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Innovations in Nuclear Resonance Fluorescence with the Clover Array

Samantha R. Johnson

20 September 2025

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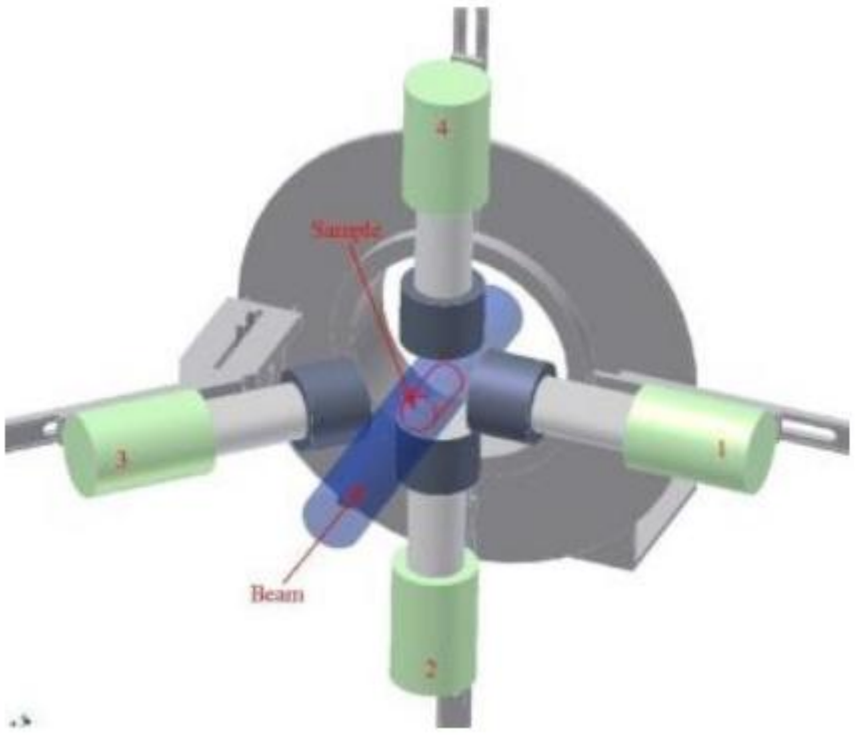
I first met Robert as an REU student at TUNL in the summer of 2018

Robert and Samantha

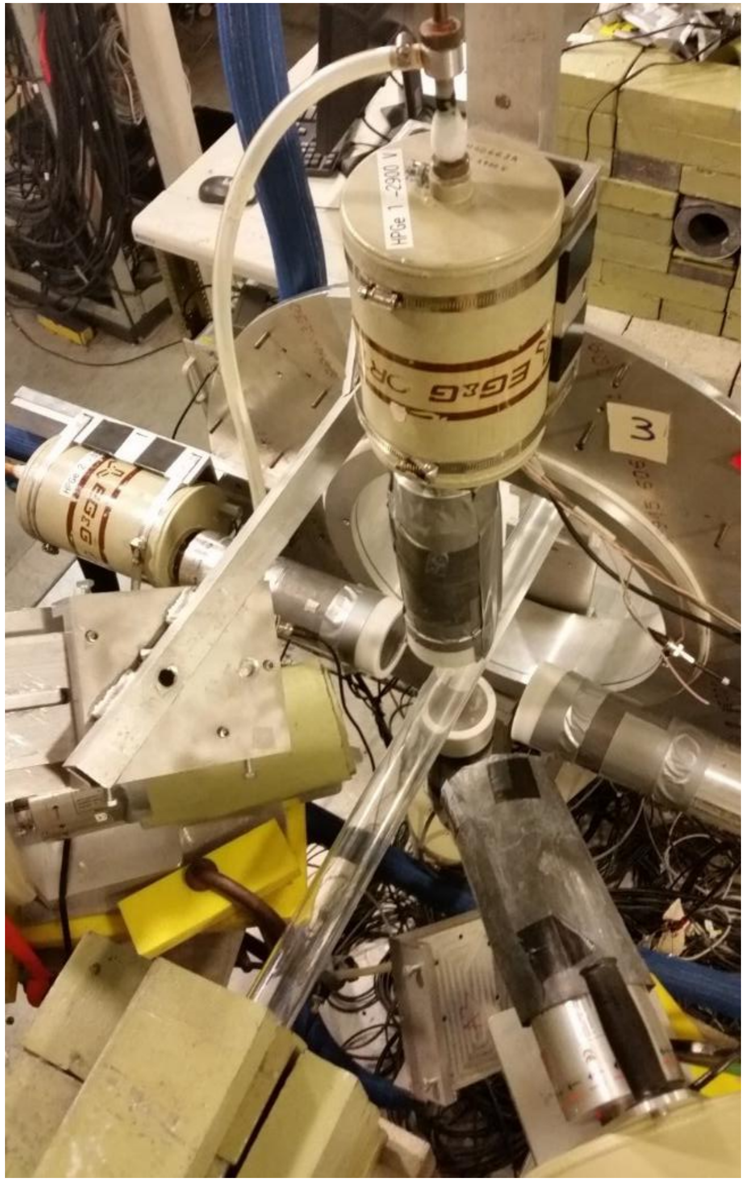
2018 TUNL REU Cohort

Early Days at TUNL

- Robert was settling in as the Bilpuch Professor at UNC
- Becoming acquainted with the nuclear structure and astrophysics work being done at TUNL
- Already plotting to improve the gamma-ray detection system at HIγS



γ^3 Array



High Intensity Gamma-Ray Source (HIγS)

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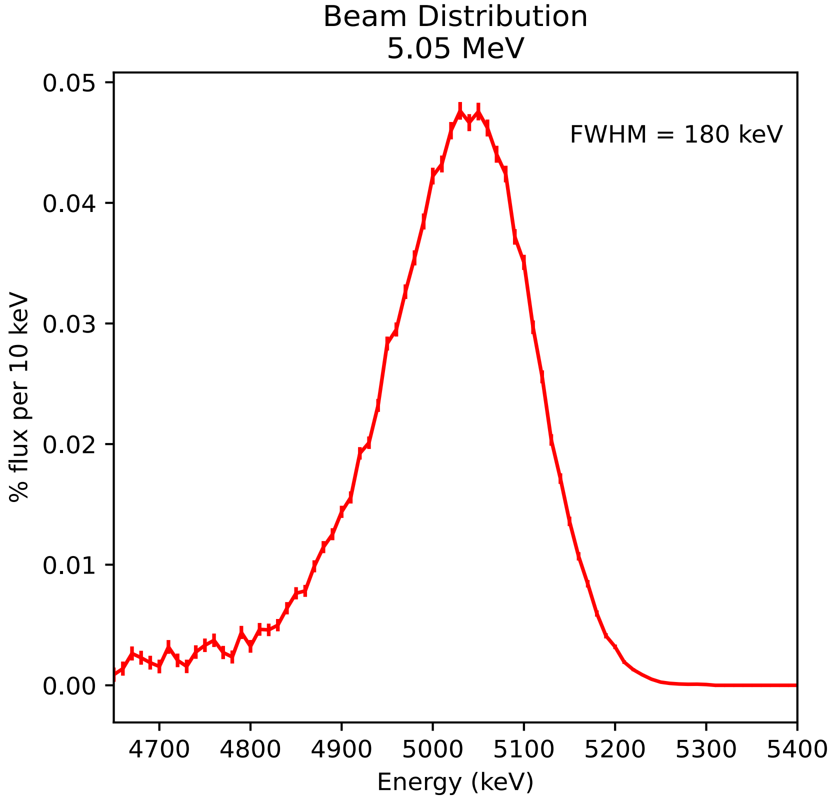
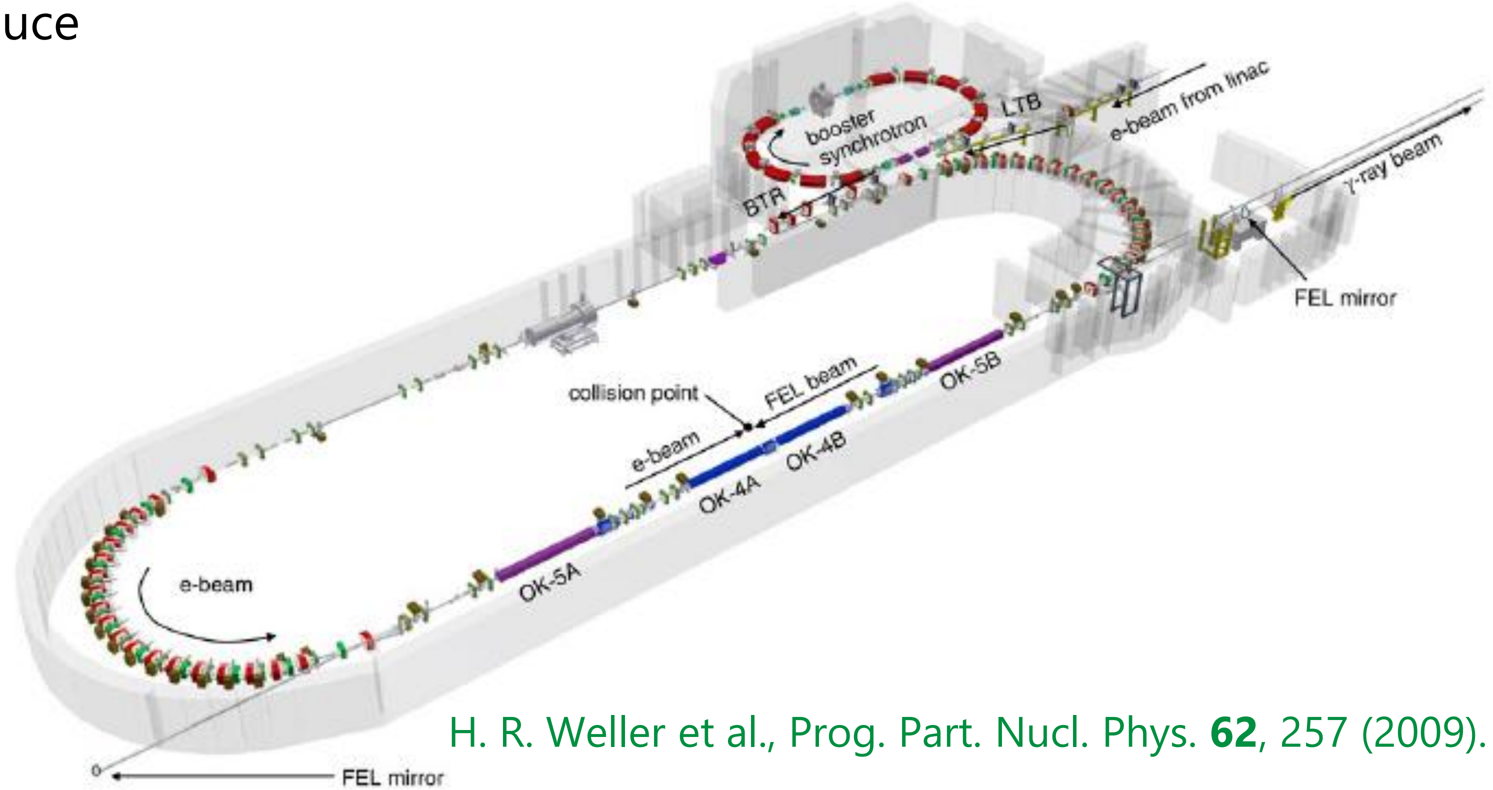
Laser Compton backscattering used to produce quasimonochromatic gamma-ray beams

- Energy ranging from 2 to 120 MeV
- Linear or circular polarization option





H. R. Weller et al., Prog. Part. Nucl. Phys. **62**, 257 (2009).

- Uniquely high-intensity facility for gamma production

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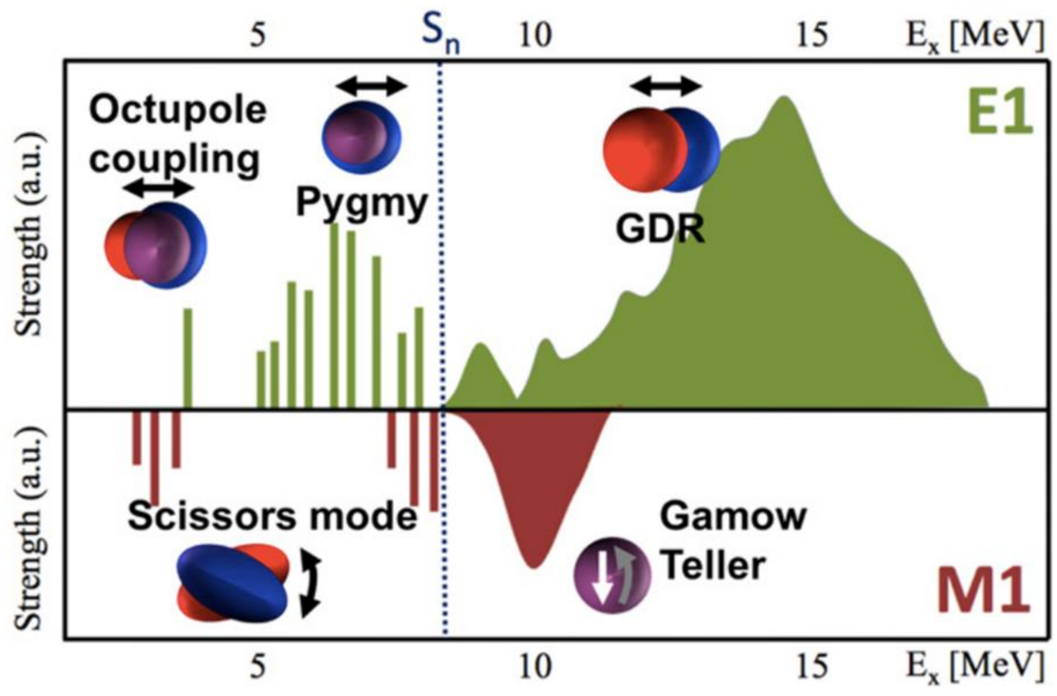
Nuclear Resonance Fluorescence (NRF)

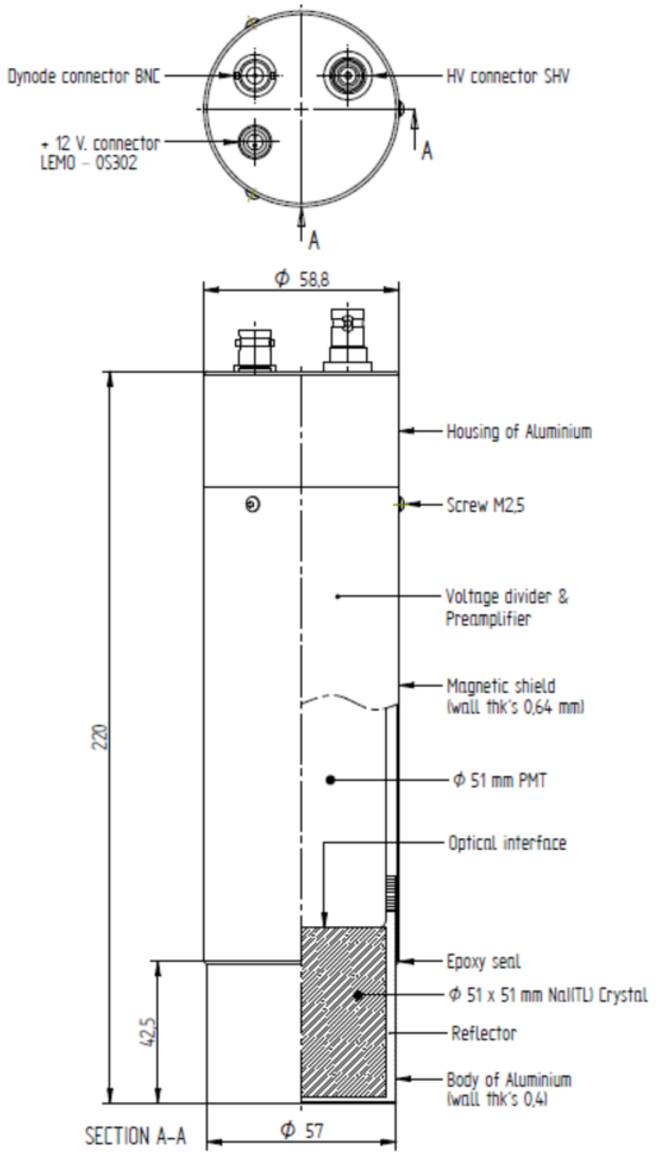
- Absorption of a resonance-energy photon by the nucleus, populating an excited state which then decays via gamma emission
- Mainly **low-spin states** are excited (E1/M1)
- Linear polarization of HIγS lets us make the E1/M1 distinction!



C. R. Howell et al., J. Phys. G: Nucl. Part. Phys. 49 010502 (2022)

Maximizing the potential of NRF: What if we could measure lifetimes?

- My REU project was to test $CeBr_3$ scintillators (no intrinsic radioactivity)
- Linearity, energy/timing resolution
- Robert ordered 12 to use in a new array!



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There are no stupid questions!

…even at 3am!

Thanks to Robert, I felt very welcome in this field.

Assembly of the Clover Array (2020, post-lockdown)

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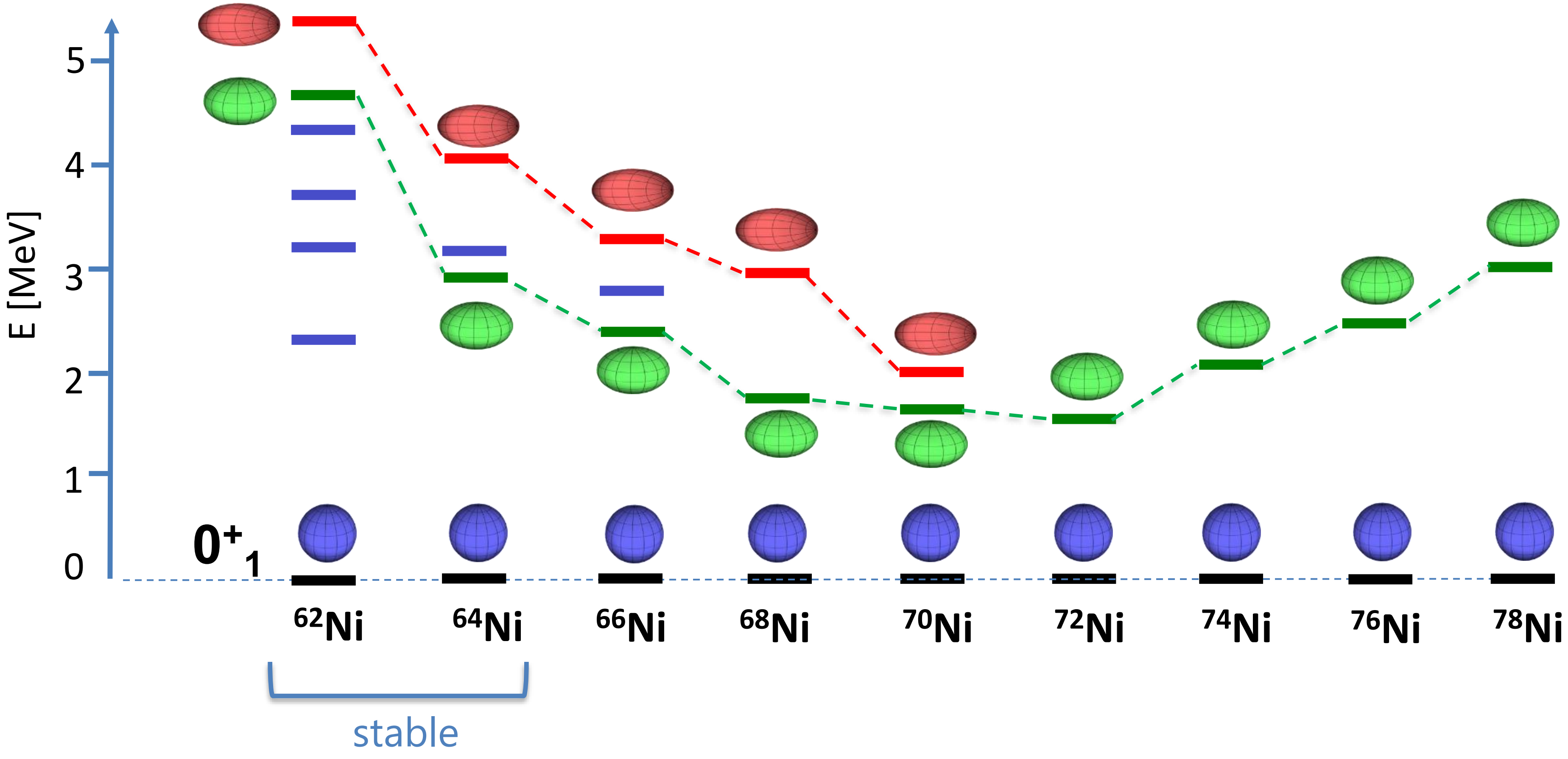
- First Clover Array measurements were motivated by shape coexistence in the Ni isotopes
- Ben Crider described already why the Ni isotopes are interesting!
- In stable ^{64}Ni, all excited 0^+ states have been seen using NRF at HIGS



N. Marginean, Bormio 2025

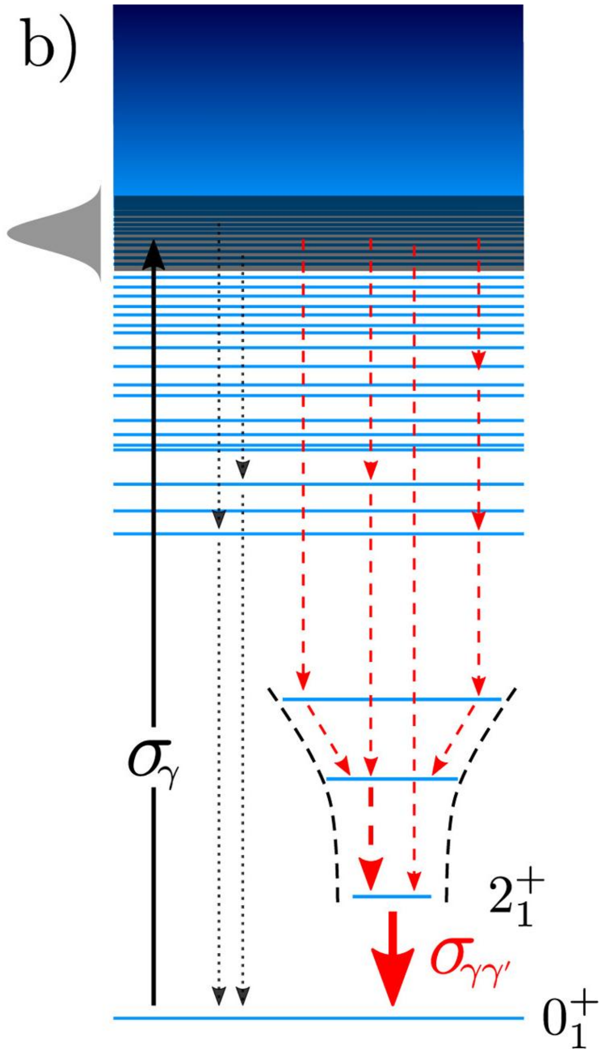
Full Characterization of ^{68}Zn up to 10 MeV

Part 1. NRF Scan

- 30 beam energies: 2.90-9.79 MeV (S_p = 9.98 MeV)
- 3 hr measurements
- Linear polarization

Part 2. Dedicated Coincidences

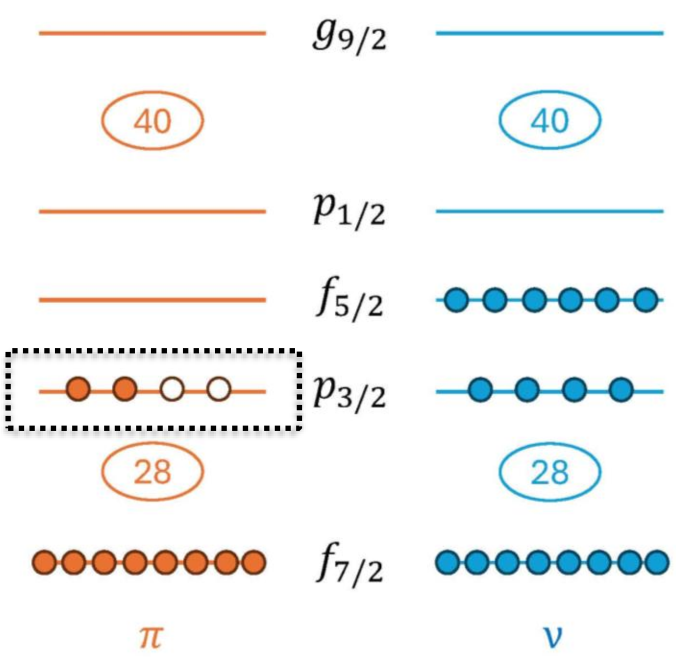
- 30 hr measurements at 9.46 and 9.79 MeV
- High level density
- Hope to see extended level structure



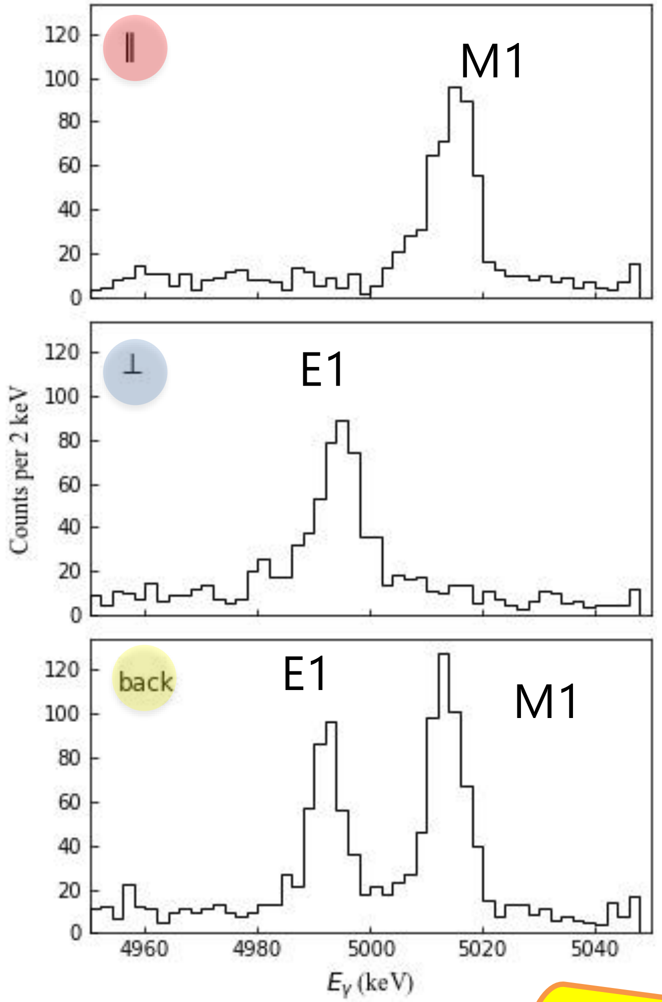
A. Zilges et al., Prog. Part. Nucl. Phys. 122, 103903 (2022).

First Measurements (2021): Shape Coexistence in/near the Ni isotopes

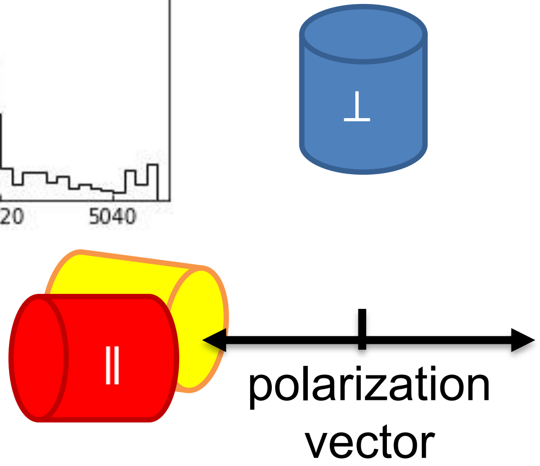
- How do the shapes change with Z?
- Do the same excitations persist in a stable system with two additional protons?



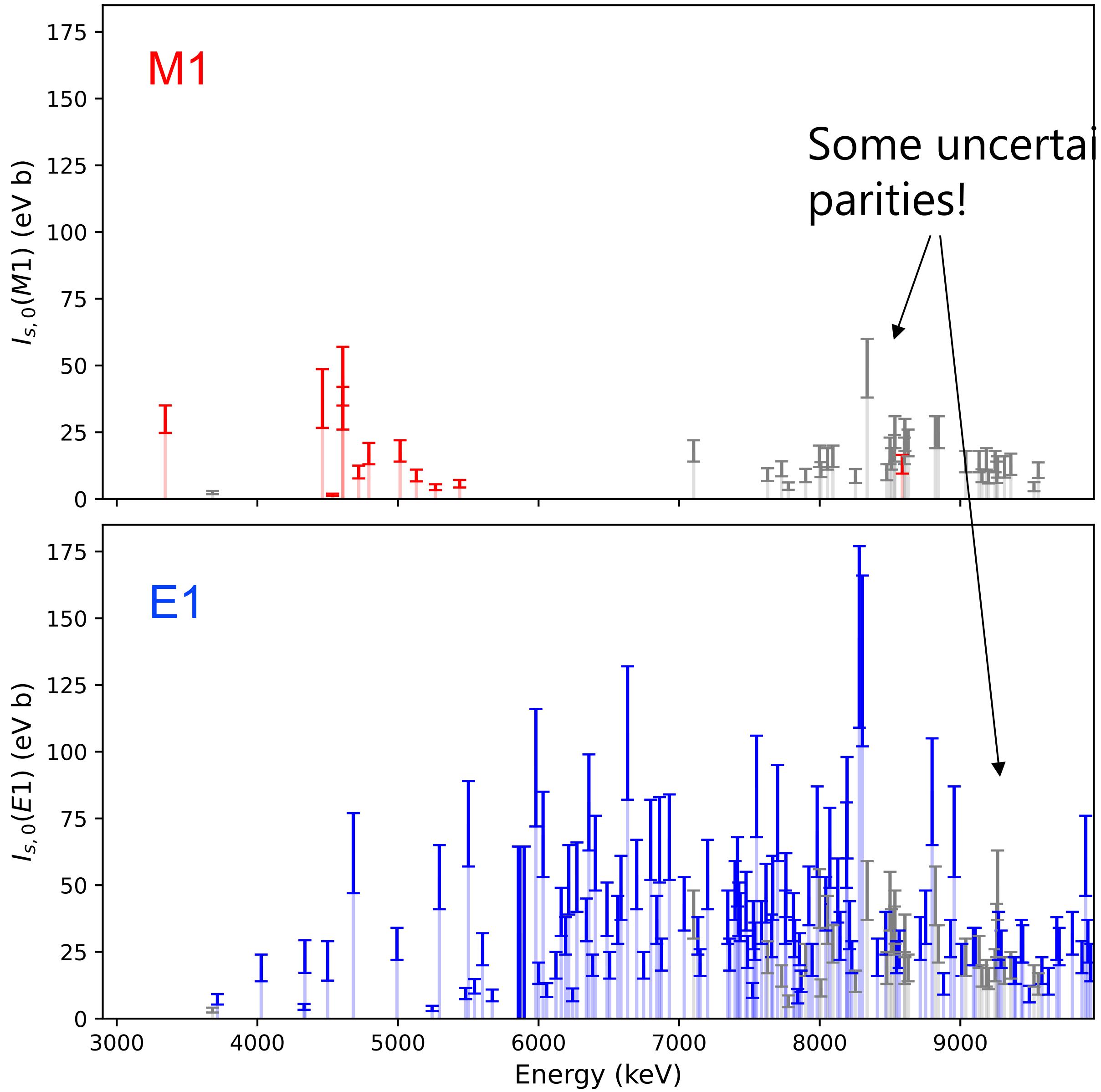
Results for ^{68}Zn



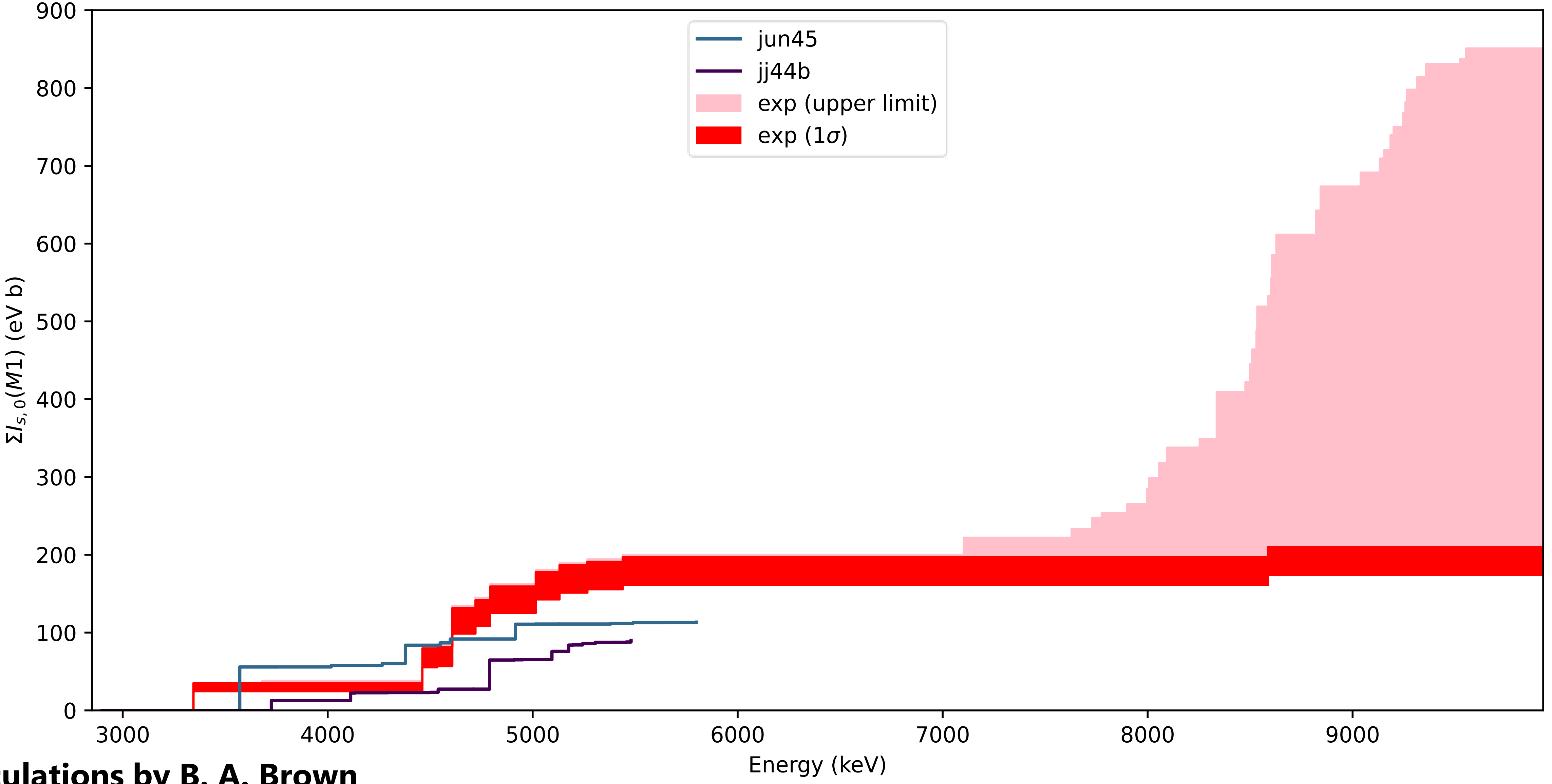
158 excited states were found below the particle threshold!



Some uncertain parities!

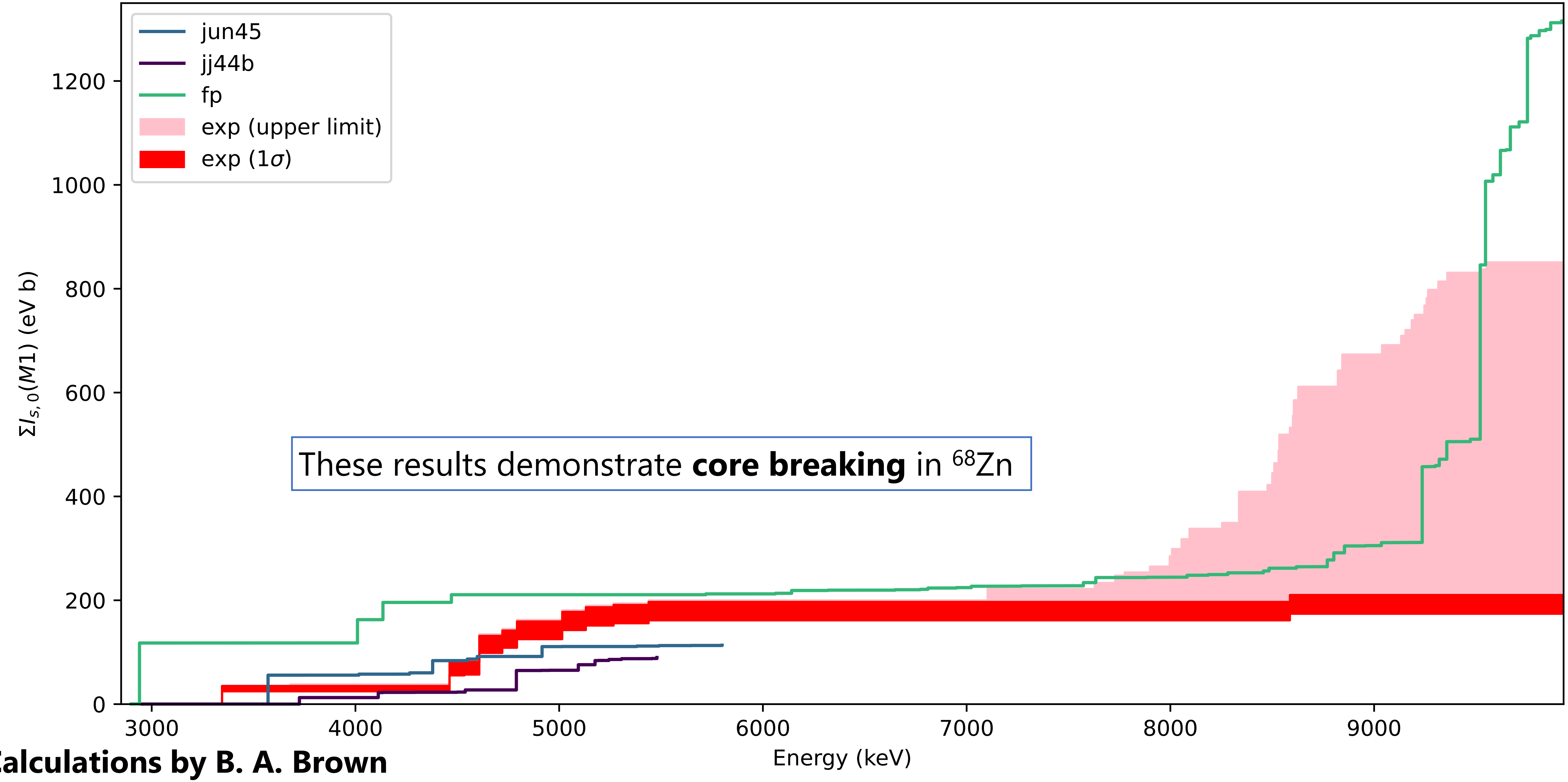


Shell-model predictions (^{56}Ni core) don't capture total M1 strength



Calculations by B. A. Brown

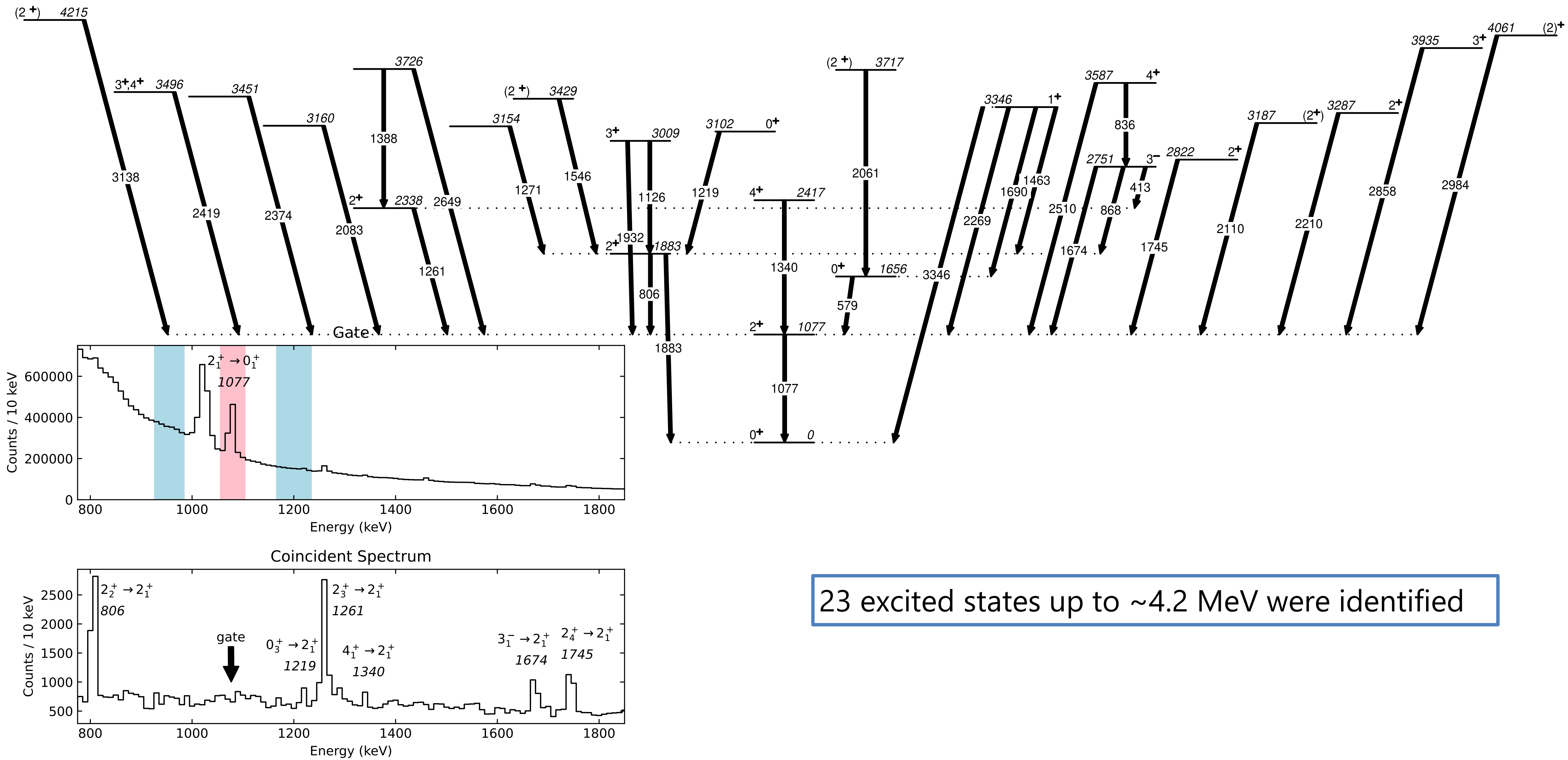
Full fp model space (^{40}Ca core) predicts additional high-energy strength



These results demonstrate **core breaking** in ^{68}Zn

Calculations by B. A. Brown

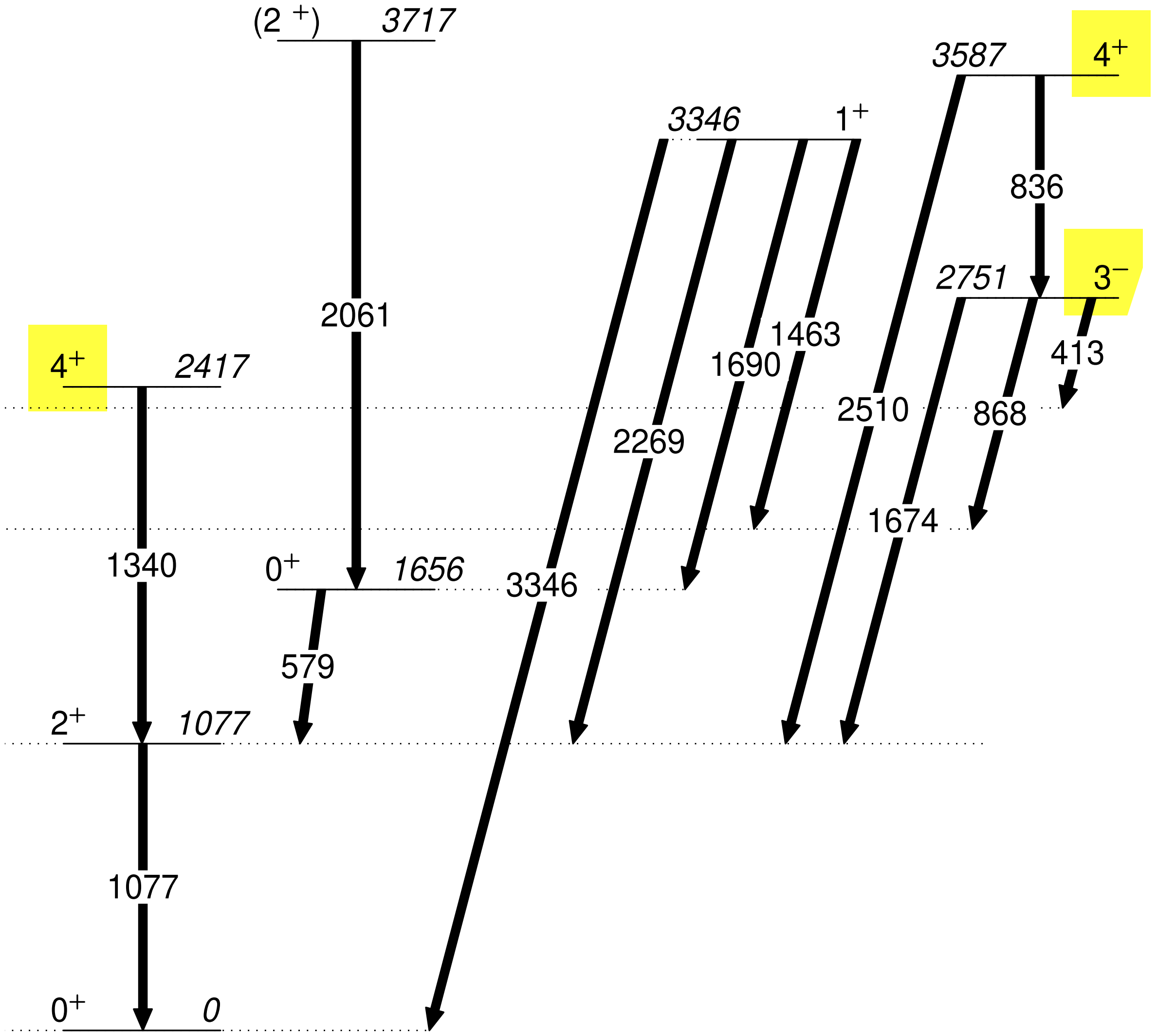
Experimental Level Scheme



23 excited states up to ~4.2 MeV were identified

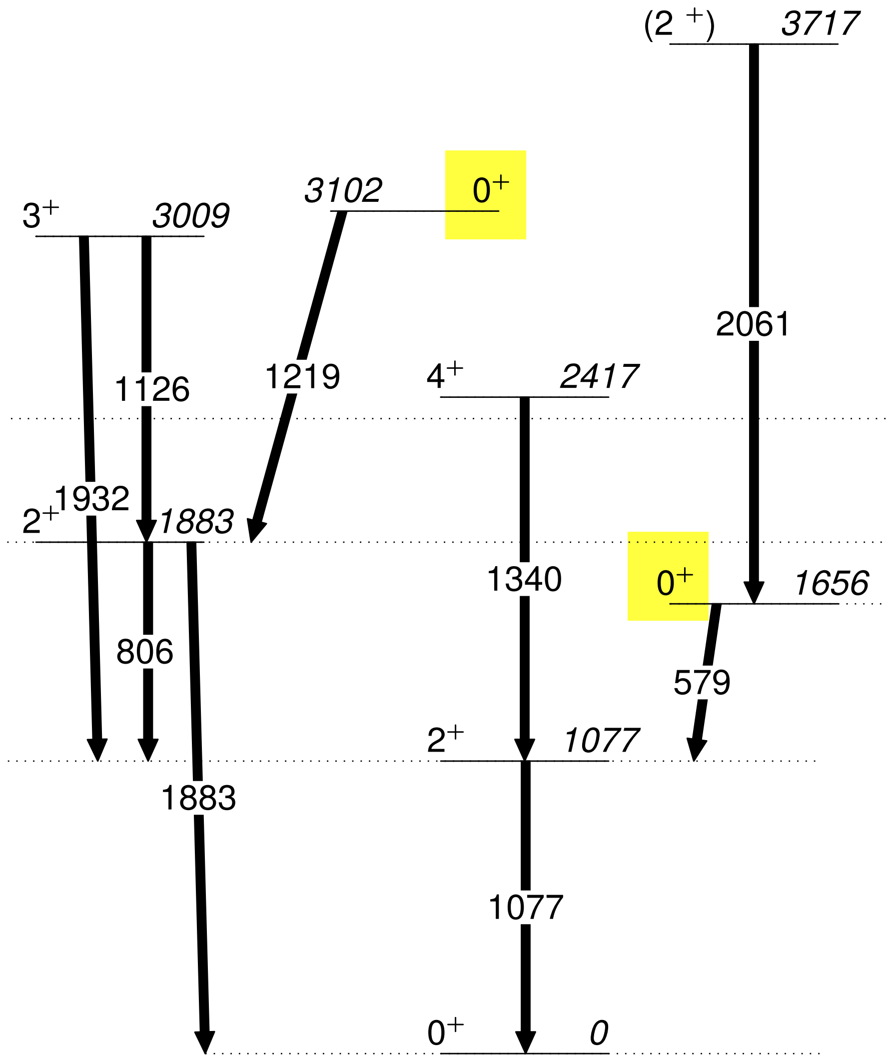
Experimental Level Scheme: High Spin for NRF!

Higher angular momentum than expected coming from multi-step decays



Experimental Level Scheme: 0^+ States

Reached several of the 0^+ states relevant for shape coexistence



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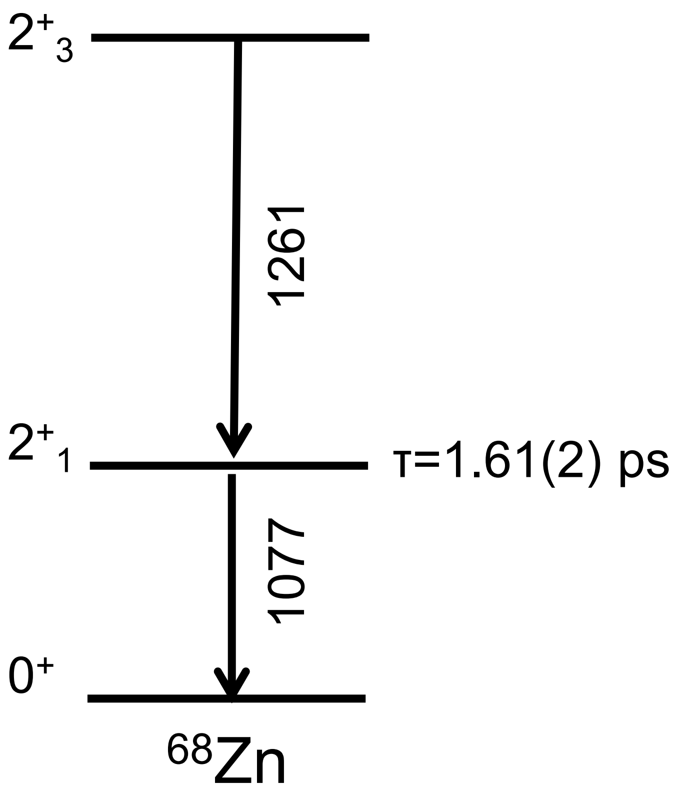
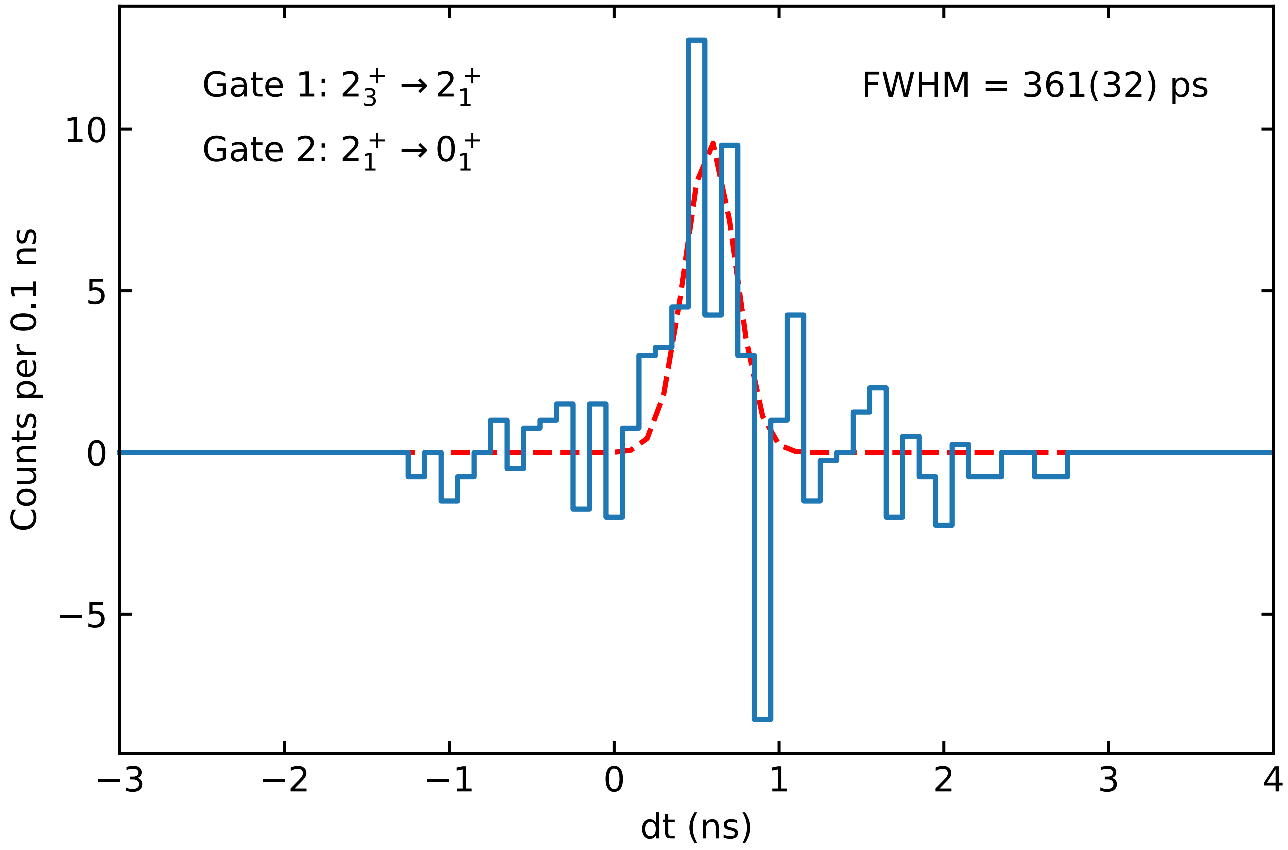
Lifetime measurements using NRF?

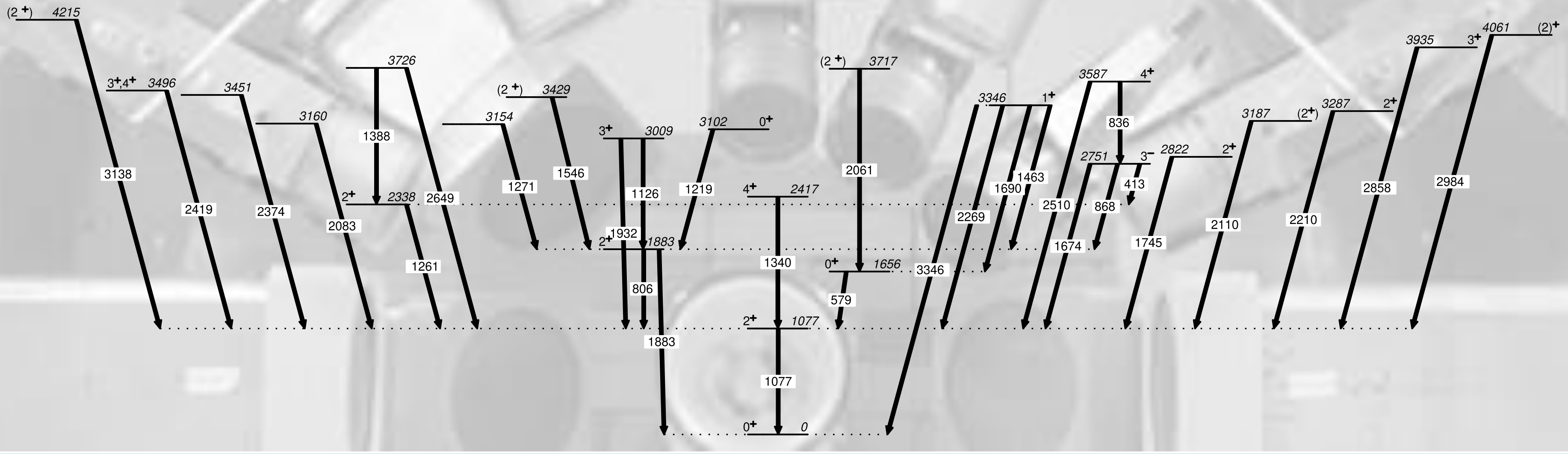
- $CeBr_3$ resolution of 250 ps demonstrated with real NRF data – a huge step forward
- Lifetime measurements may be possible after careful calibration
  - Project of Daniel Melayes, UNC





Outlook for the Clover Array

- The ^{68}Zn data allowed an extensive test of shell-model calculations at low spin, revealing which shells become active in different energy regimes
- Coincidence measurements have expanded the reach of NRF up to J=4
- In the meantime, dozens of other fascinating experiments have been performed
- Still more potential for physics discovery with this array that Robert and the team at TUNL have worked so hard to bring to life!



A year full of celebrations

Samantha’s PhD Defense, June 2025

Robert’s Retirement, February 2025

Thank you! Questions?

Robert V. F. Janssens, B. Alex Brown, Akaa D. Ayangeakaa, Soumendu Bhattacharjee, Emily Churchman, Sean Finch, Udo Friman-Gayer, S. Gaither Frye, Matteo Fulghieri, David Gribble, Xavier H.-K. James, Richard Longland, Daniel Melayes, Clay Wegner

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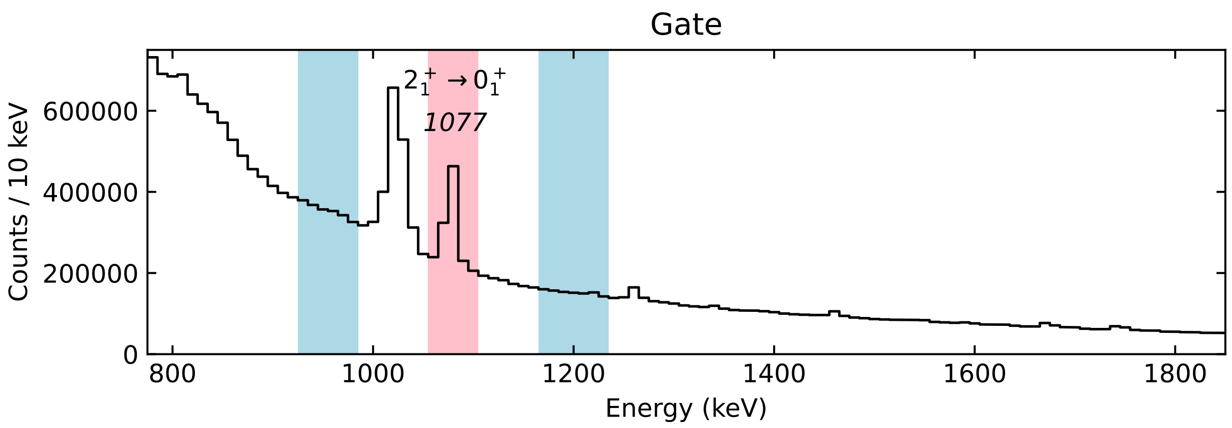
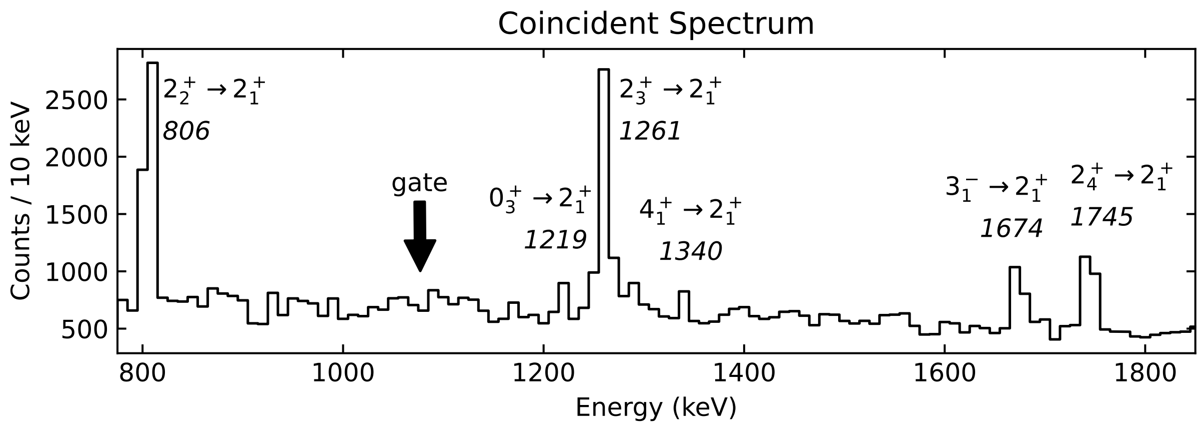
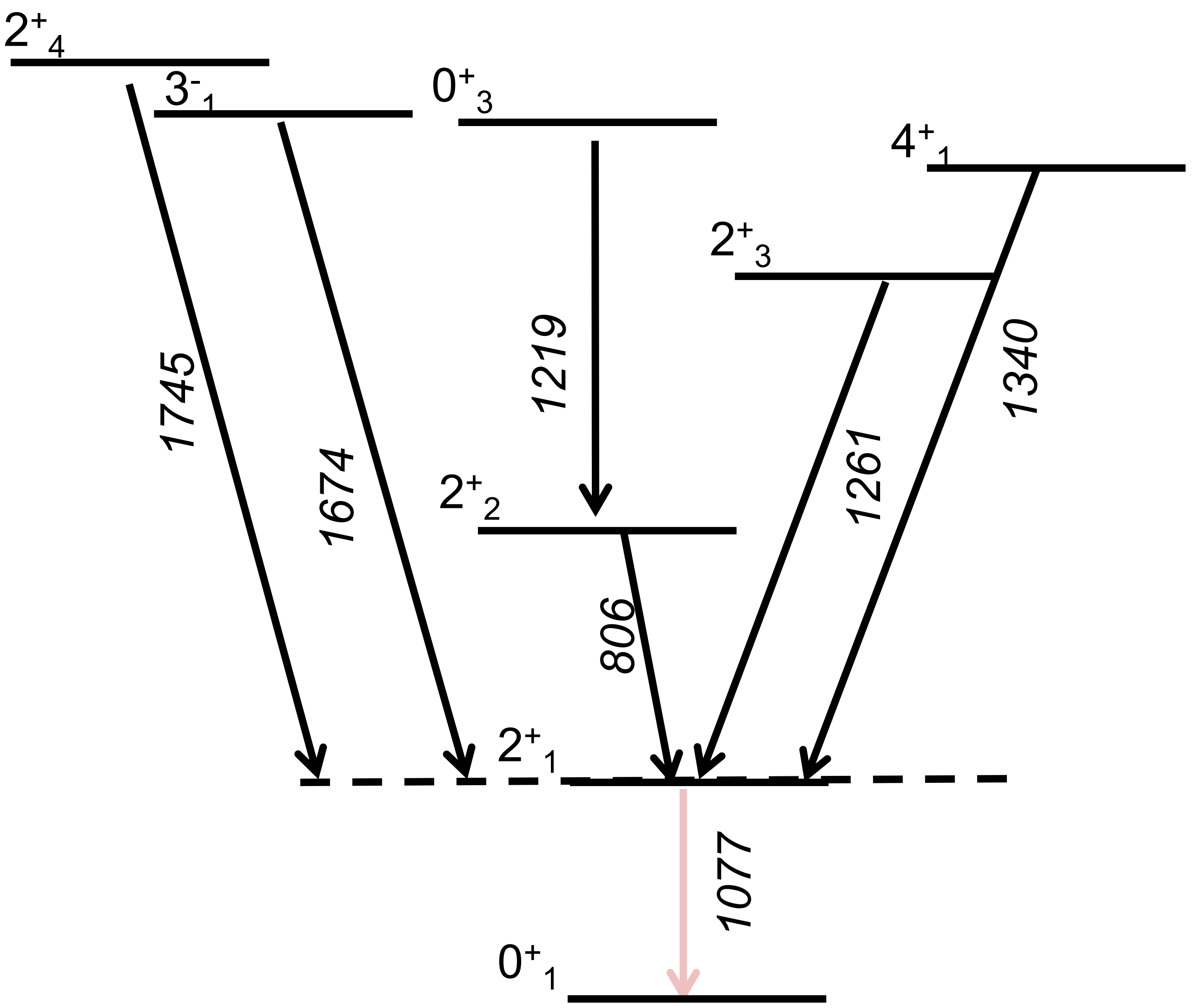
Extra Slides

Gamma-Gamma Coincidence Measurements

- Level scheme analysis
- Gating on the $2^+_1 \rightarrow 0^+_1$ transition

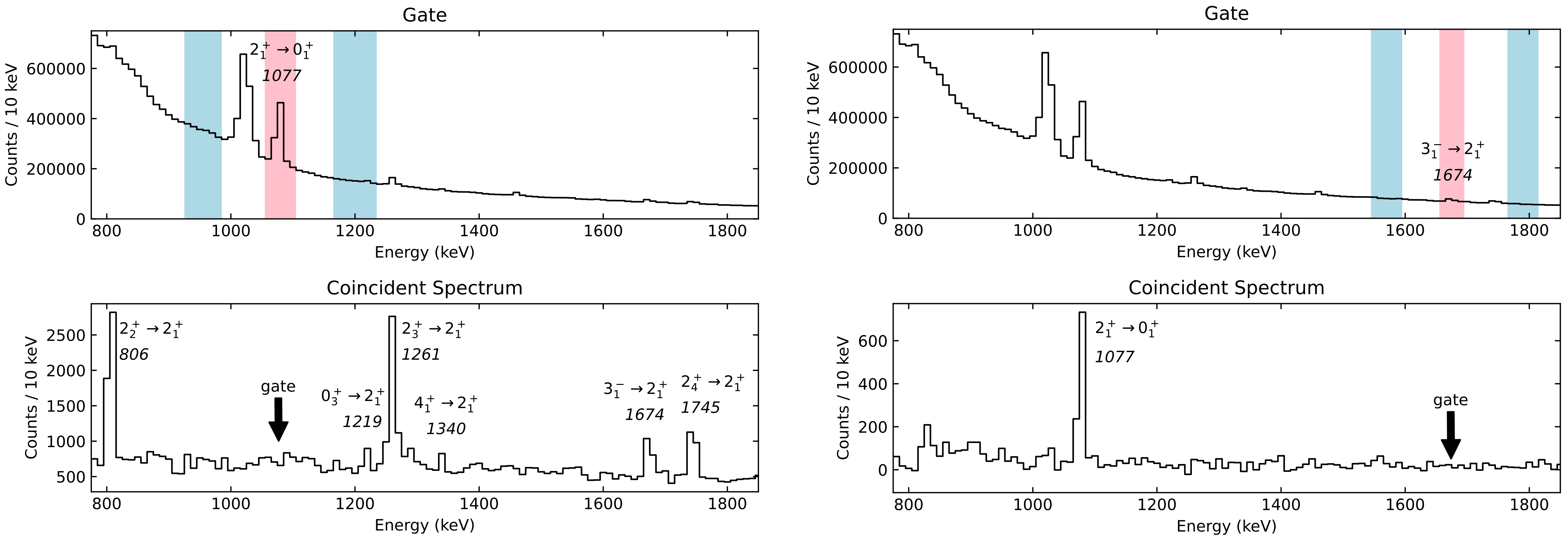




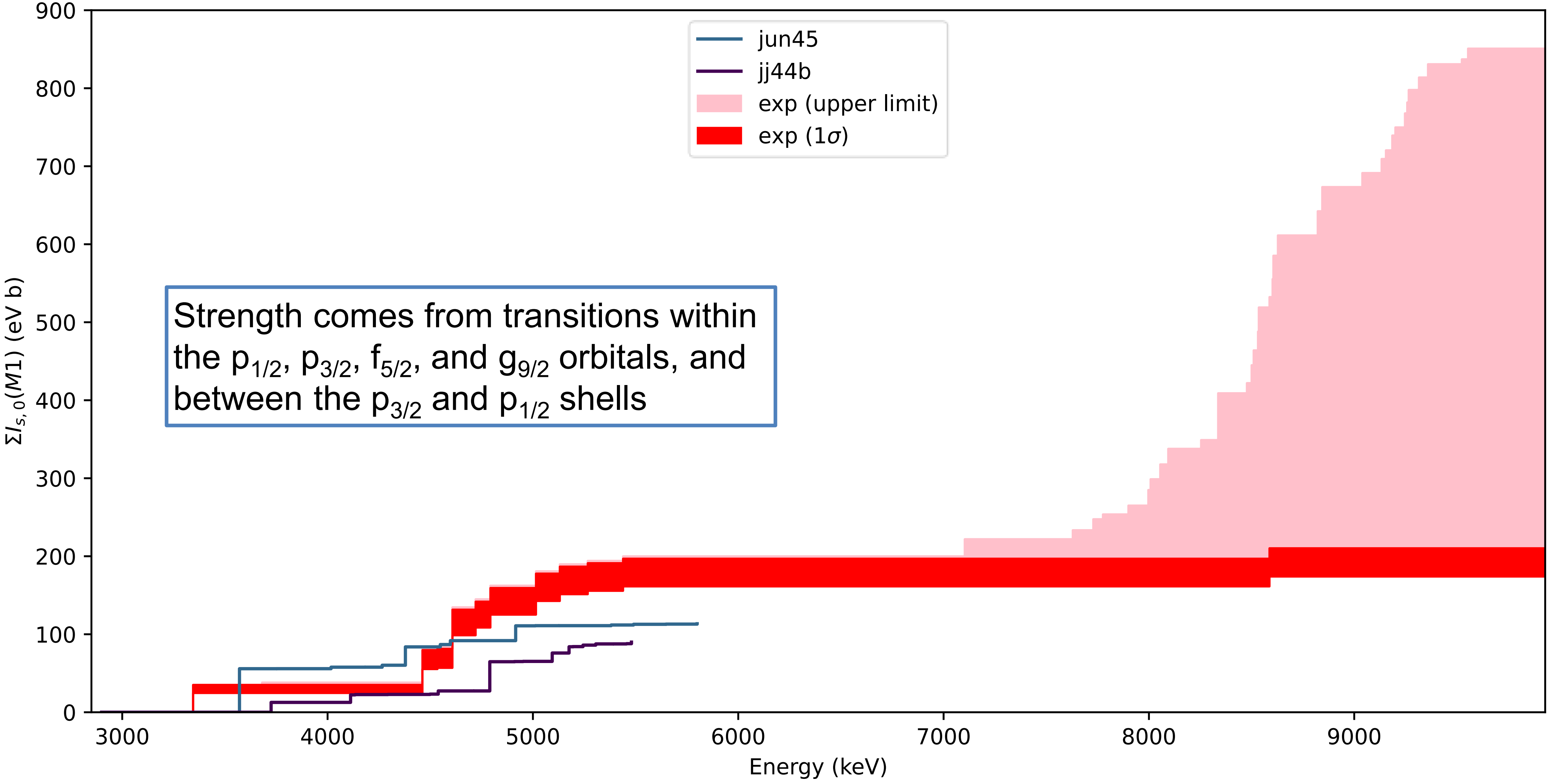


Coincidence Matrix Analysis

- Gate on one gamma and background-subtract to see what others are associated
- Example: Gating on the $2^+_1 \rightarrow 0^+_1$ transition

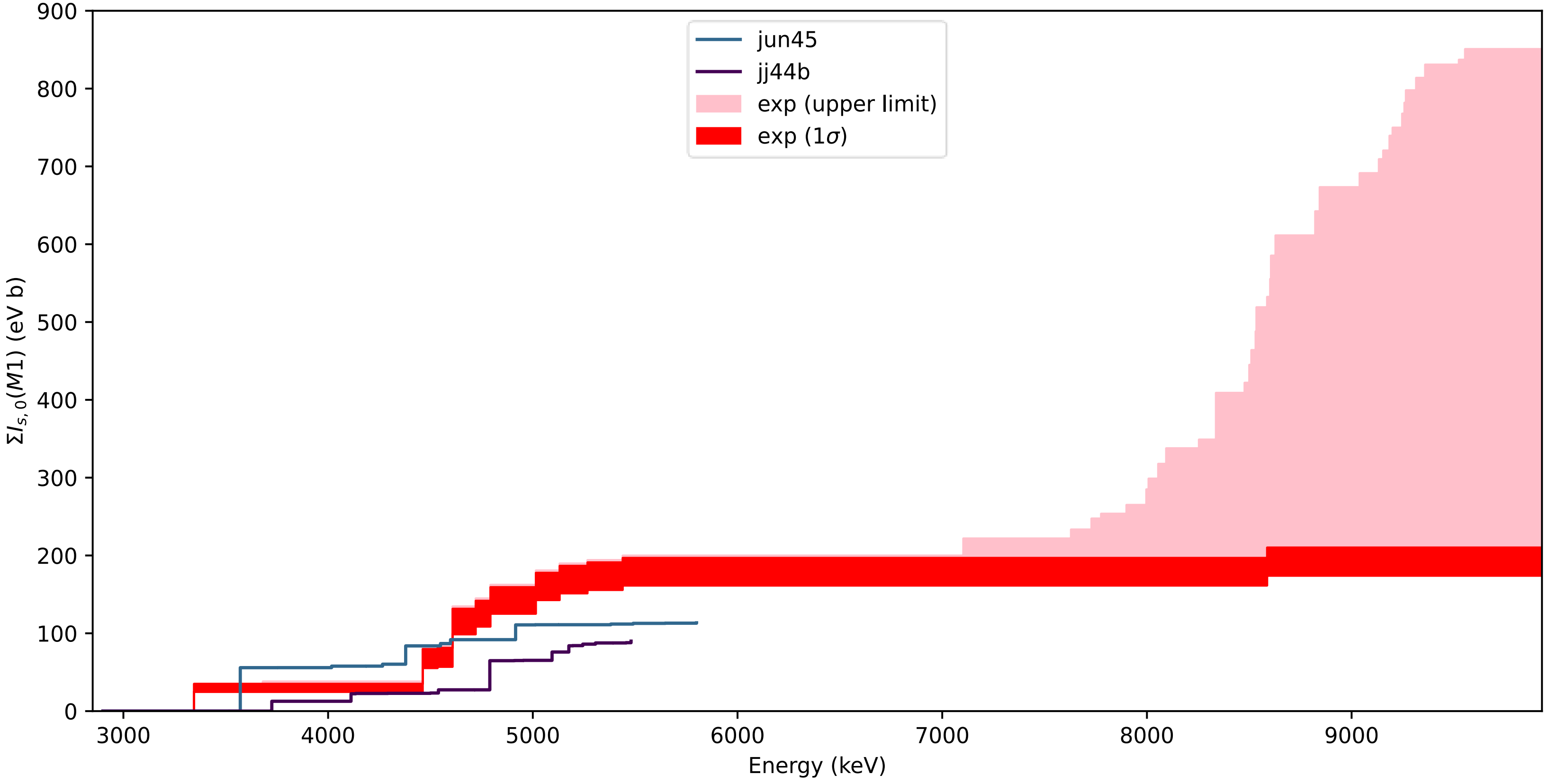


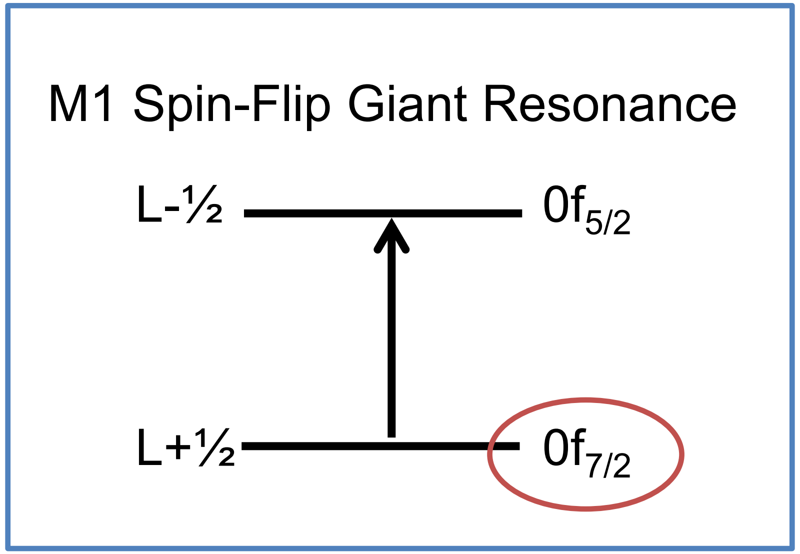
Shell-Model Predictions for M1 States



Strength comes from transitions within the $p_{1/2}$, $p_{3/2}$, $f_{5/2}$, and $g_{9/2}$ orbitals, and between the $p_{3/2}$ and $p_{1/2}$ shells

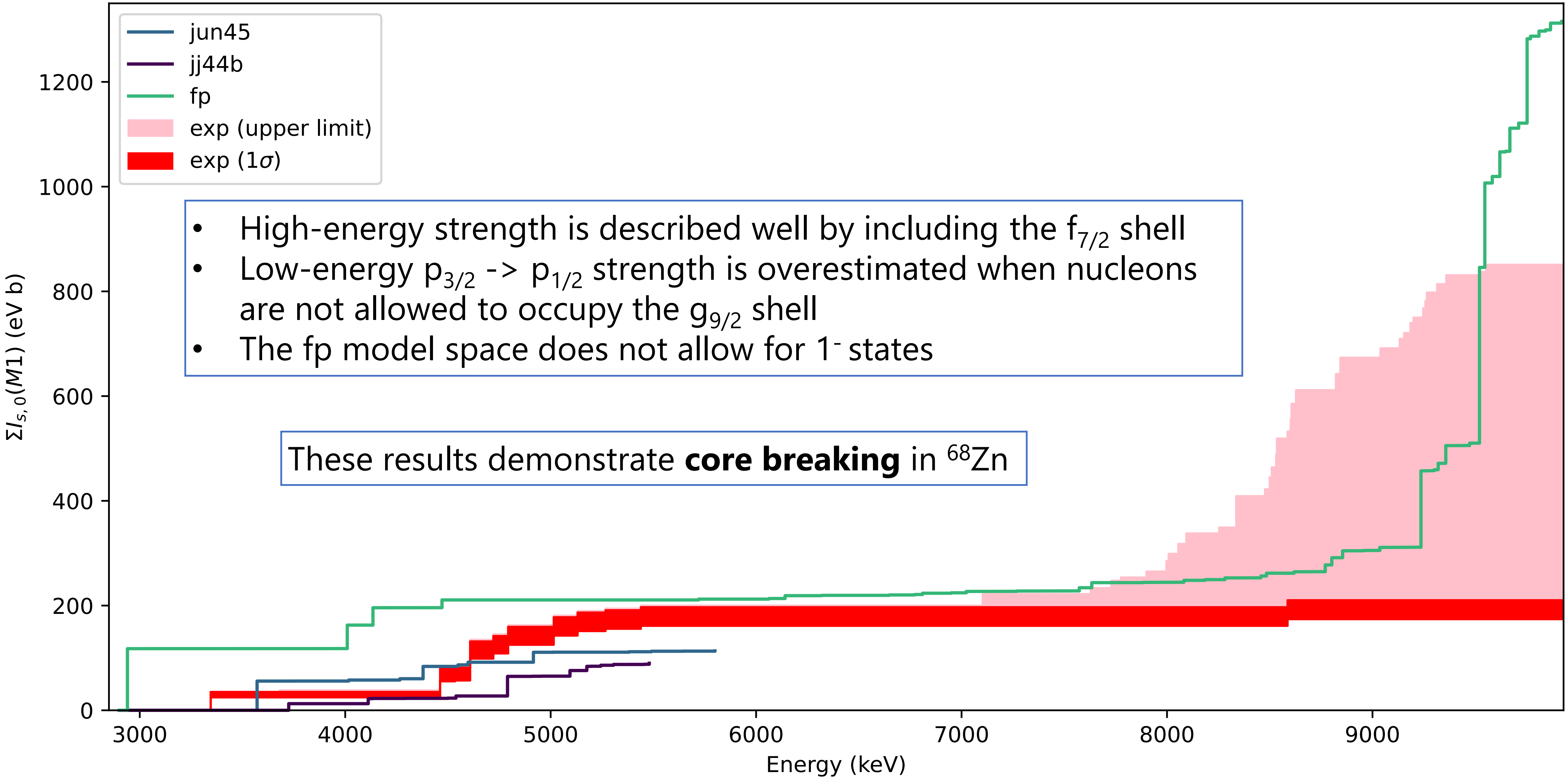
Shell-Model Predictions for M1 States





An expanded model space is needed to account for the experimental M1 strength

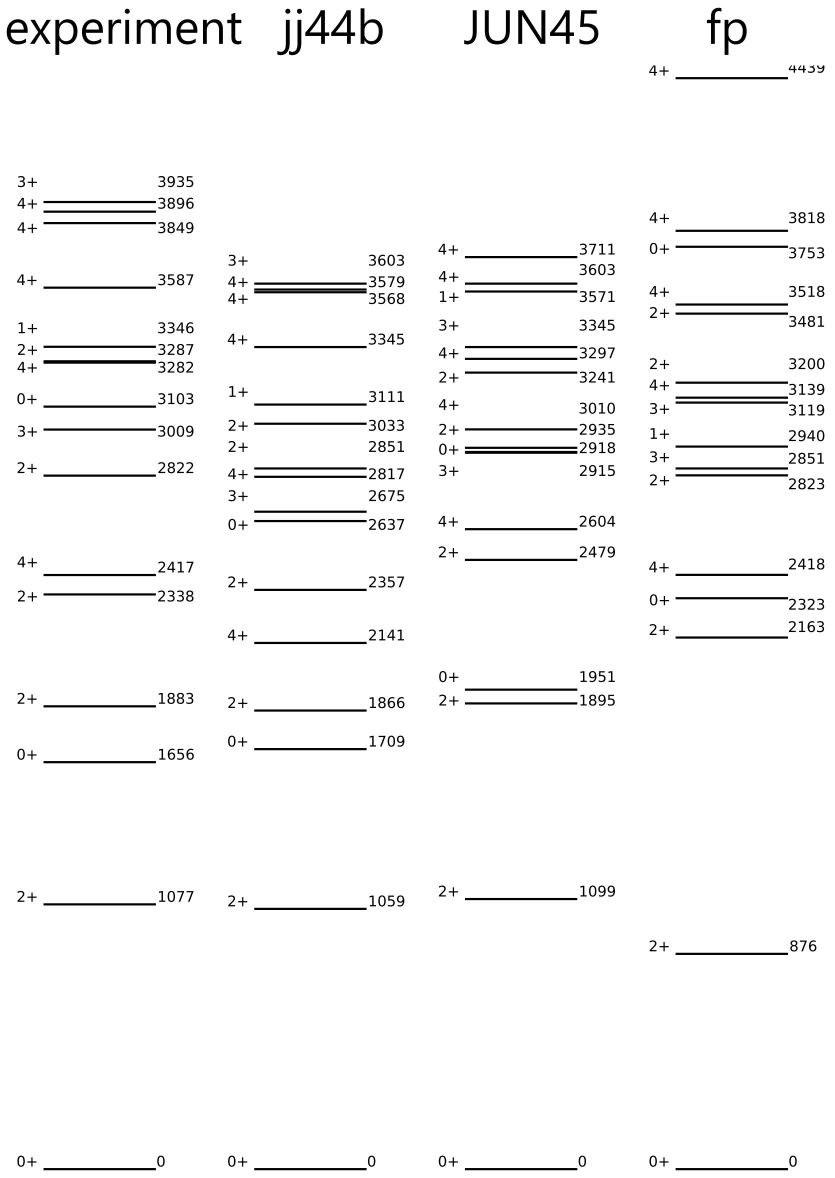
Shell Model Predictions for M1 States



- High-energy strength is described well by including the $f_{7/2}$ shell
- Low-energy $p_{3/2}$ -> $p_{1/2}$ strength is overestimated when nucleons are not allowed to occupy the $g_{9/2}$ shell
- The fp model space does not allow for 1^- states

These results demonstrate **core breaking** in ^{68}Zn

Shell-model level scheme



J_i^π	J_f^π	Branching Ratio (%)			
		exp.	$jj44b$	JUN45	fp
3_1^+	2_1^+	9.6(11)	34.7	32.6	94.1
	2_2^+	81.8(5)	65.3	67.4	4.5

- Experimental level scheme best described by the jj44 model space
  - Energy deviation ~200 keV for jj44b and JUN45 and ~300 keV for fp
- Branching ratios are best described in this model space as well using the JUN45 effective interaction
- Another indication of the importance of the $g_{9/2}$ shell at low energy

Coincidences: Fast-timing techniques for measuring lifetimes

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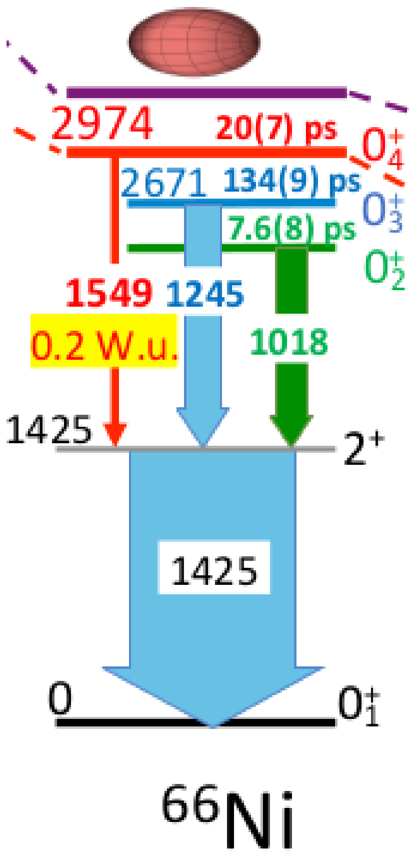
Interested in exploring the lifetimes of states populated during coincidence measurements

^{68}Zn states of interest:

- $1^{+/-}$ states: $\tau \sim$ 10 fs
- 0^{+}_{1} state: $\tau \sim$ 100 ps
- Low lying 2^{+} states: $\tau \sim$1ps

Resolution of CeBr scintillator ~200 ps



S. Leoni et al., Phys. Rev. Lett. 118, 162502 (2017)

Centroid-shift method may enable sub-picosecond timing.

^{68}Zn states of interest:

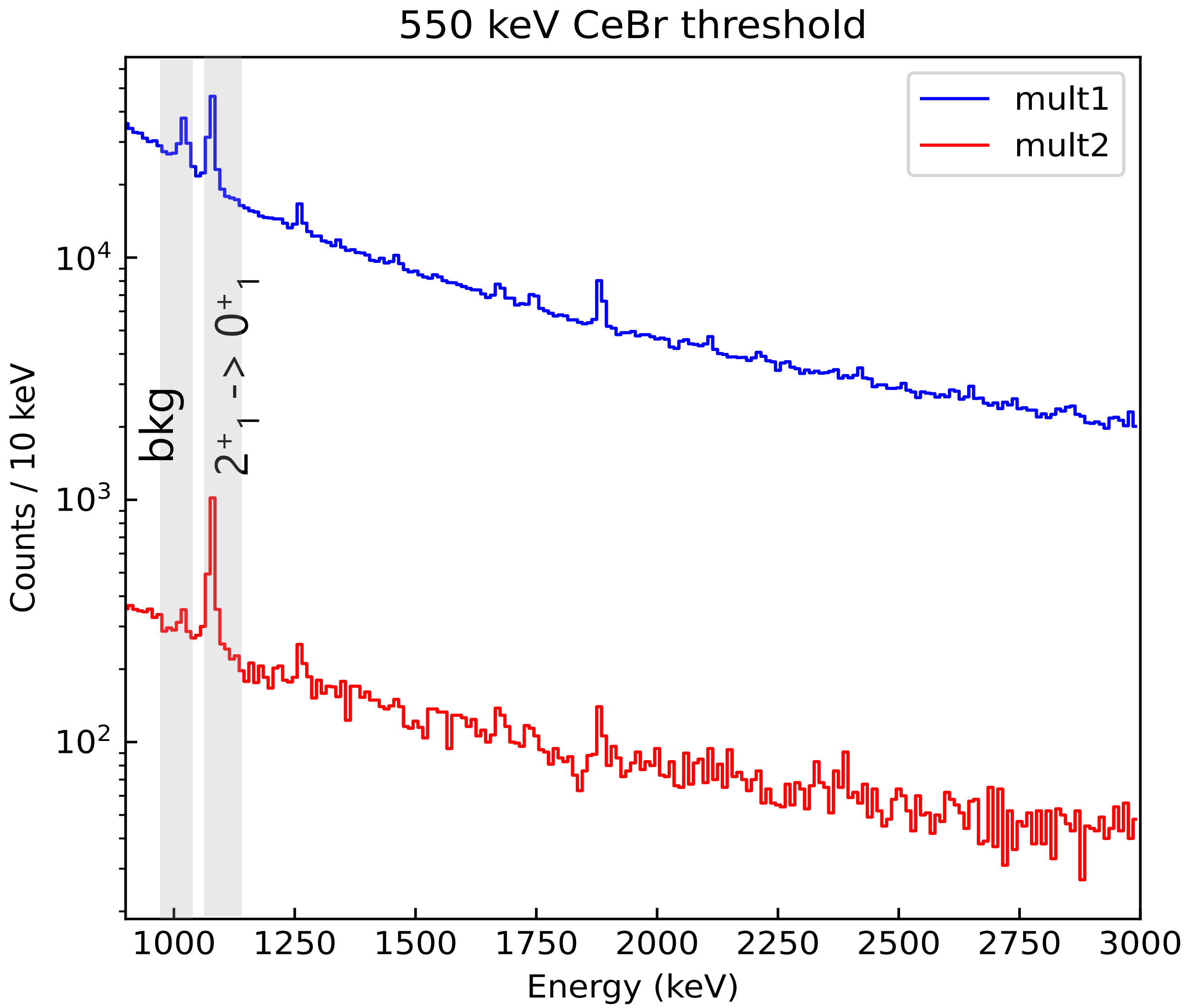
- $1^{+/-}$ states: $\tau \sim 10$ fs
- 0^{+} states: $\tau \sim 10 - 100$ ps
- Low lying 2^{+} states: $\tau \sim 1$ ps

Centroid-shift method may enable sub-picosecond timing.

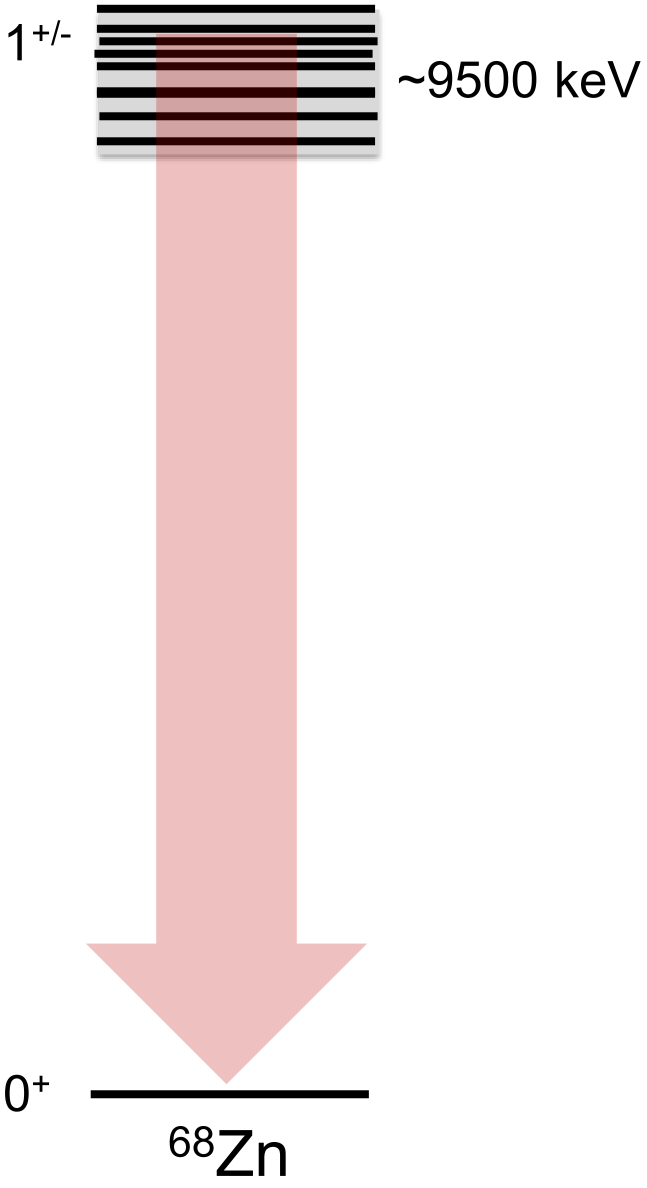
^{68}Zn states of interest:

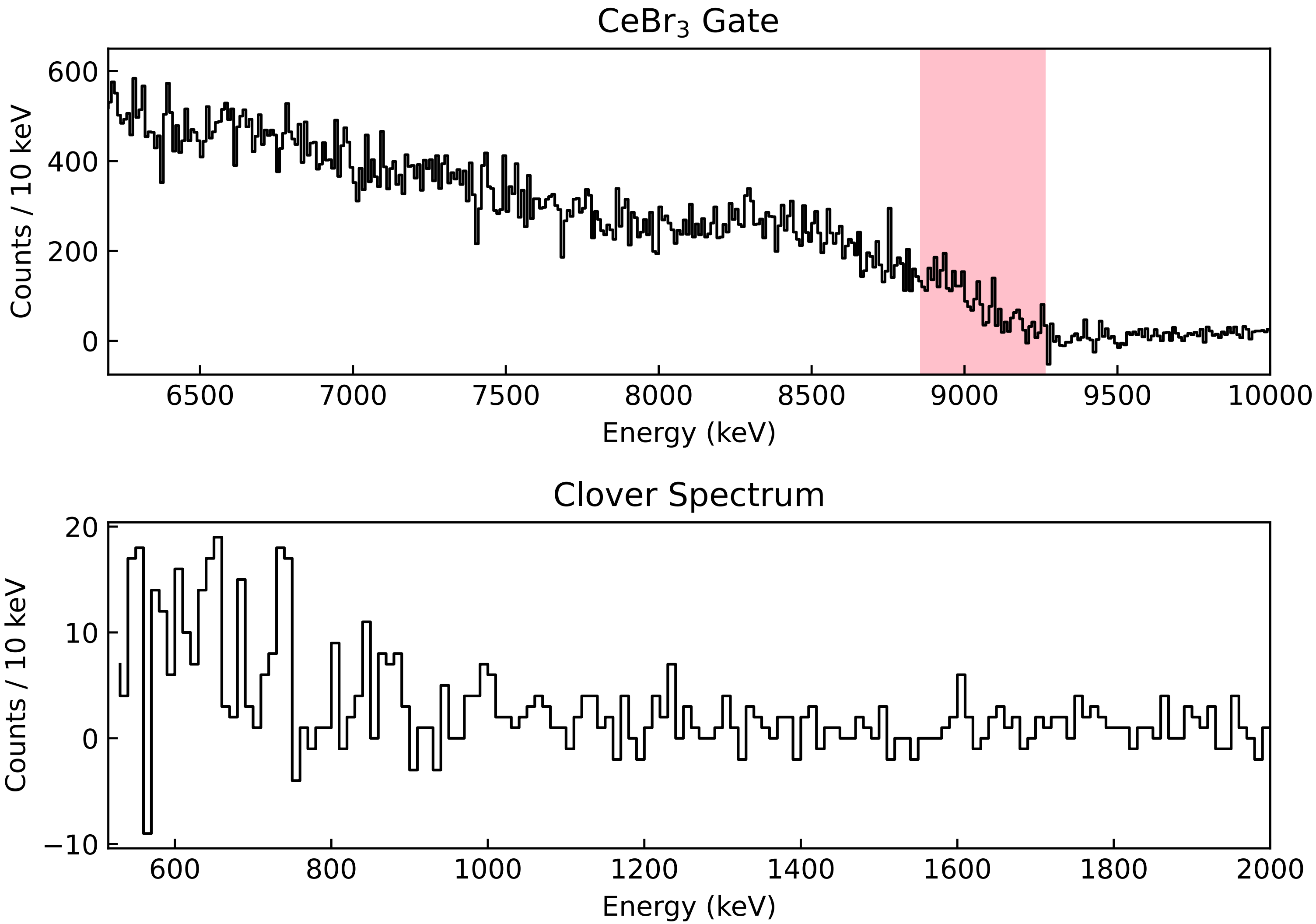
- $1^{+/-}$ states: $\tau \sim 10$ fs ← Just too short-lived
- 0^{+} states: $\tau \sim 10 - 100$ ps ← May be measurable
- Low lying 2^{+} states: $\tau \sim 1$ ps ↙

Multiplicity Cuts



Utilizing unresolved transitions





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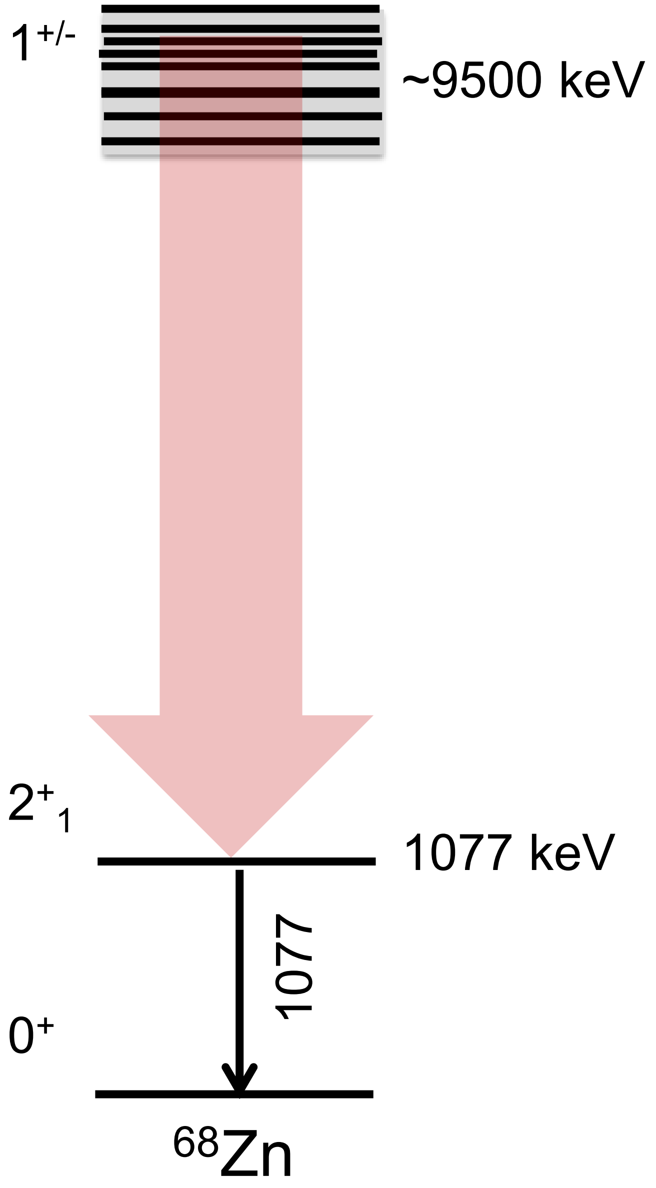

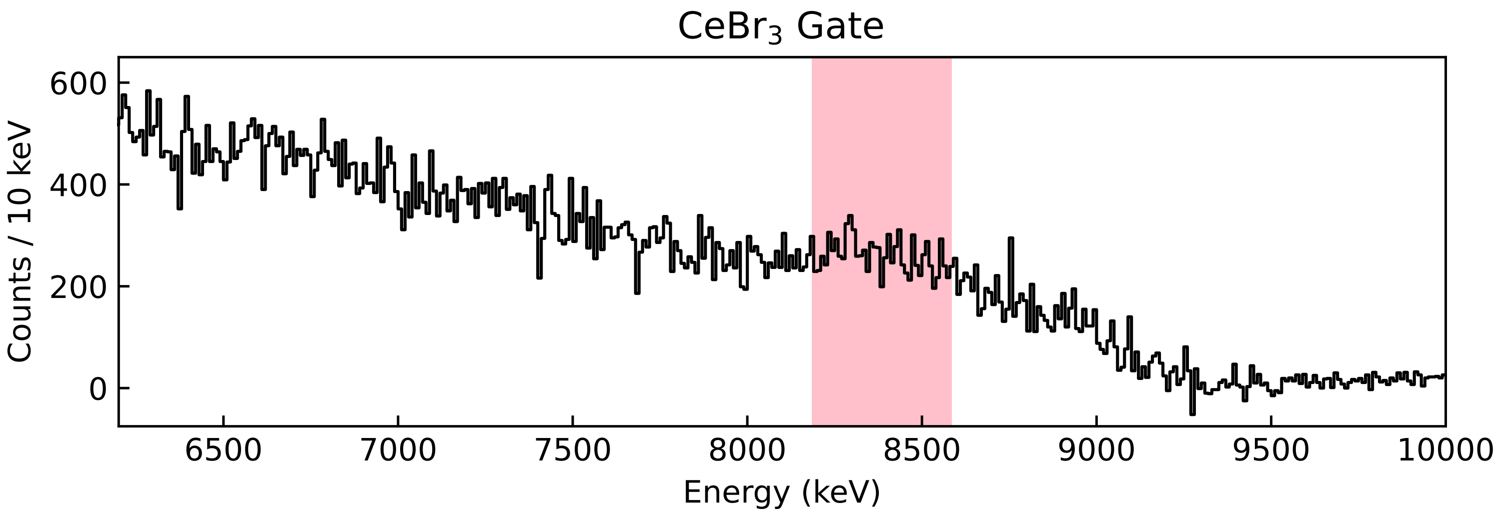

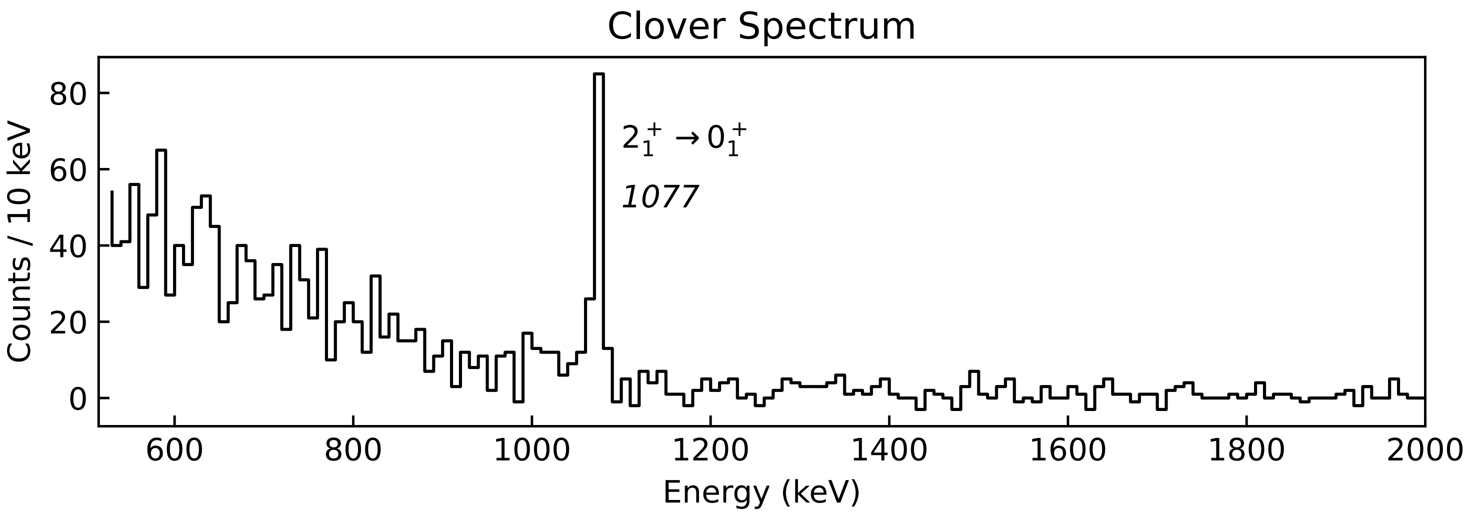

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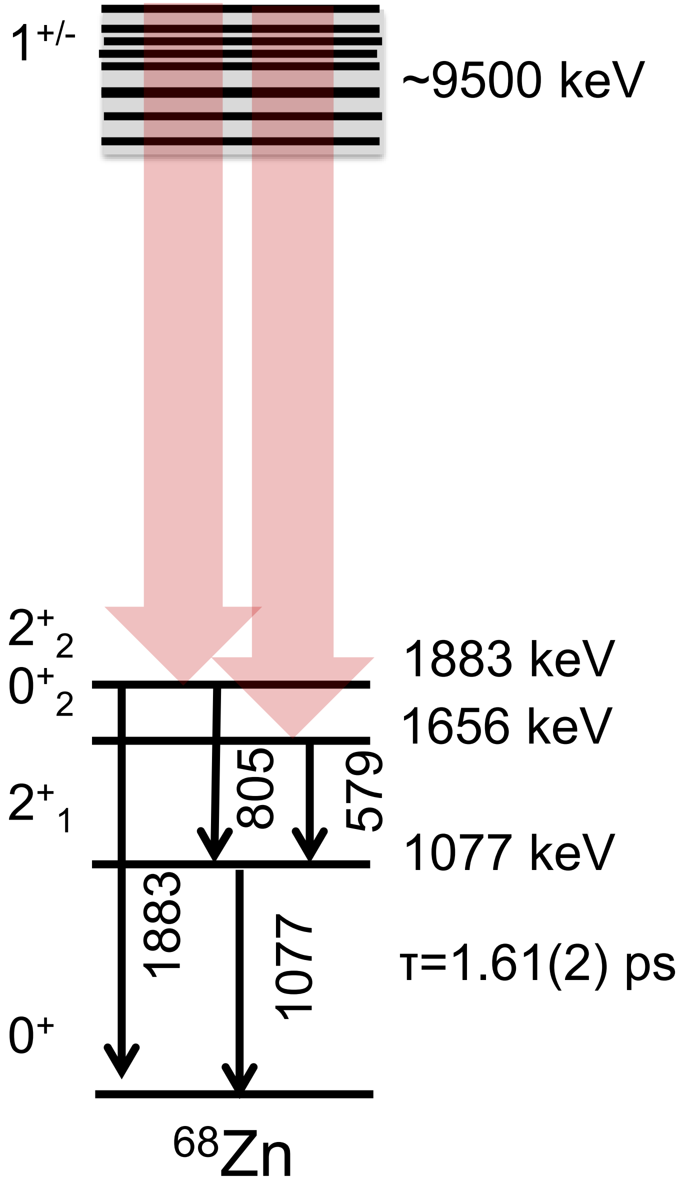

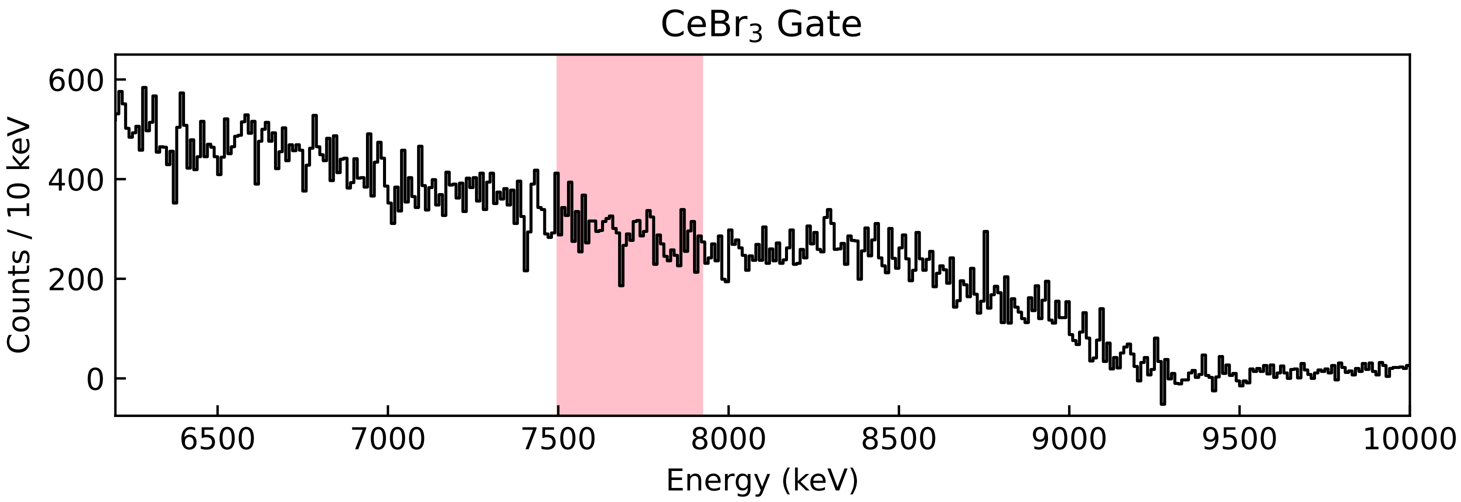

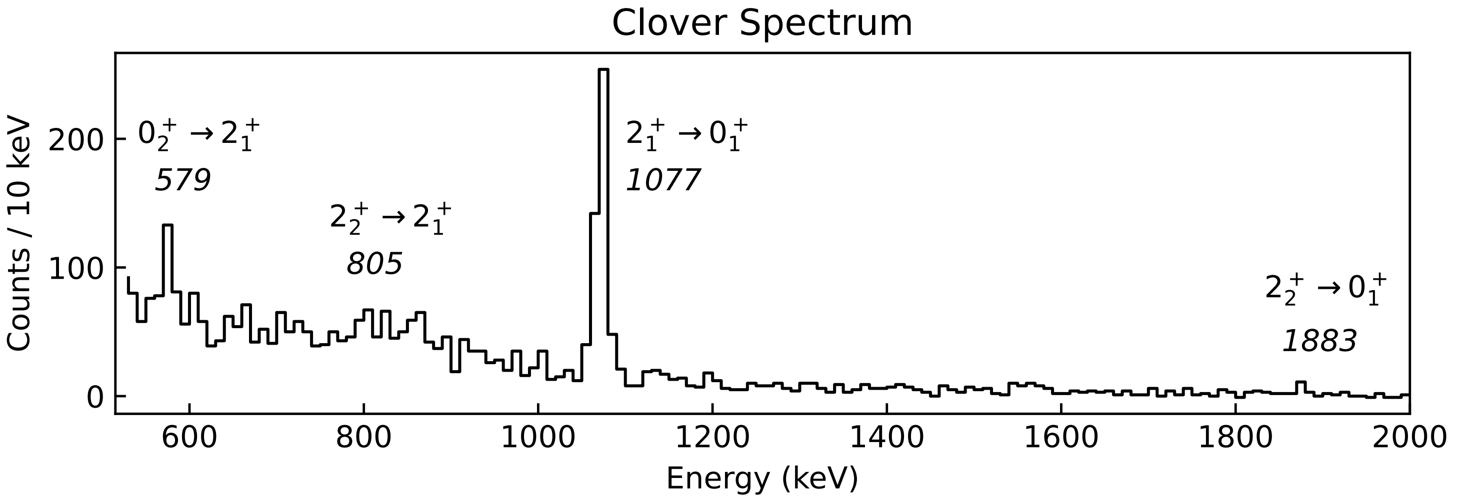

Utilizing unresolved transitions