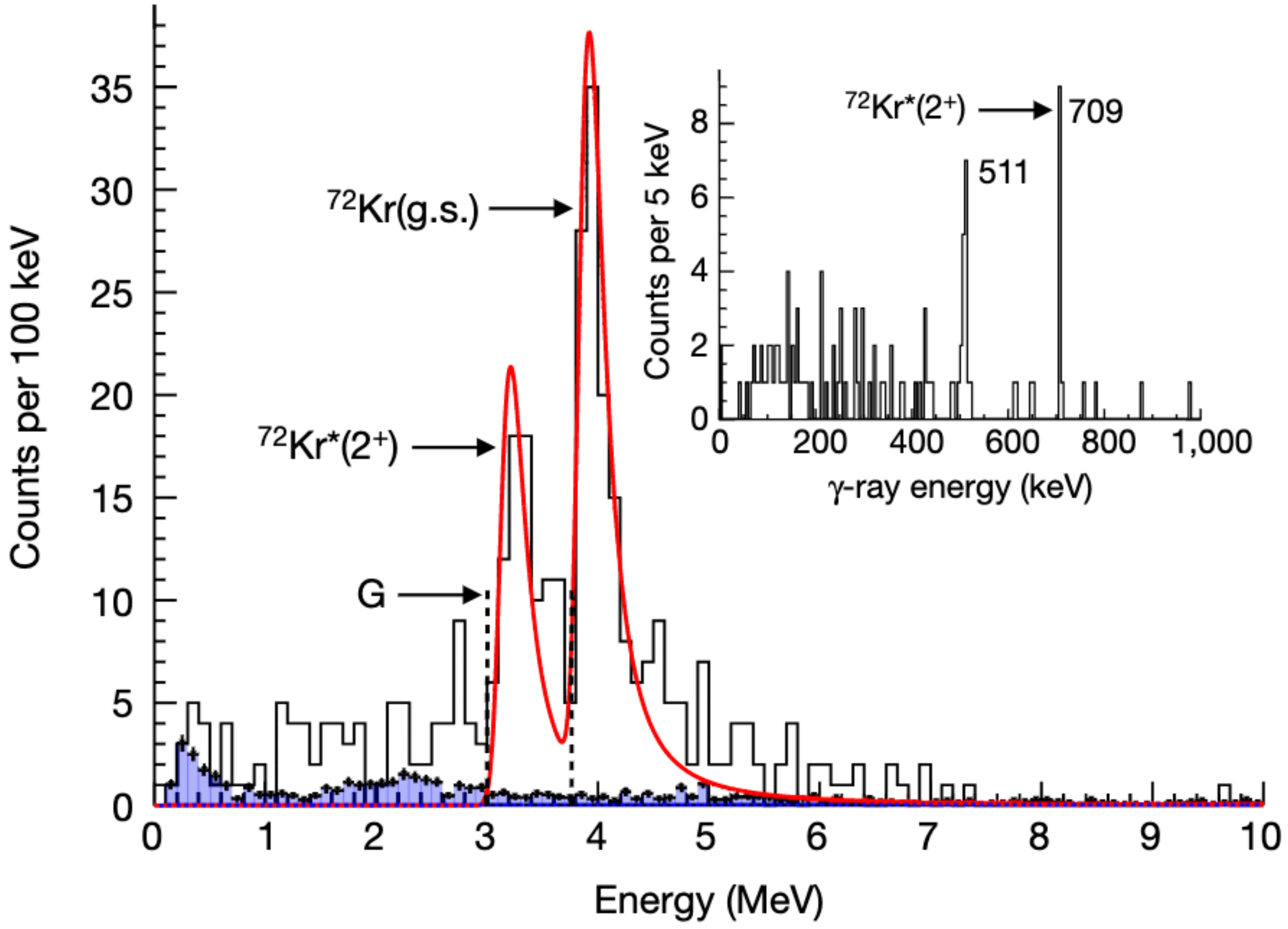
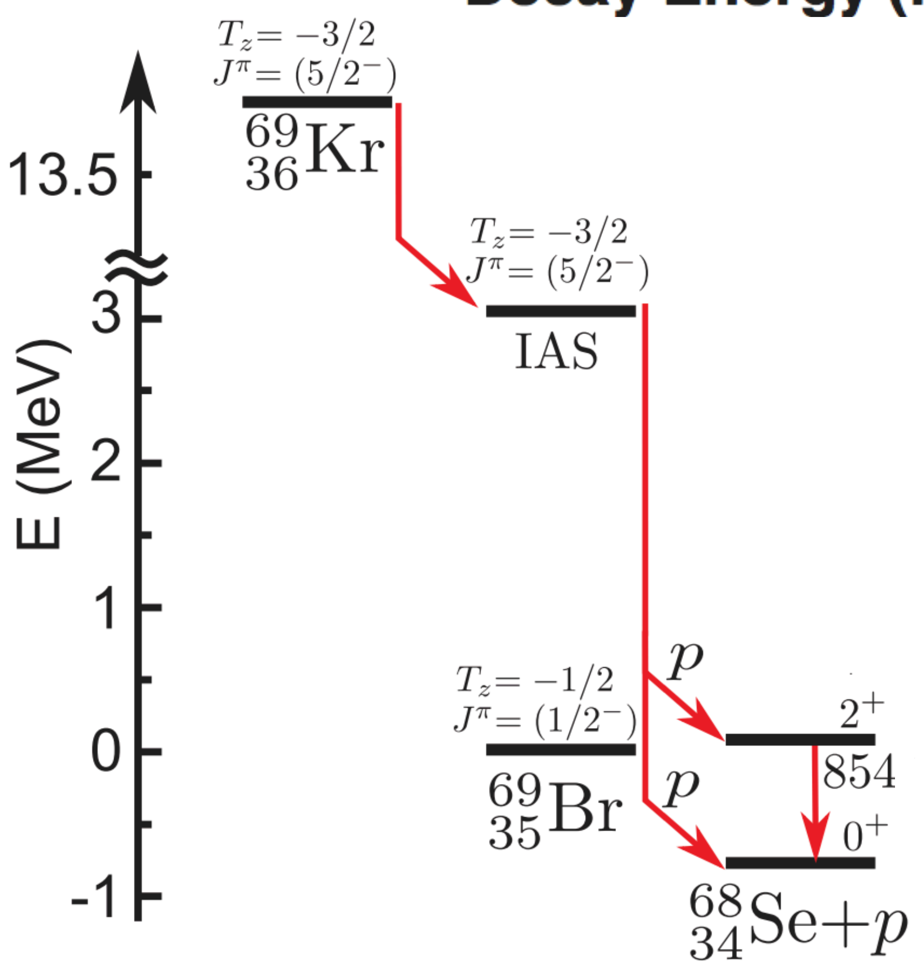
Evidence for Mirror-Symmetry Breaking

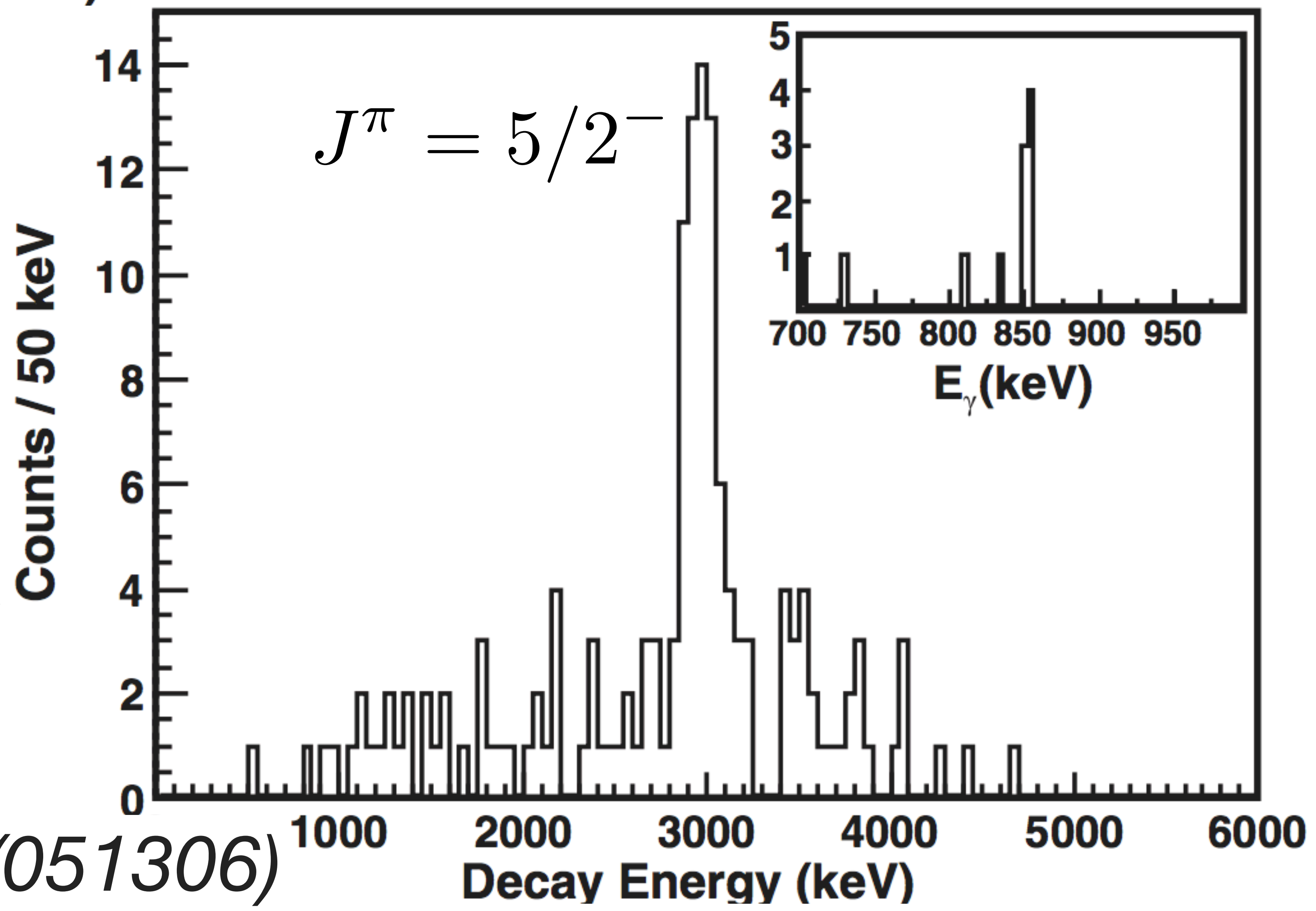




Charged-particle spectrum



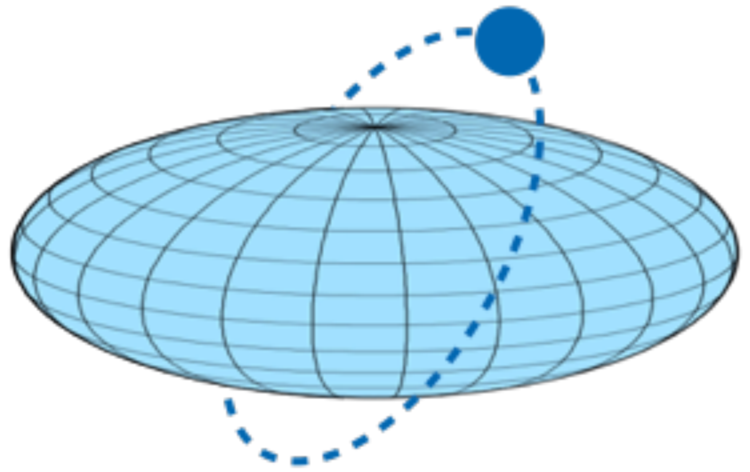




Rogers et al., *PRC 84 (051306)*

Evidence for Mirror-Symmetry Breaking

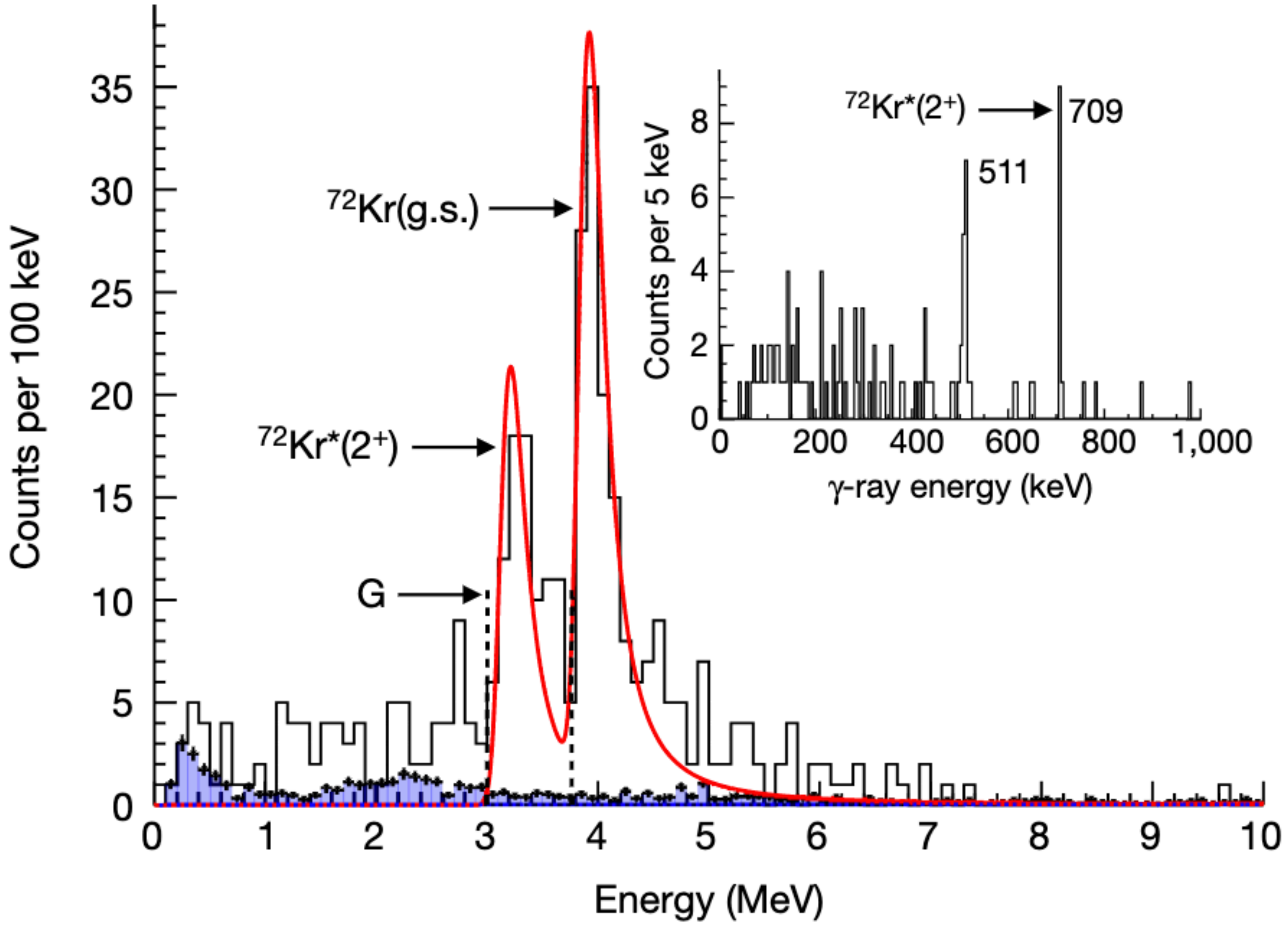
GCC Analysis by Simin Wang



Treat ^{73}Rb as deformed ^{72}Kr + valence proton

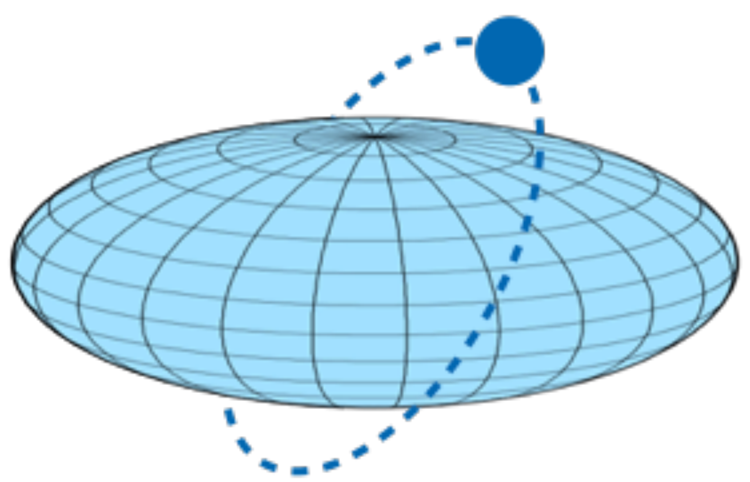
Transitions	Γ_p (keV)*	Branching	Configurations†
$5/2^- \to$ g.s. band (oblate)	1.8	49.6% 0^+ 49.5% 2^+ 1.1% 4^+	51.4%$(f_{5/2}, 0^+)$ 35.0%$(f_{5/2}, 2^+)$ 6.2%$(p_{1/2}, 2^+)$ 6.3%$(f_{5/2}, 4^+)$
$1/2^- \to$ g.s. band (oblate)	39.8	99.6% 0^+ 0.4% 2^+ 0.1% 4^+	78.8%$(p_{1/2}, 0^+)$ 19.8%$(f_{5/2}, 2^+)$ 1.0%$(p_{3/2}, 2^+)$ 0.4%$(h_{9/2}, 4^+)$
$5/2^- \to$ g.s. band (prolate)	7.3	8.2% 0^+ 90.5% 2^+ 1.2% 4^+	23.1%$(f_{5/2}, 0^+)$ 40.7%$(p_{1/2}, 2^+)$ 20.2%$(f_{5/2}, 2^+)$ 10.8%$(f_{5/2}, 4^+)$
$1/2^- \to$ g.s. band (prolate)	30.5	98.5% 0^+ 0.8% 2^+ 0.6% 4^+	52.3%$(p_{1/2}, 0^+)$ 42.8%$(f_{5/2}, 2^+)$ 2.6%$(p_{3/2}, 2^+)$ 1.9%$(h_{9/2}, 4^+)$

Charged-particle spectrum



Evidence for Mirror-Symmetry Breaking

GCC Analysis by Simin Wang



Treat ^{73}Rb as deformed ^{72}Kr + valence proton

Only 5/2$^-$ spin assignment is consistent with observed branching!

Transitions	Γ_p (keV)*	Branching	Configurations†
$5/2^- \to$ g.s. band (oblate)	1.8	49.6% 0^+ 49.5% 2^+ 1.1% 4^+	51.4%$(f_{5/2}, 0^+)$ 35.0%$(f_{5/2}, 2^+)$ 6.2%$(p_{1/2}, 2^+)$ 6.3%$(f_{5/2}, 4^+)$
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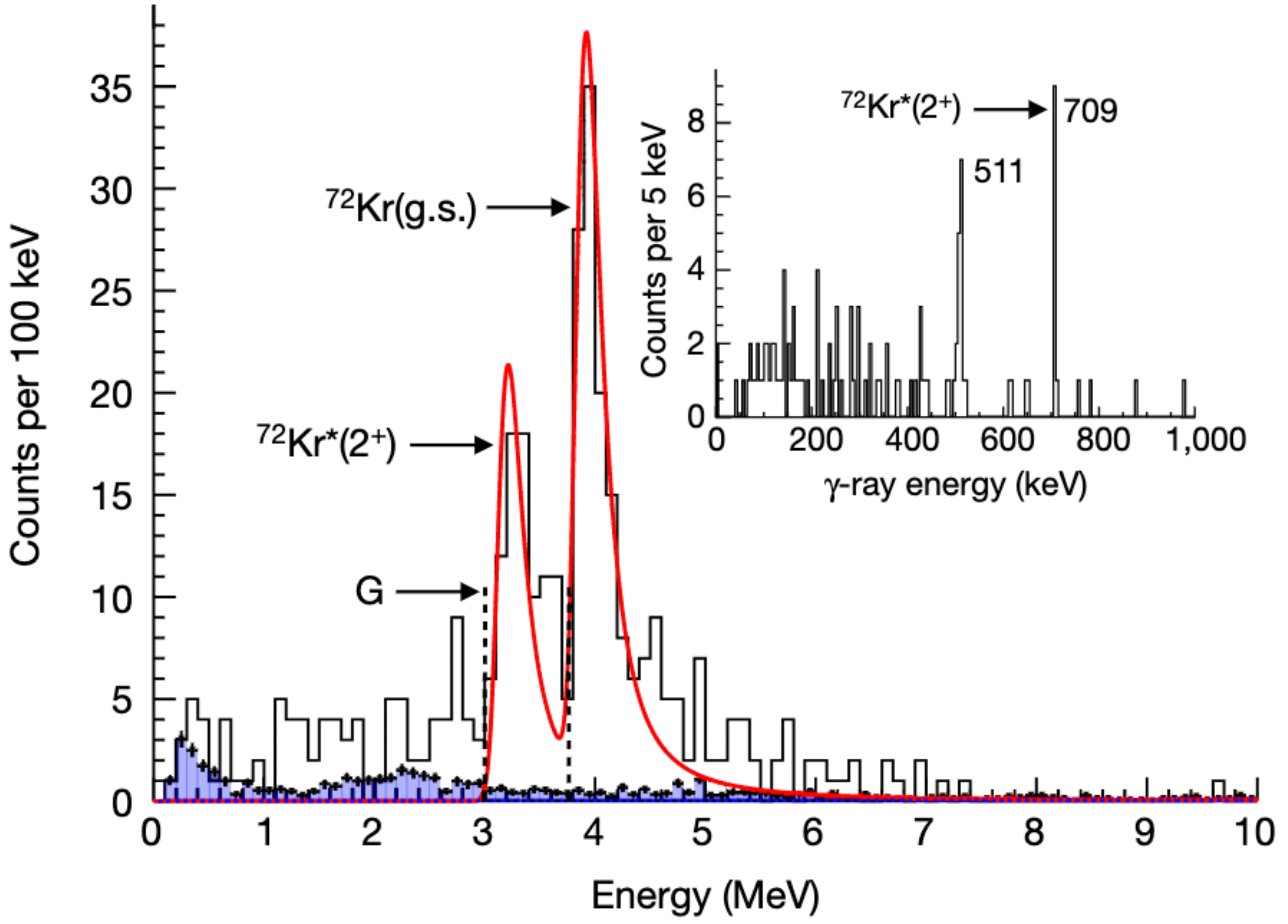
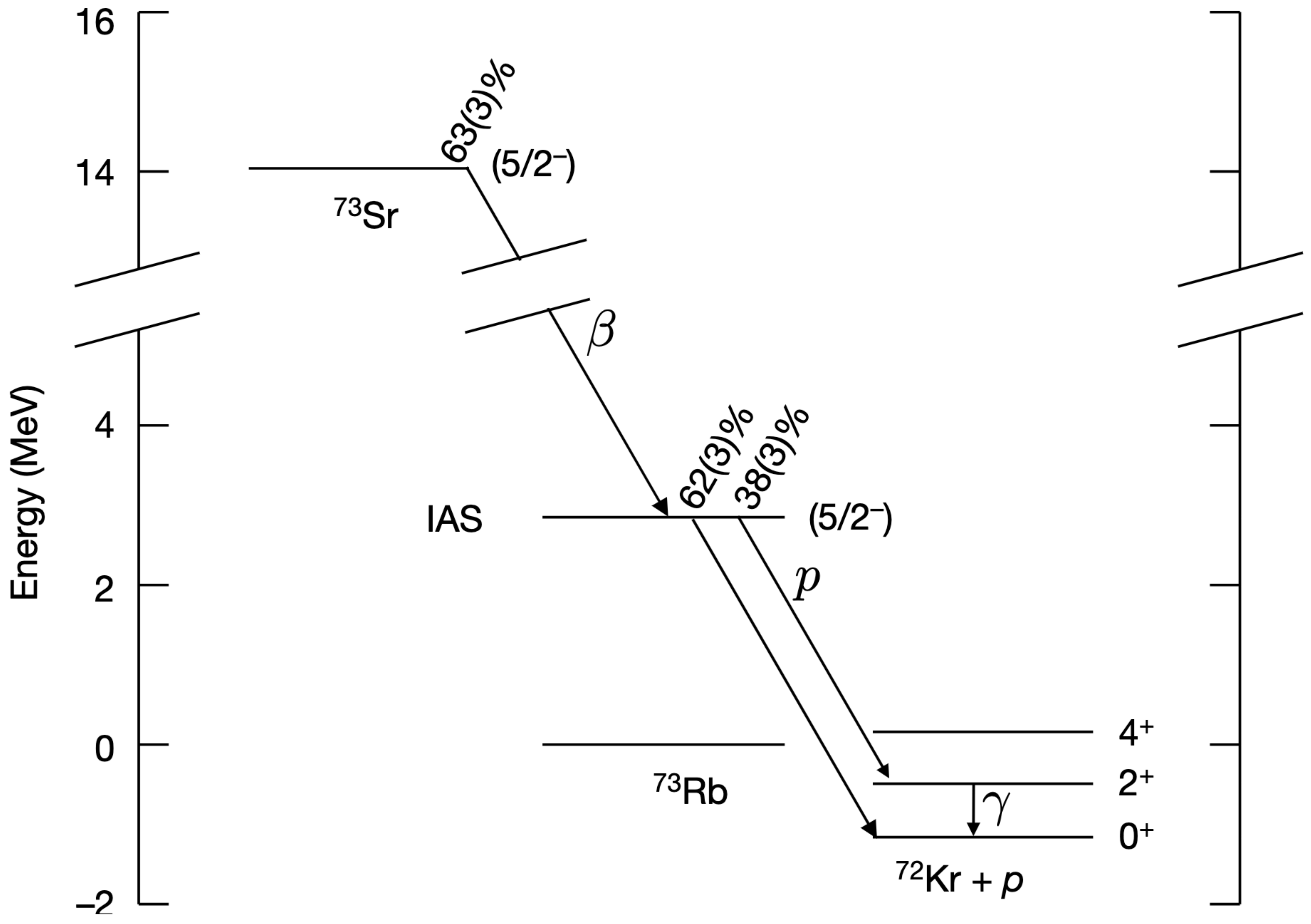
Charged-particle spectrum

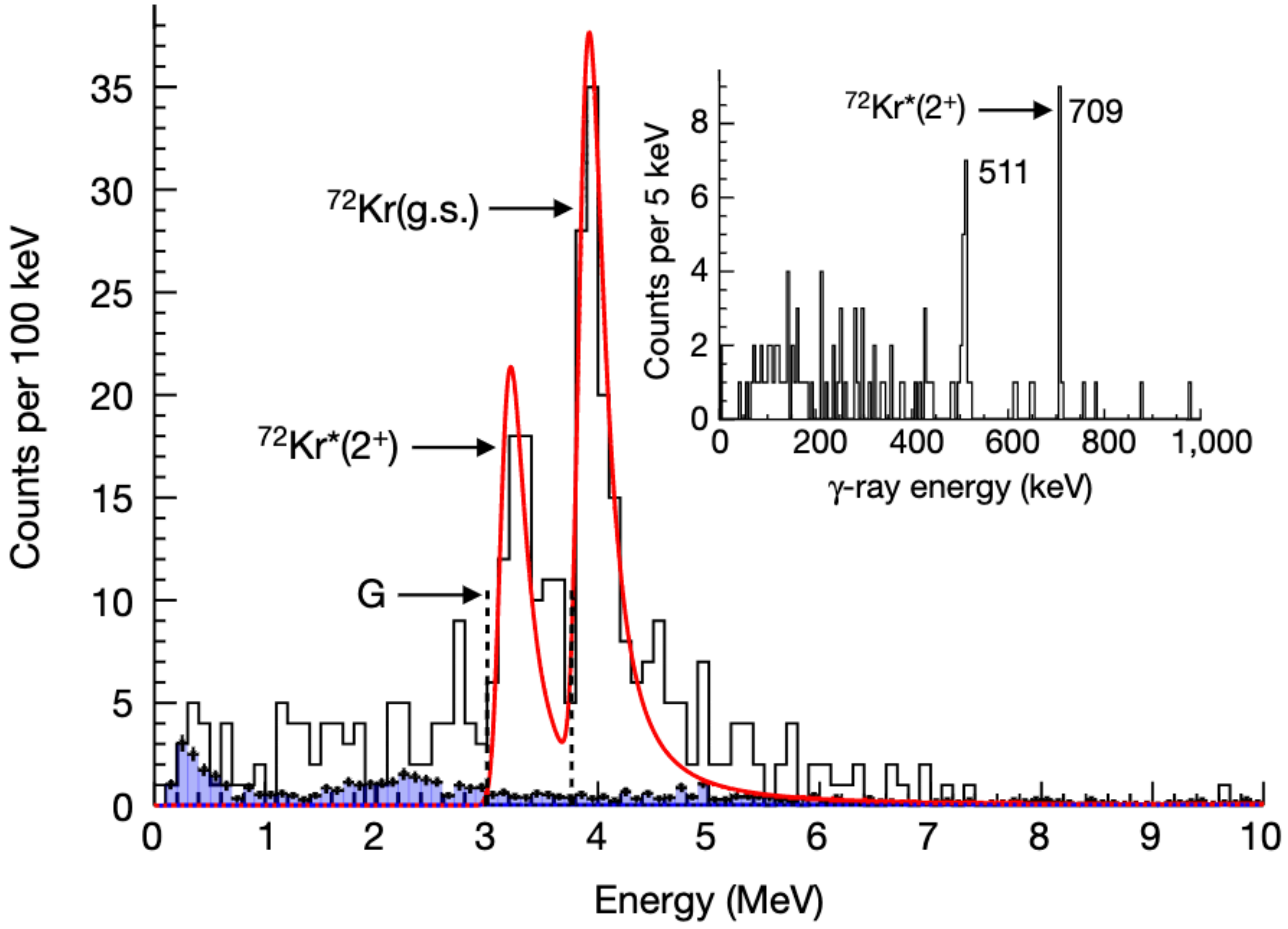


Small $p_{1/2}$ component allows for significant branching to first excited state of ^{72}Kr!

Evidence for Mirror-Symmetry Breaking



Charged-particle spectrum



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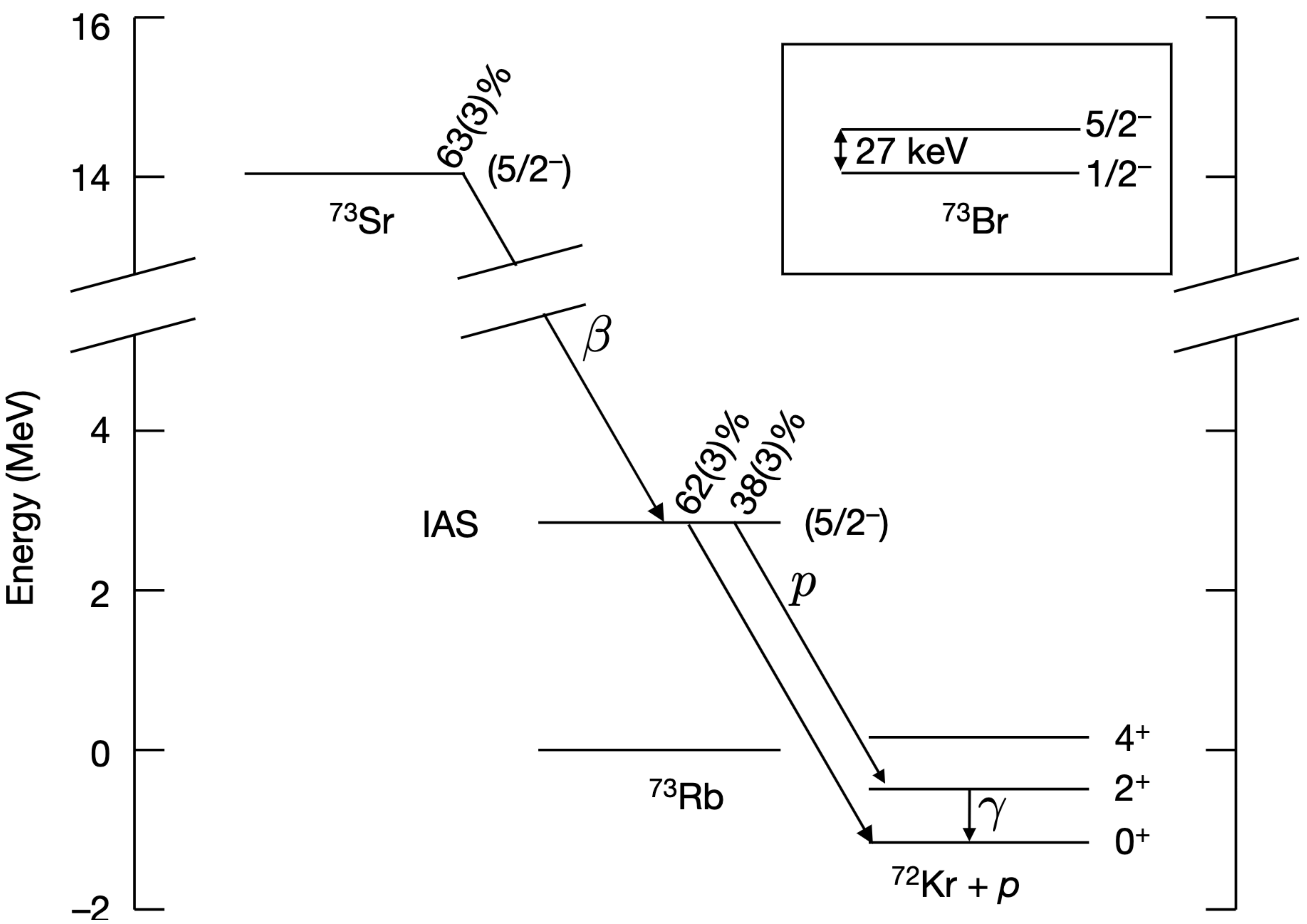
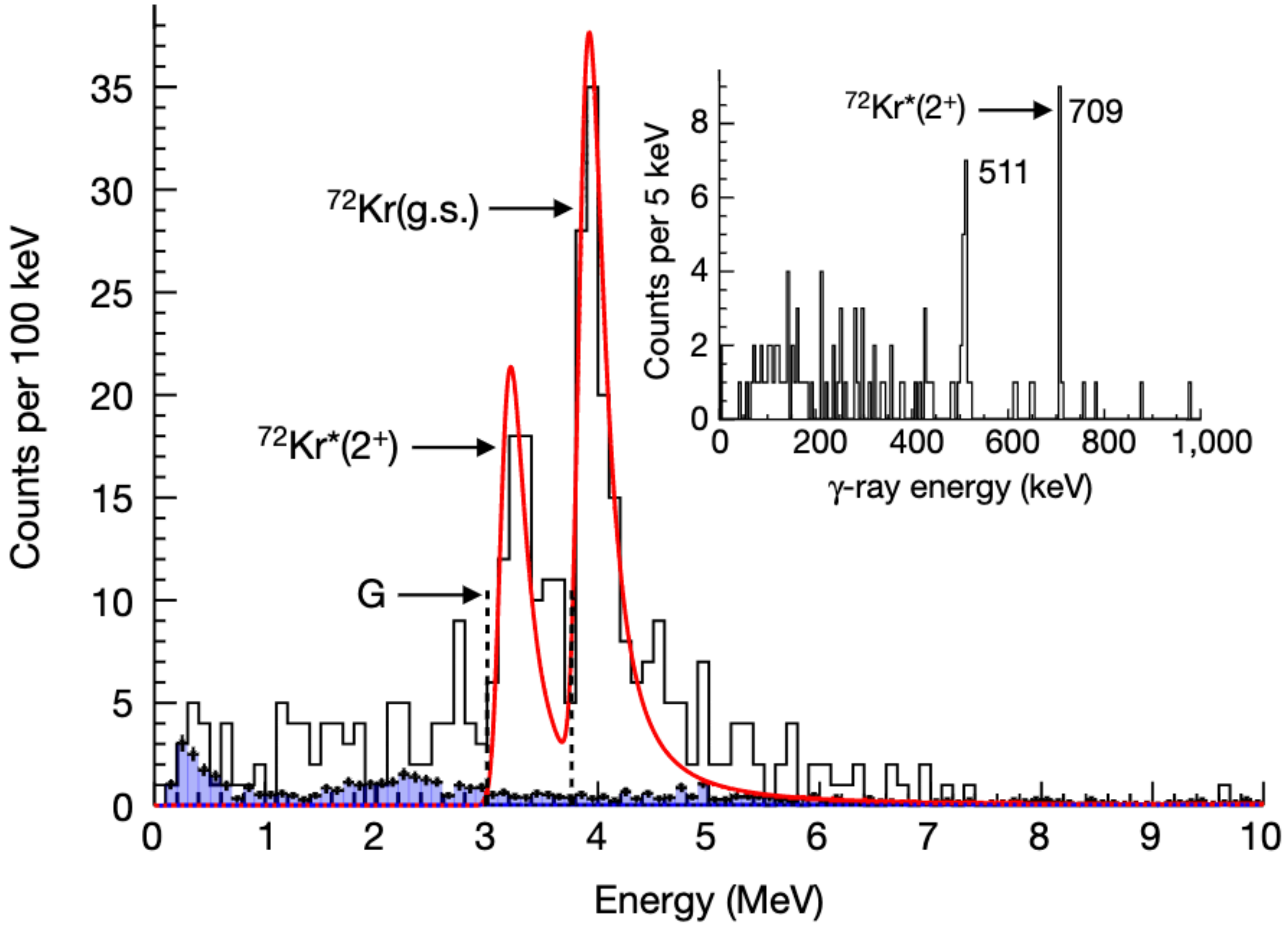
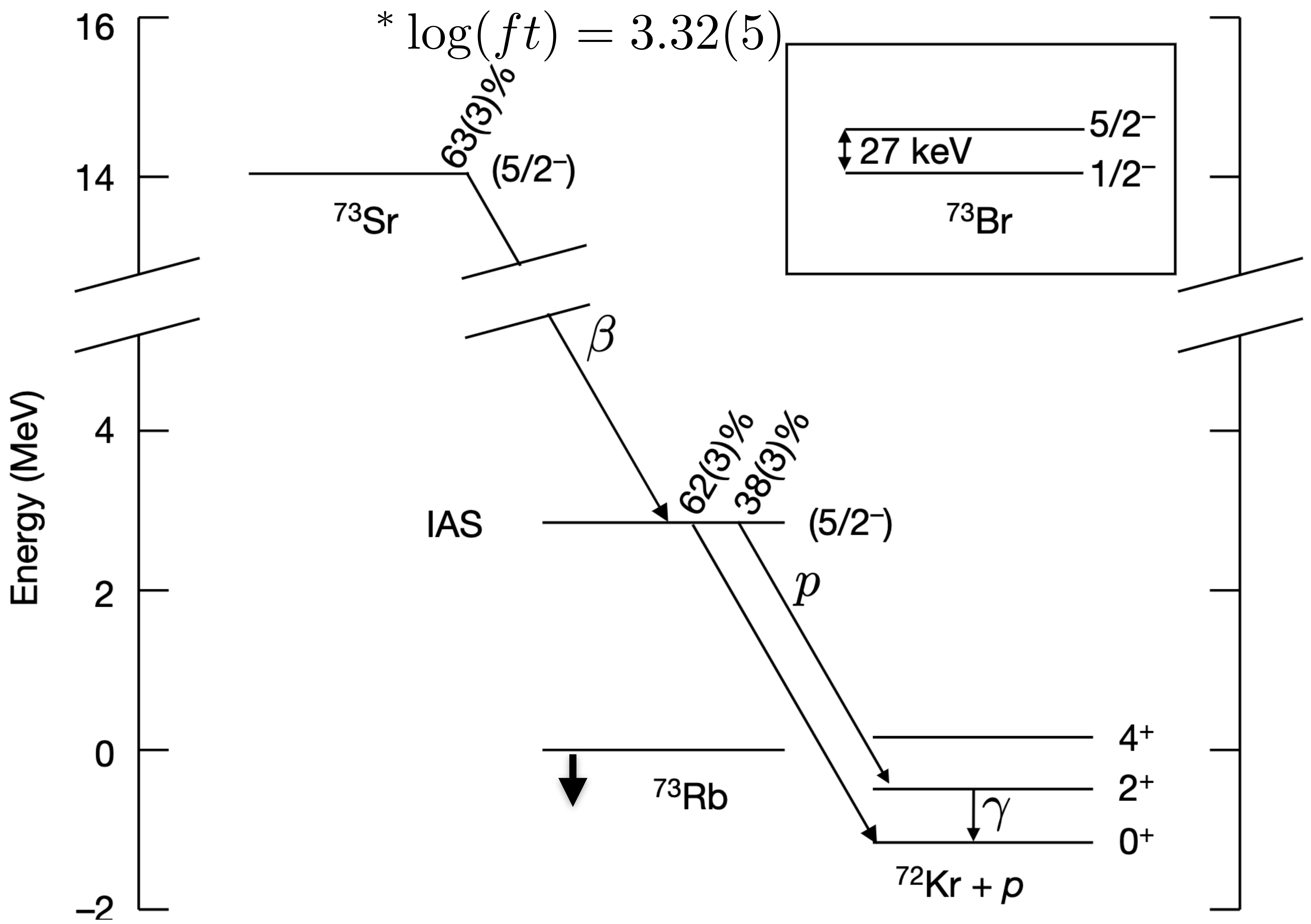
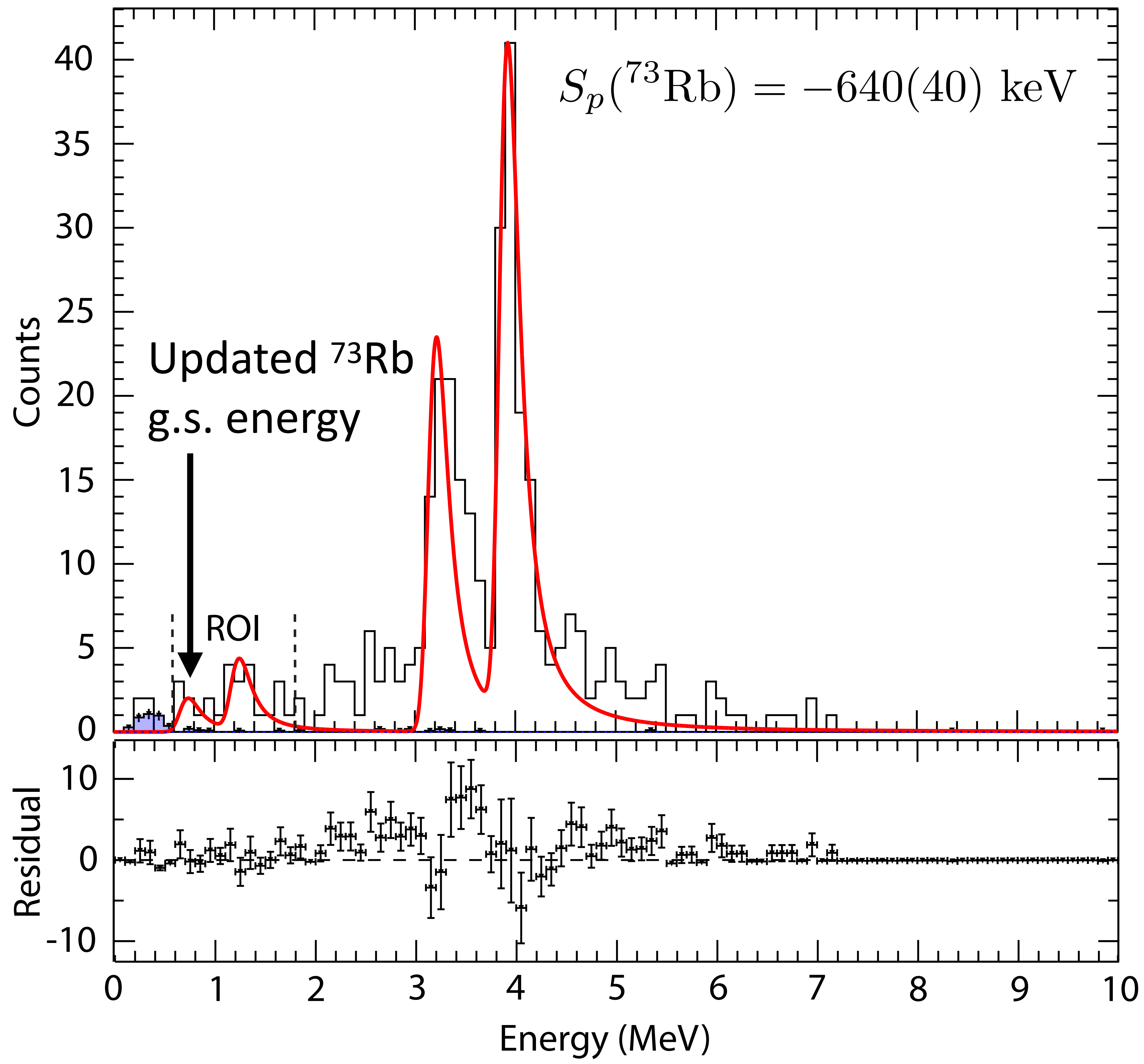


Charged-particle spectrum



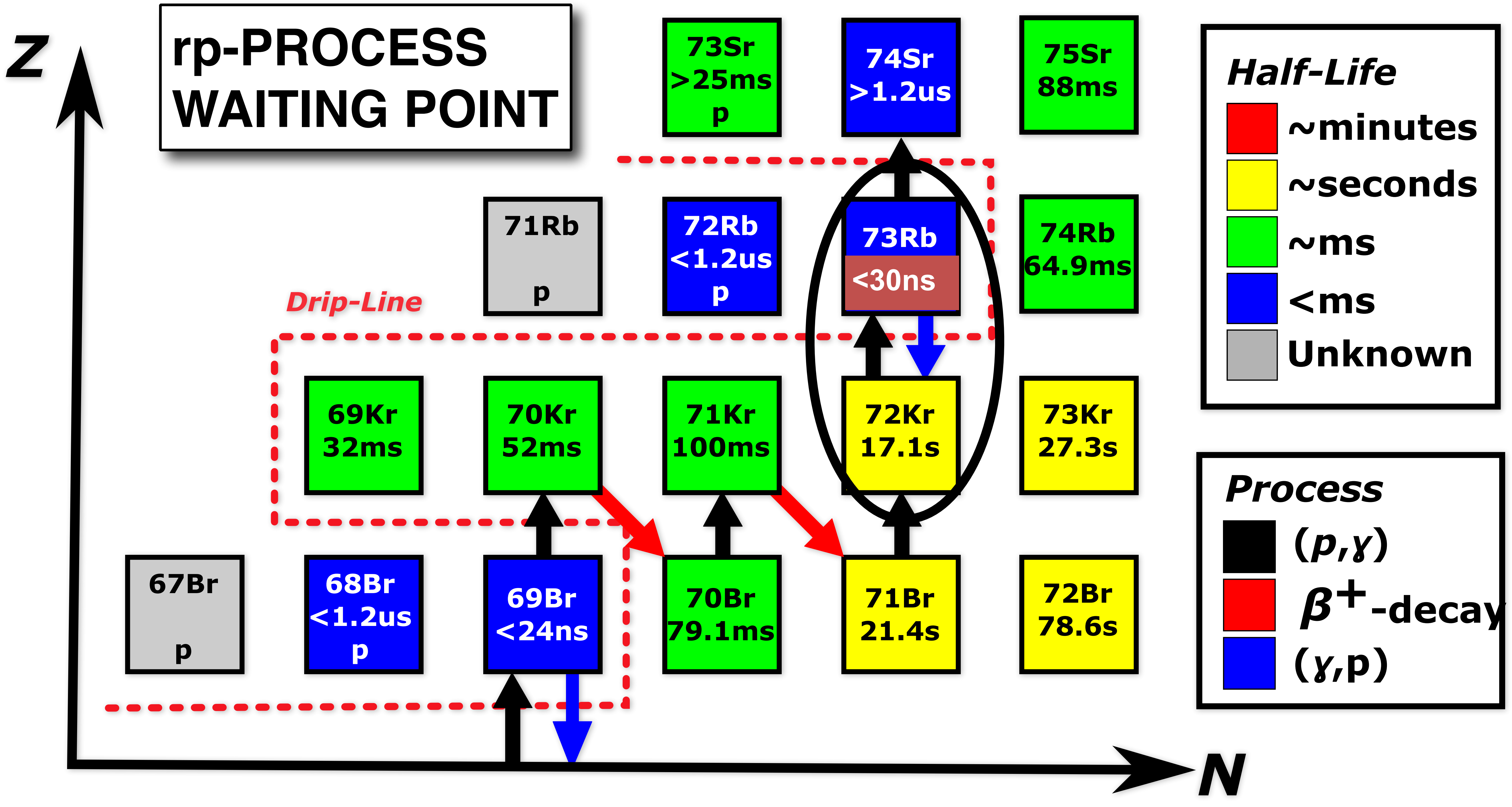
Updated ^{73}Rb g.s. energy

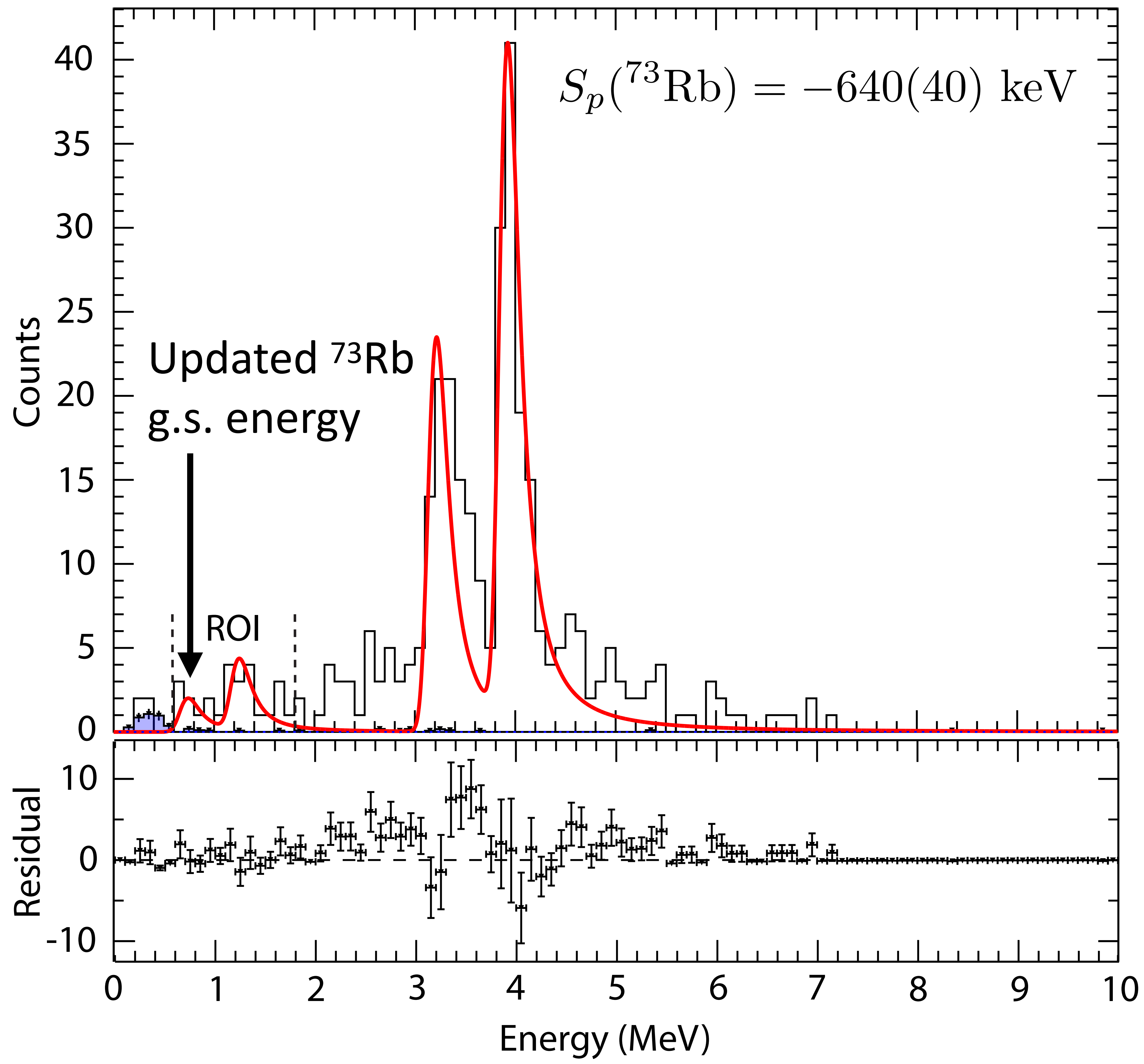




Filtered out a significant amount of background through event-by-event trace analysis.

Updated ^{73}Rb g.s. energy





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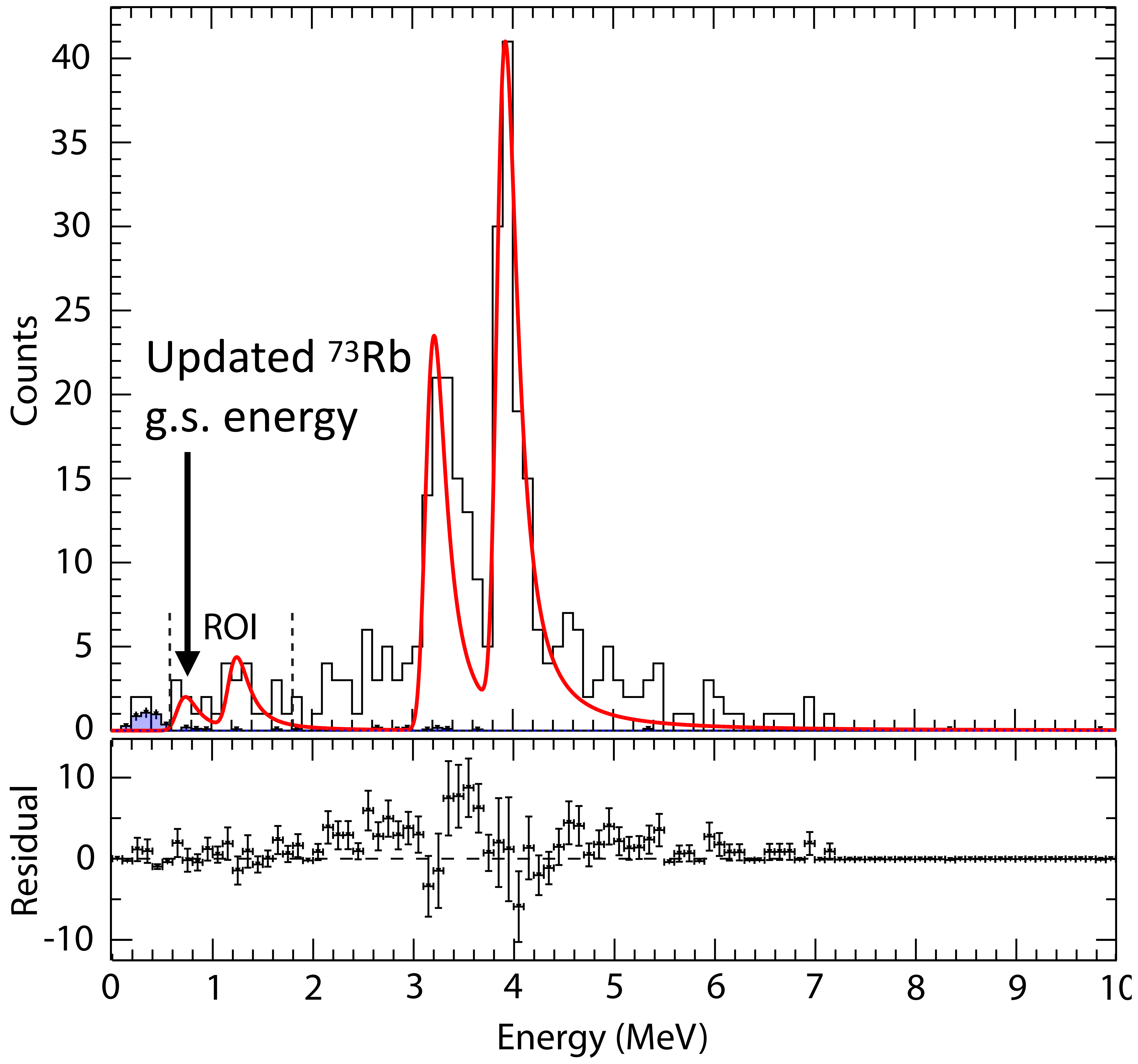
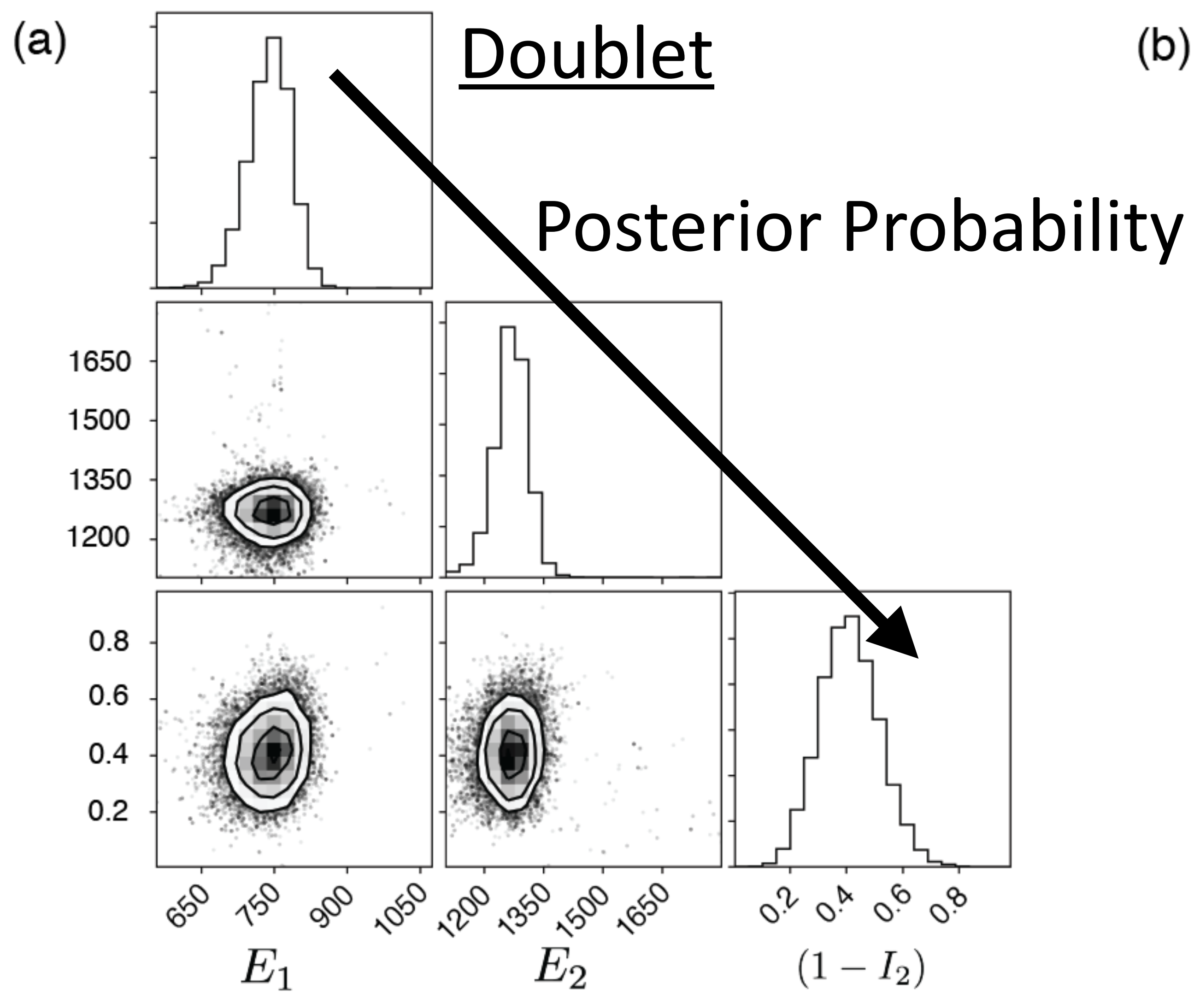
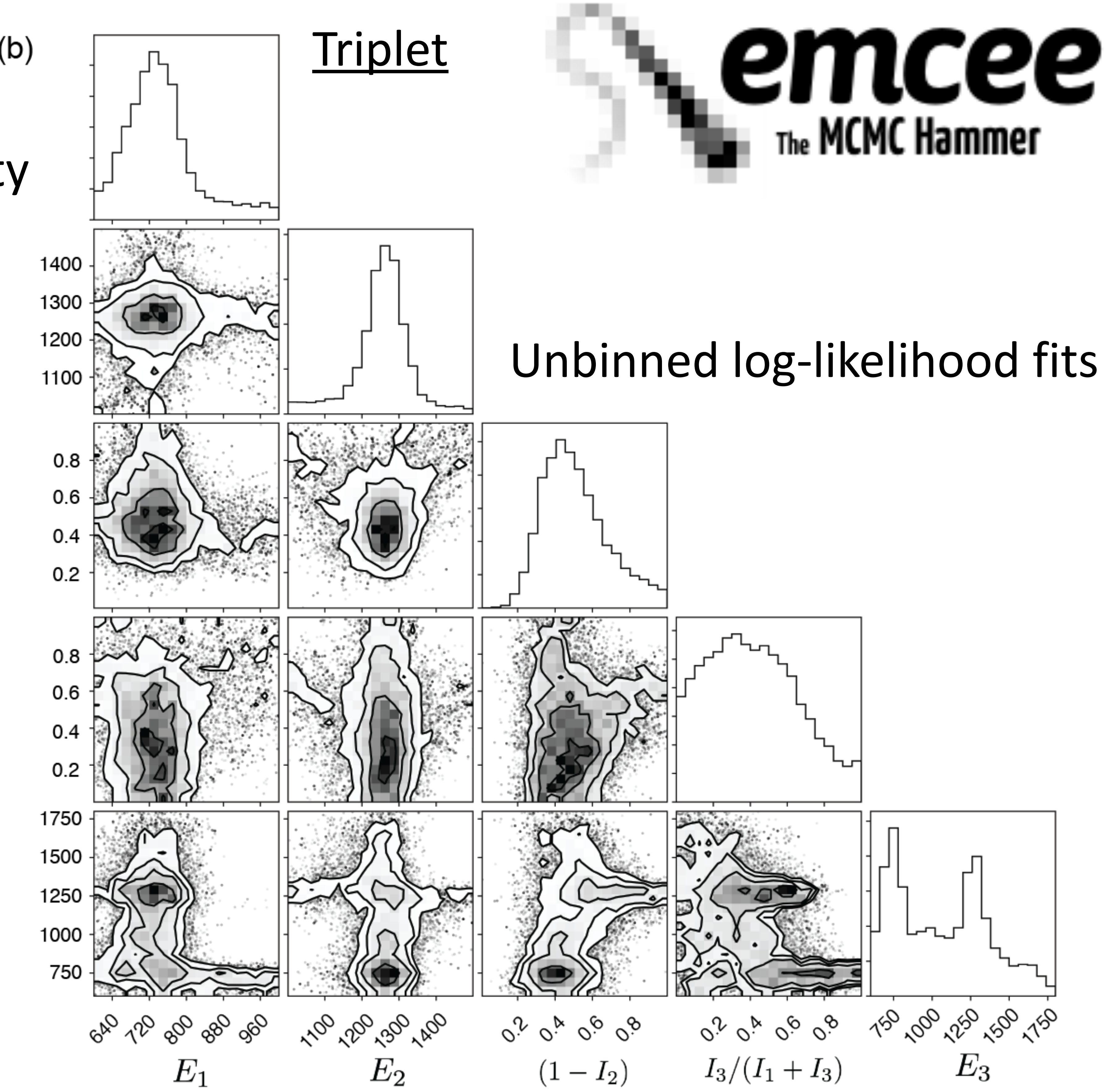
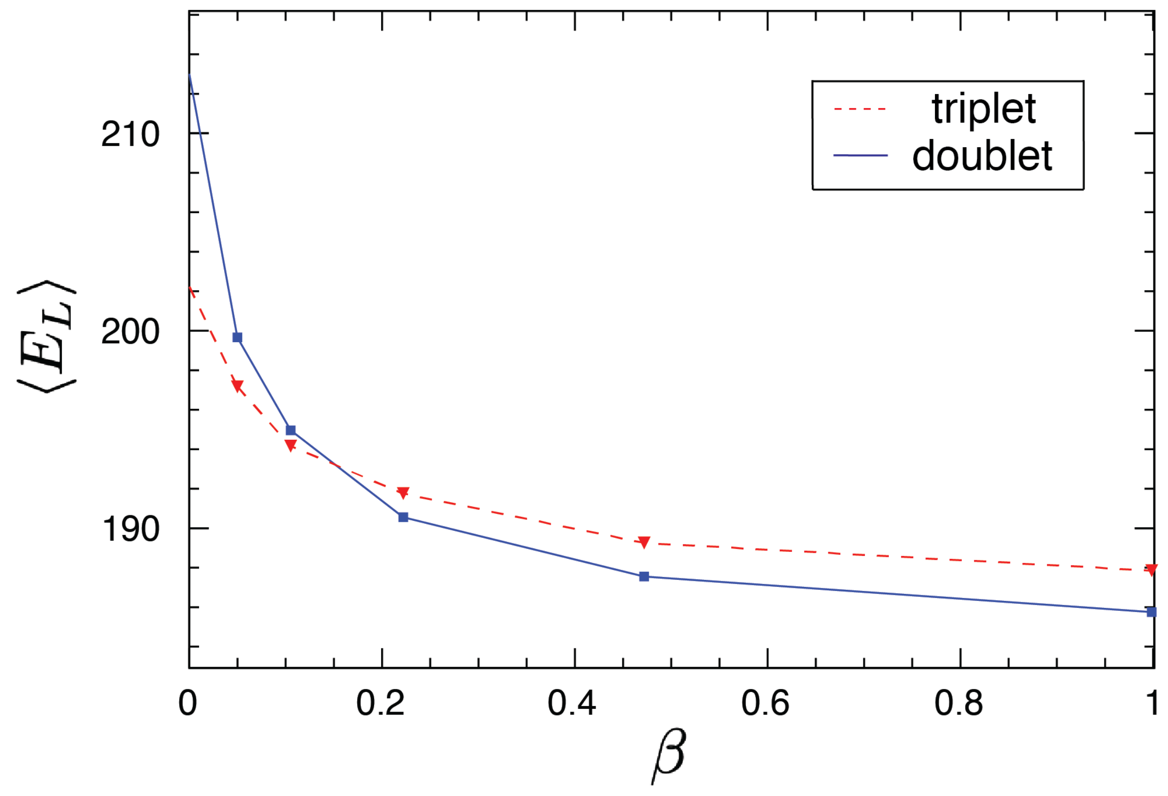
Bayesian Analysis





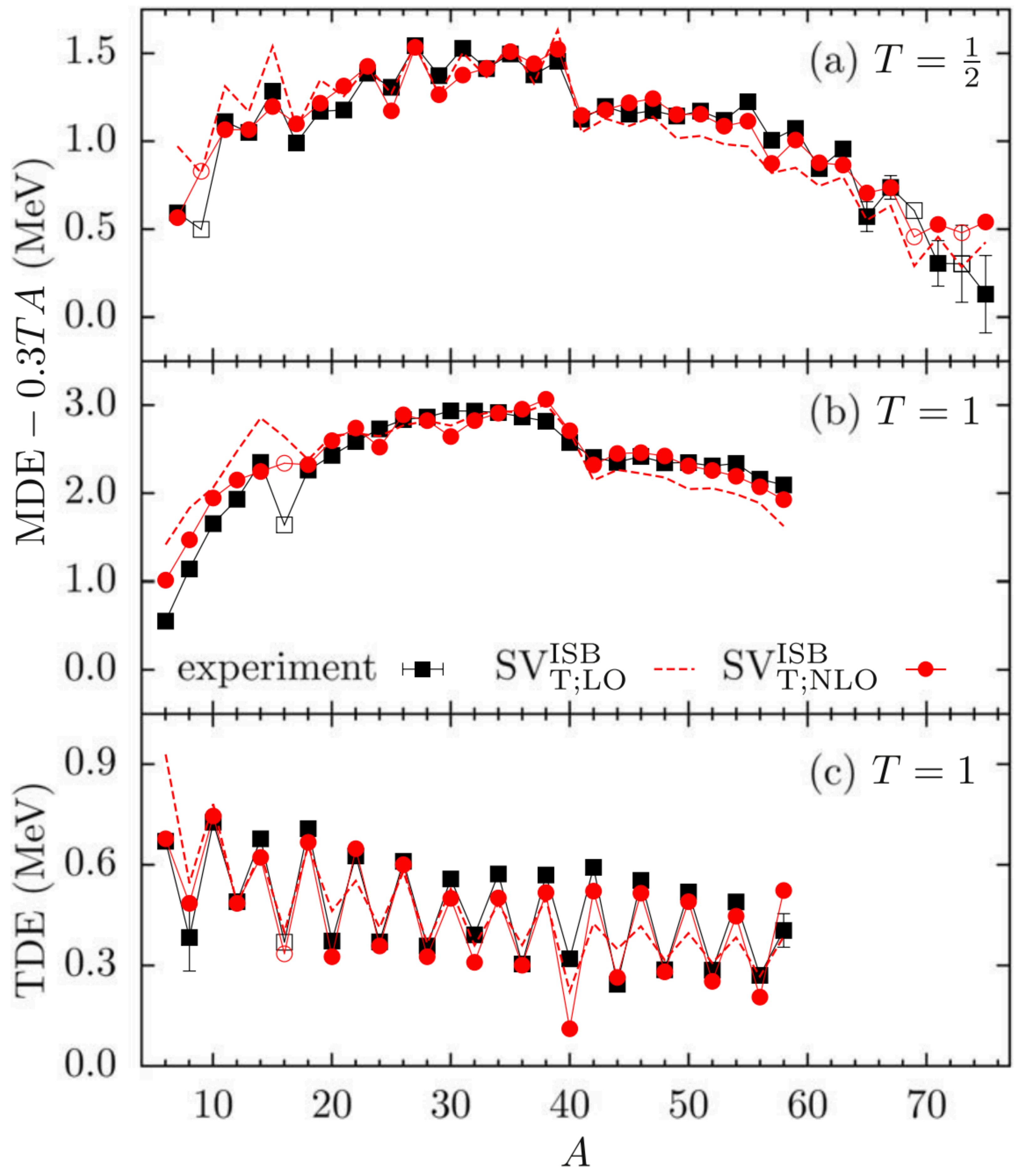




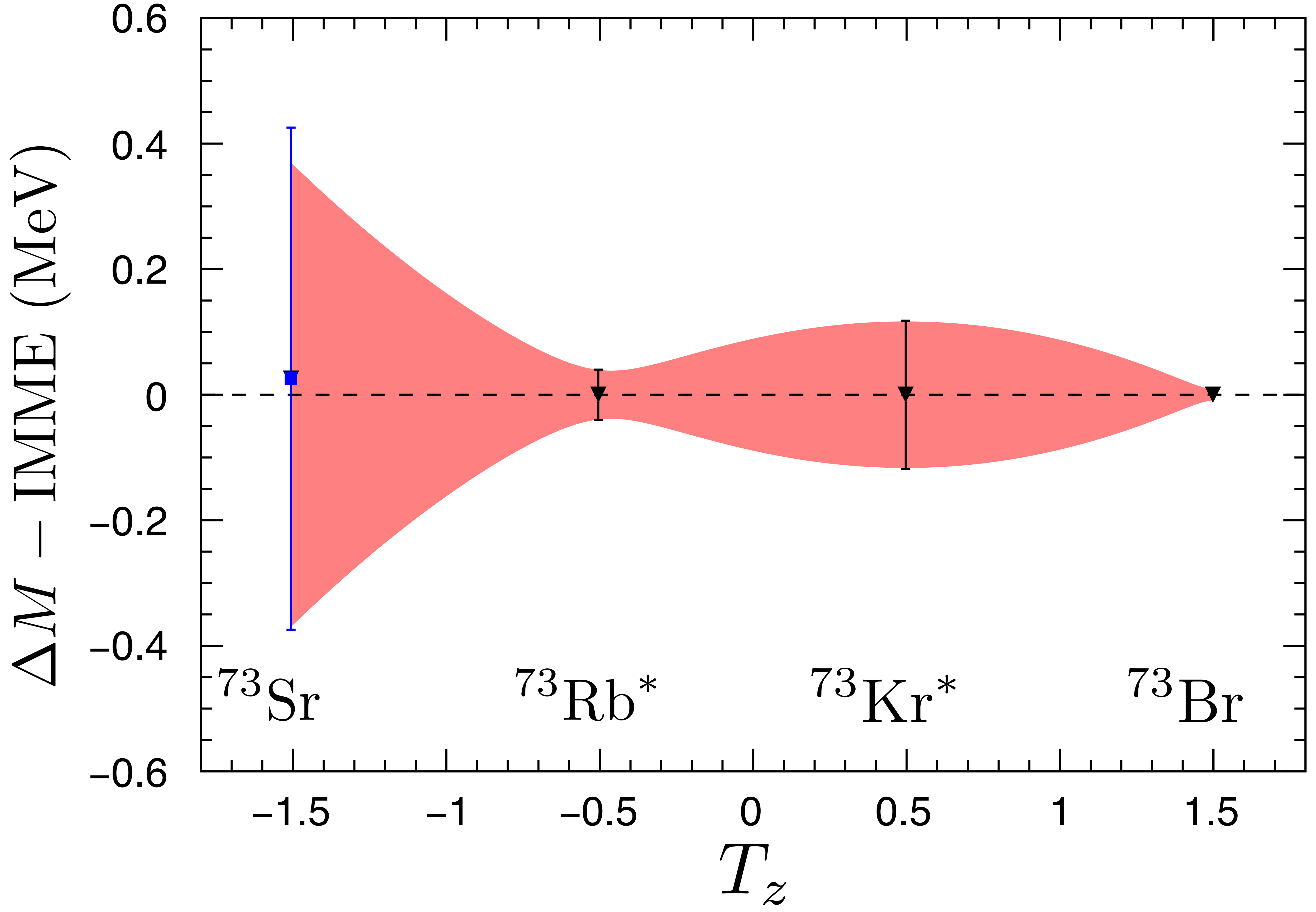
$\ln(L) \to \beta \ln(L)$

Thermodynamic annealing for Bayes' Factor:
Computationally expensive but no complicated integrals

IMME for A=73 T=3/2 multiplet



Used MEDs to see how much isospin breaking was needed in DFT calculations. Found similar Coulomb contributions to GFMC calculations in light nuclei.



Bączyk, P., Satuła, W., Dobaczewski, J., & Konieczka, M. *J. Phys. G, 03LT01*

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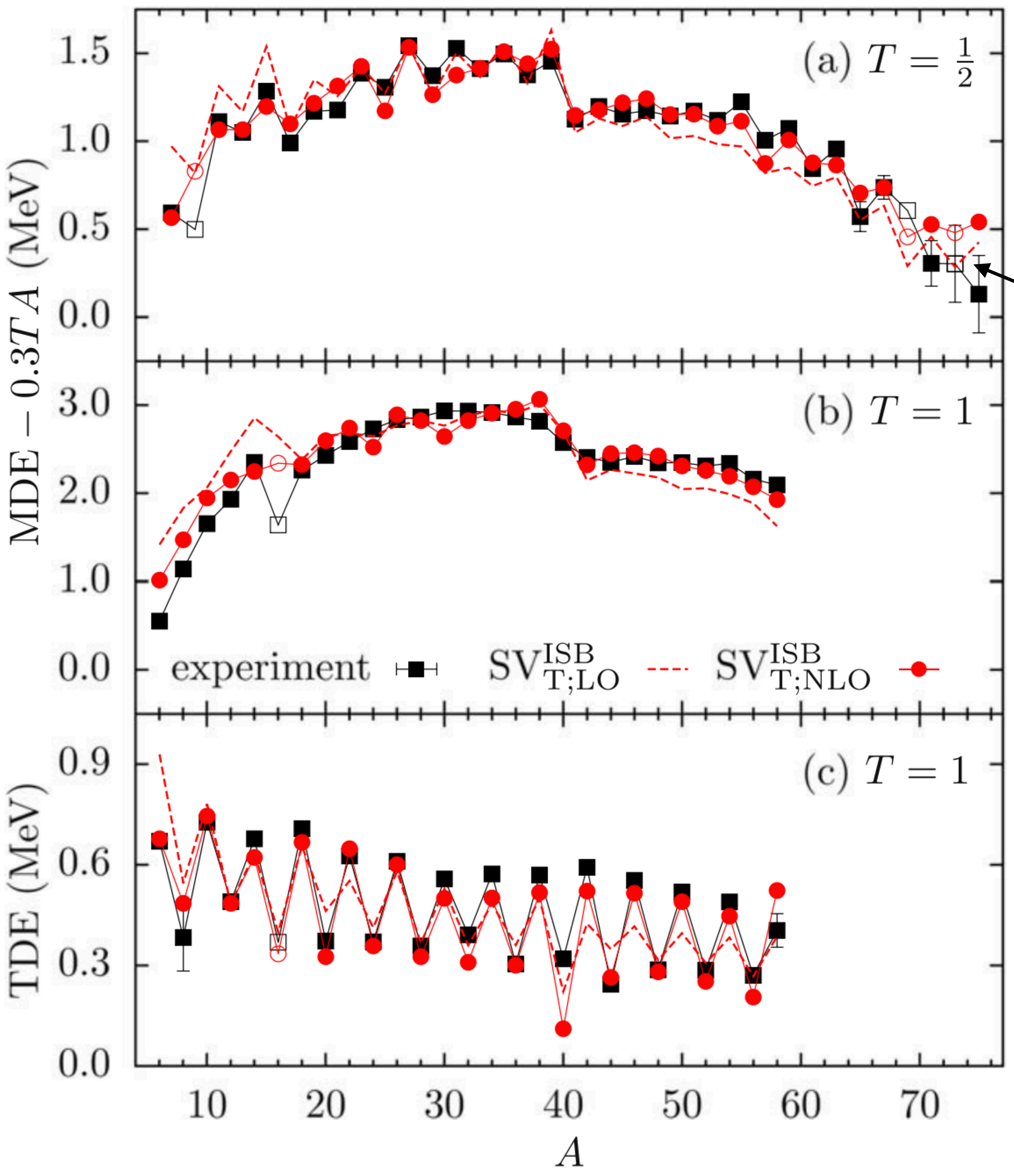
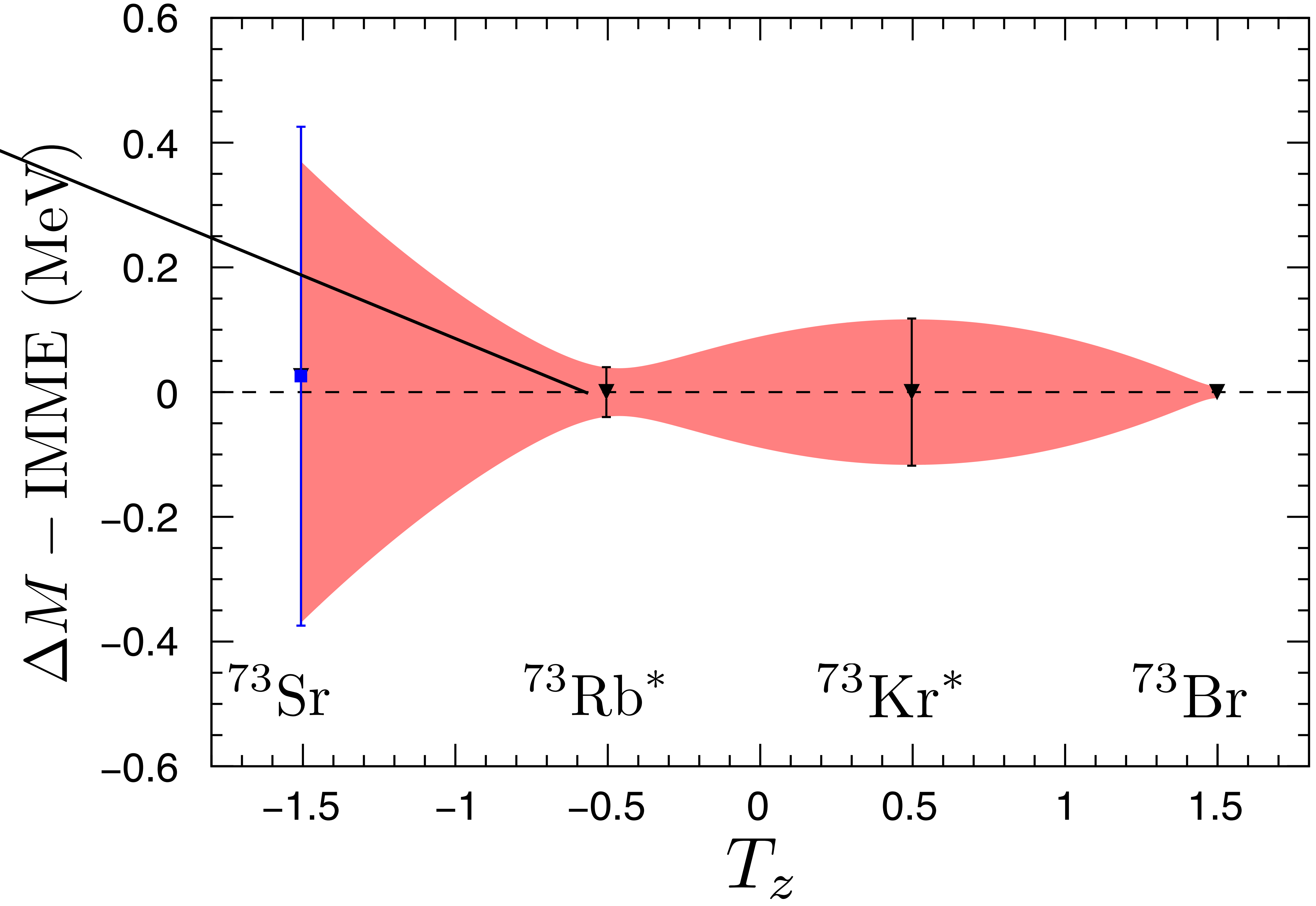


Used MDEs to see how much isospin breaking was needed in DFT calculations. Found similar Coulomb contributions to GFMC calculations in light nuclei.



Bączyk, P., Satuła, W., Dobaczewski, J., & Konieczka, M. *J. Phys. G, 03LT01*

Summary

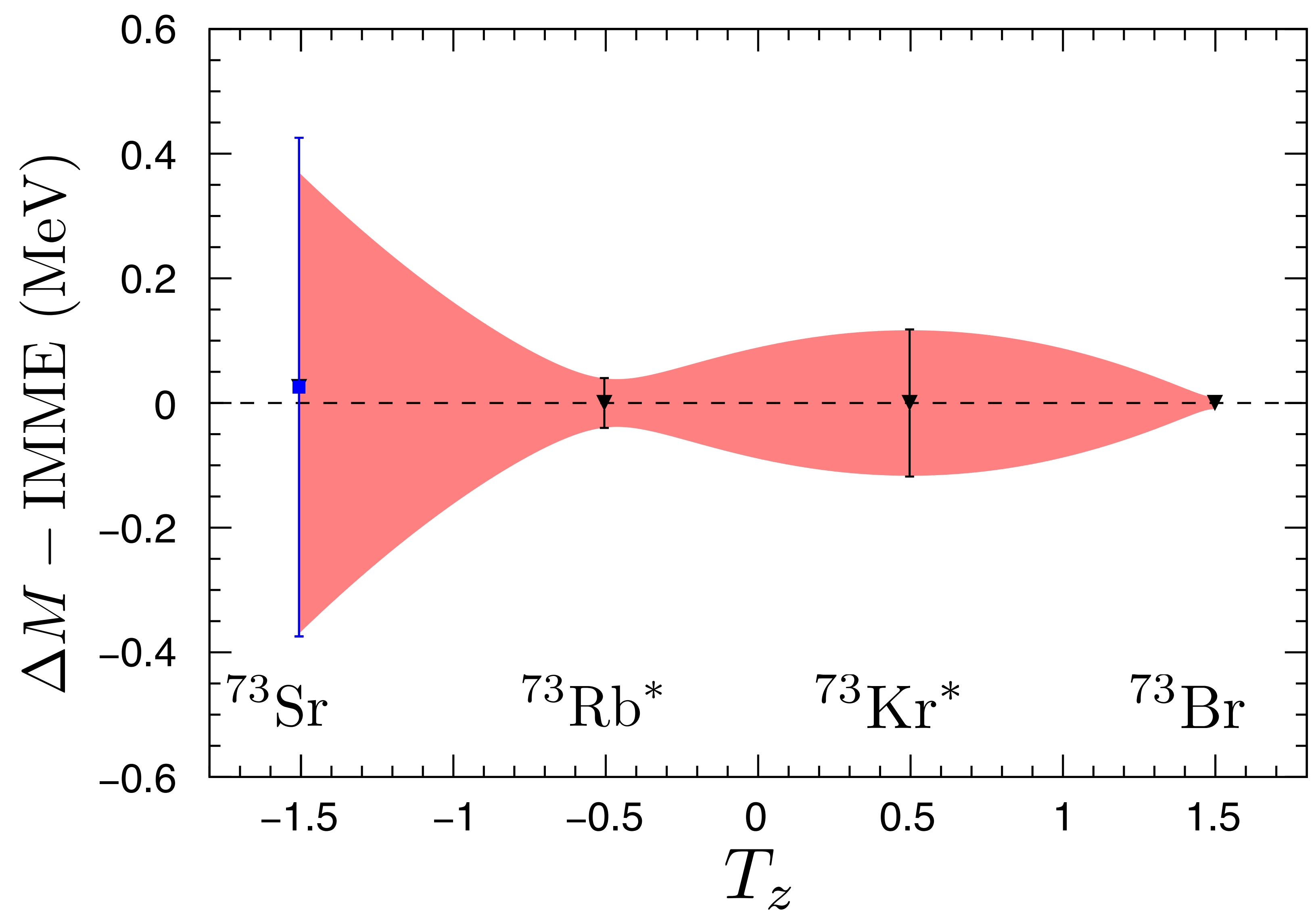
^{73}Sr ground state different w/ respect to mirror ^{73}Br in violation of mirror symmetry.

How can that come about?

- Likely rearrangement of almost degenerate g.s. between mirror pair.
- ^{73}Br assigned the wrong spin? (no direct measurements)
- Peculiar collective shape coexistence in this region of the chart?
- Charge-symmetry breaking in the nucleon-nucleon force?

Future Experiments:

- β-NMR of ^{73}Br & β-NMR of ^{73}Sr
- Precision Mass Measurement of ^{73}Sr to test IMME



Summary

^{73}Sr ground state different w/ respect to mirror ^{73}Br in violation of mirror symmetry.

Isospin symmetry breaking in the mirror pair ^{73}Sr-^{73}Br

S. M. Lenzi,[1] A. Poves,[2] and A. O. Macchiavelli[3]
[1] *Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, and INFN, Sezione di Padova, I-35131 Padova, Italy*
[2] *Departamento de Física Teórica and IFT-UAM/CSIC, Universidad Autónoma de Madrid, 28049 Madrid, Spain*
[3] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

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The recent experimental observation of isospin symmetry breaking (ISB) in the ground states of the $T = 3/2$ mirror pair ^{73}Sr-^{73}Br is theoretically studied using large-scale shell-model calculations. The large valence space and the successful PFSDG-U effective interaction used for the nuclear part of the problem capture possible structural changes and provide a robust basis to treat the ISB effects of both electromagnetic and nonelectromagnetic origin. The calculated shifts and mirror-energy differences are consistent with the inversion of the $I^\pi = 1/2^-, 5/2^-$ states between ^{73}Sr and ^{73}Br and suggest that the role played by the Coulomb interaction is dominant. An isospin breaking contribution of nuclear origin is estimated to be $\approx$25 keV.

DOI: 10.1103/PhysRevC.102.031302

- Charge-symmetry breaking in the nucleon-nucleon force?

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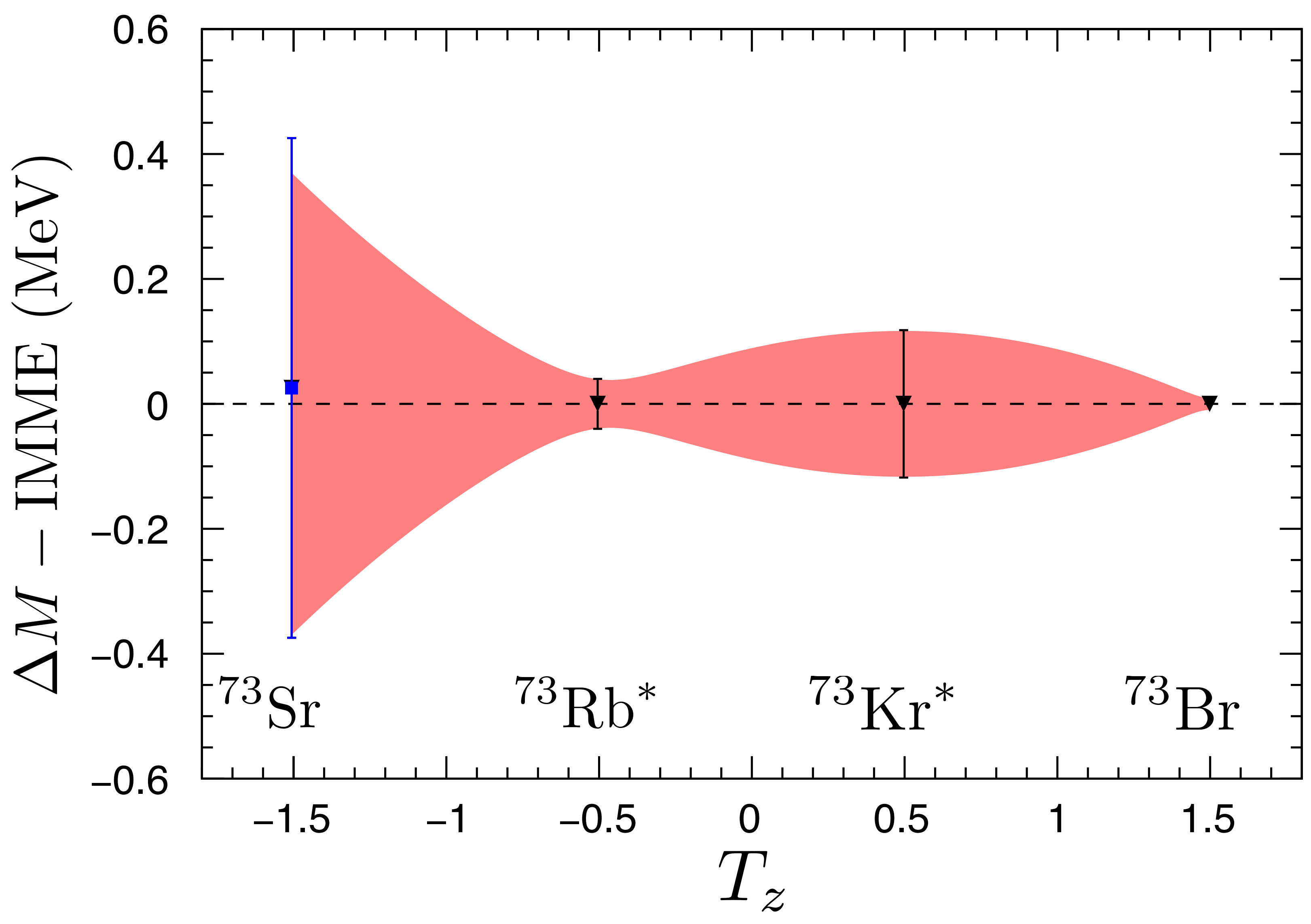

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Mirror-symmetry violation in bound nuclear ground states

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D. E. M. Hoff[1]✉, A. M. Rogers[1]✉, S. M. Wang[2], P. C. Bender[1], K. Brandenburg[3], K. Childers[2,4], J. A. Clark[5], A. C. Dombos[2,6,7], E. R. Doucet[1], S. Jin[2,7], R. Lewis[2,4], S. N. Liddick[2,4], C. J. Lister[1], Z. Meisel[3], C. Morse[1,9], W. Nazarewicz[6,8], H. Schatz[2,6,7], K. Schmidt[2,7,10], D. Soltesz[3], S. K. Subedi[3] & S. Waniganeththi[1]

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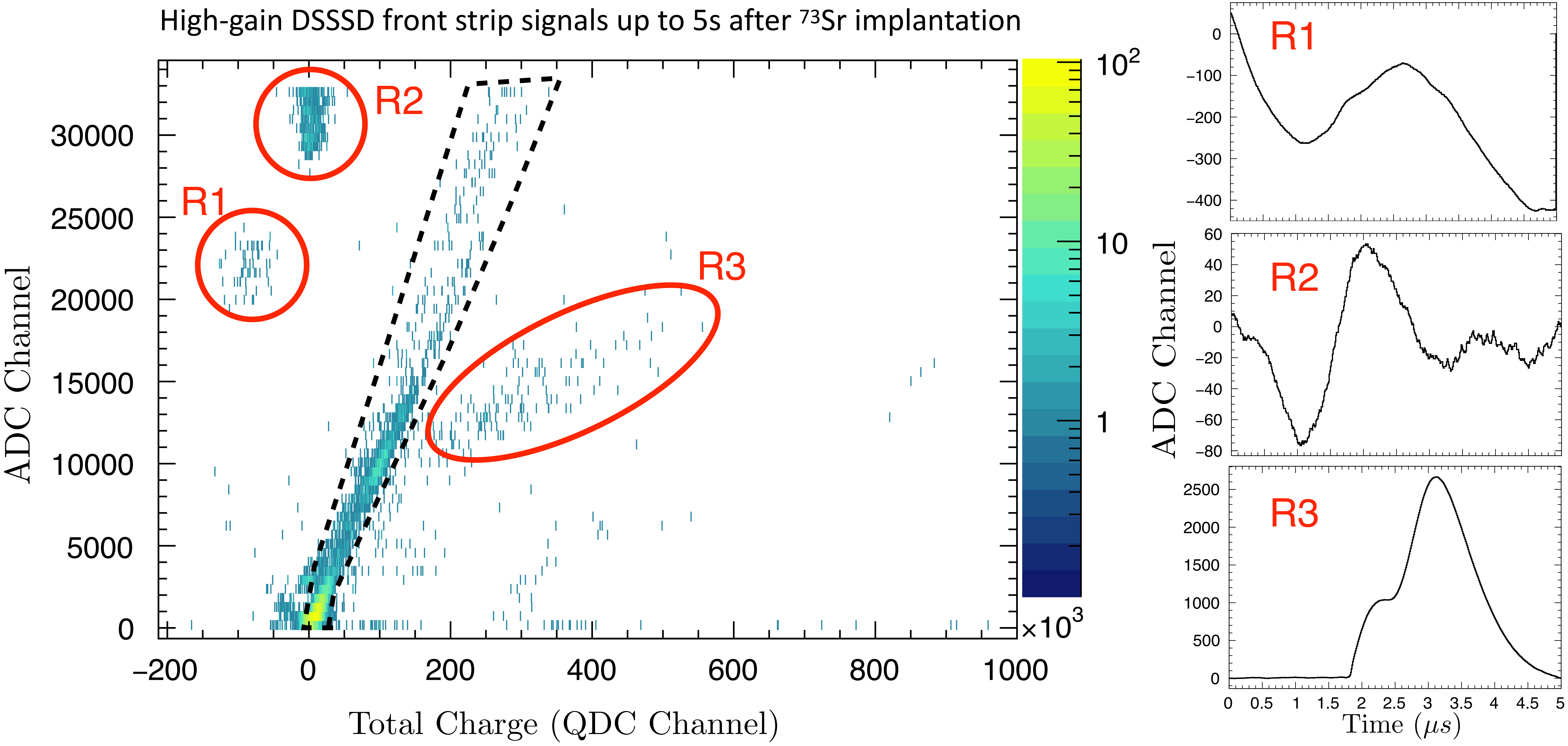
Public Full Access Link: https://rdcu.be/b3lHY

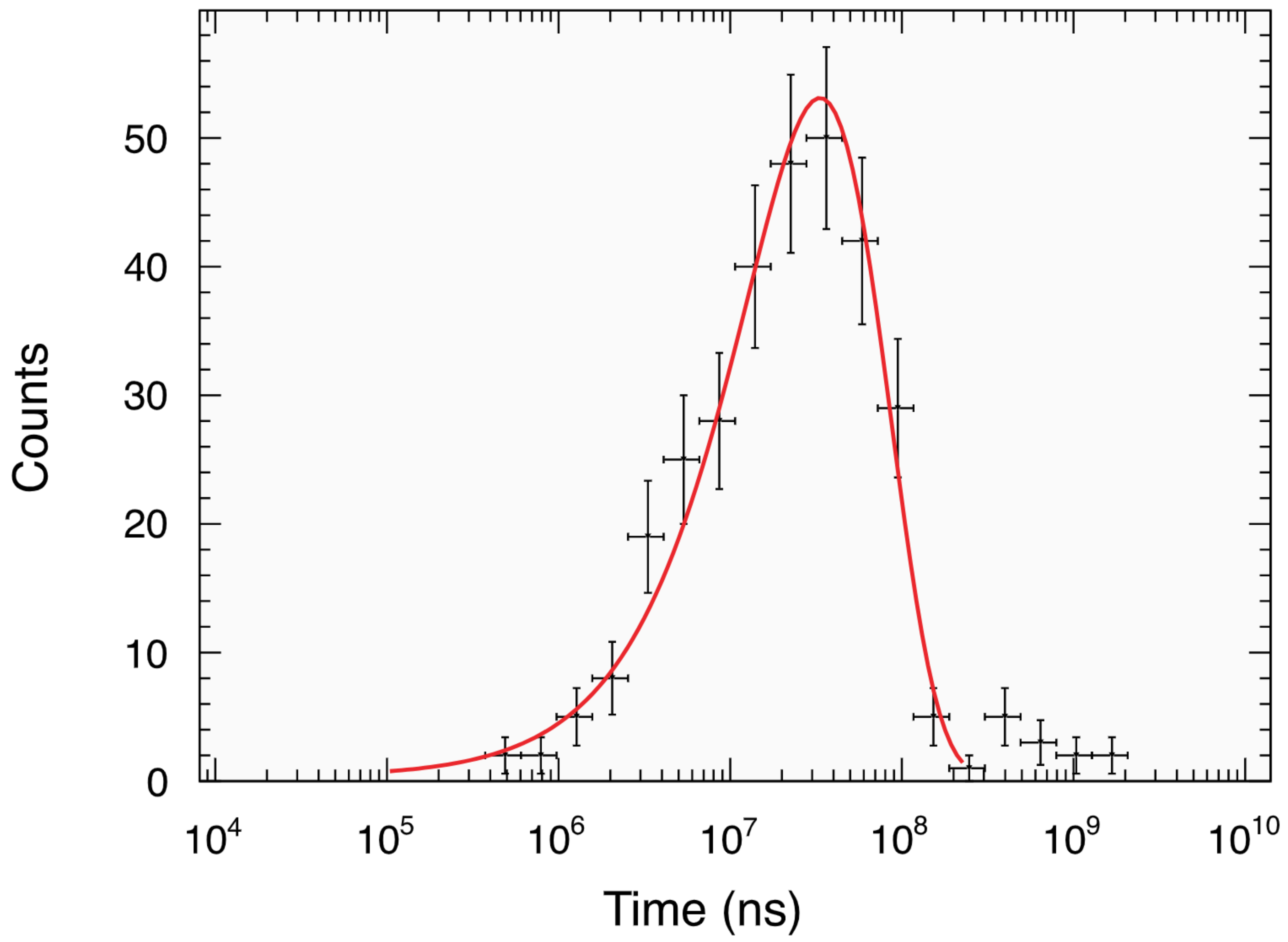
Trace Analysis

High-gain DSSSD front strip signals up to 5s after ^{73}Sr implantation



Potential β-decaying Isomer?

Time between implantation and first decay event with logarithmic bins

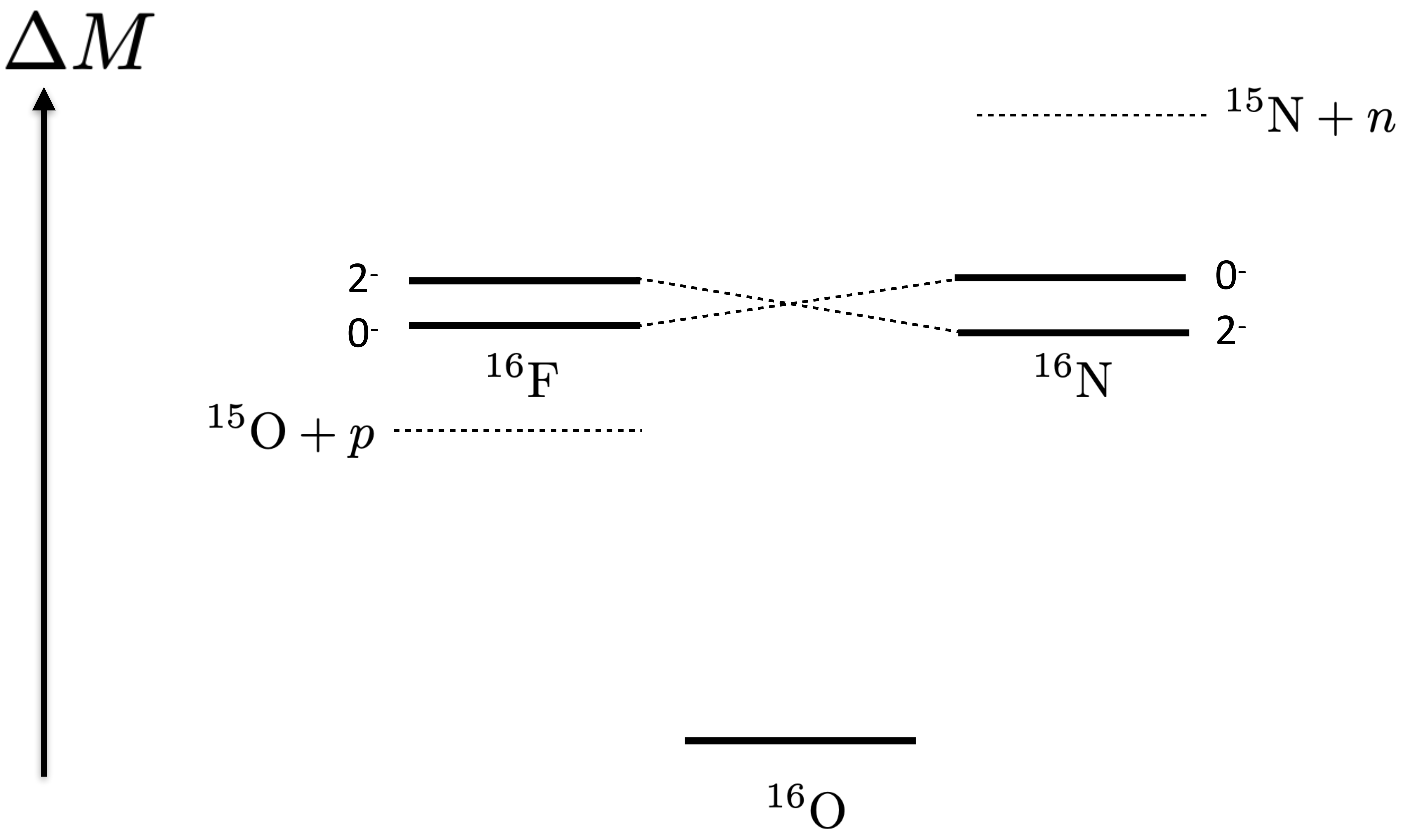


- Only evidence for one species, or multiple with nearly identical half-lives
- After implantation, internal conversion will become competitive decay mode of isomer.
  - Given systematics in the region, assuming ~10 keV E2 transition ($1/2^-$ —> $5/2^-$) internal conversion should have 1-100 microsecond halflife.
  - Our dead time ~5 microseconds
  - Gating on prominent energy peaks in charged-particle spectrum produce the same halflife.

No evidence for β-decaying isomer.

Thomas-Ehrman Shift

$^{16}F/^{16}N$ case well-explained by Thomas-Ehrman shift!



- Thomas and Ehrman independently showed that unbound proton *s* states are shifted less by Coulomb interaction
  - Unbound proton *s* state extends well outside the nucleus resulting in reduced Coulomb energy shift

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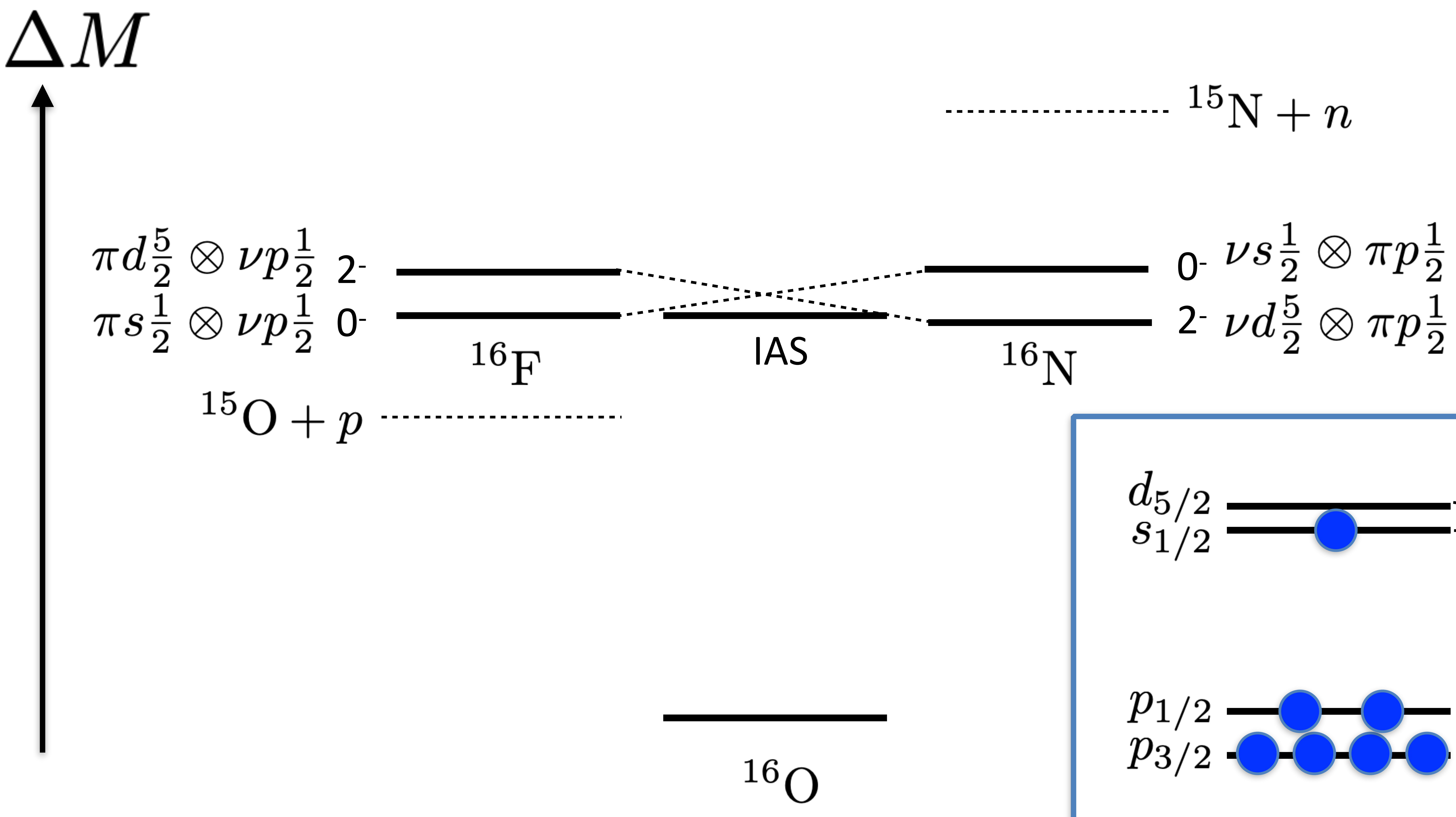

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