Cross Sections for Neutron Reactions from Surrogate Measurements: Revisiting the Weisskopf-Ewing Approximation

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DNP20 Session FD: Nuclear Theory II: Structure and Reactions
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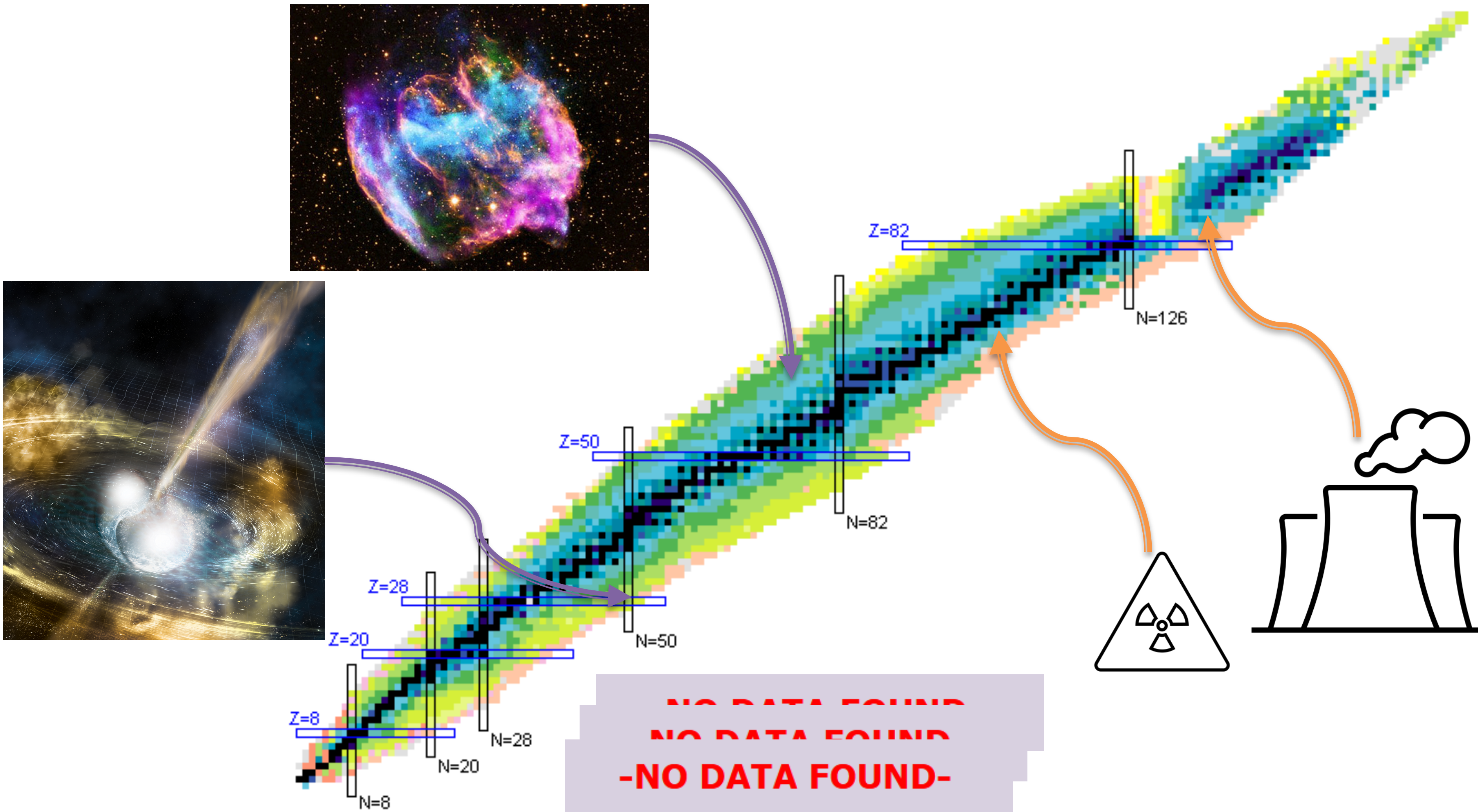
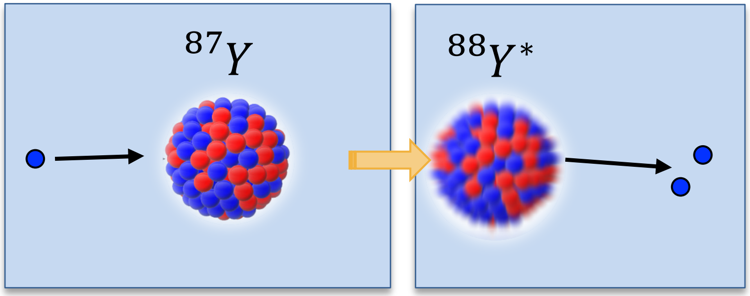
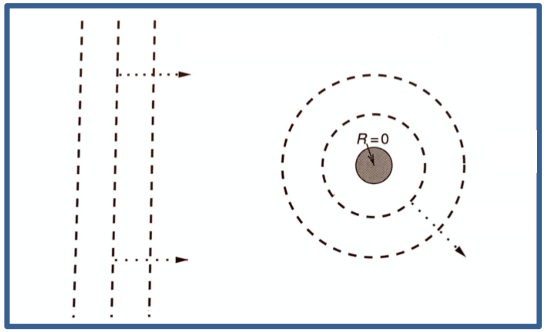
Nuclear reaction networks rely on vast amounts of data that has never been measured

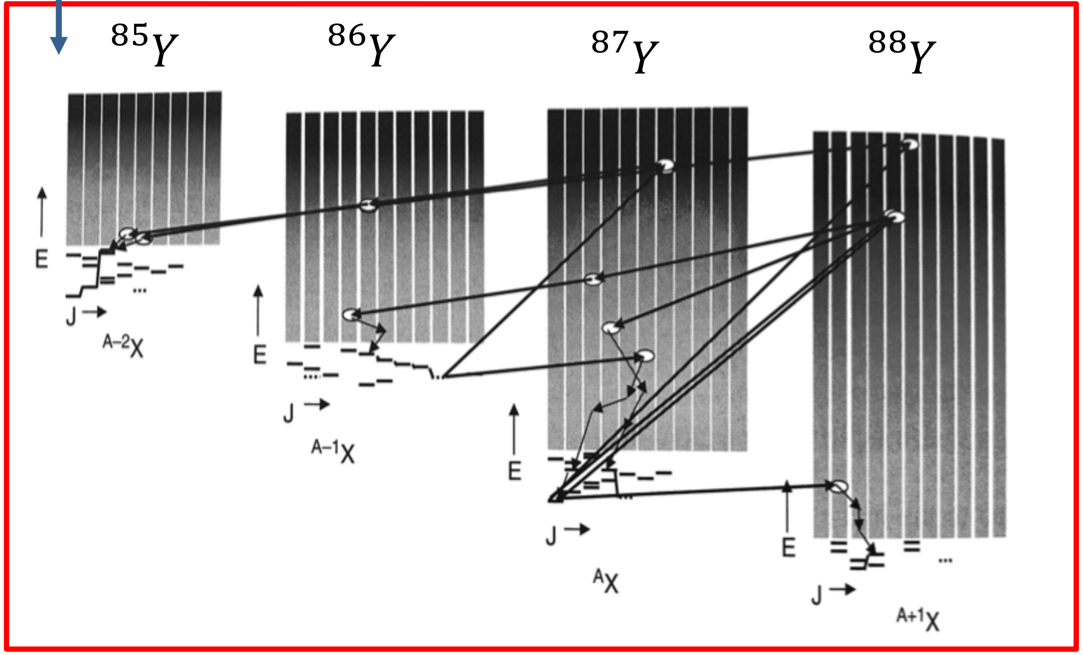


We don't have nuclear structure calculations detailed enough to model decays off-stability

Desired reaction





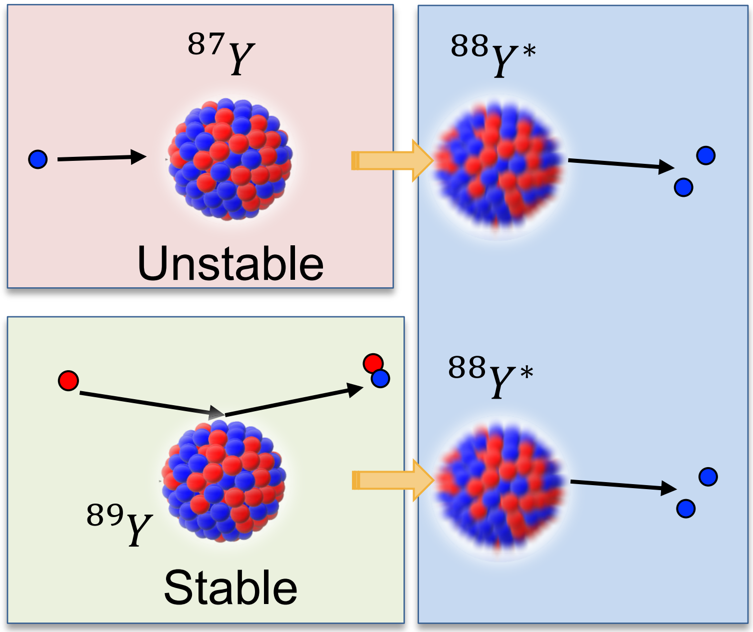


Figures from: "Nuclear Reactions for Astrophysics" Thompson and Nunes

Physicists have developed surrogate methods for measuring unstable nuclei

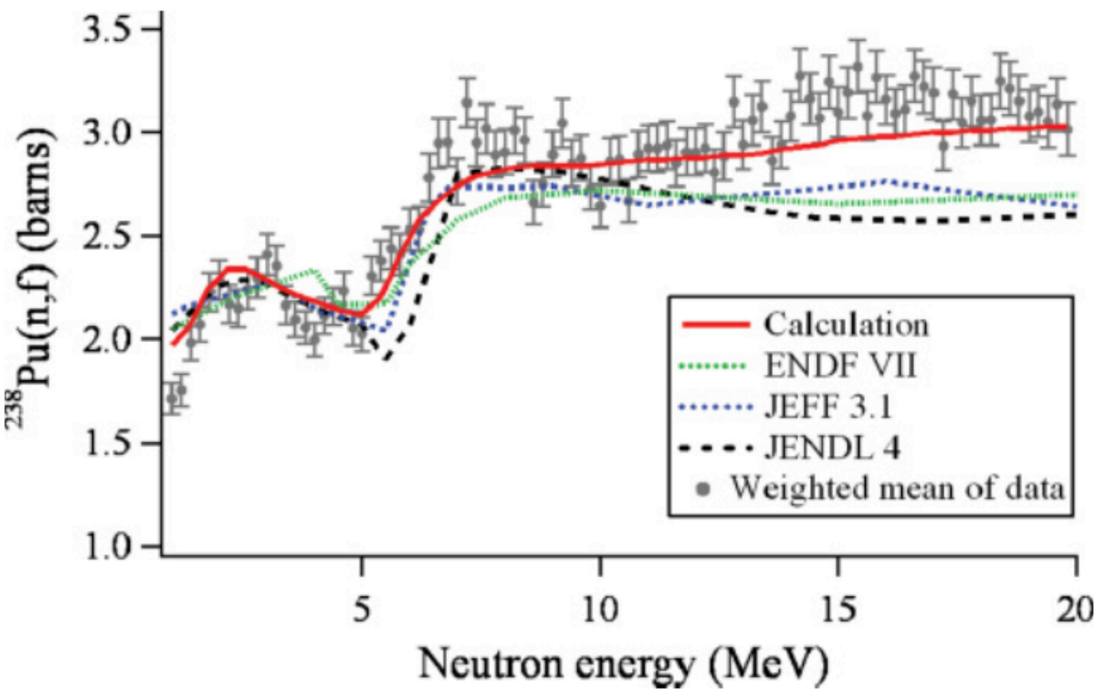
Desired reaction

Surrogate reaction



Fission	
Gamma-ray emission	
Neutron emission	

Surrogate method succeeds in predicting fission cross sections

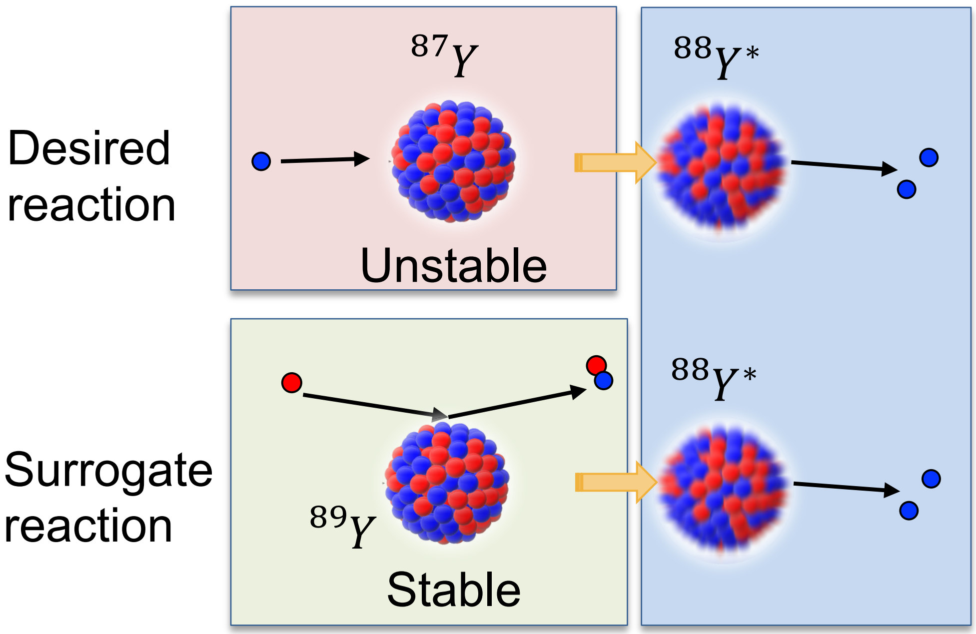


Fission	✓

Ressler, Burke, Escher PRC 83 (2011) 054610

See also:
Kessedjian et al. CENBG PLB 692 (2010) 297
Escher et al. RMP 84 (2012) 353

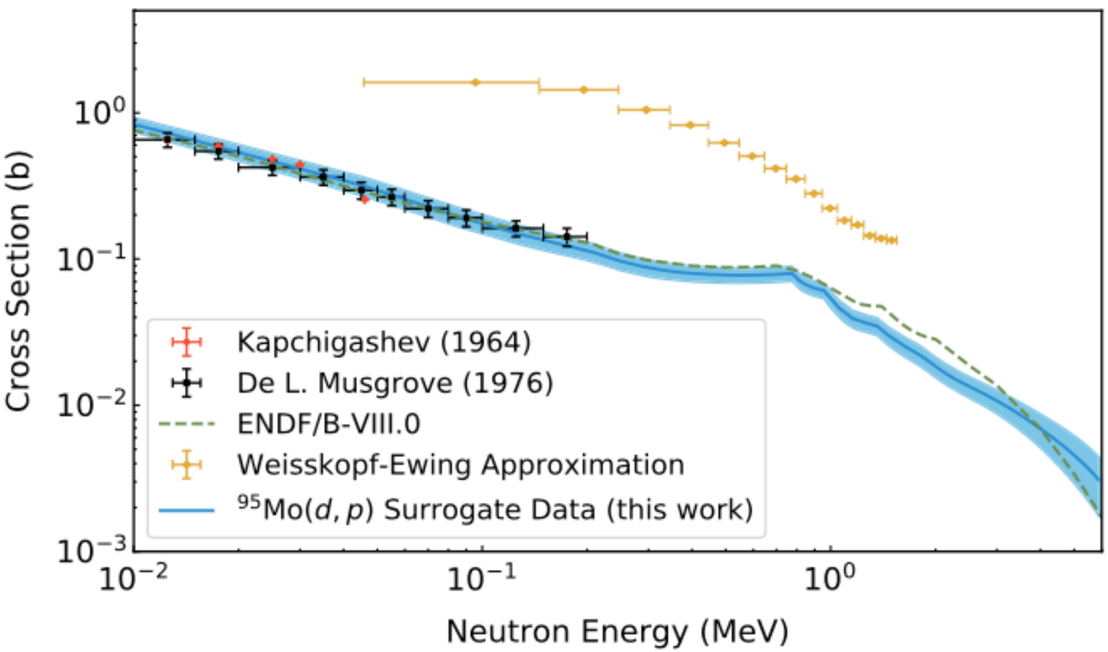
Surrogate method succeeds in predicting fission cross sections – using an approximation

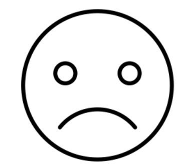


Fission	✓
Gamma-ray emission	
Neutron emission	

Weisskopf-Ewing approximation assumes nucleus forgets how it was formed

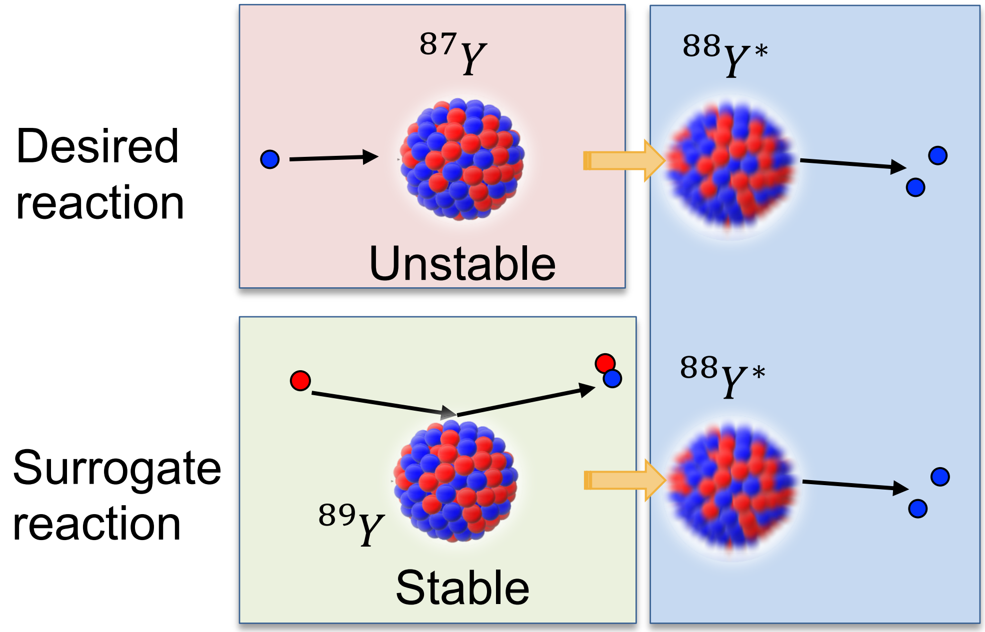
$^{95}Mo(n,\gamma)$ neutron capture cross section via surrogate method



Gamma-ray emission	

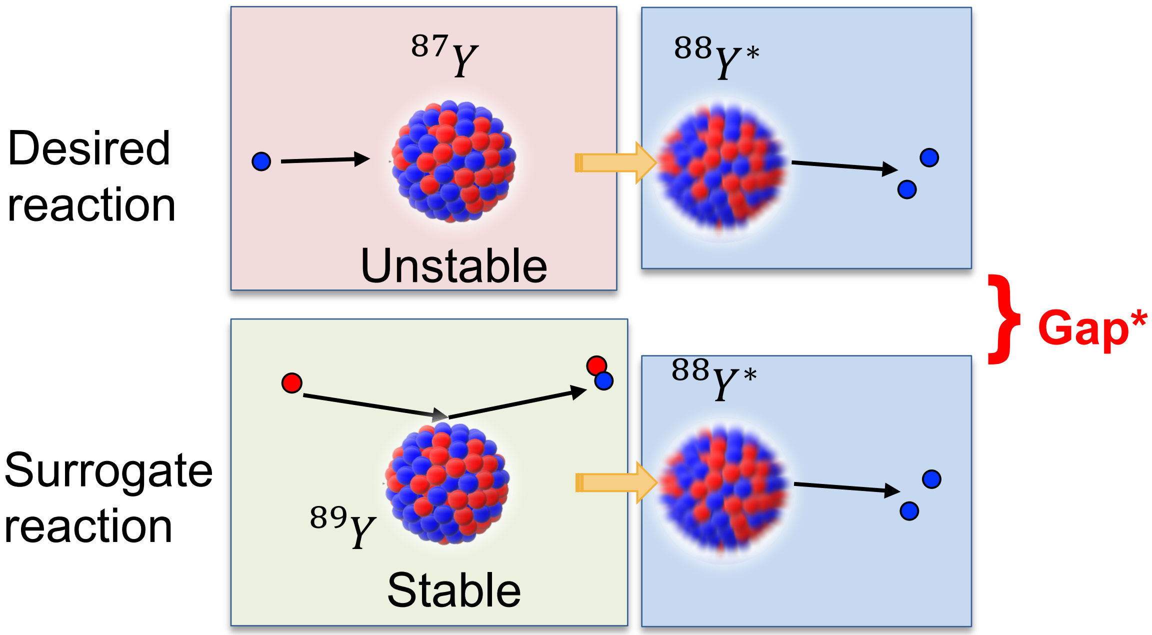
Ratkiewicz et al. PRL 122, 052502 (2019)

The method (approximation) used for fission, fails for neutron capture



Fission	✓
Gamma-ray emission	☹
Neutron emission	

We know why Weisskopf-Ewing doesn't work for neutron capture

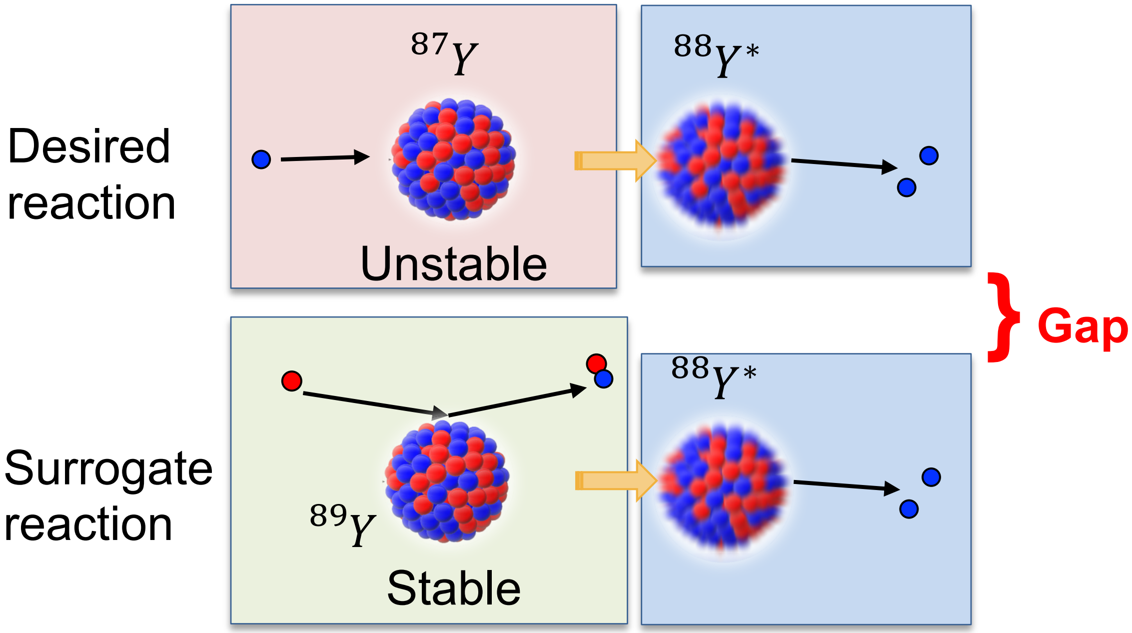


*Breaking news: angular momentum and parity are conserved

Fission	
Gamma-ray emission	
Neutron emission	

Weisskopf-Ewing approximation ignores spin and parity

The type decay channel determines sensitivity to any mismatch in spin and parity



Fission	Low sensitivity to spin mismatch
Gamma-ray emission	High sensitivity to spin mismatch
Neutron emission	

More sophisticated theory can be used to account for spin-parity mismatch

Surrogate method still possible for neutron capture!

- PRL 121, 052501 (2018)
- PRL 122, 052502 (2019)
- Complex multi-step-reaction theory

That's a lot of work!

Fission	Low sensitivity to spin mismatch
Gamma-ray emission	High sensitivity to spin mismatch
Neutron emission	?

How sensitive are neutron emission reactions to a spin-parity mismatch?

More sophisticated theory can be used to account for spin-parity mismatch

Surrogate method still possible for neutron capture!

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- PRL 122, 052502 (2019)
- Complex multi-step-reaction theory

That's a lot of work!

Fission	Low sensitivity to spin mismatch
Gamma-ray emission	High sensitivity to spin mismatch
Neutron emission	?

I will answer this

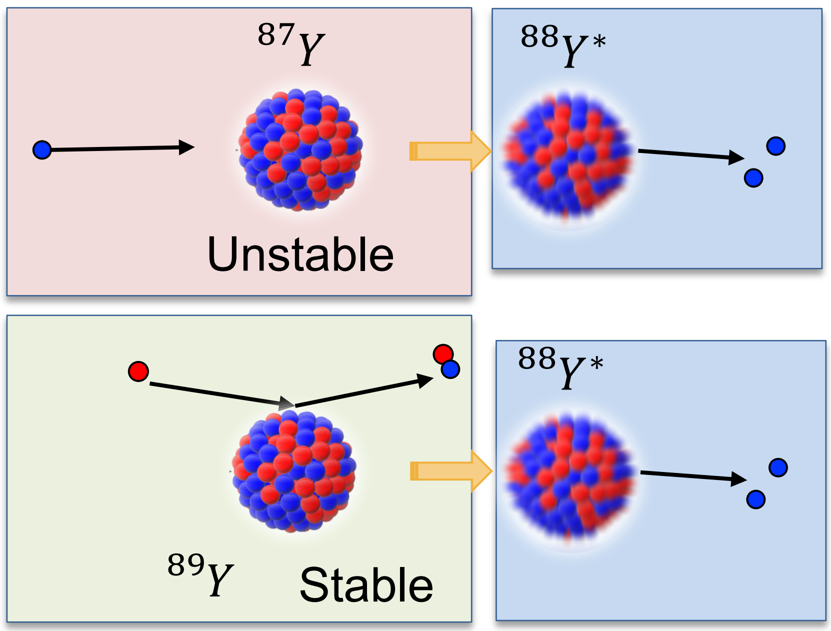
How sensitive are neutron emission reactions to a spin-parity mismatch?

The simplified "Weisskopf-Ewing" equations are a limiting case of a more complete theory

σ_α G_χ

Desired reaction

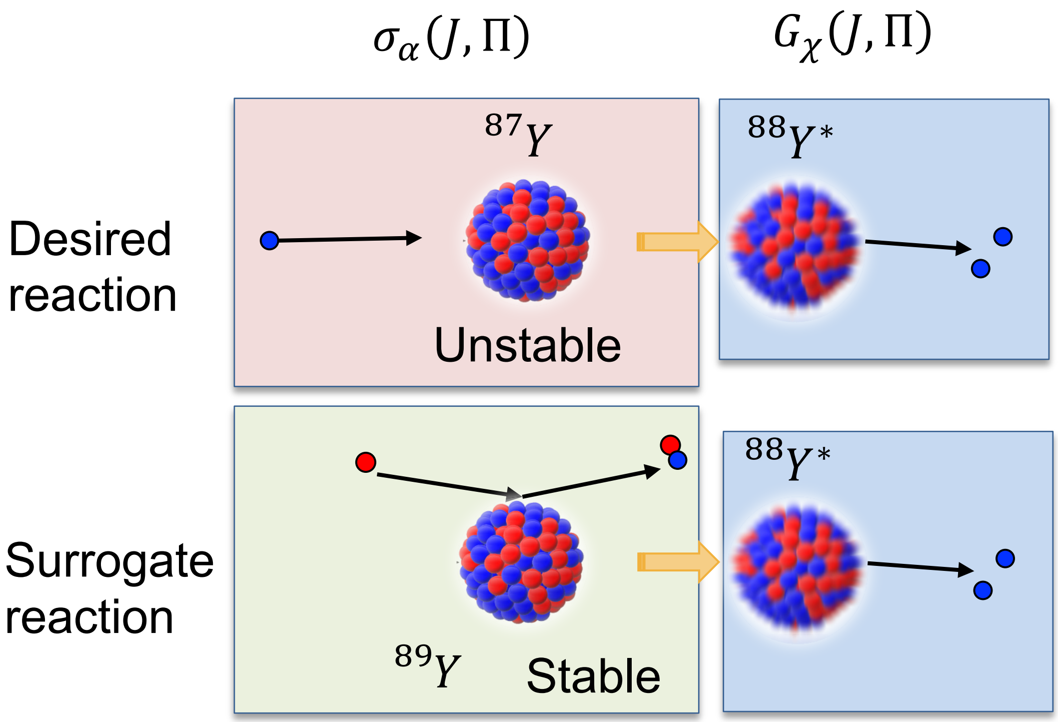
Surrogate reaction



$$\sigma_{\alpha\chi} = \sigma_\alpha G_\chi$$

$$P_{\delta\chi} = \frac{\mathrm{N}_{\delta\chi}}{\epsilon\, N_\delta} \qquad P_{\delta\chi} = G_\chi$$

Spin and parity must be considered in the general case



$$\sigma_{\alpha\chi} = \sum_{J\Pi} \sigma_\alpha(J,\Pi) G_\chi(J,\Pi)$$

$$P_{\delta\chi} = \sum_{J\Pi} F_\delta(J,\Pi) G_\chi(J,\Pi)$$

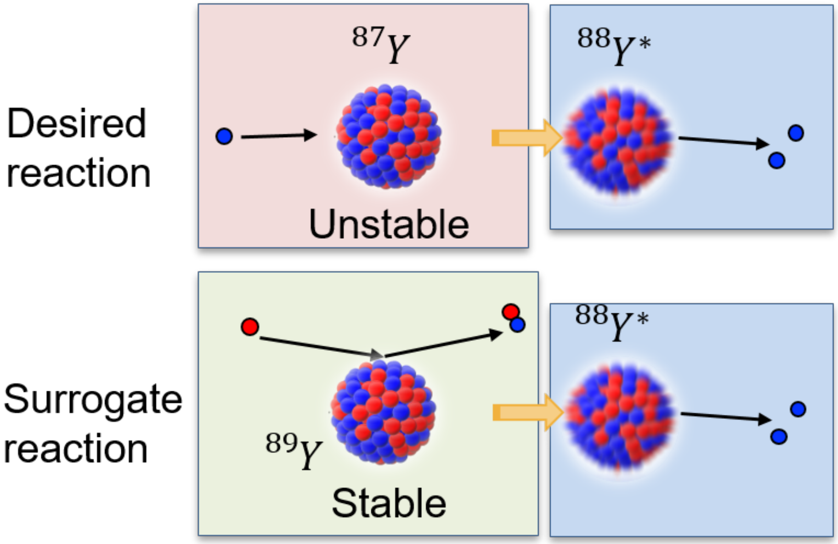
The Weisskopf-Ewing equations are equivalent under two scenarios

$$\sigma_{\alpha\chi} = \sum_{J\Pi} \sigma_\alpha(J,\Pi) G_\chi(J,\Pi)$$

$$P_{\delta\chi} = \sum_{J\Pi} F_\delta(J,\Pi) G_\chi(J,\Pi)$$

$$\sigma_{\alpha\chi} = \sigma_\alpha G_\chi$$

$$P_{\delta\chi} = G_\chi$$



Equivalence scenarios

1. Surrogate reaction produces the <u>same spin distribution</u> $F_\delta(J,\Pi)$ as the desired reaction

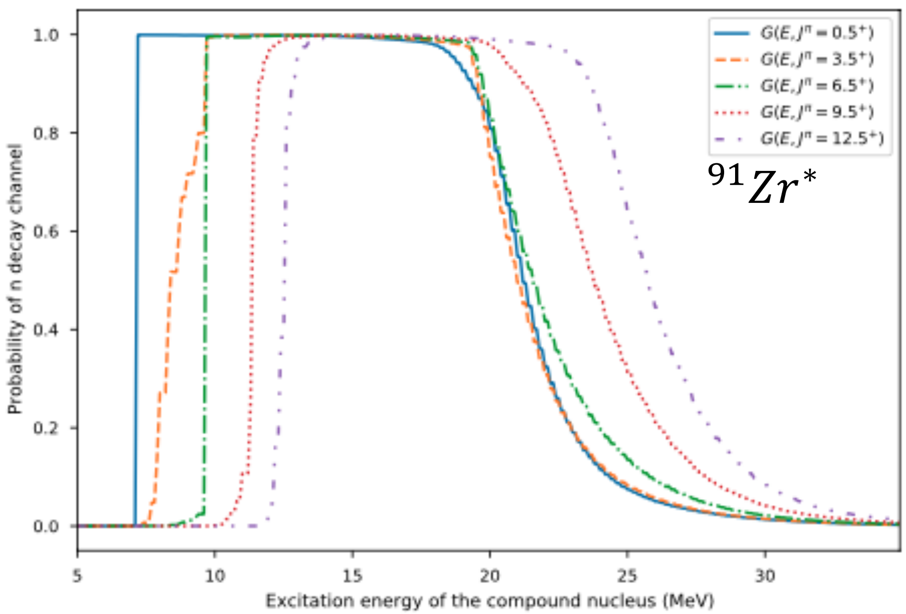
   or

2. The decay probabilities $G_\chi(J,\Pi)$ are <u>independent of spin and parity</u>

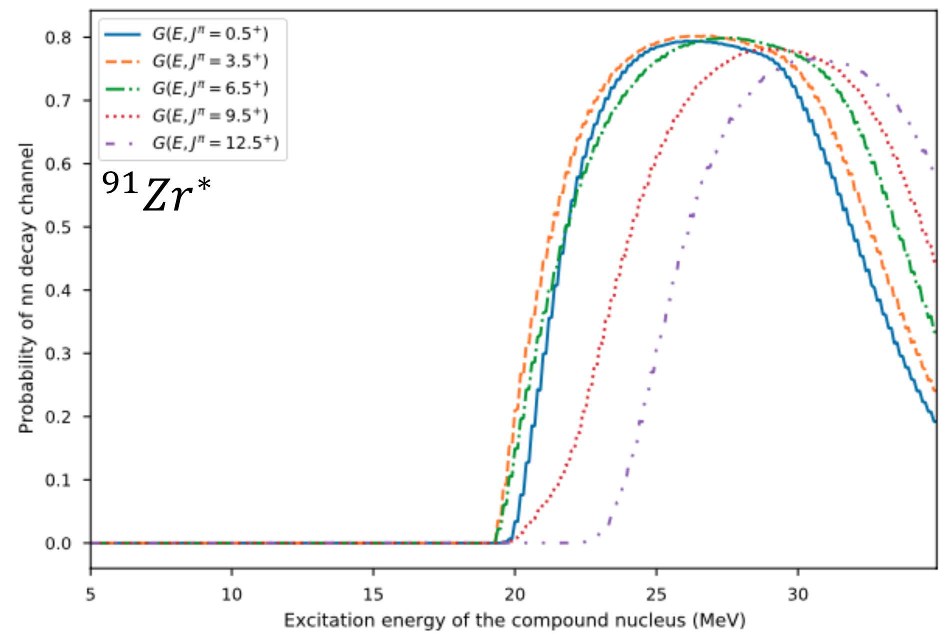
Are the decay probabilities $G_\chi(J,\Pi)$ independent of spin and parity?

$$\sigma_{\alpha\chi} = \sum_{J\Pi} \sigma_\alpha(J,\Pi)\boxed{G_\chi(J,\Pi)}$$

One-neutron emission

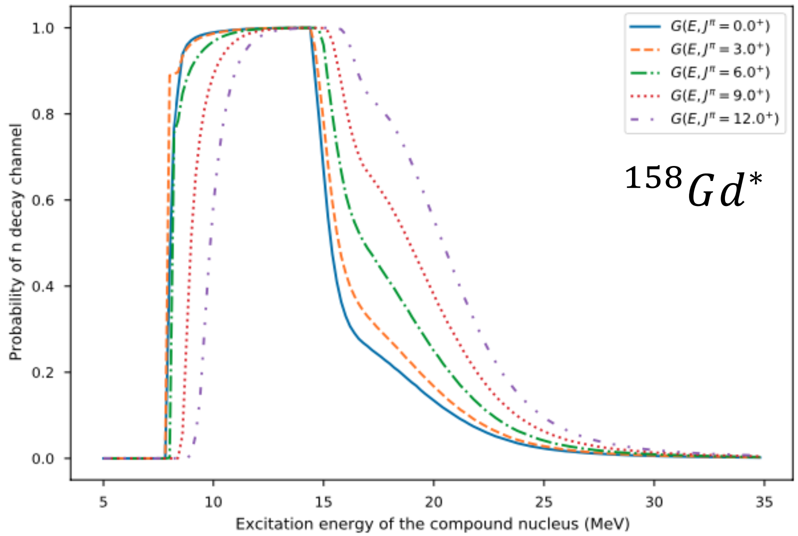


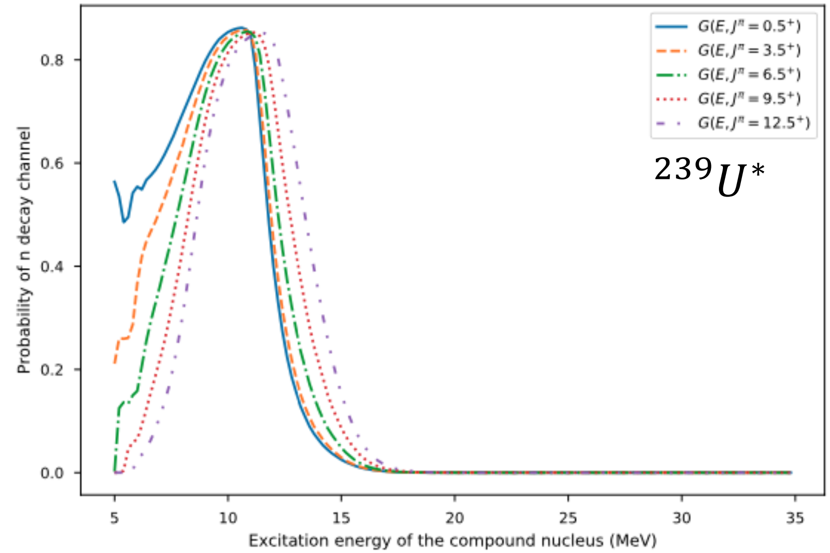
Two-neutron emission



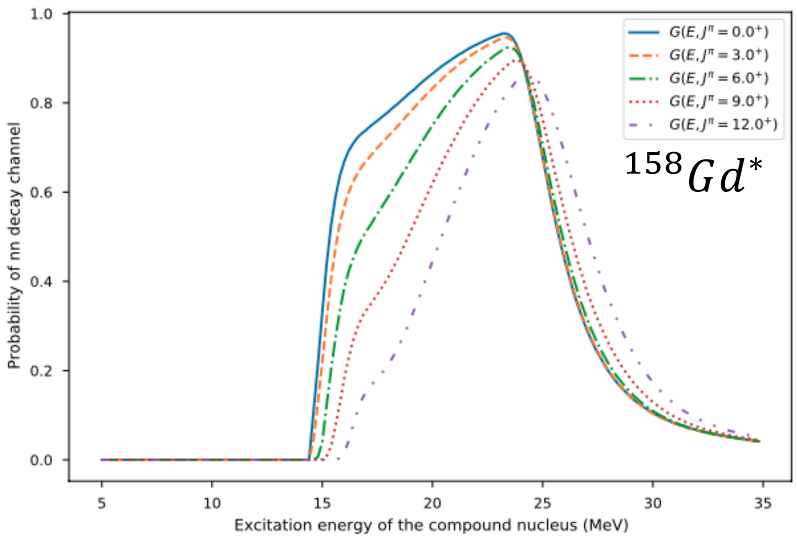
Rare earth and actinide neutron decay probabilities

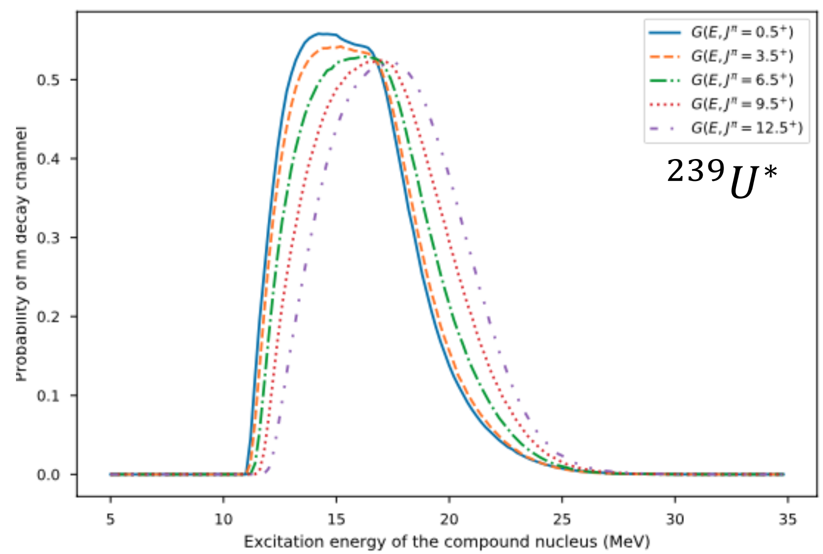
One-neutron





Two-neutron





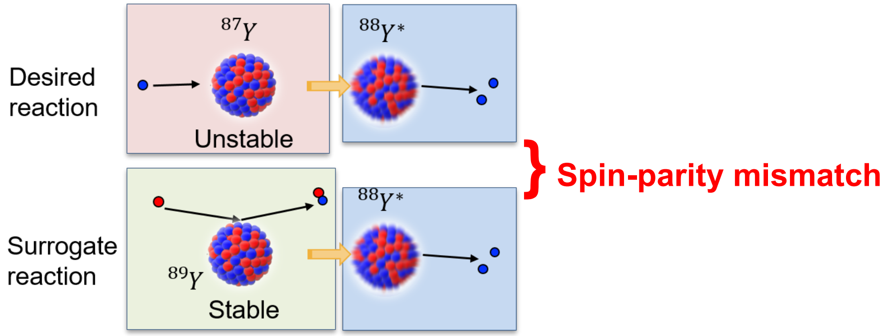
Neutron emission channels violate the Weisskopf-Ewing assumptions

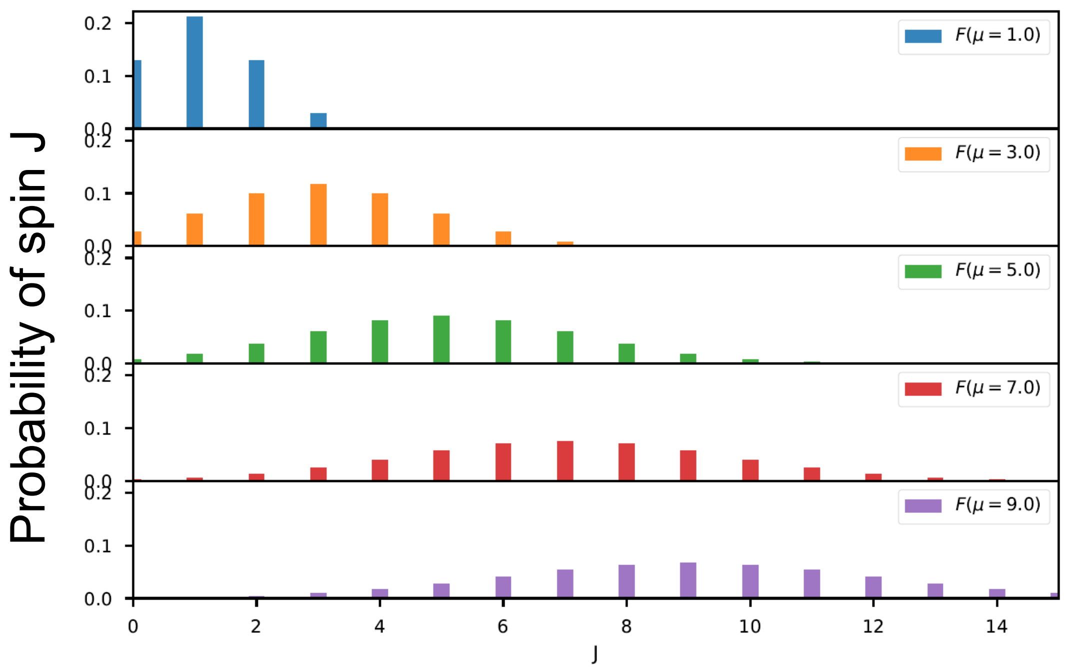
- Equivalence scenario doesn't hold
- Expect neutron emission to be sensitive to a spin-parity mismatch

Fission	Low sensitivity to spin mismatch ✓
Gamma-ray emission	High sensitivity to spin mismatch ☹
Neutron emission	?

What happens if we used the Weisskopf—Ewing equations anyway?

Test the impact of spin-parity mismatch on predictive power of WE formula





Step 1: Simulate surrogate experiment data by proposing schematic spin distribution F.

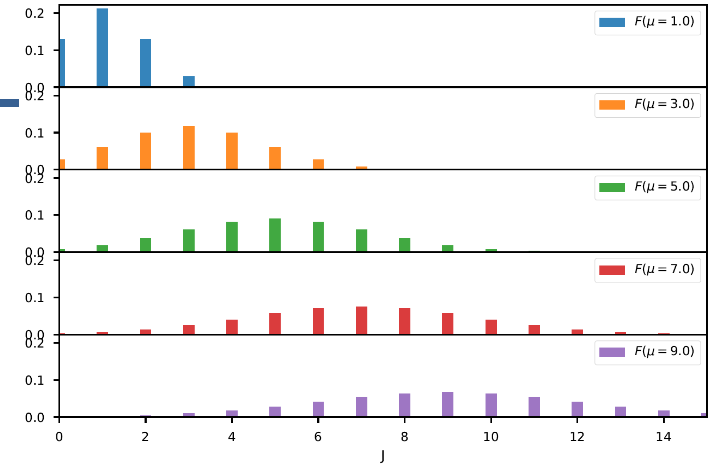
$$P_{\delta\chi} = \sum_{J\Pi} F_\delta(J,\Pi) G_\chi(J,\Pi)$$

Step 2: Treat the simulated data as if WE applies:

$$P_{\delta\chi} = G_\chi$$

$$\sigma_{\alpha\chi} = \sigma_\alpha G_\chi$$

90Zr(n,xn) WE predictions based on simulated data

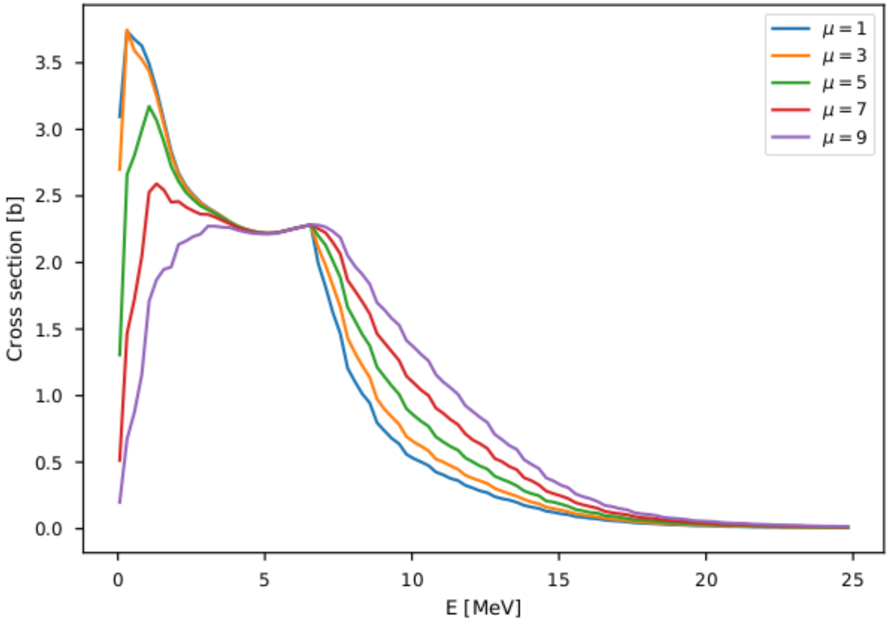


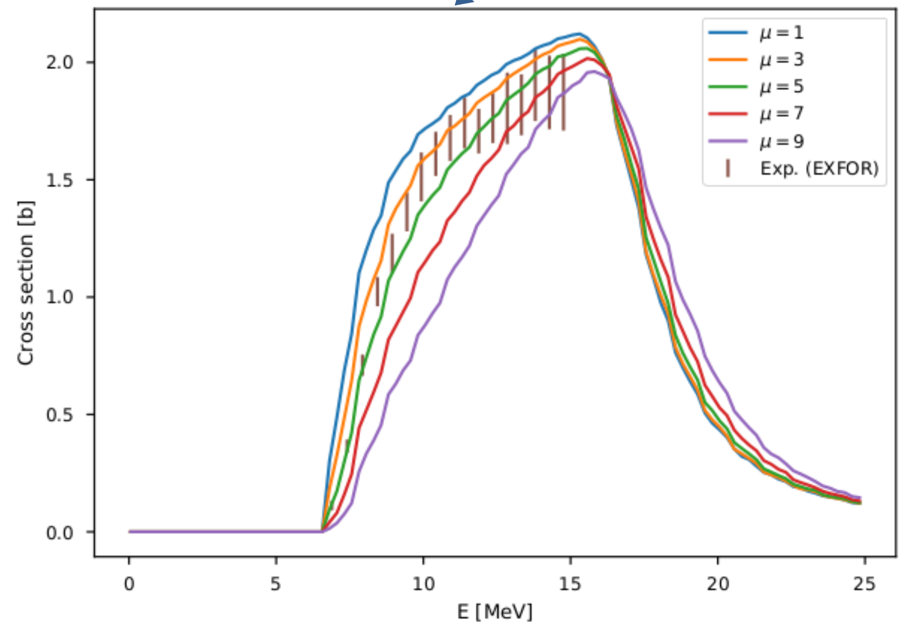
Simulate: $P_{\delta\chi} = G_{\chi}$

Predict: $\sigma_{\alpha\chi} = \sigma_{\alpha} G_{\chi}$

One-neutron emission

Two-neutron emission

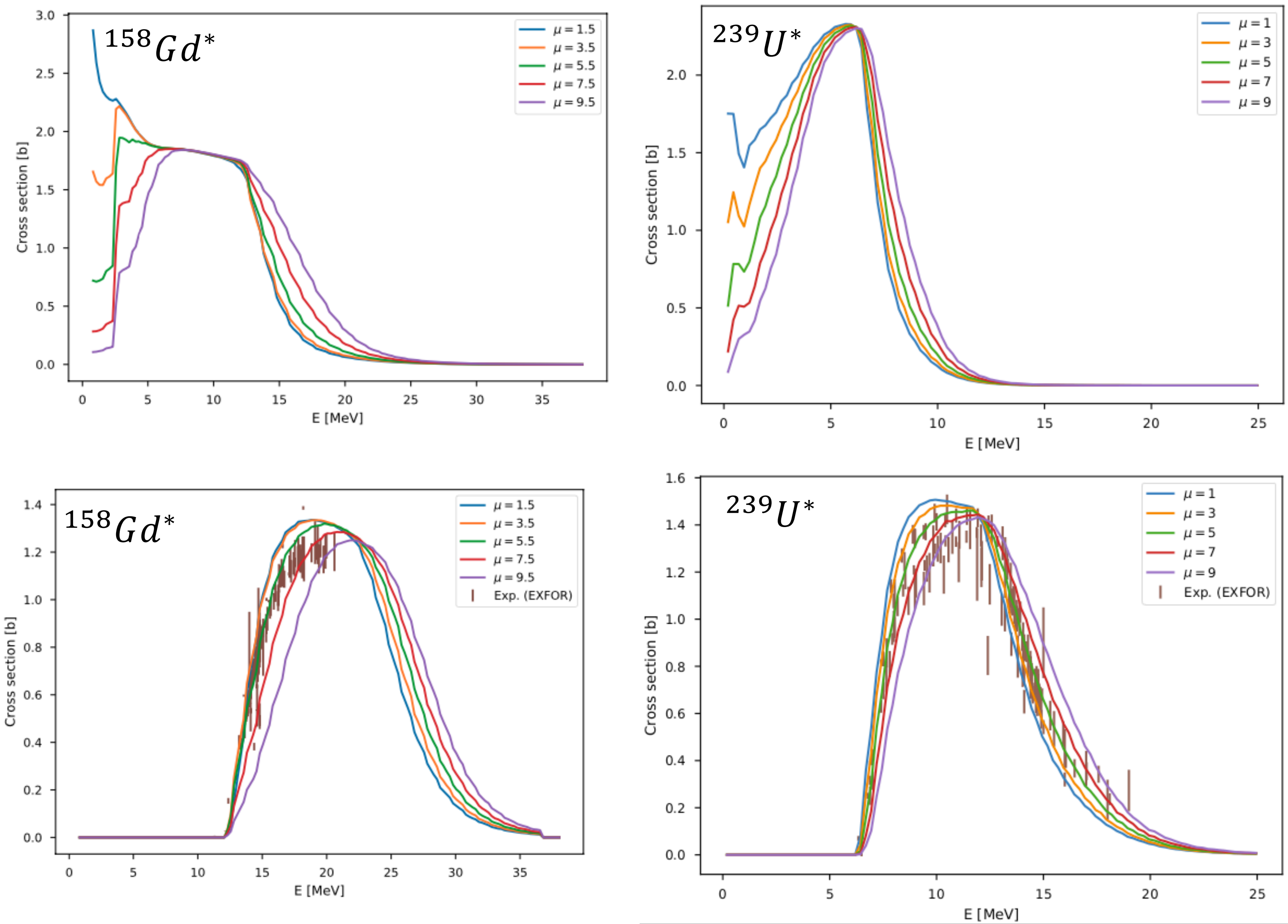




Rare earth and actinide neutron cross section simulations

One-neutron

Two-neutron



The Weisskopf-Ewing equations won't work for neutron emission reactions

Results

- Neutron emission reactions are also sensitive to spin-parity mismatch
- Weisskopf-Ewing equations won't produce accurate results

So what?

- Experimentalists and theorists need to work together
- More theory works needs to be done for the surrogate method to measure cross sections of unstable nuclei

What now?

Fission	Low sensitivity to spin mismatch
Gamma-ray emission	High sensitivity to spin mismatch
Neutron emission	Still sensitive to spin mismatch!

We need to combine surrogate data with advanced nuclear structure theory.

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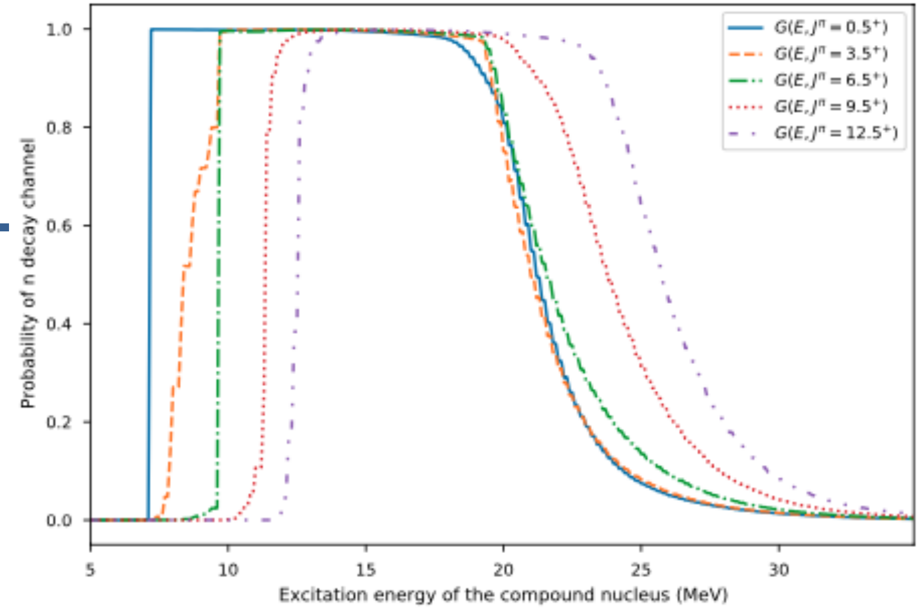
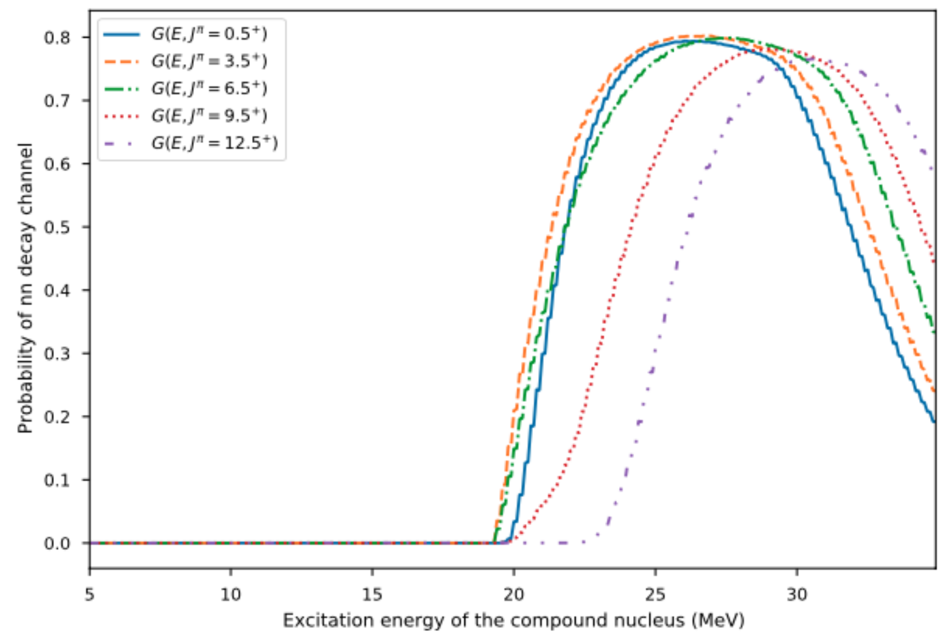
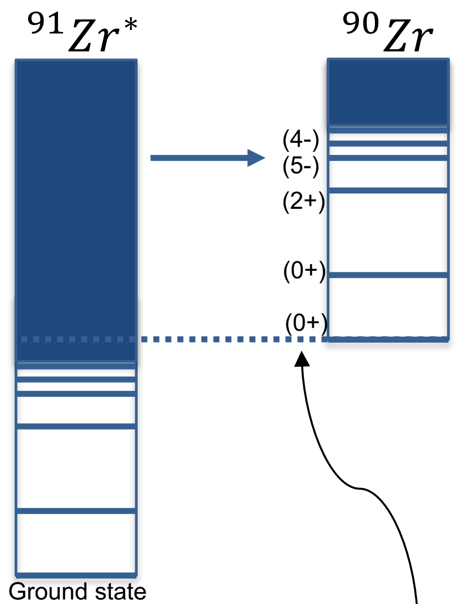
91Zr decay probabilities

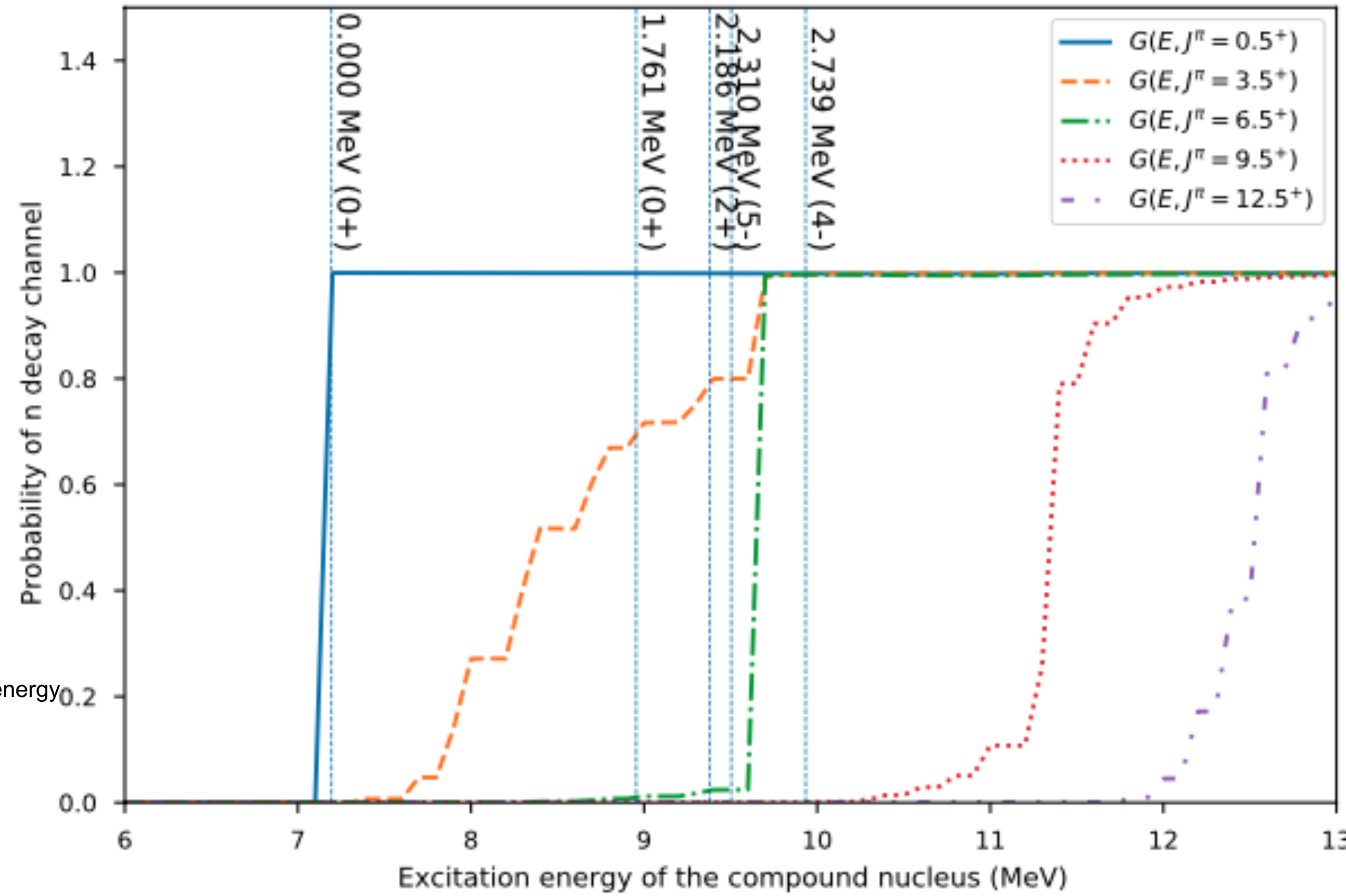
- High sensitivity near Sn
- Sensitivity directly related to 90Zr low-lying spins (next slide)
- Significantly reduced sensitivity at peak of cross section
- Sensitivity returns at S_2n, but is not significant for J<=6.5





91Zr decay probabilities in relation to 90Zr spectra

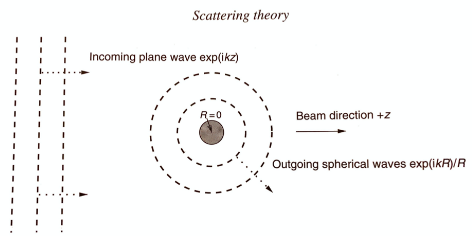


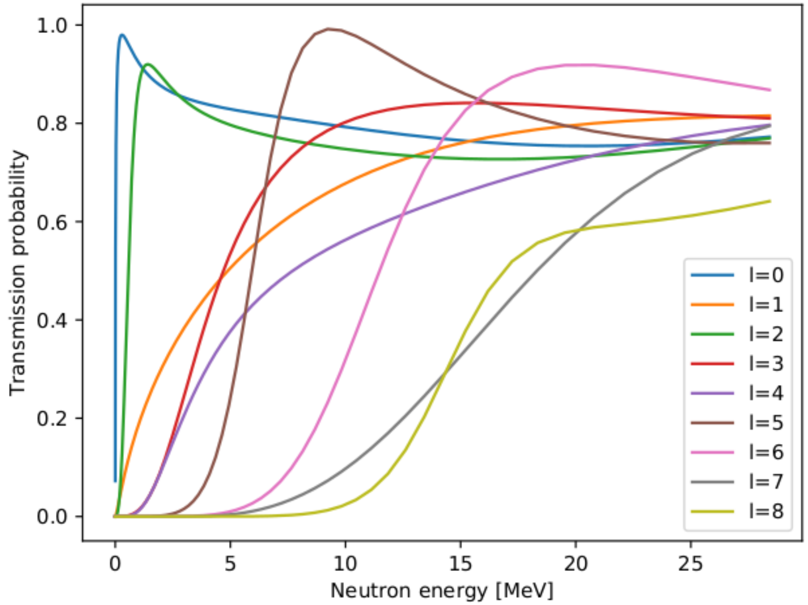


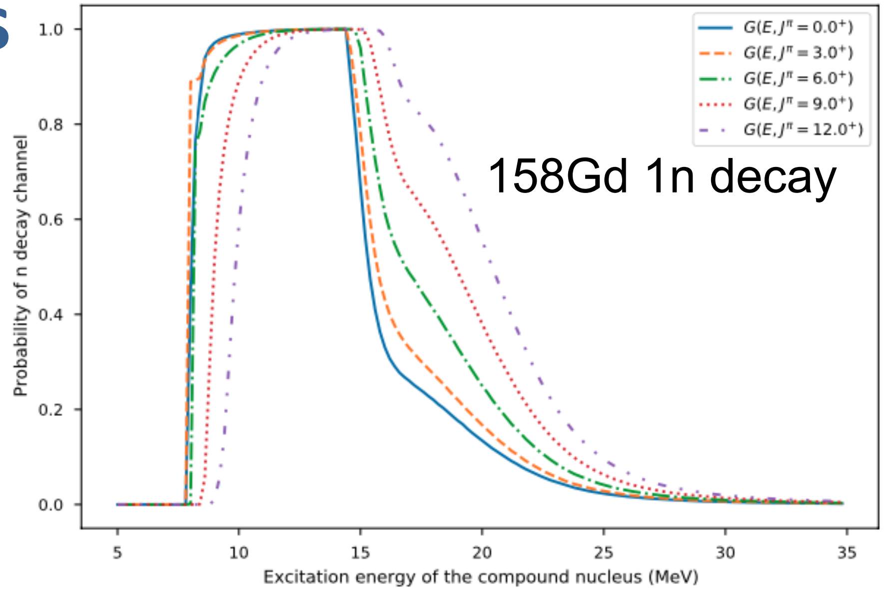
Level structure in residual nucleus explain the delayed neutrons at high spin.

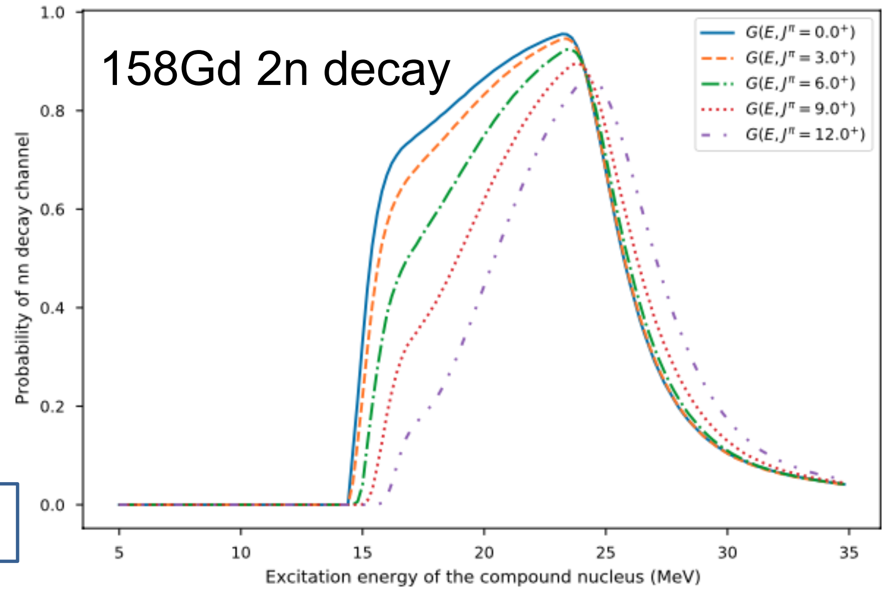
158Gd decay probabilities

T(J,l,E) for n+Gd157



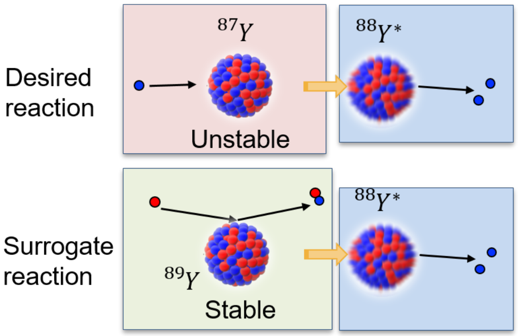






Transmission coefficients explain this pattern.

Test the impact of spin-parity mismatch on predictive power of WE formula



$$\sigma_{\alpha\chi} = \sum_{J\Pi} \sigma_\alpha(J,\Pi) G_\chi(J,\Pi)$$

From previous slide

$$P_{\delta\chi} = \sum_{J\Pi} \boxed{F_\delta(J,\Pi)} G_\chi(J,\Pi)$$

$$P_{\delta\chi} = \frac{N_{\delta\chi}}{N_\delta}$$

Spin distribution from desired reaction