



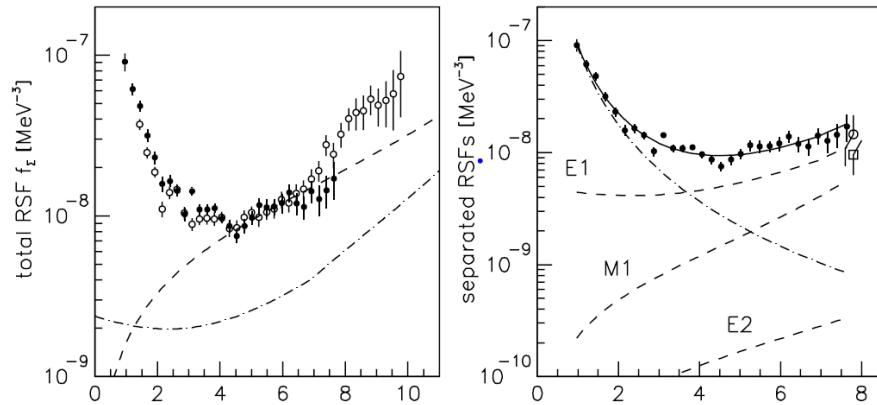
Determining the electric or magnetic nature of the low-energy enhancement in nuclei (and isomers)

S.N. Liddick
FRIB/MSU
5/19/2026



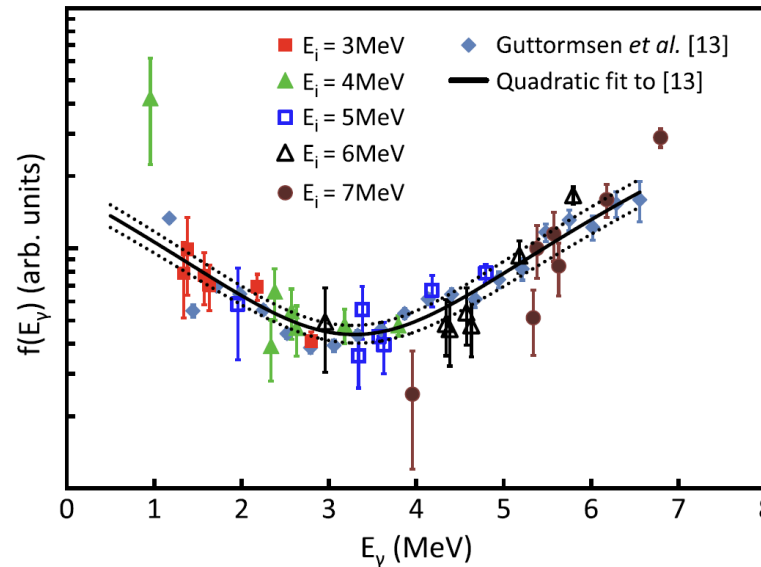
The Low-Energy Enhancement

First Observation in $^{56,57}\text{Fe}$



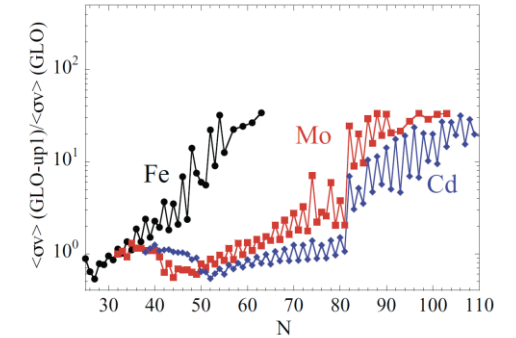
A. Voinov et al., PRL 93, 142504 (2004)

Observation in ^{95}Mo

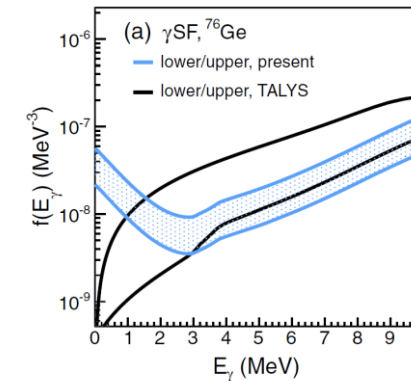


M. Weideking et al., PRL 108, 162503 (2012)

Impact on (n,γ)



A.C. Larsen S. Goriely,
PRC 82, 014318 (2010)



βOslo

A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL 113, 232502 (2014)

Today

LEE
observed

Impact on (n,γ)
demonstrated

LEE
confirmed

βOslo

2004

2010

2012

2013

2013

2014

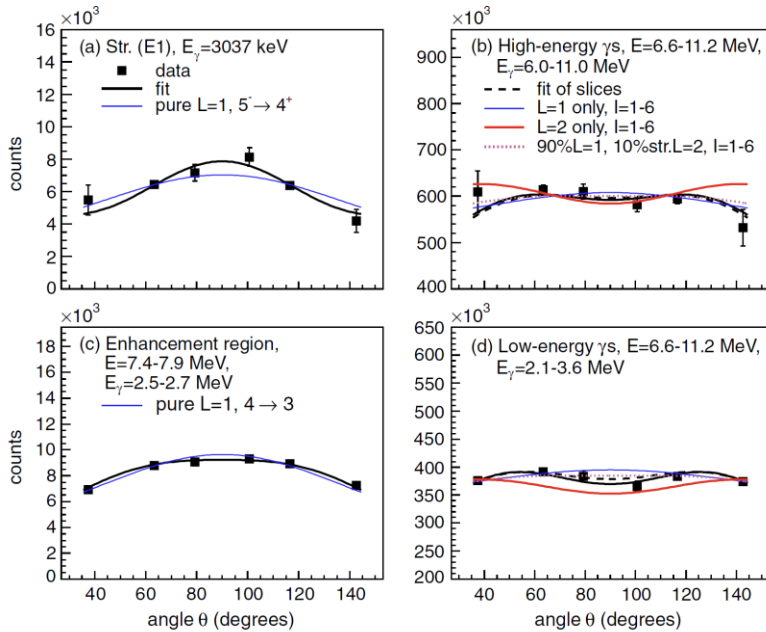
2017

2025



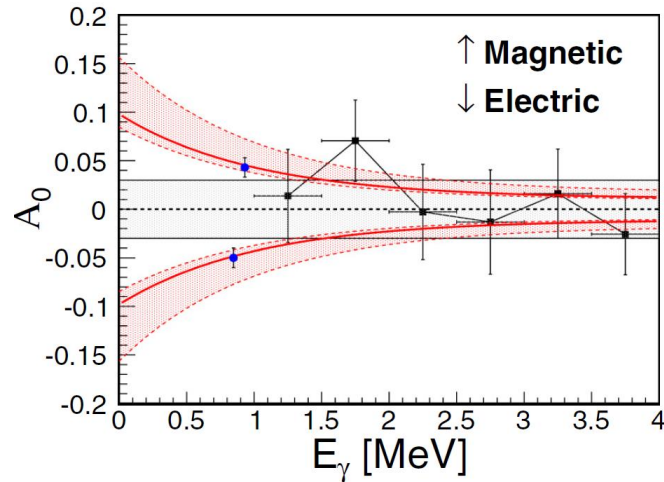
Characteristics of the Low-Energy Enhancement

Dipole confirmed



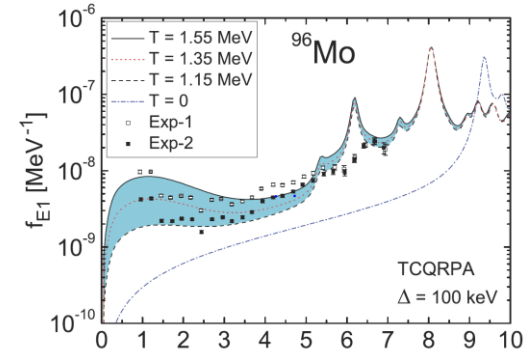
A.C. Larsen et al., PRL 111, 242504 (2013)

Suggestion of M1?



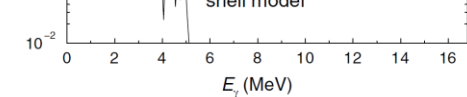
M. Jones et al., PRL 97, 024327 (2017)

Theory – E1



E. Litvinova et al.,
 PRL 88, 031302(R)
 (2013)

Theory – M1



Today

LEE observed

Impact on (n,g) demonstrated

LEE confirmed

Dipole demonstrated
 E1/M1 theory

β Oslo

Exp measurement attempts

2004

2010

2012

2013

2013

2014

2017

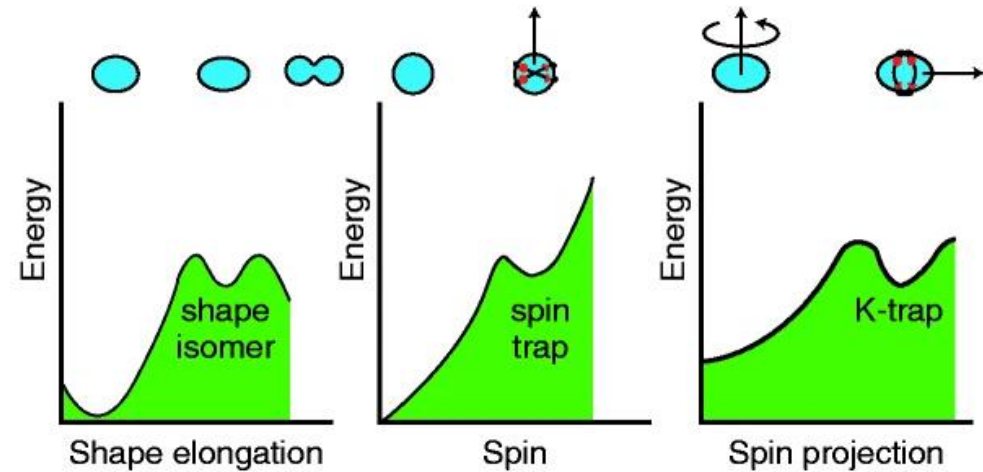
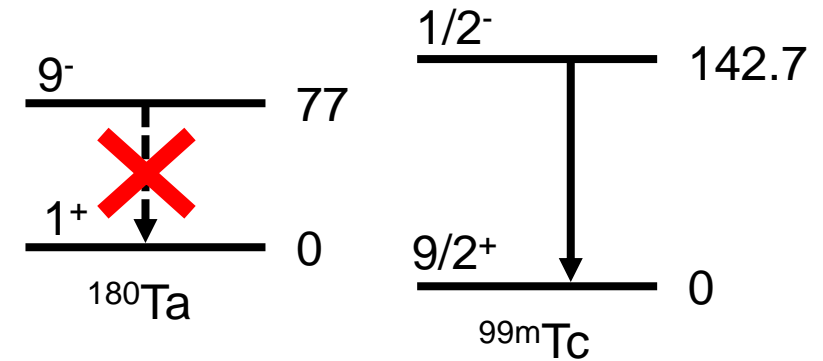
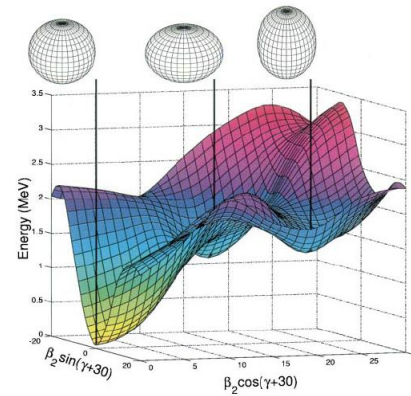
Many other studies

2025

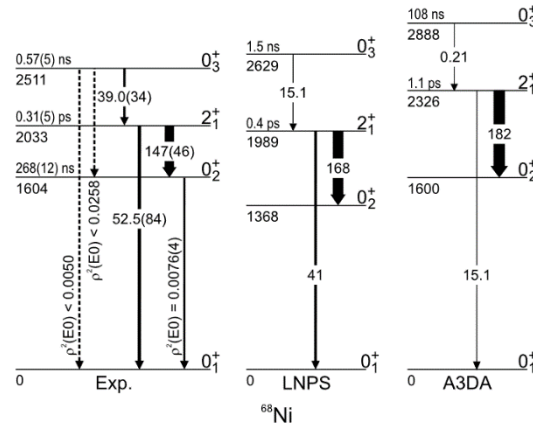
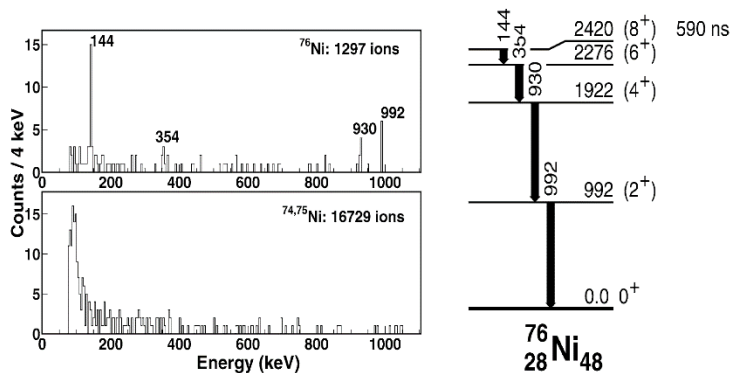


Isomeric States Contain Fingerprints of Underlying Nuclear Structure

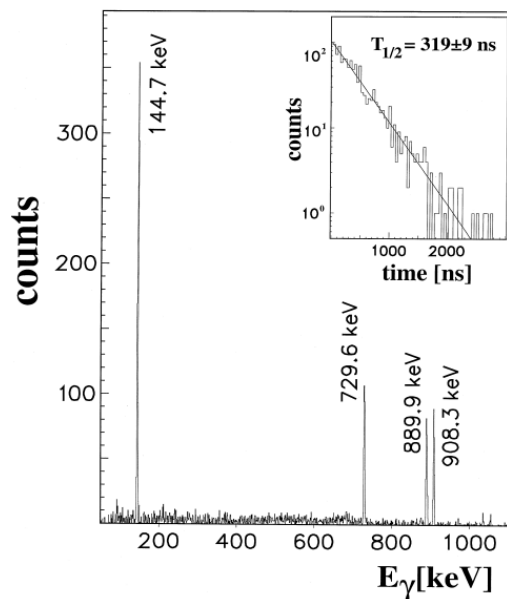
- Half-life greater than a fraction of nanoseconds.
- Wide range of excitation energies and half-lives.
- Wide range of spins and parities within a single nucleus
- Sometimes simple configurations.
 - Many can be related to a few single-particle shell-model states.
- Energies, half-lives, J^π can inform nuclear models.



Isomeric States Contain Fingerprints of Underlying Nuclear Structure (and they're everywhere)



- Wide variety of isomeric states in mass 70-80 isotopes.
- Focus on mass 70

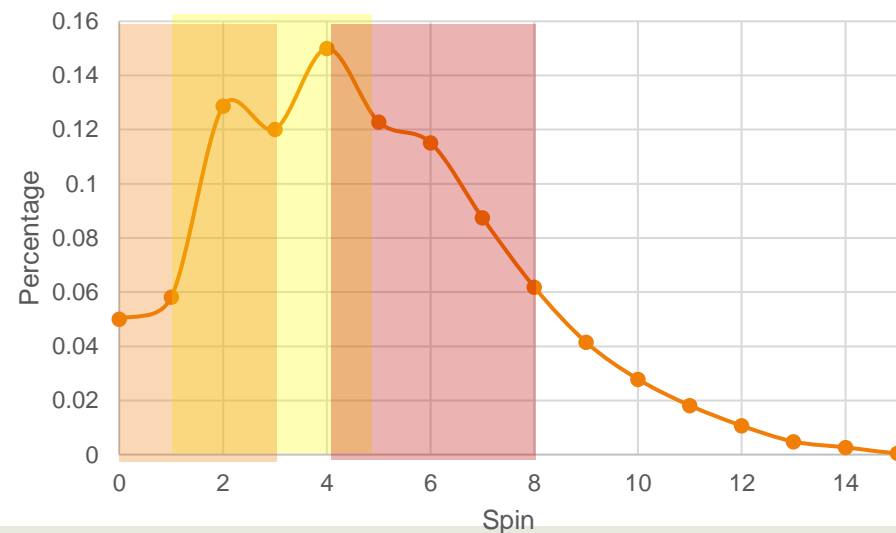
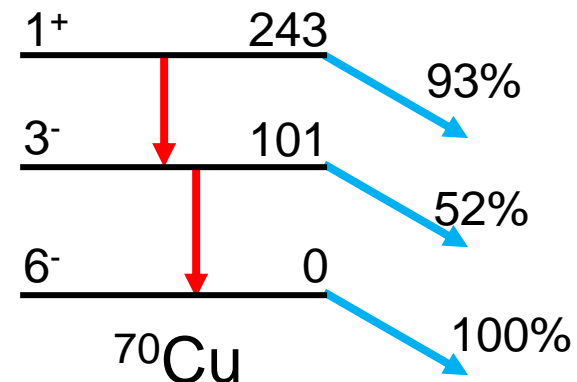


71Ge 11.43 d $\epsilon = 100.00\%$	72Ge STABLE 27.45%	73Ge STABLE	74Ge STABLE 36.50%	75Ge 82.75 m $\beta^- = 100.00\%$	76Ge STABLE 7.73%	77Ge 11.23 h $\beta^- = 100.00\%$	78Ge 88.0 m $\beta^- = 100.00\%$	79Ge 18.08 s $\beta^- = 100.00\%$	80Ge 29.5 s $\beta^- = 100.00\%$	81Ge 7.6 s $\beta^- = 100.00\%$	82Ge 4.56 s $\beta^- = 100.00\%$
70Ga 21.14 m $\beta^- = 99.99\%$ $\epsilon = 0.41\%$	71Ga STABLE 39.892%	72Ga 14.10 h $\beta^- = 100.00\%$	73Ga 4.86 h $\beta^- = 100.00\%$	74Ga 8.13 m $\beta^- = 100.00\%$	75Ga 126 s $\beta^- = 100.00\%$	76Ga 32.6 s $\beta^- = 100.00\%$	77Ga 12.7 s $\beta^- = 100.00\%$	78Ga 5.09 s $\beta^- = 100.00\%$	79Ga 2.847 s $\beta^- = 100.00\%$ $\beta^- n = 0.09\%$	80Ga 1.0 s $\beta^- = 100.00\%$ $\beta^- n = 0.86\%$	81Ga 1.217 s $\beta^- = 100.00\%$ $\beta^- n = 11.90\%$
69Zn 56.4 m $\beta^- = 100.00\%$	70Zn $\geq 2.3E+17$ y 2 β^-	71Zn 46.5 h $\beta^- = 100.00\%$	72Zn 46.5 h $\beta^- = 100.00\%$	73Zn 23.5 s $\beta^- = 100.00\%$	74Zn 95.6 s $\beta^- = 100.00\%$	75Zn 10.2 s $\beta^- = 100.00\%$	76Zn 5.7 s $\beta^- = 100.00\%$	77Zn 2.08 s $\beta^- = 100.00\%$	78Zn 1.47 s $\beta^- = 100.00\%$	79Zn 0.746 s $\beta^- = 100.00\%$ $\beta^- n = 1.70\%$	80Zn 561.9 ms $\beta^- = 100.00\%$ $\beta^- n = 1.00\%$
68Cu 30.9 s $\beta^- = 100.00\%$	69Cu 2.85 m $\beta^- = 100.00\%$	70Cu 44.5 s $\beta^- = 100.00\%$	71Cu 19.4 s $\beta^- = 100.00\%$	72Cu 6.63 s $\beta^- = 100.00\%$	73Cu 4.2 s $\beta^- = 100.00\%$	74Cu 1.594 s $\beta^- = 100.00\%$	75Cu 1.234 s $\beta^- = 100.00\%$	76Cu 0.639 s $\beta^- = 100.00\%$ $\beta^- n = 7.20\%$	77Cu 468.1 ms $\beta^- = 100.00\%$ $\beta^- n = 30.30\%$	78Cu 335 ms $\beta^- = 100.00\%$ $\beta^- n = 100.00\%$	79Cu 241.0 ms $\beta^- = 100.00\%$ $\beta^- n = 55.00\%$
67Ni 21 s $\beta^- = 100.00\%$	68Ni 29 s $\beta^- = 100.00\%$	69Ni 11.4 s $\beta^- = 100.00\%$	70Ni 6.0 s $\beta^- = 100.00\%$	71Ni 2.56 s $\beta^- = 100.00\%$	72Ni 1587 ms $\beta^- = 100.00\%$ $\beta^- n ?$	73Ni 842 ms $\beta^- = 100.00\%$ $\beta^- n ?$	74Ni 507.7 ms $\beta^- = 100.00\%$ $\beta^- n ?$	75Ni 331.8 ms $\beta^- = 100.00\%$ $\beta^- n = 10.00\%$	76Ni 234.7 ms $\beta^- = 100.00\%$ $\beta^- n = 14.00\%$	77Ni 158.4 ms $\beta^- = 100.00\%$ $\beta^- n ?$	78Ni 122.2 ms $\beta^- = 100.00\%$ $\beta^- n ?$



Isomeric States in ^{70}Cu Lead to Specific Spin Ranges in ^{70}Zn

- ^{70}Cu has three different isomeric states:
 - 6^- ground state ($t_{1/2} = 44.5$ s)
 - 3^- 101-keV state ($t_{1/2} = 33$ s)
 - 1^+ 243-keV state ($t_{1/2} = 6.4$ s)
- All three states undergo β decay to high energy states in ^{70}Zn ($Q_\beta = 6.58$ MeV). The three states are separable.
- Within the allowed approximation, β decay will populate within $\Delta J=1$ and same parity as the parent J^π .
- Offers the ability for multiple studies on γ SF and NLD as a function of spin in child nucleus



Using beta decay and total absorption spectroscopy to infer critical nuclear data

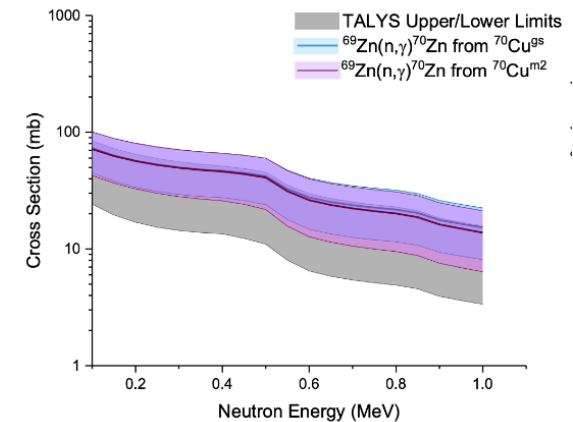
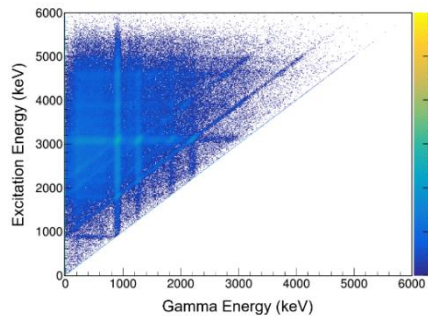
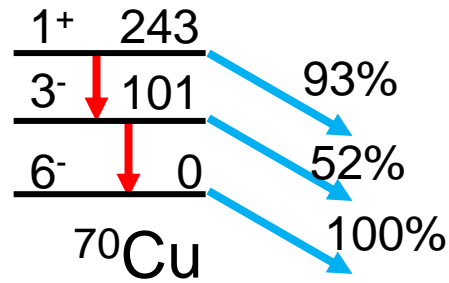
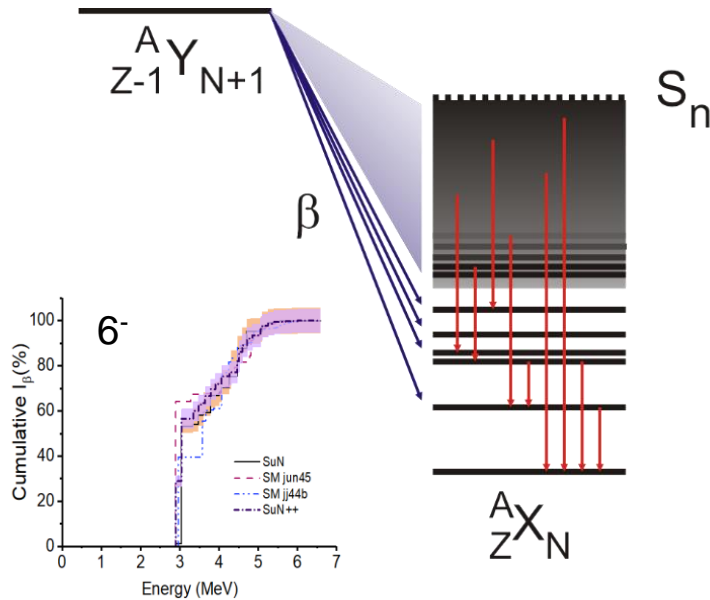
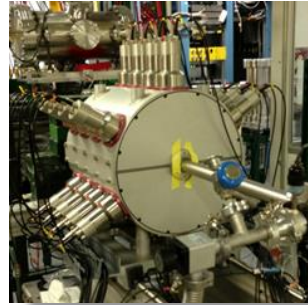
- Measure beta decay of nucleus using TAS.
- Extract critical nuclear data for structure, astrophysics, and stockpile stewardship

- I_β
- avg. e^-/γ energy
- n/γ competition

- nuclear level density,
- γ -ray strength function,
- gBA tests
- Spin cutoff studies

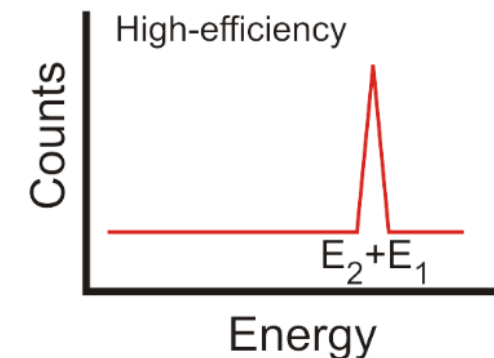
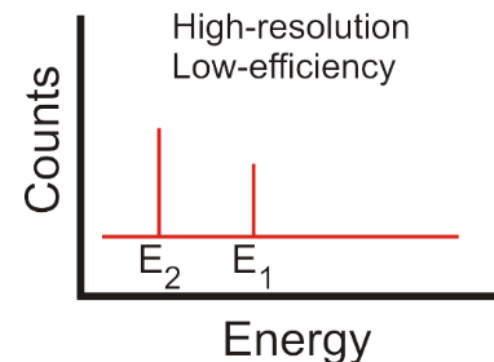
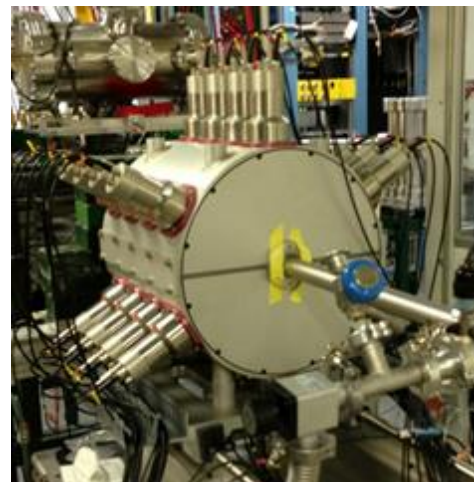
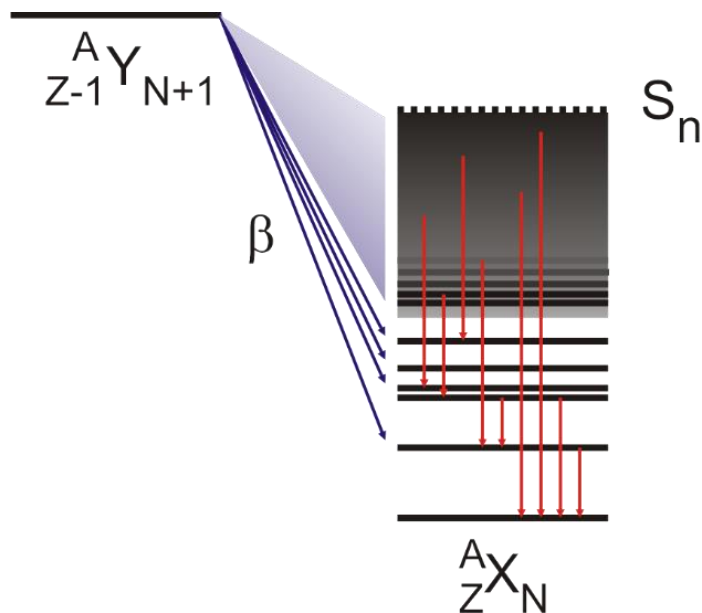
- neutron capture cross section

SuN



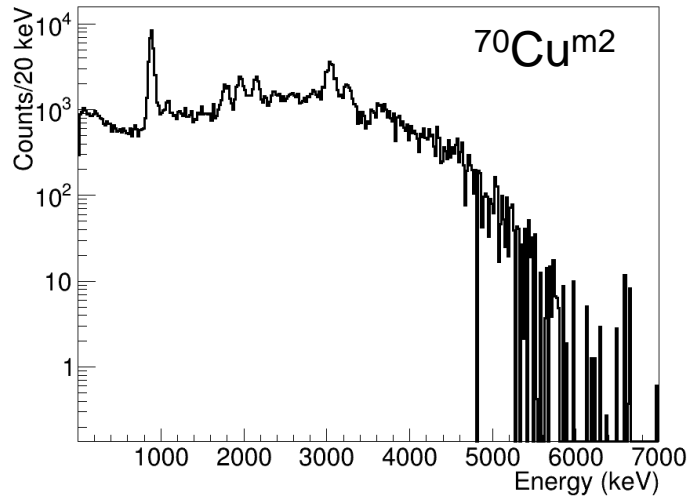
Using beta decay total absorption spectroscopy to infer neutron capture cross sections

- Measure beta decay of nucleus.
 - Extract level densities and gamma-ray strength function
- Need total excitation energy of the daughter isotope.
 - Can't use beta-decay electron (three body process)
- Instead, measure total emitted photon energy.

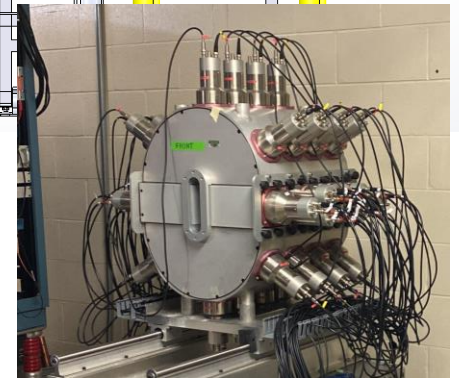
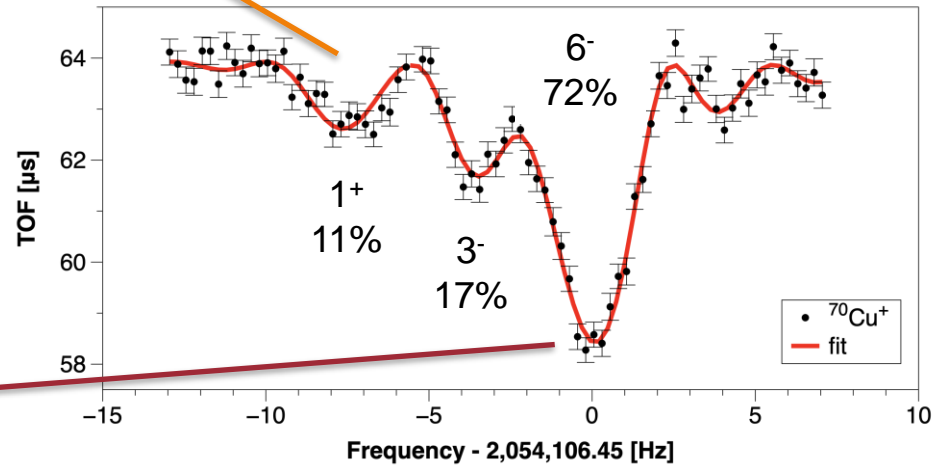
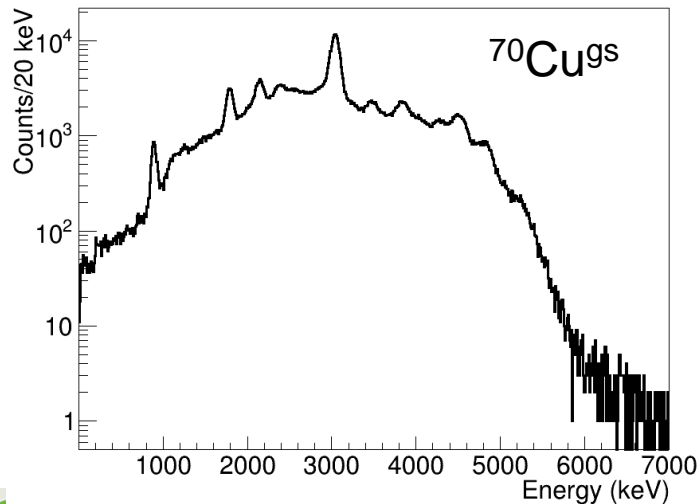
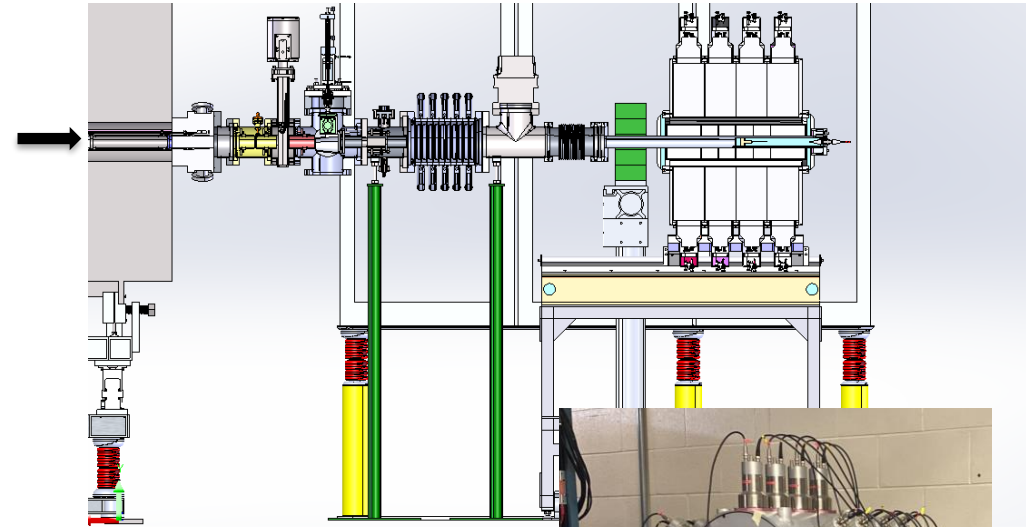


- Require high detection efficiency.
- Extract nuclear level density and γ -ray strength function.
- Insert both quantities into a statistical reaction model to constrain (n,γ) rate.

Isomers Produced, Isolated, and Delivered



Beam containing ^{70}Cu ions produced, separated (ARIS), thermalized (Gas Cell) and isomers isolated and delivered (LEBIT) to experimental end-station



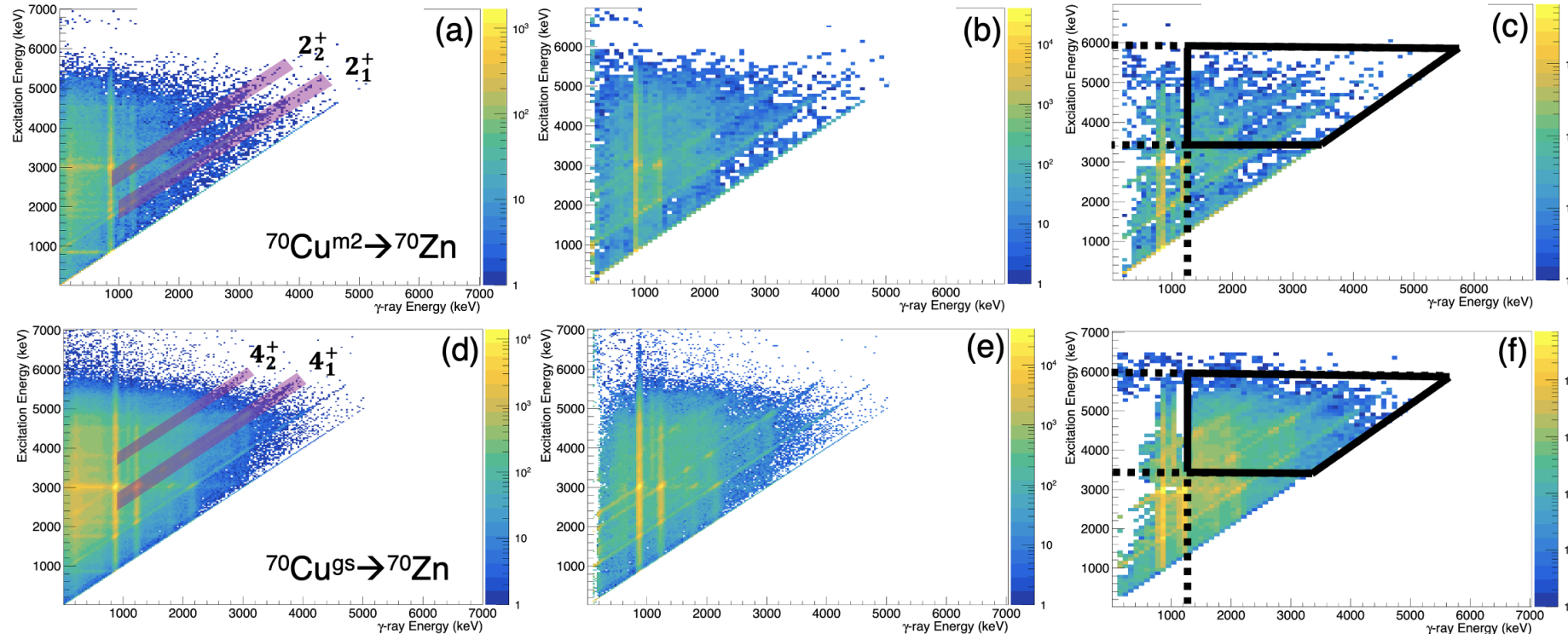
SuN was upgraded to SuN++, 12 NaI and 8 CeBr₃ detectors added



Oslo Method To Get Functional Form of γ SF

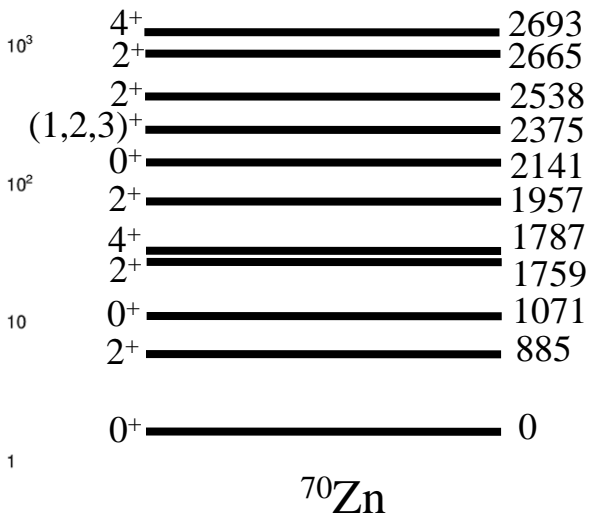
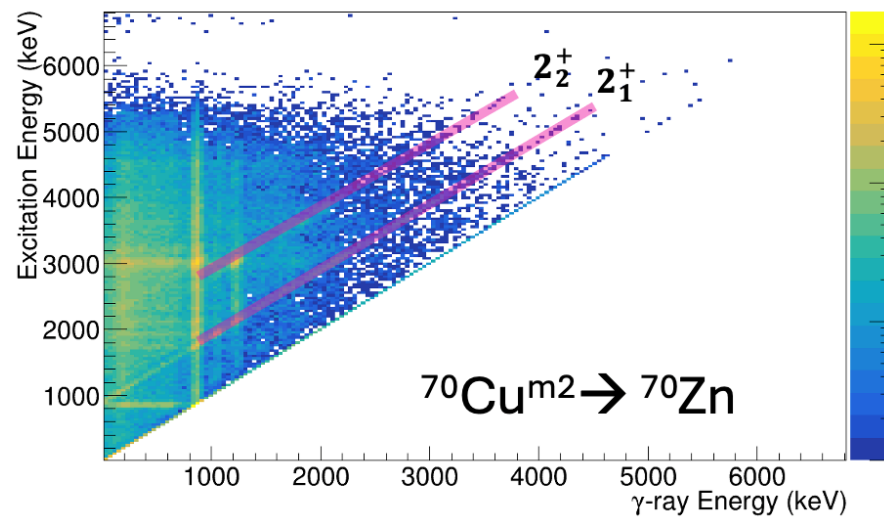
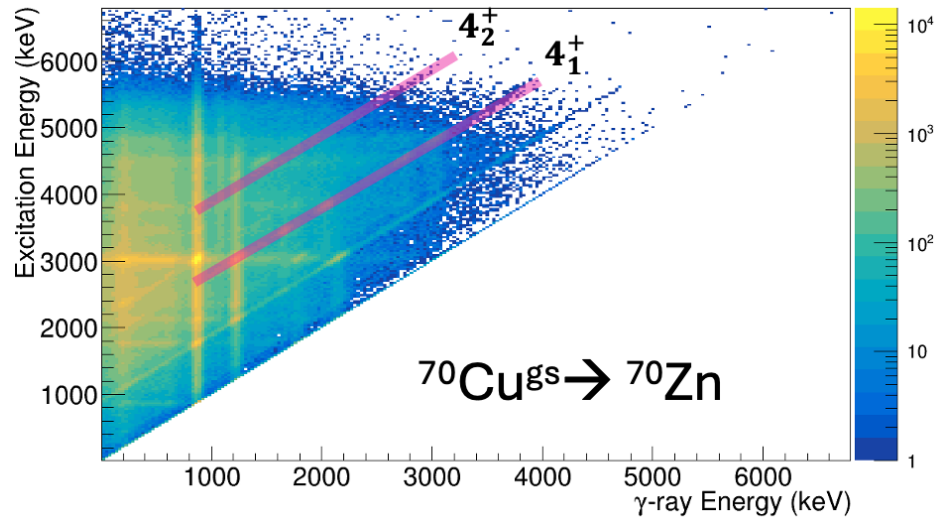
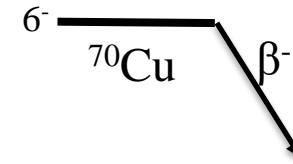
Oslo Method Steps:

1. Create raw E_x vs E_γ
2. Generate a response function for SuN++ and unfold the matrix to account for detector response
3. Use an iterative subtraction procedure to extract the first-generation γ -rays
4. Extract functional form of the NLD and γ SF
5. Normalize the NLD and γ SF



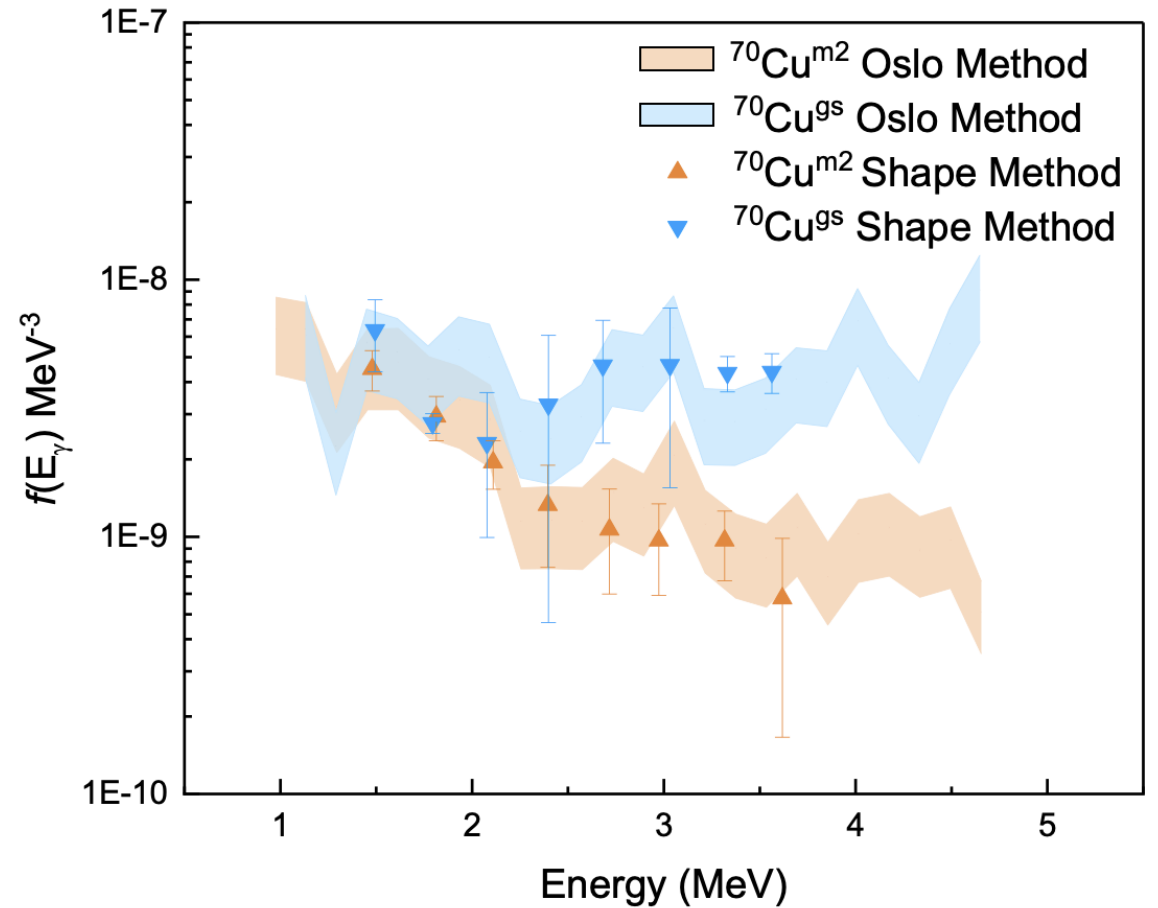
The Shape Method

- Use shape method to extract model independent slope of the γ SF following β decay
- Requires similar known spin and parity states
 - Two 2^+ states following the decay of $^{70}\text{Cu}^{m2}$.
 - Two 4^+ states following the decay of $^{70}\text{Cu}^{gs}$.
- “Diagonals observed in the E_x vs E_γ matrix corresponding to all four states.



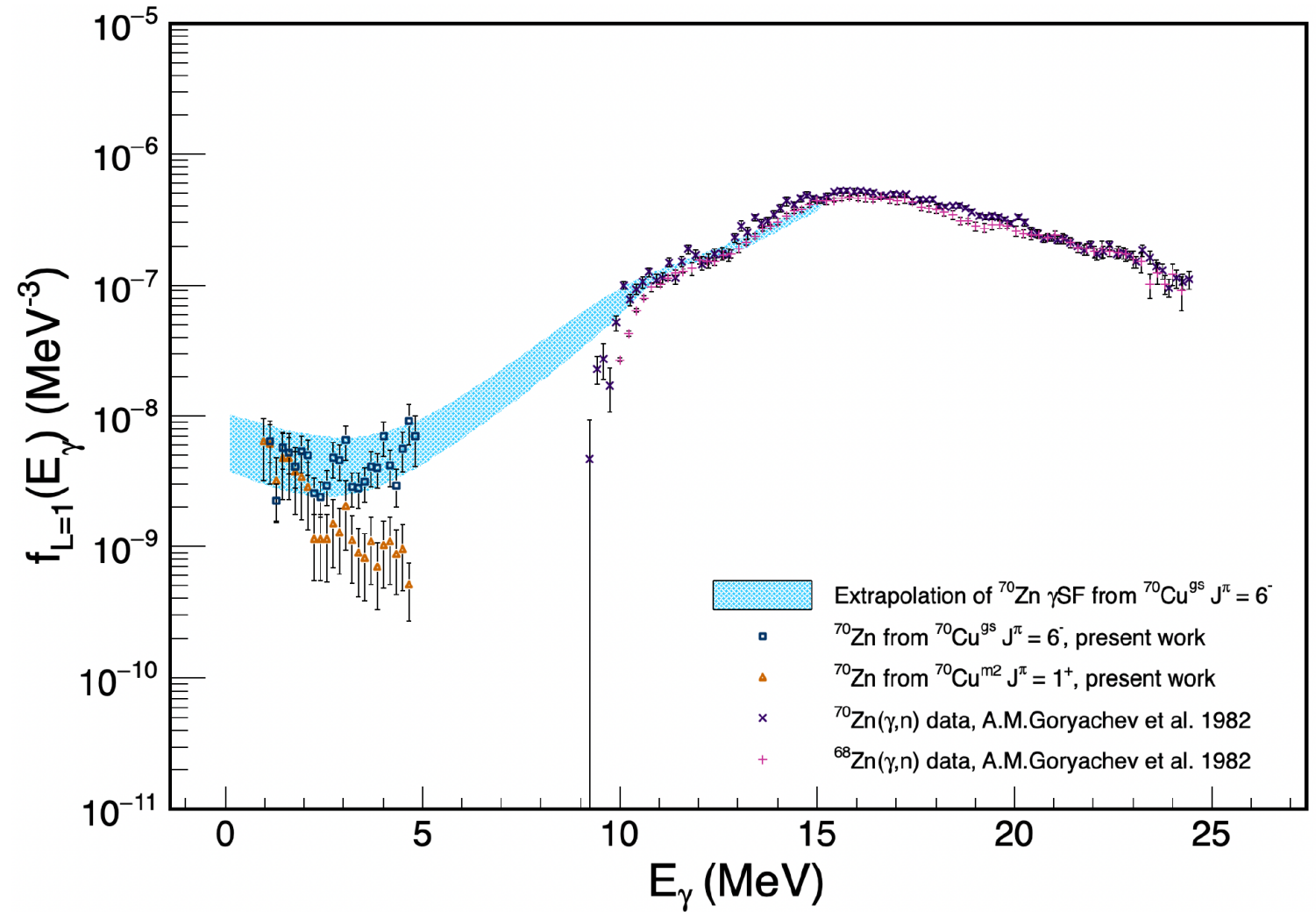
^{70}Zn γ -ray Strength Function (γSF)

- Functional form of γSF from β -Oslo method matched to γSF slope from Shape Method
- Shapes between the γSF extracted following the decay of $^{70}\text{Cu}^{\text{m}2}$ and $^{70}\text{Cu}^{\text{gs}}$ are different.



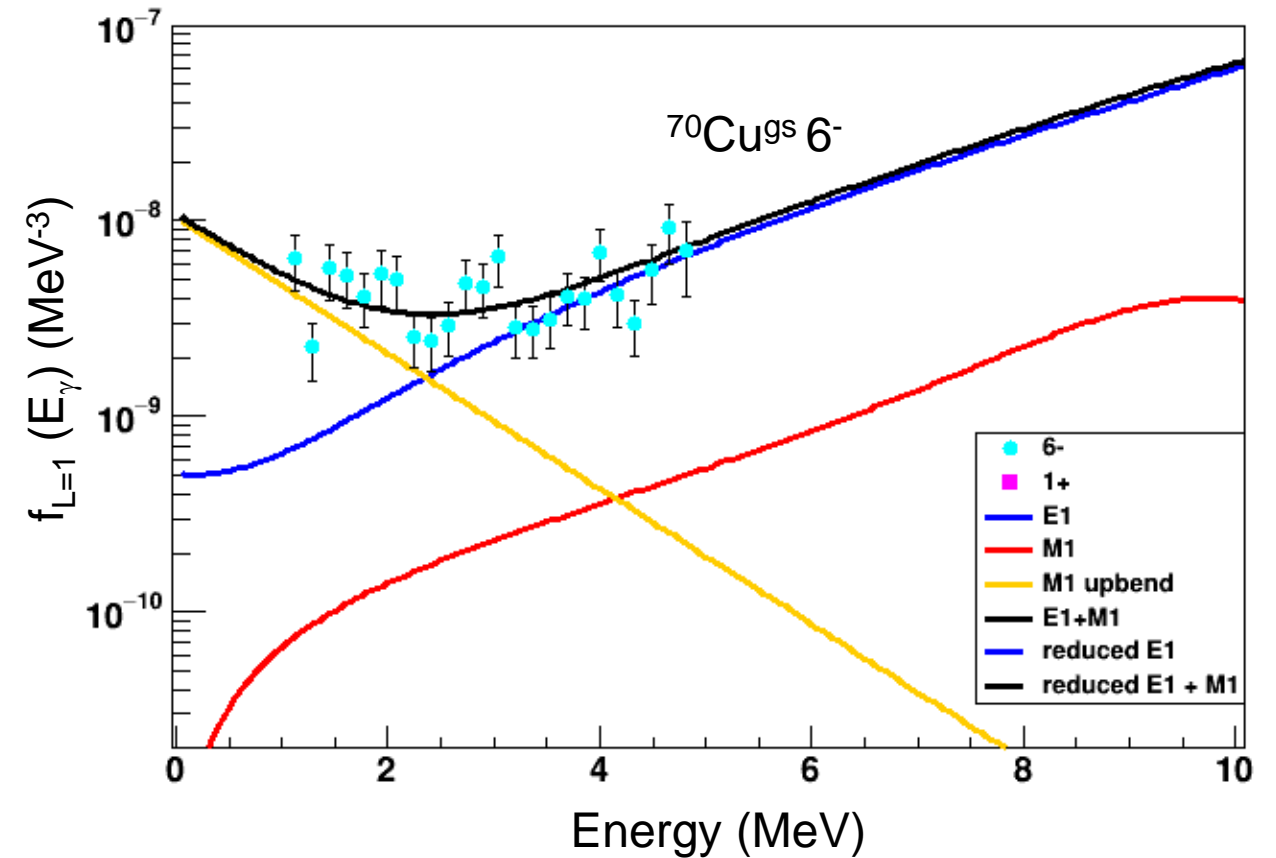
^{70}Zn γ -ray Strength Function (γSF) Extracted from $^{70}\text{Cu}^{\text{gs}}$ and $^{70}\text{Cu}^{\text{m}2}$ are Different

- Match the γSF extrapolation to tail of GDR.
- GDR data taken from:
 - $^{70}\text{Zn}(\gamma, n)^{69}\text{Zn}$
 - $^{68}\text{Zn}(\gamma, n)^{67}\text{Zn}$
- Shapes between the γSF extracted following the decay of $^{70}\text{Cu}^{\text{m}2}$ and $^{70}\text{Cu}^{\text{gs}}$ are different.



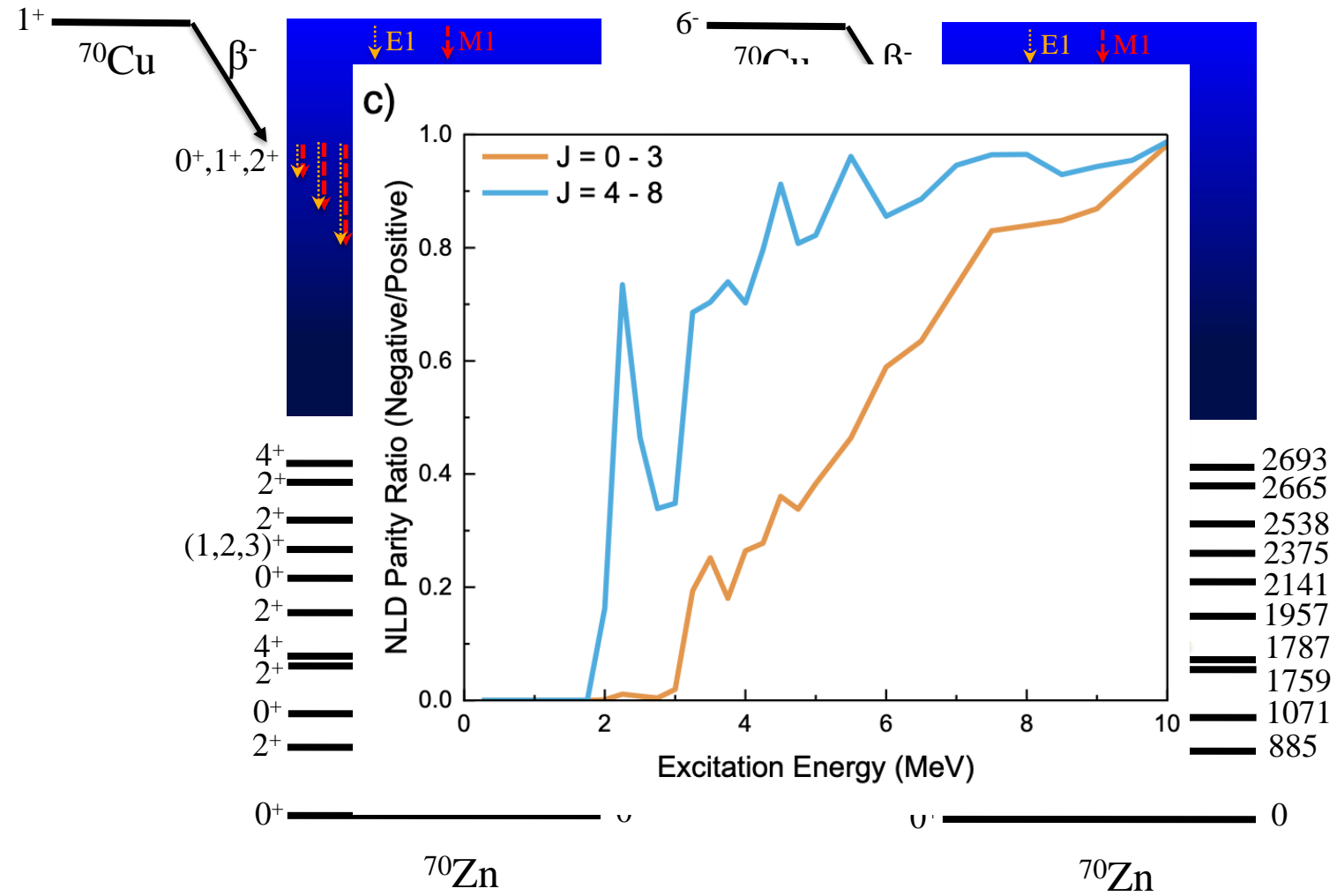
Model the Strength Function (γ SF) from $^{70}\text{Cu}^{\text{gs}}$ Using Three Components

- Model the γ SF with three components taken from TALYS (option 8, model 2 for M1)
 - E1
 - M1
 - M1 exponential upbend
- Constrain M1 component to be an order of magnitude less than E1 (based on data from neighboring nuclei).
- Fit three components to experimental data allowing relative amplitudes of E1 and exponential upbend to vary.



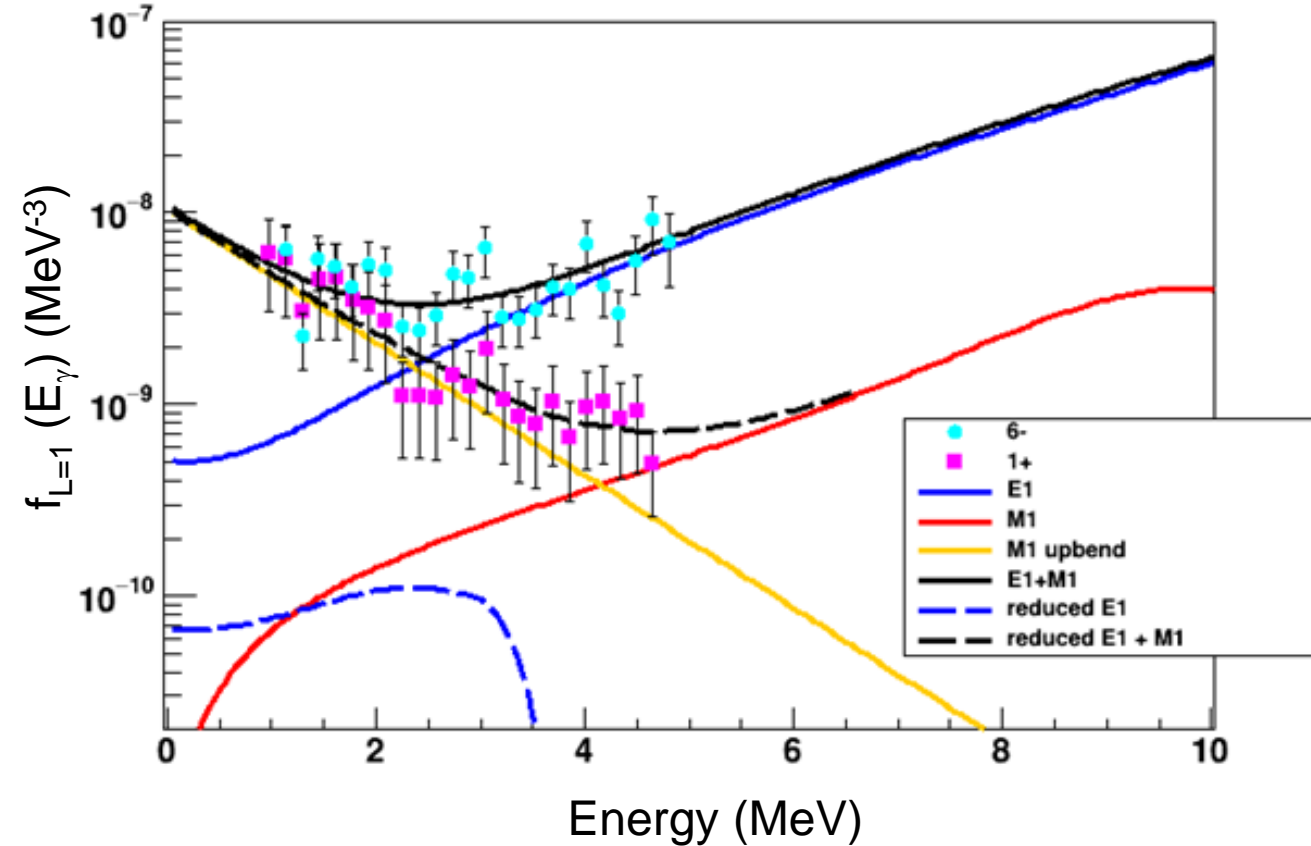
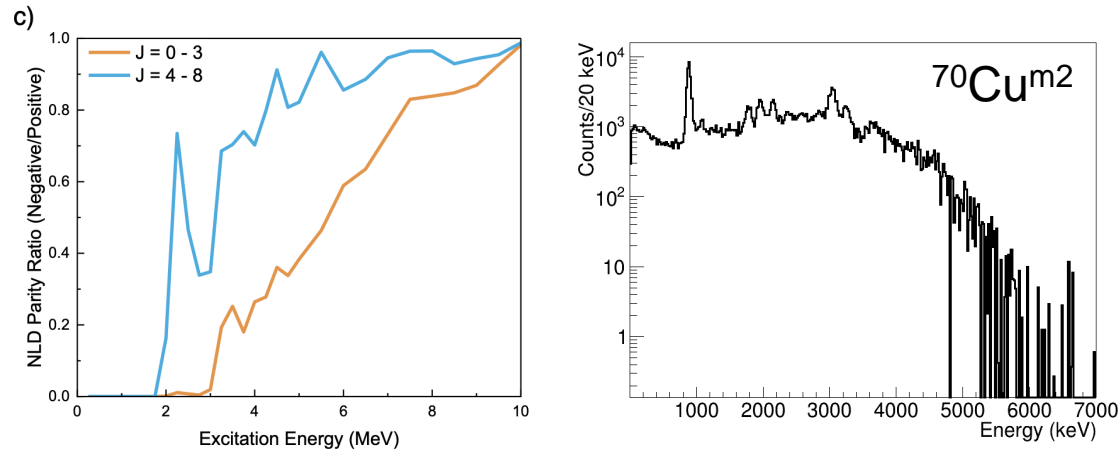
The Strength Function (γ SF) from $^{70}\text{Cu}^{m2}$ Lacks High-Energy E1 transitions

- In decay of $^{70}\text{Cu}^{m2}$ state ($Q_\beta = 6.58$ MeV) positive parity states from spin 0-2 are populated.
- Below ~ 3 MeV in ^{70}Zn only positive parity states are present.
- In the decay of the $1+$ state:
 - high-energy transitions between the initial population and the low-energy level scheme must proceed through M1 transitions.



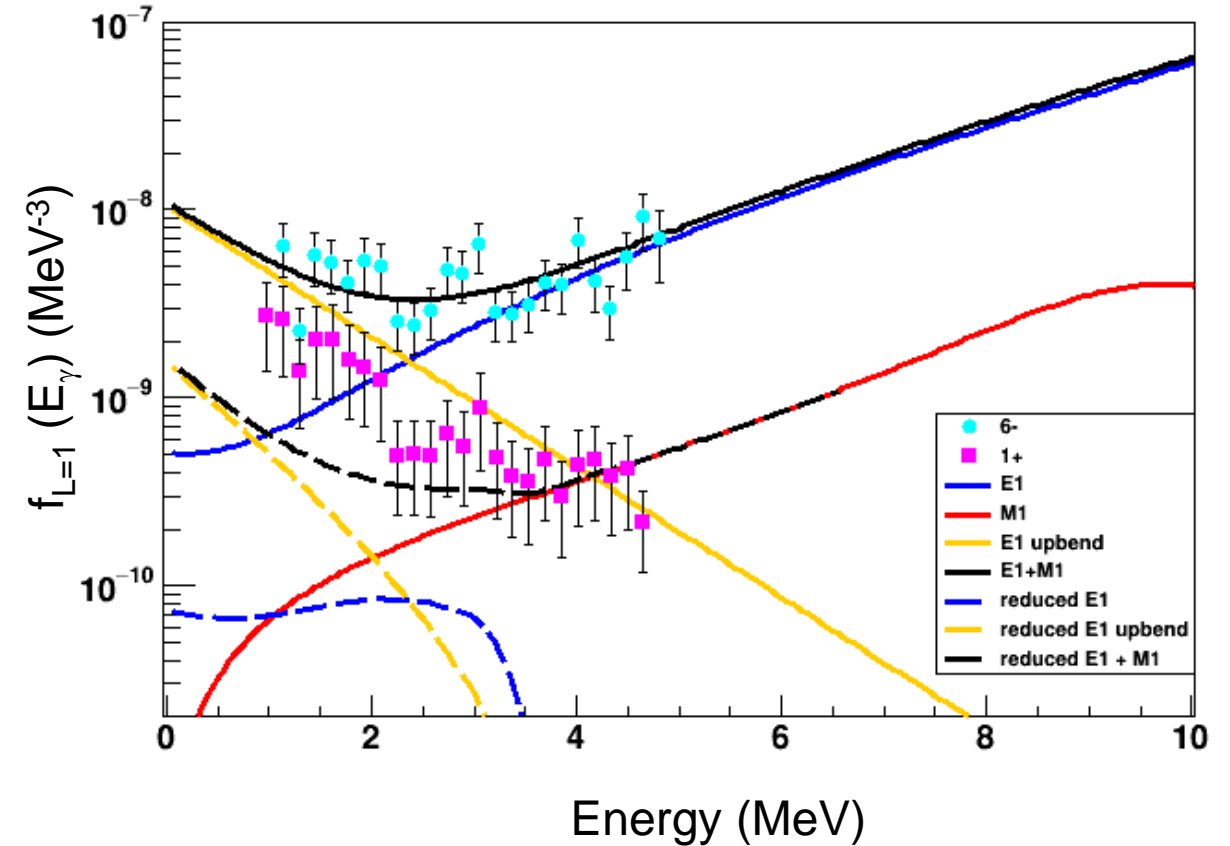
Modifying γ SF from $^{70}\text{Cu}^{\text{gs}}$ to Account for Lack of High-Energy E1 transitions Matches Shape of γ SF from $^{70}\text{Cu}^{\text{m}2}$

- Use parity asymmetry from TALYS and reduce E1 strength by a weighted factor to account for the absence of states which allow E1 transitions.
- The $^{70}\text{Cu}^{\text{m}2}$ data lies along the reduced curve.

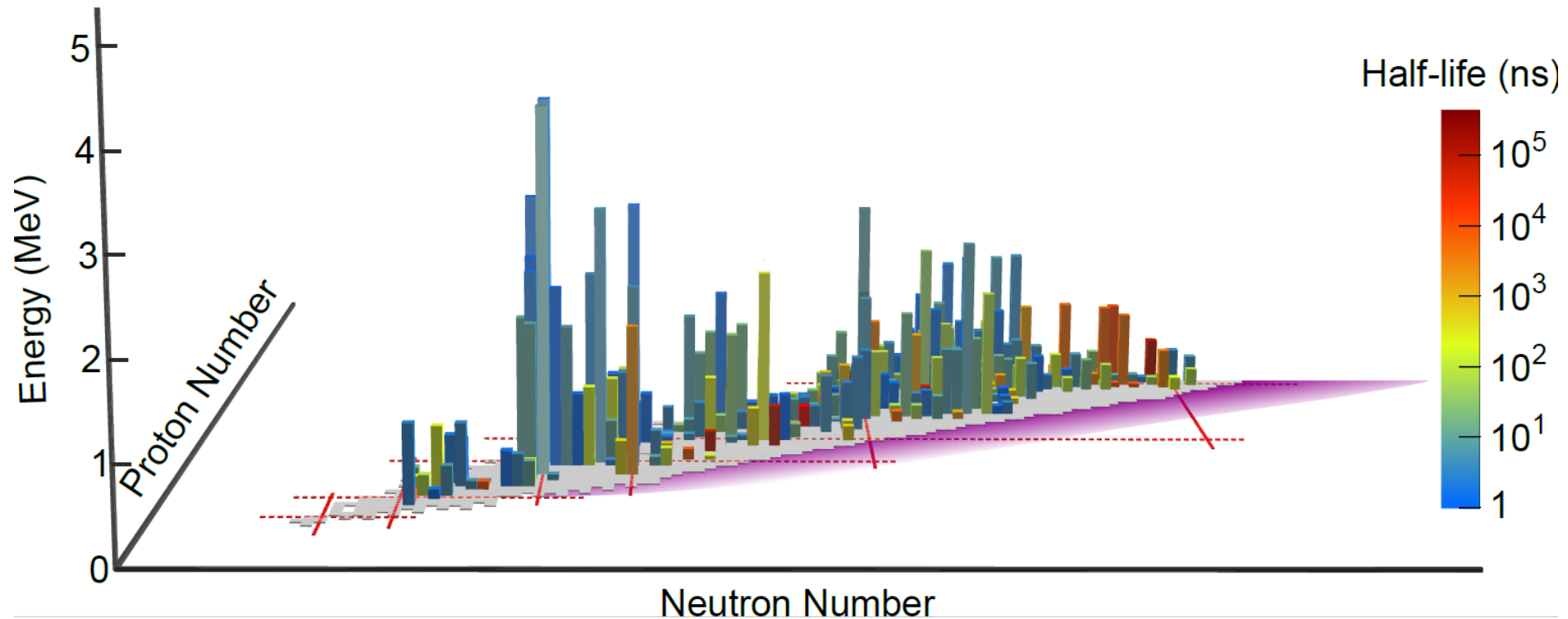


Modifying γ SF from $^{70}\text{Cu}^{\text{gs}}$ Assuming an E1 LEE Does Not Match Shape of γ SF from $^{70}\text{Cu}^{\text{m2}}$

- Performed identical analysis assuming an E1 upbend instead of an M1 upbend.
- The curves do not match
- Demonstrates that the upbend is M1.



A Wealth of Isomeric States Exist to Perform Future Studies: nuclear isomeric skyline



- Nuclear chart up to Z=51 (Sb)
- Nuclei with known half-lives between 1-500 ms
- Height represents decay energy and color represents half-life

Summary

- The LEE is M1
- Isomeric states offer an important mechanism to prepare specific, known sets of spins and parities. Enables explorations of:
 - Strength functions from well defined set of initial states
 - Partial level densities
 - » Spin cutoff parameters
 - Isomer decays
- Questions/Discussion:
 - In ^{70}Cu , is the γSF modified, or do we just not have the available states for transitions to occur? (philosophical)
 - Where do we expect the LEE enhancement?
 - » Related to deformation?
 - How well can we constrain spin cutoff parameters? (future work)

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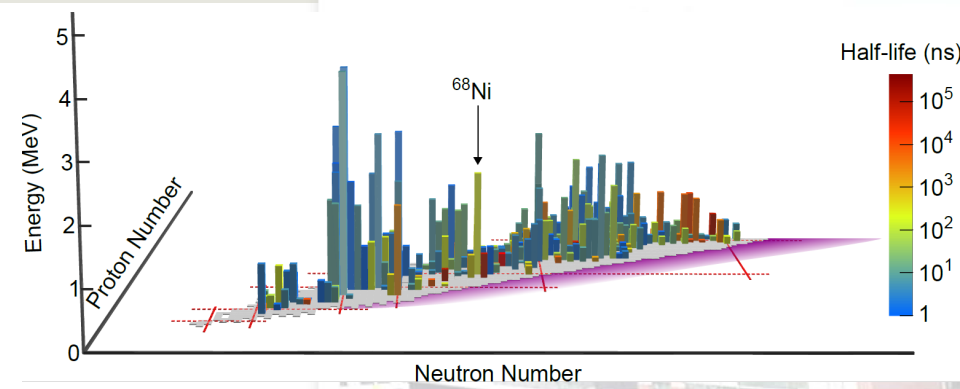


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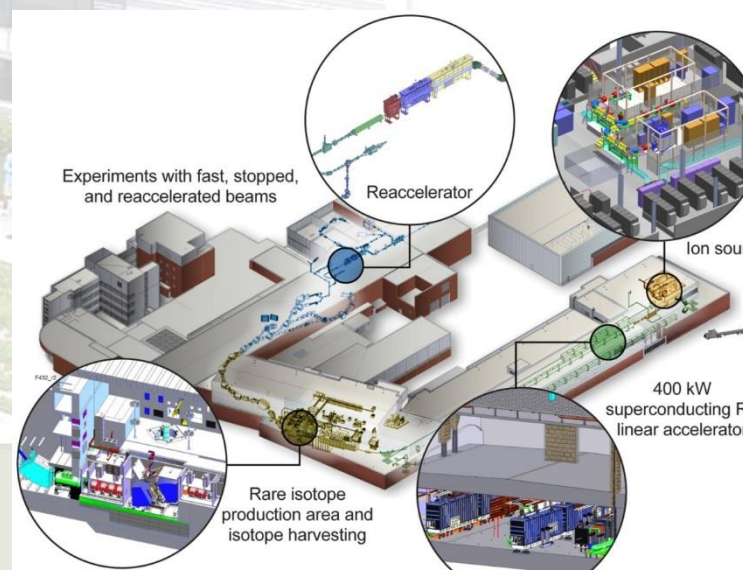
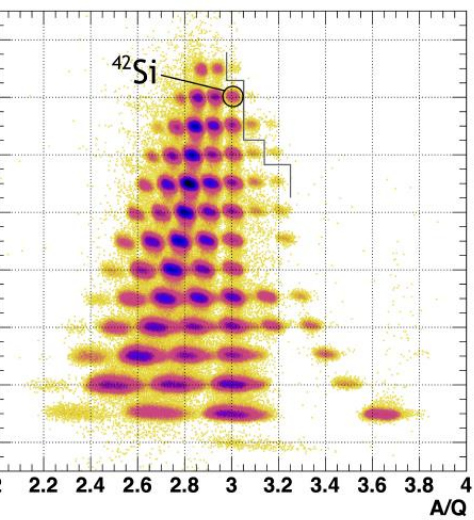
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Facility for Rare Isotope Beams
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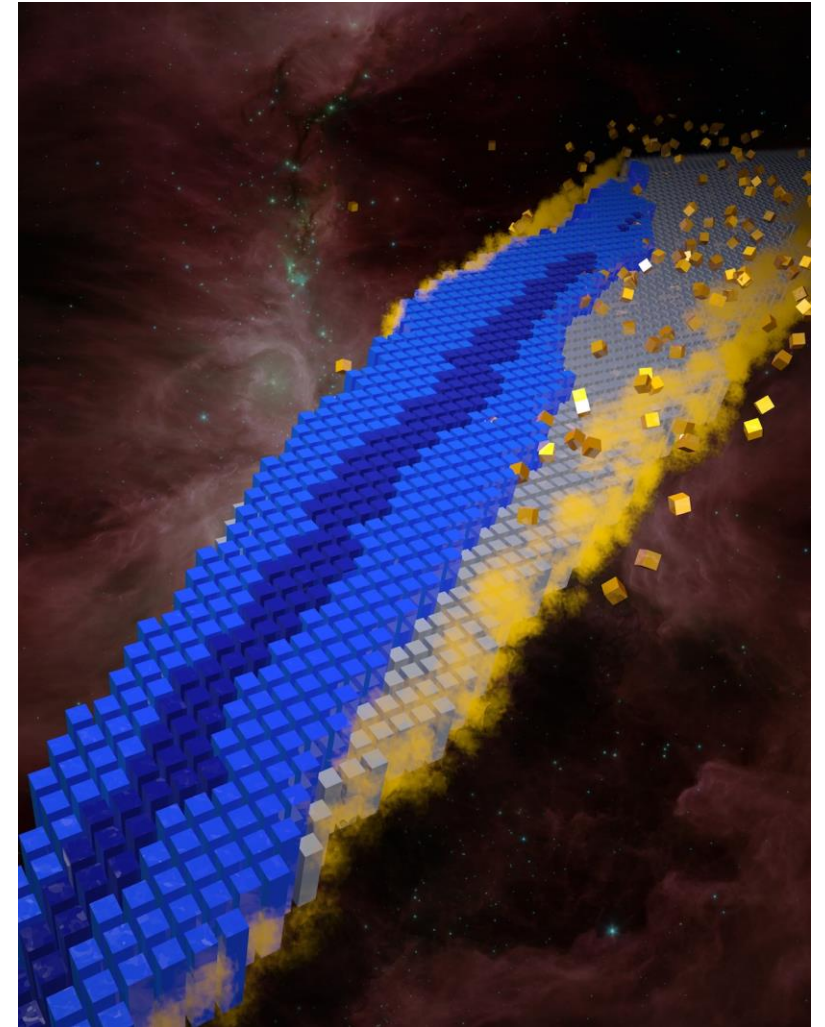
Thanks
Questions?



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Nuclear Science Challenges

- Comprehensive and predictive model of atomic nuclei.
- Evolving structure of atomic nuclei as a function of protons and neutrons from first principles.
 - Understanding the origin of the elements.
 - Explosive nucleosynthesis
- Use of atomic nuclei to test fundamental symmetries.
- Search for new applications of isotopes and solutions to societal problems.



A. Sproles, Oak Ridge National Laboratory

2015 Long Range Plan for Nuclear Science

