Lawrence Livermore National Laboratory

Surrogate Methods for Neutron Reactions Between Capture and Fission: Sensitivity study of the Weisskopf-Ewing limit in (n,n') and (n,2n) reactions

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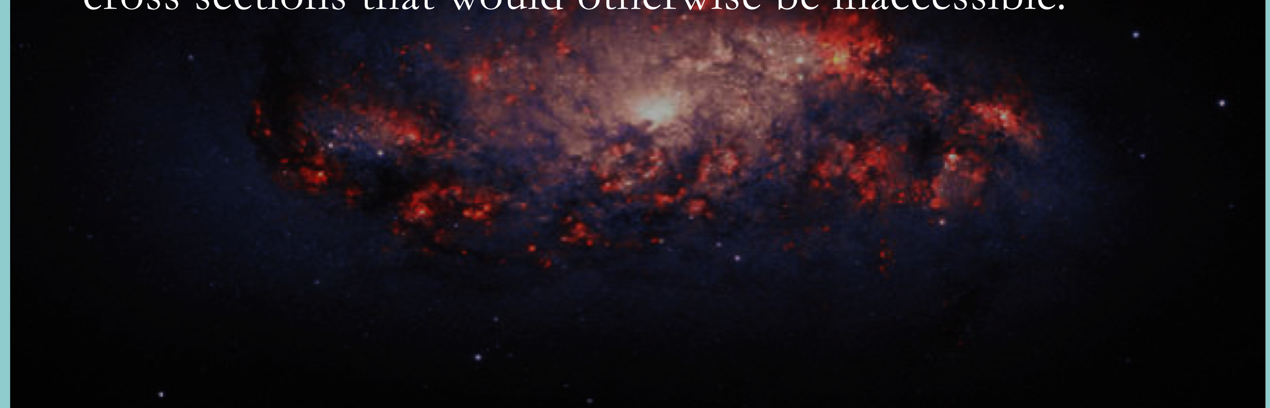
BIG PICTURE

- Inelastic scattering of neutrons (n,n') and 2n reactions (n,2n) are important for nuclear astrophysics and national security applications.
- It is difficult or impossible to measure cross sections for radioactive targets directly.
- The surrogate approach is an indirect method which combines surrogate data and theory to constrain nuclear cross sections that would otherwise be inaccessible.



SPECIFIC QUESTION

Here, we will examine the validity of the Weisskopf-Ewing approximation for (n,n') and (n,2n) reactions.

- The surrogate approach has historically been used for fission applications, where the Weisskopf-Ewing (WE) approximation is known to be valid [Escher 2006, 2010]: the spin and parity dependence of the decay channel branching probabilities, $G_\beta^{CN}(E,J,\pi)$, can be ignored.

$$G_\beta^{CN}(E,J,\pi) \rightarrow G_\beta^{CN}(E)$$

- The Hauser-Feshbach (HF) calculations simplify in the WE limit:

$$\sigma_{\alpha\beta}(E) = \sum_{J\pi} \sigma_\alpha^{CN}(E,J,\pi) G_\beta^{CN}(E,J\pi) \rightarrow \sigma_{\alpha\beta}^{WE}(E) = \sigma_\alpha^{CN}(E) G_\beta^{CN}(E)$$

$$P_{\delta\beta}(E) = \sum_{J\pi} F_\delta^{CN}(E,J,\pi) G_\beta^{CN}(E,J\pi) \rightarrow P_{\delta\beta}^{WE}(E) = G_\beta^{CN}(E)$$

For neutron induced fission (n,f) reactions, α=n and β=f.

- The WE approach is known to break down for (n,g) reactions since gamma decay of the compound nucleus is highly dependent on the initial spin of the compound nucleus. Recently it has been shown that a more sophisticated surrogate approach, requiring significantly more theoretical work (F_δ^{CN}), can be successfully applied to (n,g) reactions [Escher 2018].

METHODS

TEST 1: Dependence of branching probabilities on spin and parity

We simulate the decay of the compound nucleus (CN) using the HF model code STAPRE:

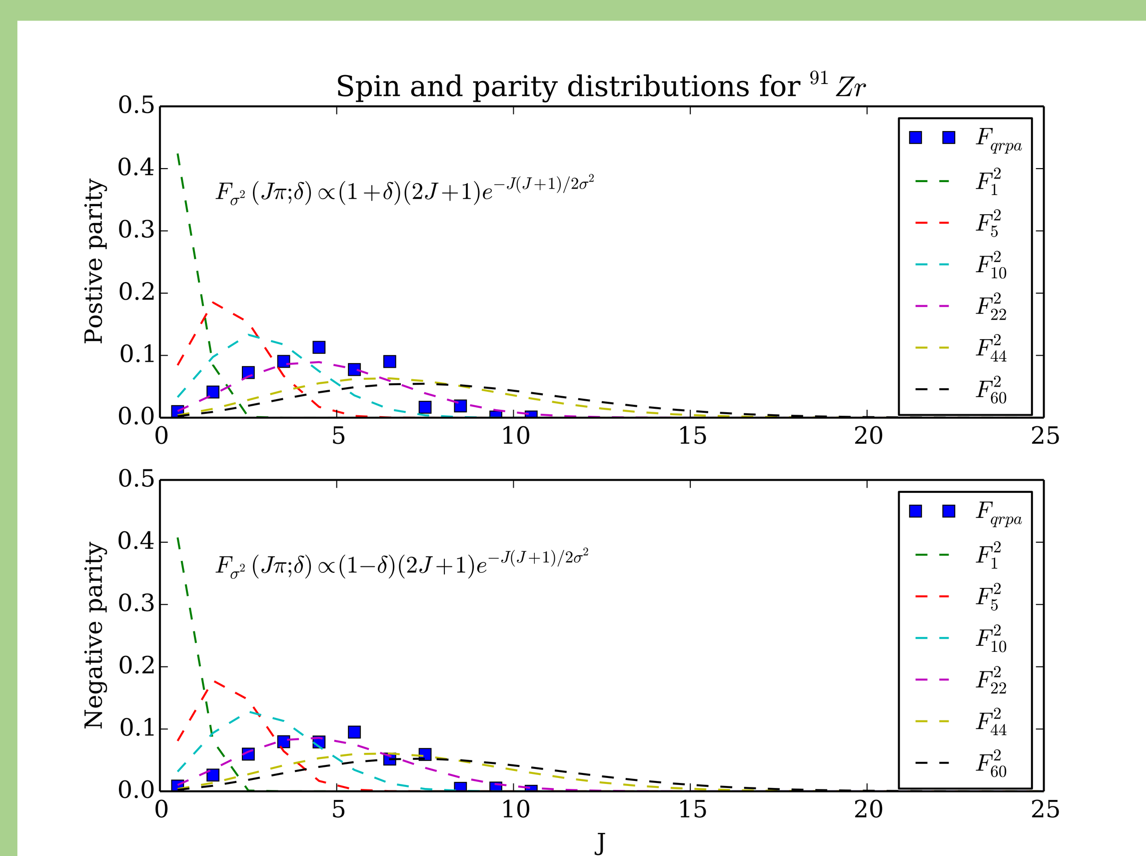
- A nucleus is populated with energy E, spin J, parity π
- The probabilities to decay via different channels are added up

This tests the dependence of $G_\beta^{CN}(E,J,\pi)$ on spin and parity for realistic nuclear systems.

TEST 2: Impact on cross sections extracted from surrogate data

We conducted a sensitivity analysis that assumes the validity of the WE limit then compares its predictions given simulated data of a surrogate experiment. We follow the investigative model conducted in references [Escher 2006, 2010].

1. **Generate ad hoc spin and parity distributions** for the compound nucleus, which are meant to stand in for a realistic calculation of the formation reaction.



2. **Create simulated surrogate data ($P_{\delta\beta}^{WE}$):** model the decay of compound nuclei with these made-up spin distributions.
3. **Compute the WE limit ($\sigma_{\alpha\beta}^{WE}$):** multiply the simulated probabilities by standard calculations of formation cross section.

If WE is a good approximation, then these cross sections will not be far from each other.

RESULTS

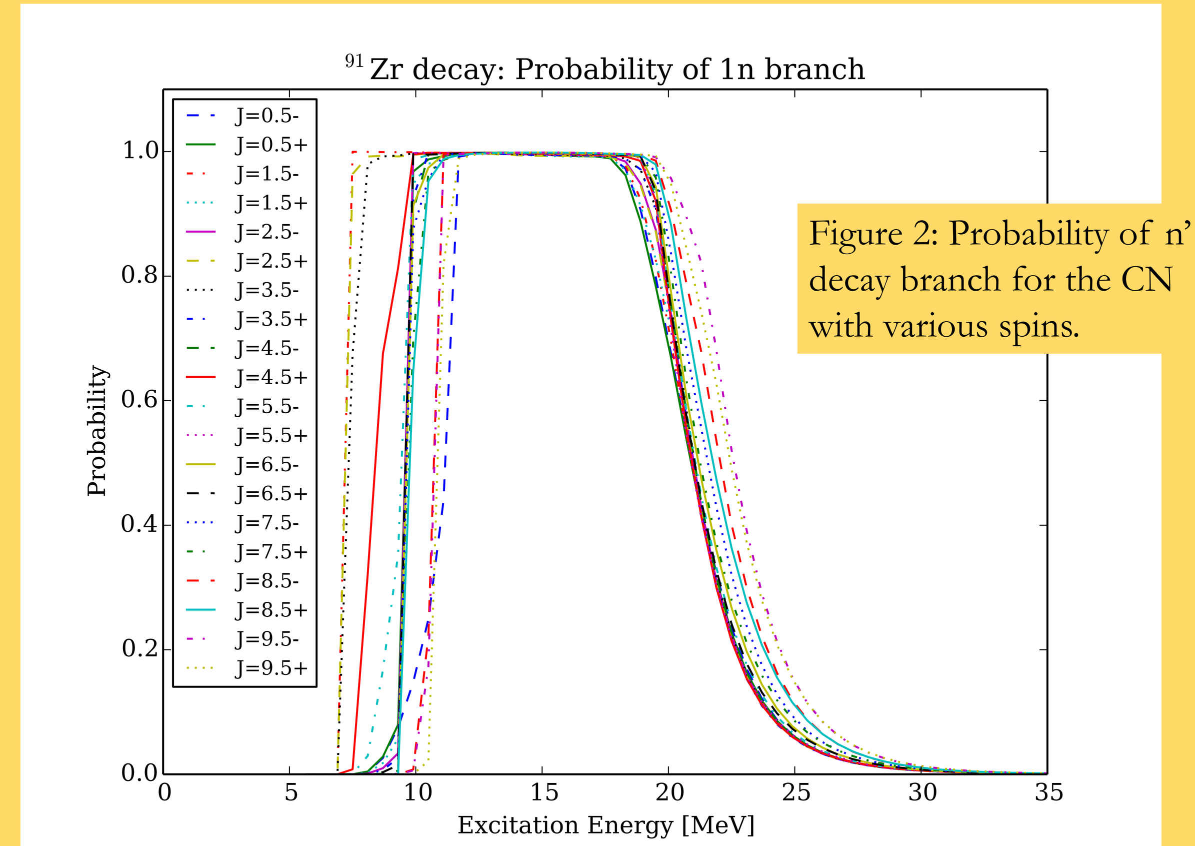


Figure 2: Probability of n' decay branch for the CN with various spins.

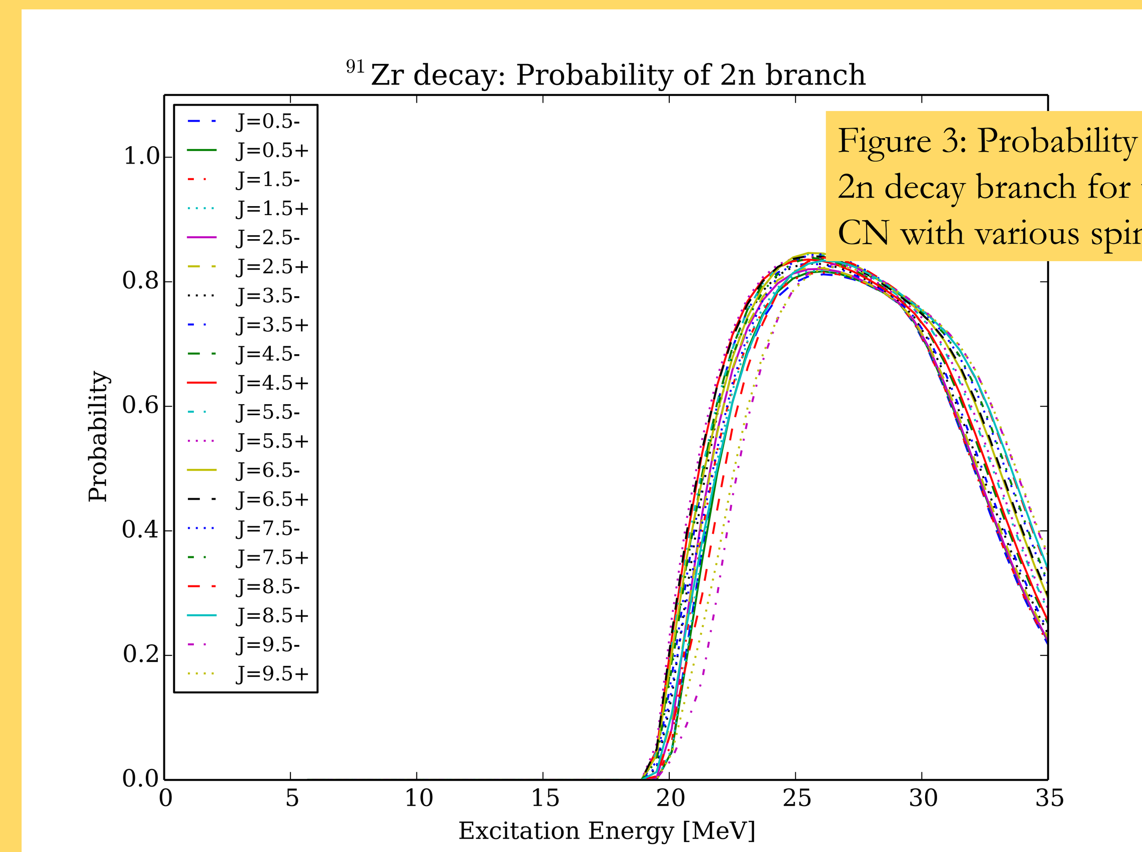


Figure 3: Probability of 2n decay branch for the CN with various spins.

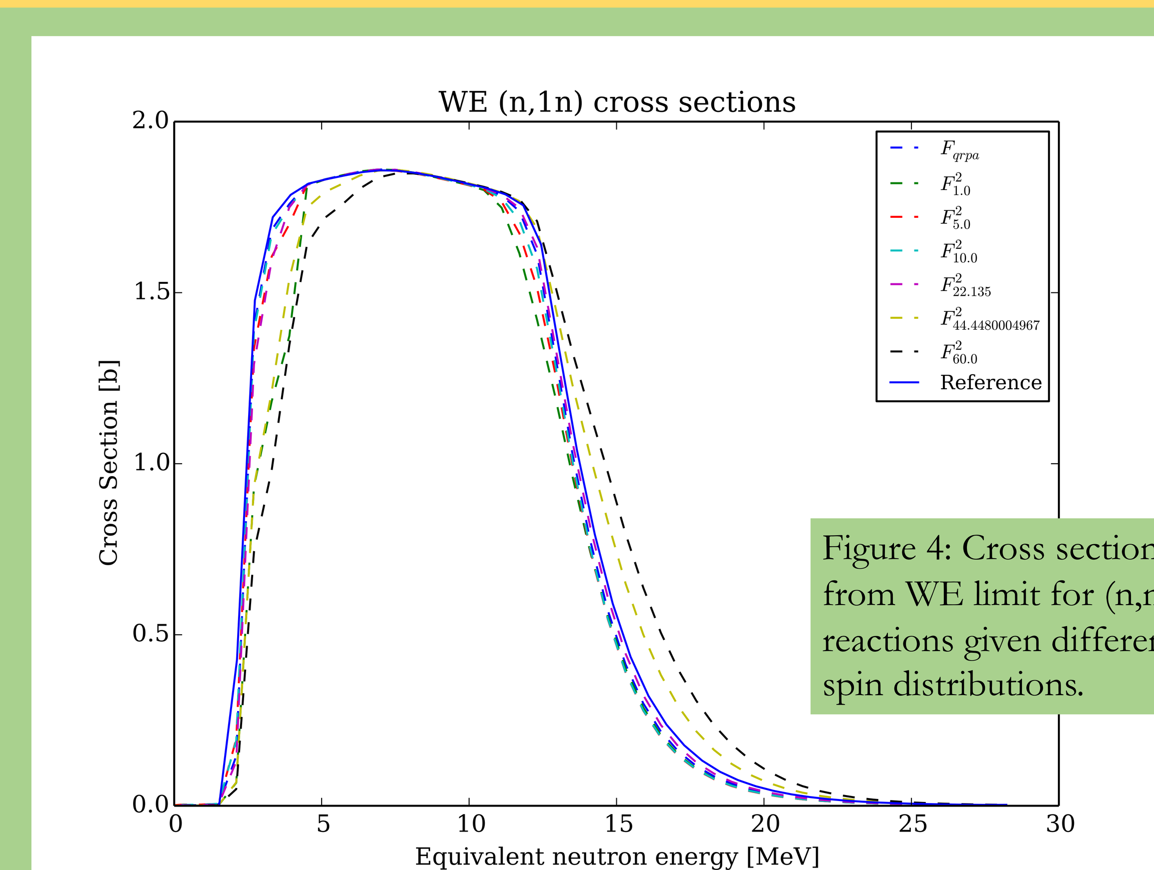


Figure 4: Cross sections from WE limit for (n,n') reactions given different spin distributions.

RESULTS

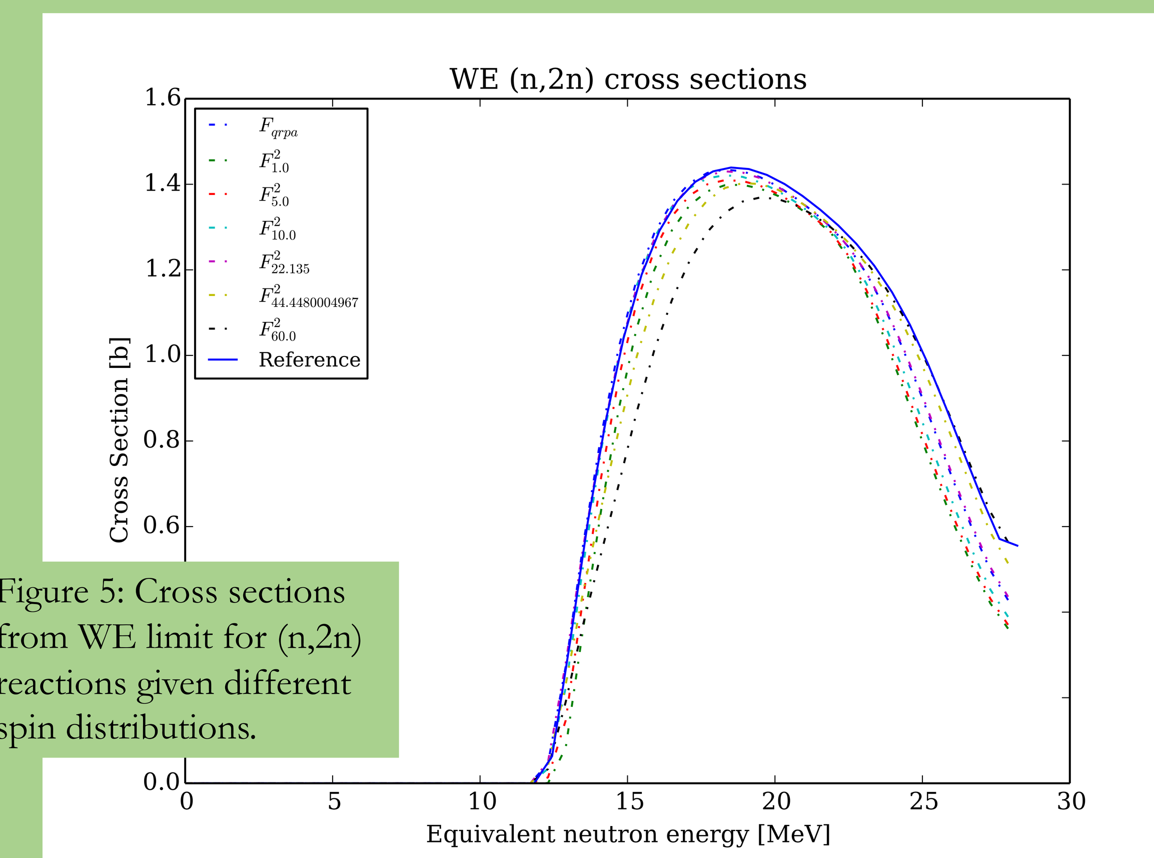


Figure 5: Cross sections from WE limit for (n,2n) reactions given different spin distributions.

CONCLUSION

TEST 1: Dependence of $G_\beta^{CN}(E,J,\pi)$ on spin and parity

E(CN)	(N,N')	E(CN)	(N,2N)
9 MeV	SD 170%	20 MeV	SD 20%
15 MeV	SD 0.2%	25 MeV	SD 2%
21 MeV	SD 20%	32 MeV	SD 10%

TEST 2: Impact on cross sections extracted from surrogate data

E(CN)	(N,N')	E(CN)	(N,2N)
9 MeV	48%	20 MeV	30%
15 MeV	0.1%	25 MeV	3%
21 MeV	14%	32 MeV	8%

Conclusions:

- **The Weisskopf-Ewing approximation for (n,n') and (n,2n) reactions on Zr can be expected to have a variance up to 50% at worst and <5% at best, depending on the energy range.**
- **Whether this is sufficient depends on the application.**
- **These results tell us which energies to probe first with surrogate experiments.**

REFERENCES

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