Compound-Nuclear Reaction Cross Sections from Surrogate Measurements: A Theorist's Perspective

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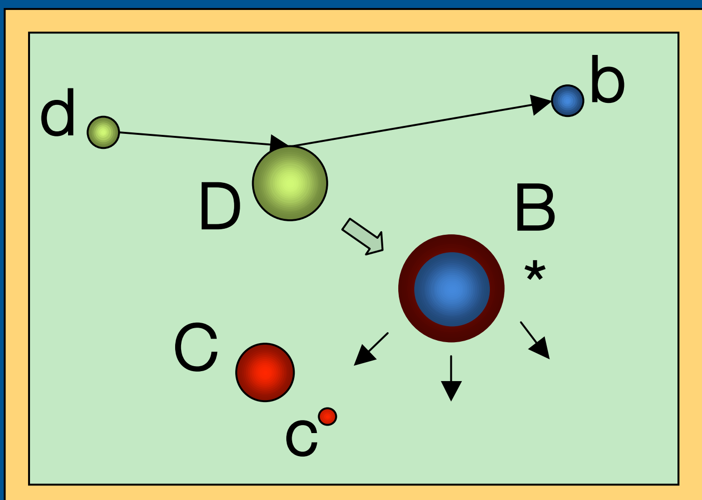

International Workshop on Compound-Nuclear Reactions And Related Topics

(CNR* 2007)

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Physics & Advanced Technologies N Division

Outline

1. The Surrogate idea
2. Approximation schemes
3. Testing the assumptions
4. The importance of spin -
   or: the need to move beyond current approximations
5. Surrogate approach for (n,γ)?
6. Challenges for theory
7. Summary

Collaborators

Theory:

F.S. Dietrich, V. Gueorguiev, R. Hoffman, I. Thompson *(LLNL)*

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Experiment:

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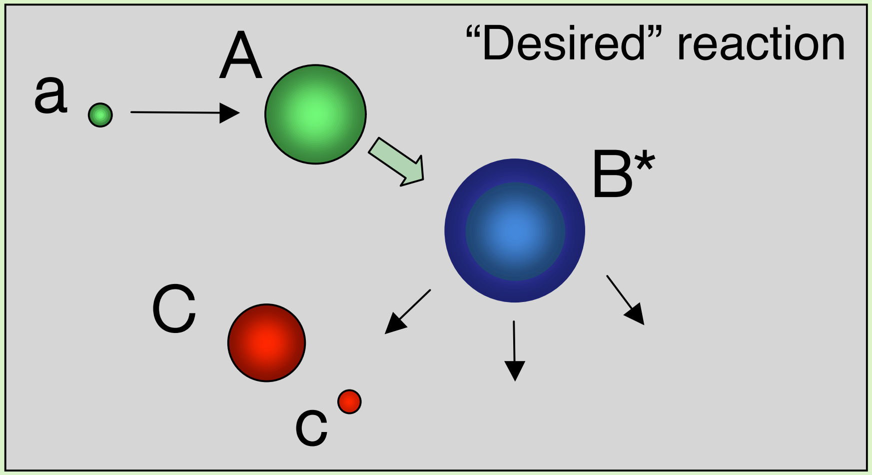
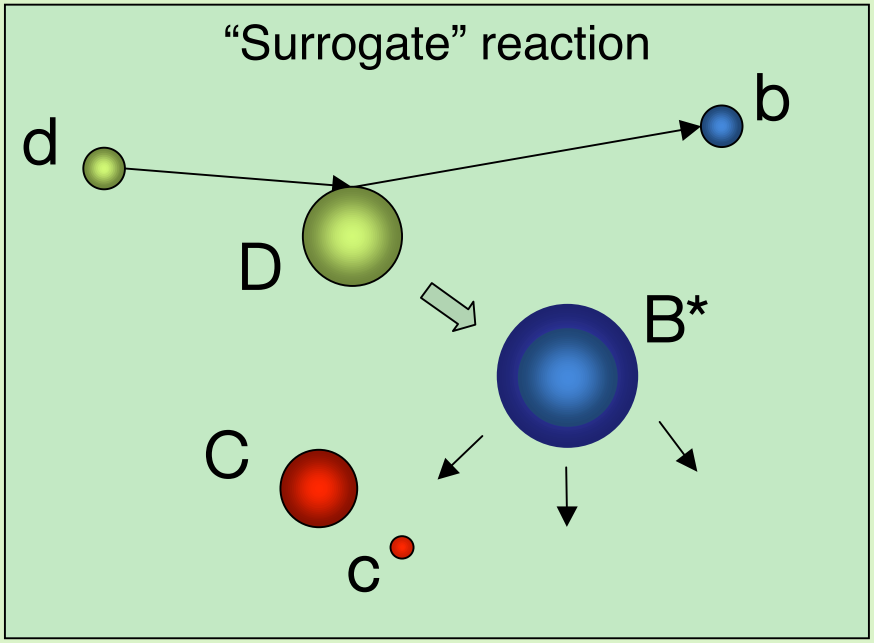
H. Ai, C. Beausang, B. Crider *(Yale/University of Richmond)*

R. Hatarik, J. Cizewski, et al. *(Rutgers/ORNL)*

The Surrogate Idea

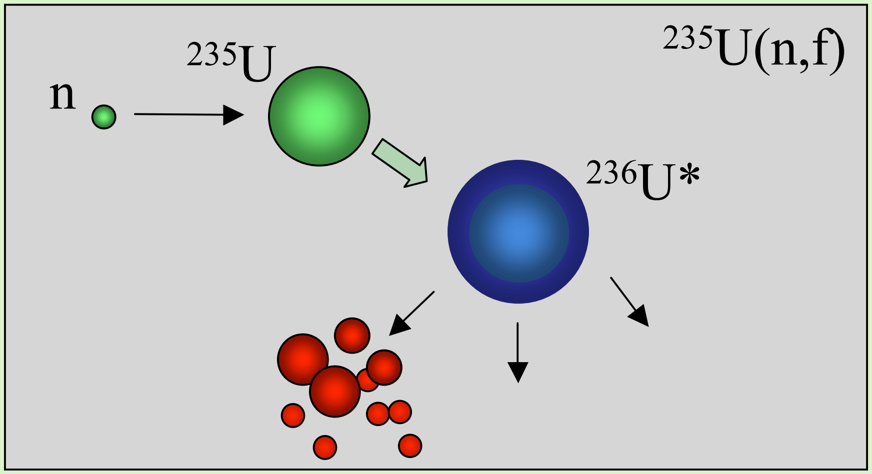
The Surrogate Nuclear Reactions approach is an indirect method for determining cross sections of compound-nuclear reactions that are difficult/impossible to measure directly.

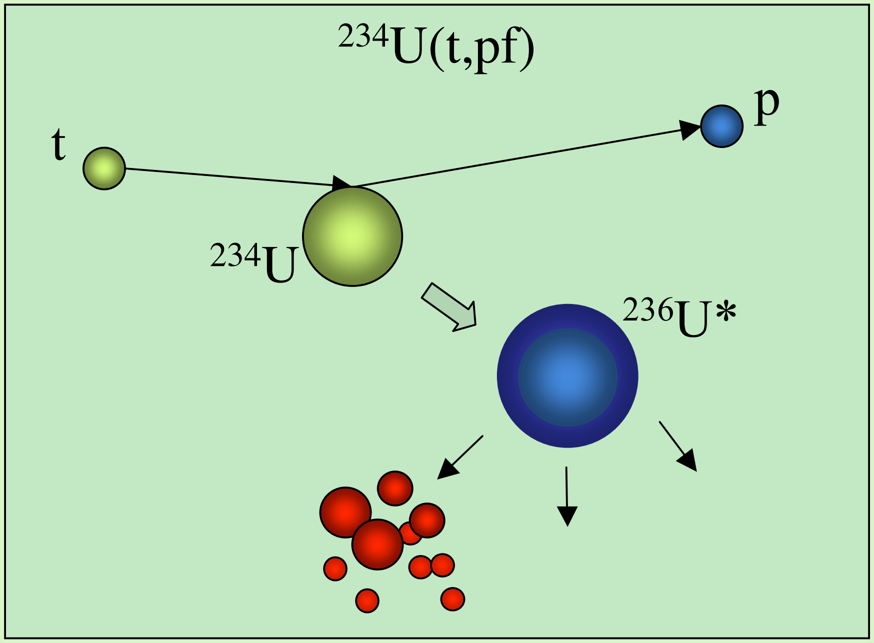




The Surrogate Idea

Various direct-reaction mechanisms can be employed to create the compound nucleus of interest.





The Surrogate Idea

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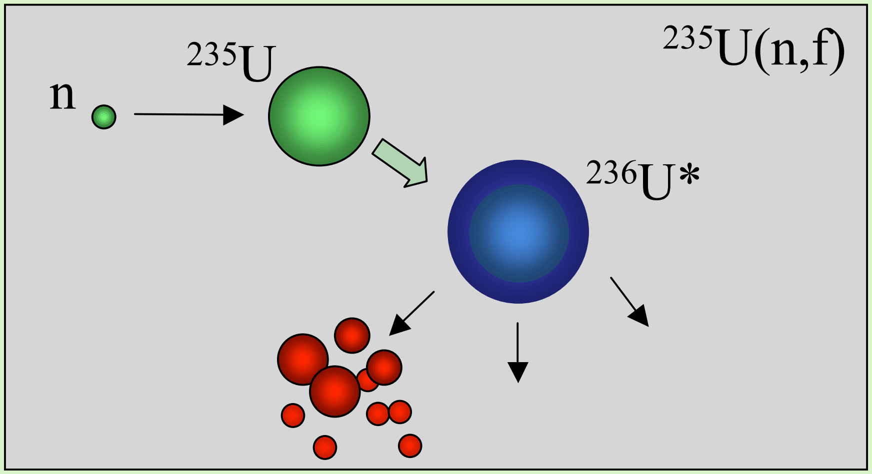
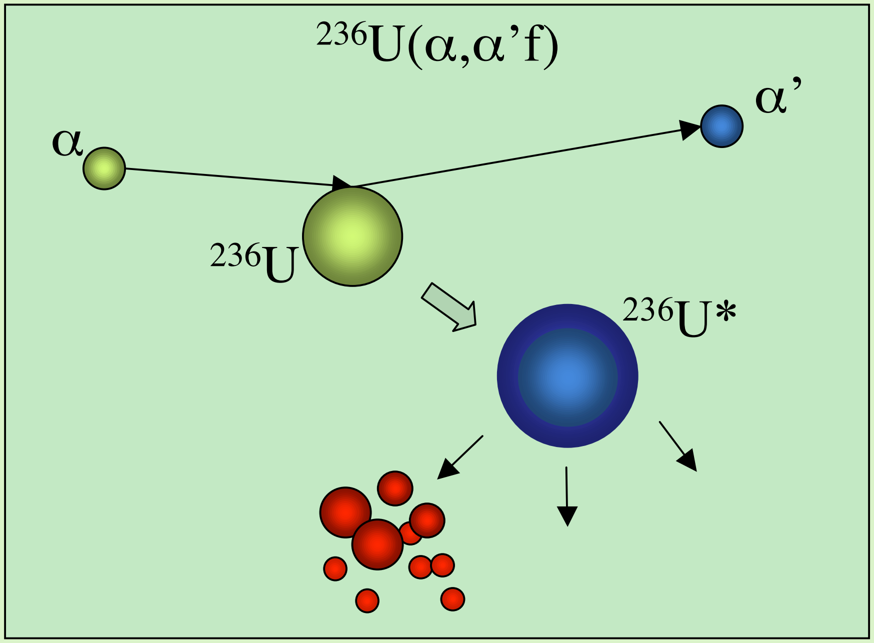
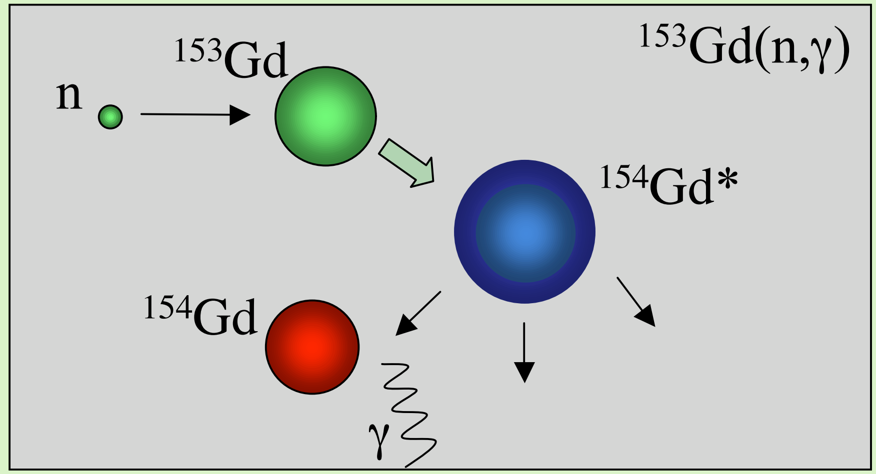
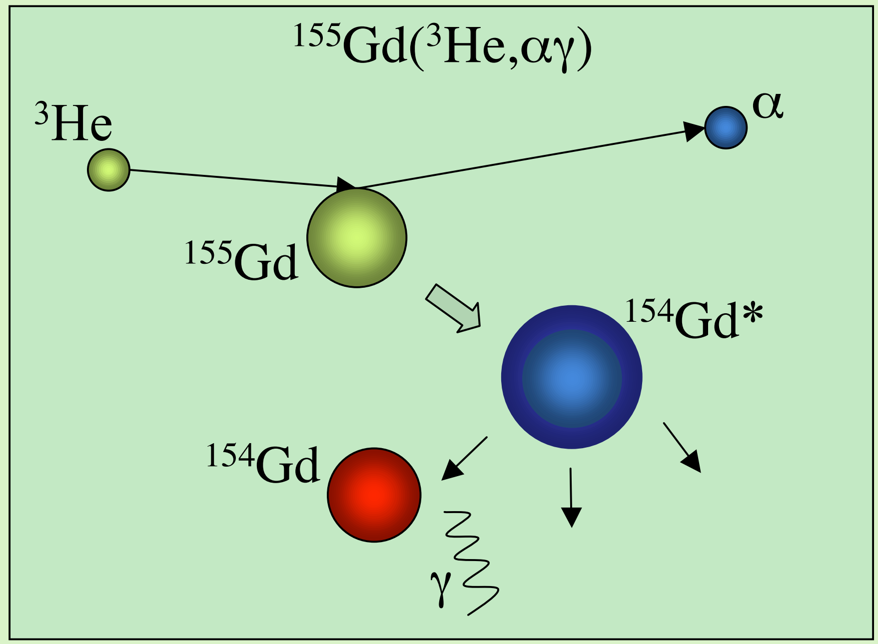




The Surrogate Idea

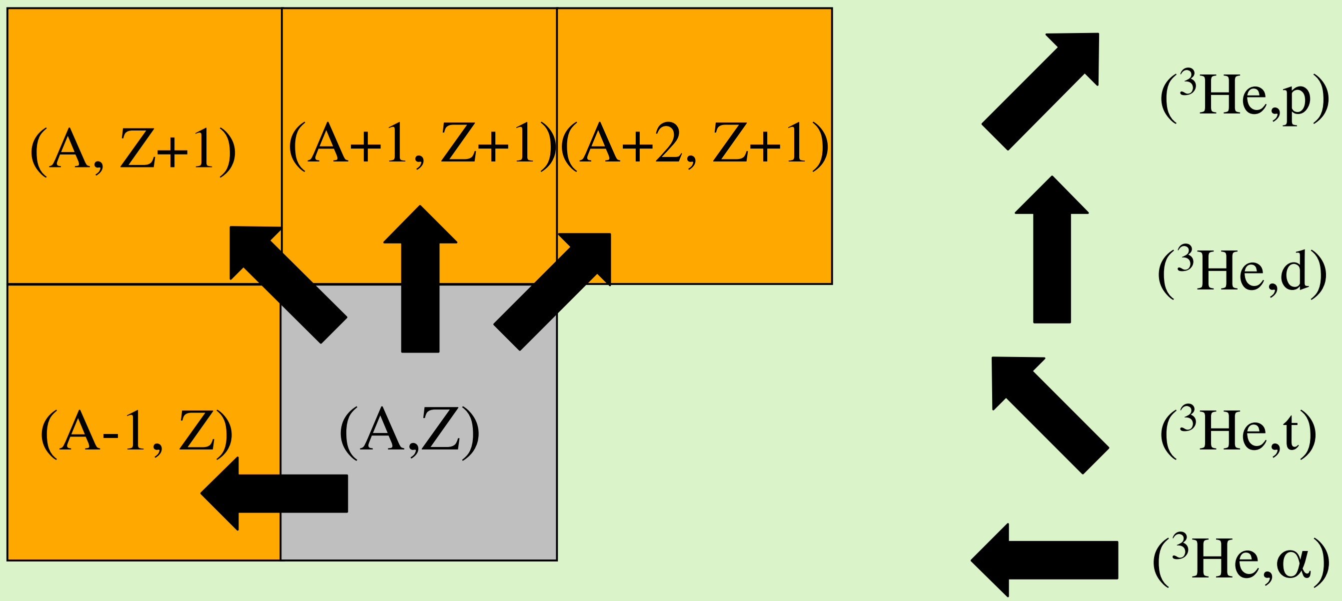
Different compound-nuclear decays can be considered.





The Surrogate Idea

One experiment can be used to determine several cross sections.



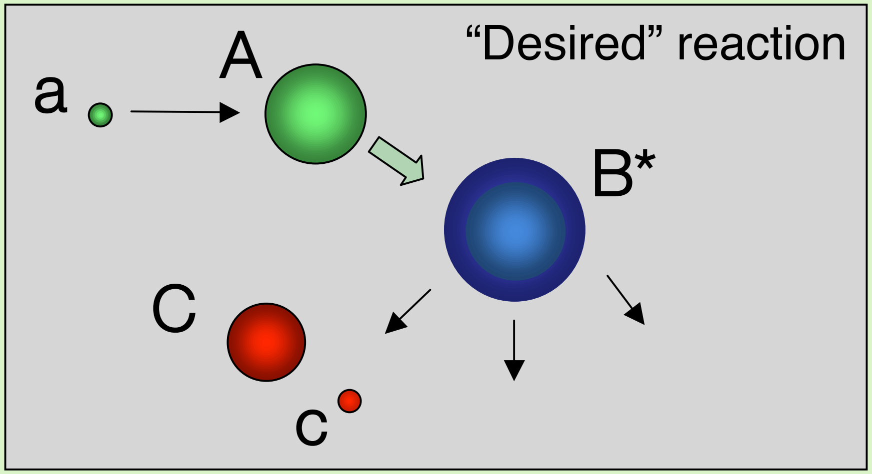
The Surrogate Idea - Formalism

Hauser-Feshbach (HF) theory describes the "desired" CN reaction

$\sigma_{\alpha\chi} = \Sigma_{J,\pi}\, \sigma_{\alpha}^{CN}(E,J,\pi) \cdot G^{CN}_{\chi}(E,J,\pi)$

The issue:

- σ_{α}^{CN} can be calculated
- G^{CN}_{χ} are difficult to predict



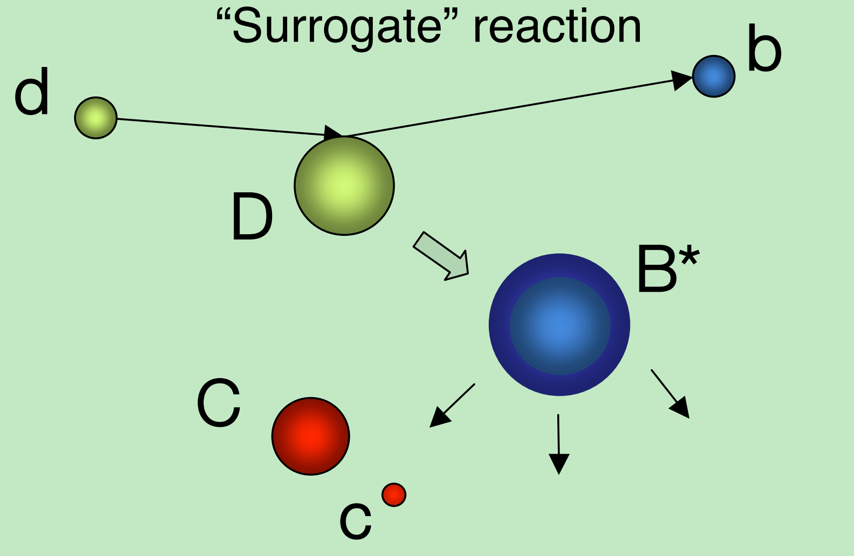
A Surrogate experiment gives

$P_{\chi}(E) = \Sigma_{J,\pi}\, F_{\delta}^{CN}(E,J,\pi) \cdot G^{CN}_{\chi}(E,J,\pi)$

I. Ideal procedure: calculate $F_{\delta}^{CN}(E,J,\pi)$, extract $G^{CN}_{\chi}(E,J,\pi)$, and insert into HF formula

II.Realistic: model CN decay, adjust parameters to reproduce measured $P_{\chi}(E)$, obtain G^{CN}_{χ}

III. Most common approach - *approximations:* assume (J,π)-independent G^{CN} and employ simplified formulae ("Weisskopf-Ewing" and "Surrogate Ratio" approaches)



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

Approximation schemes

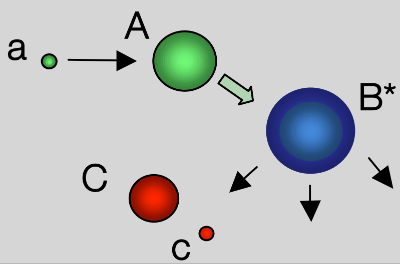
Weisskopf-Ewing approximation

Surrogate Ratio approach

The Weisskopf-Ewing limit

HF theory of the “desired” reaction:

$$\sigma_{\alpha\chi} = \Sigma_{J,\pi}\, \sigma_\alpha^{CN}(E,J,\pi) \cdot G^{CN}_\chi(E,J,\pi)$$



Weisskopf-Ewing description of the “desired” reaction:

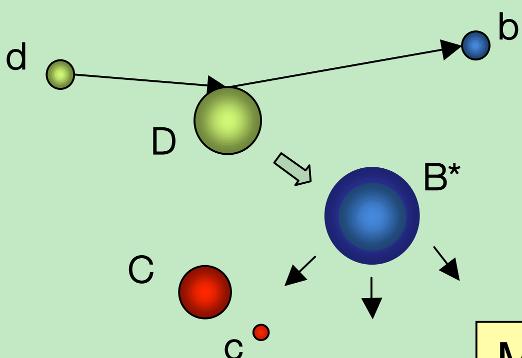
$$G^{CN}_\chi(E,J,\pi) \text{ ------> } \mathcal{G}^{CN}_\chi(E)$$

Thus:

$$\sigma_{\alpha\chi}^{WE}(E) = \sigma_\alpha^{CN}(E) \cdot \mathcal{G}^{CN}_\chi(E)$$

HF expression for the “Surrogate” measurement :

$$P_\chi(E) = \Sigma_{J,\pi}\, F_\delta^{CN}(E,J,\pi) \cdot G^{CN}_\chi(E,J,\pi)$$



Weisskopf-Ewing expression for the “Surrogate” measurement:

$$\text{------> } P_\chi(E) = \mathcal{G}^{CN}_\chi(E)$$

Cross section for the desired reaction:

$$\sigma_{\alpha\chi}^{WE}(E) = \underbrace{\sigma_\alpha^{CN}(E)}_{\text{calculated}} \cdot \underbrace{P_\chi(E)}_{=N_{coinc}/N_{single}\ \text{measured}}$$

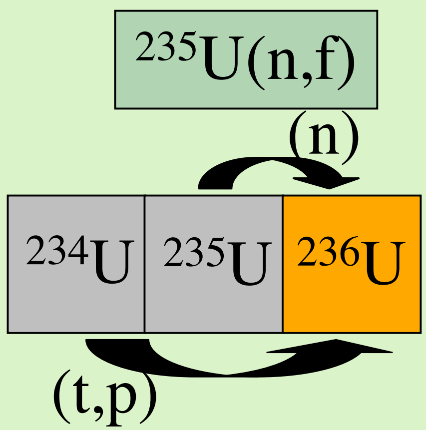
Most applications to date use the WE approximation!

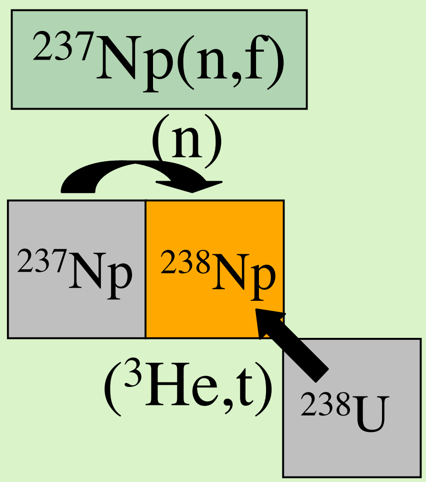
Surrogate experiments analyzed in the WE approximation

Cramer and Britt, Nucl. Sci. Eng. **41** (1970) 177

Britt and Wilhelmy, Nucl. Sci. Eng. **72** (1979) 222

(n,f) cross section estimates for actinides based on Surrogate (t,p), (^{3}He,d) and (^{3}He,t) experiments

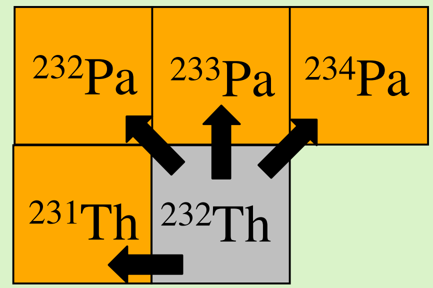




$\sigma_{(n,f)}(E) = \sigma^{CN}_{(n+A)}(E) \cdot P_f(E)$ **with** $P_f = N_{coinc}/N_{single}$

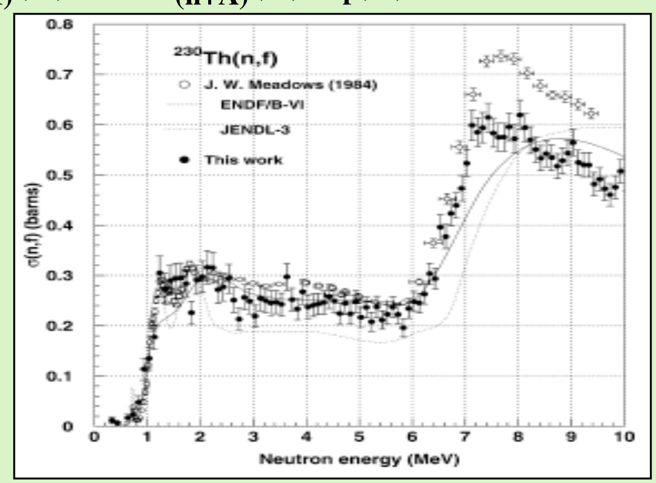
Petit et al., Nucl. Phys. A **735** (2004) 345

(n,f) cross sections for Th, Pa from Surrogate (^{3}He,x) experiments (x=α,t,d,p)



$\sigma_{(n,f)}(E)$ is from a semi-microscopic optical-model

$\sigma_{(n,f)}(E) = \sigma^{CN}_{(n+A)}(E) \cdot P_f(E)$



Approximations justified *a posteriori* by comparison with direct measurements.

The Surrogate Ratio approach

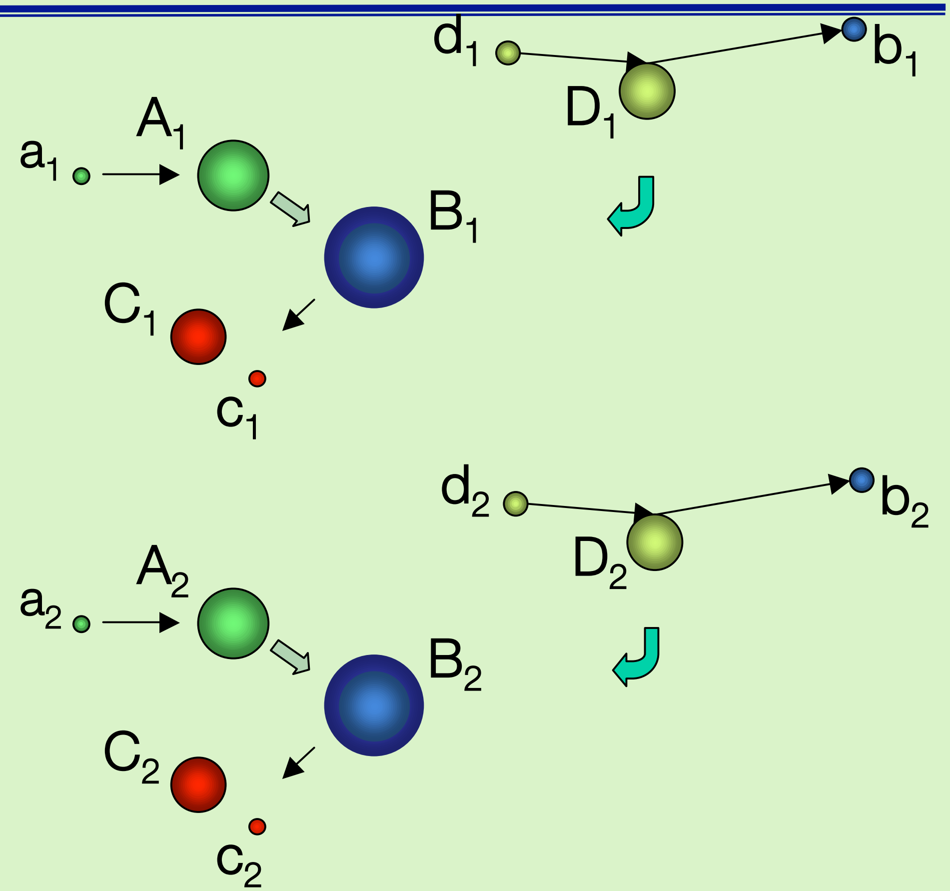
Goal: Determine experimentally

$$R(E) = \frac{\sigma_{\alpha_1 x_1}(E)}{\sigma_{\alpha_2 x_2}(E)}$$

$$\xrightarrow{\text{WE}} \frac{\sigma^{CN}_{\alpha_1}(E)}{\sigma^{CN}_{\alpha_2}(E)} \cdot \frac{\mathcal{G}^{CN}_{\chi_1}(E)}{\mathcal{G}^{CN}_{\chi_2}(E)}$$

calculated (first factor) — measured (second factor)

measured $= N_{\delta_1\chi_1}/N_{\delta_1} \times N_{\delta_2}/N_{\chi_2\delta_2}$



$N_{\delta_2}/N_{\delta_1}$ = const

Advantages of the Ratio approach:
- Eliminates need to measure direct-reaction "singles" events in N_{coinc}/N_{single}
- Small systematic errors or violations of assumptions underlying a Surrogate WE analysis might cancel

The Ratio approach has only been used recently!

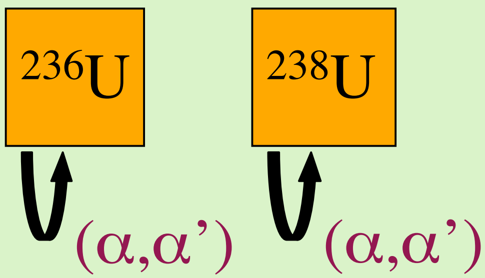
First results from the Surrogate Ratio approach

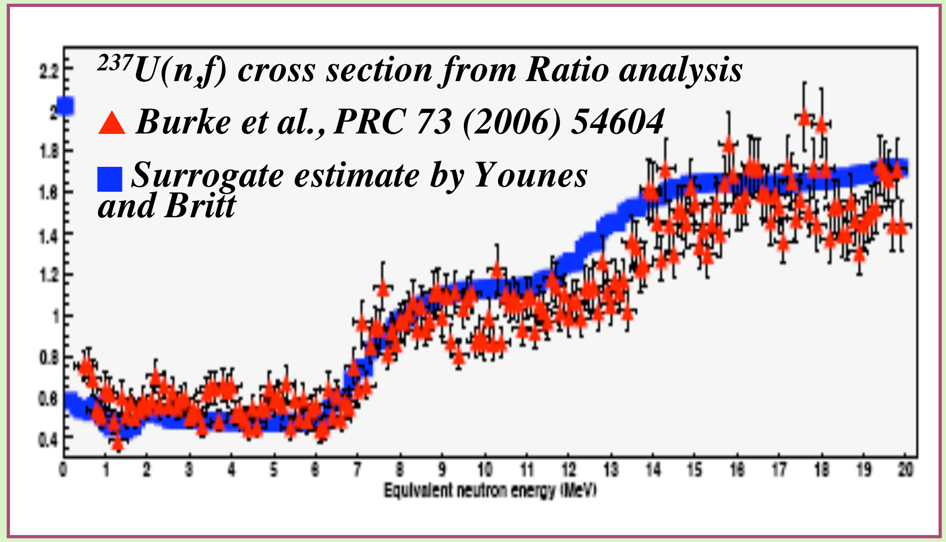
Plettner et al., PRC 71 (2005) 051602:

- (d,pf) and (d,d'f) on ^{238}U and ^{236}U

Burke et al., PRC 73 (2006) 054604:

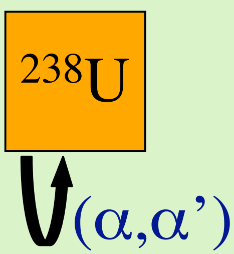
- (α,α'f) on ^{238}U and ^{236}U

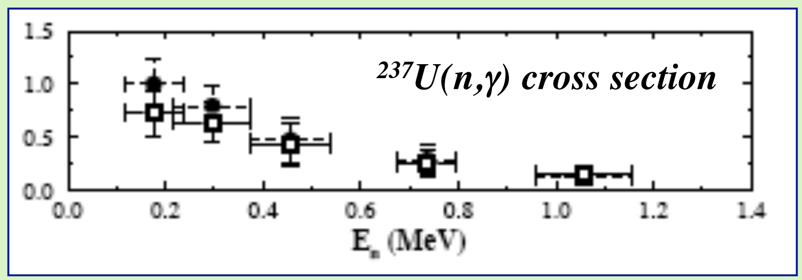




Bernstein et al., submitted (2006):

- (α,α'x) on ^{238}U, with x=f,γ,2n





Testing the assumptions

Validity of the Weisskopf-Ewing assumption:

- Are the decay probabilities independent of spin and parity?
- Does a Surrogate analysis in the WE approximation yield reliable results?

Validity of the Surrogate Ratio approach:

- Does a Ratio analysis yield reliable results?

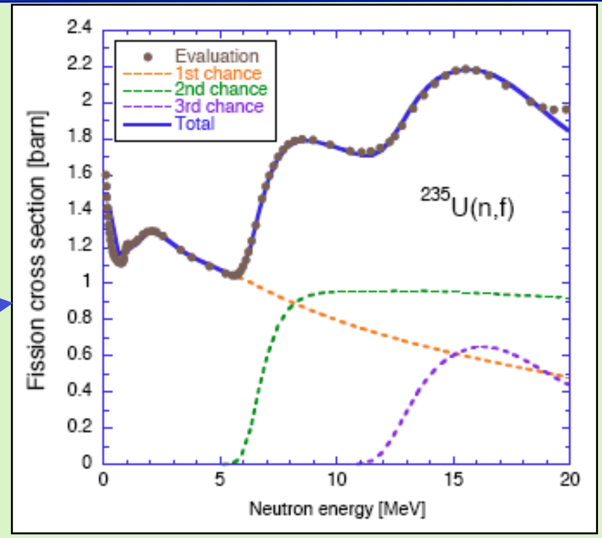
Testing the assumptions with a simulated experiment

J. Escher and F.S. Dietrich
Phys. Rev. C 74 (2006) 054601

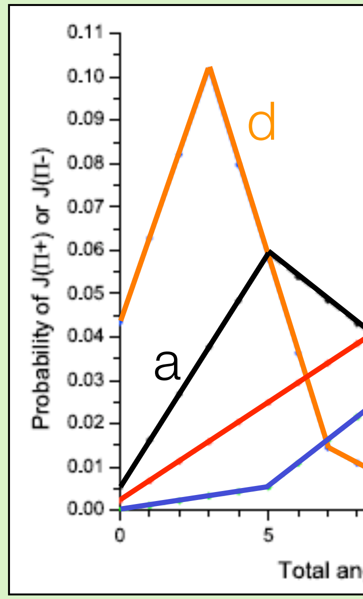
Simulation procedure:

1. Determine "reference cross sections" with a statistical-model calculation.
2. Extract fission probabilities for each (J,π) and study as function of E_n.
3. Simulate a Surrogate experiment and carry out an analysis in the WE limit.
4. Simulate two Surrogate experiments and carry out a Ratio analysis.

$$P_\chi(E) = \Sigma_{J,\pi}\, F_\delta^{CN}(E,J,\pi) \cdot G^{CN}{}_\chi(E,J,\pi)$$

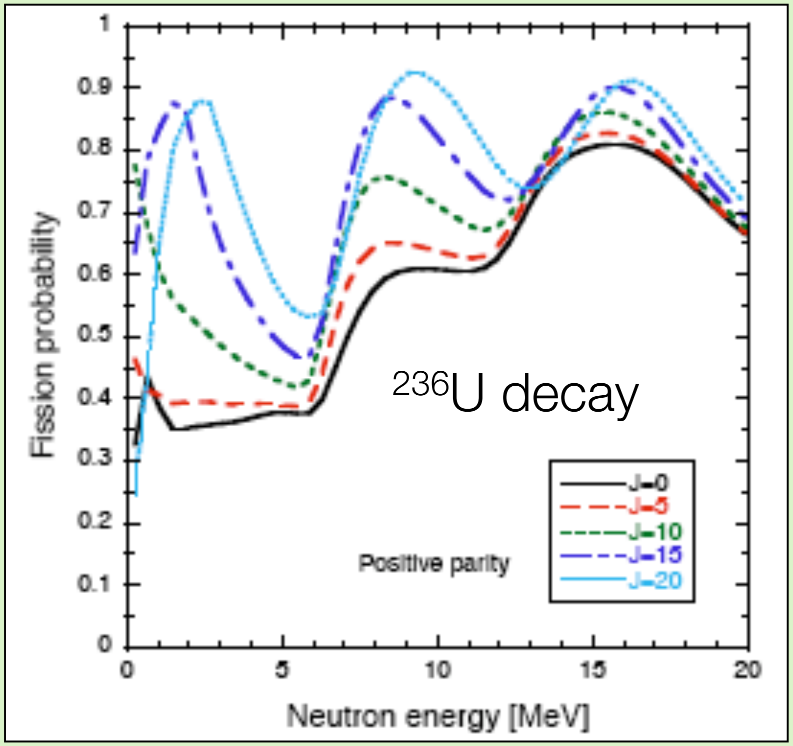


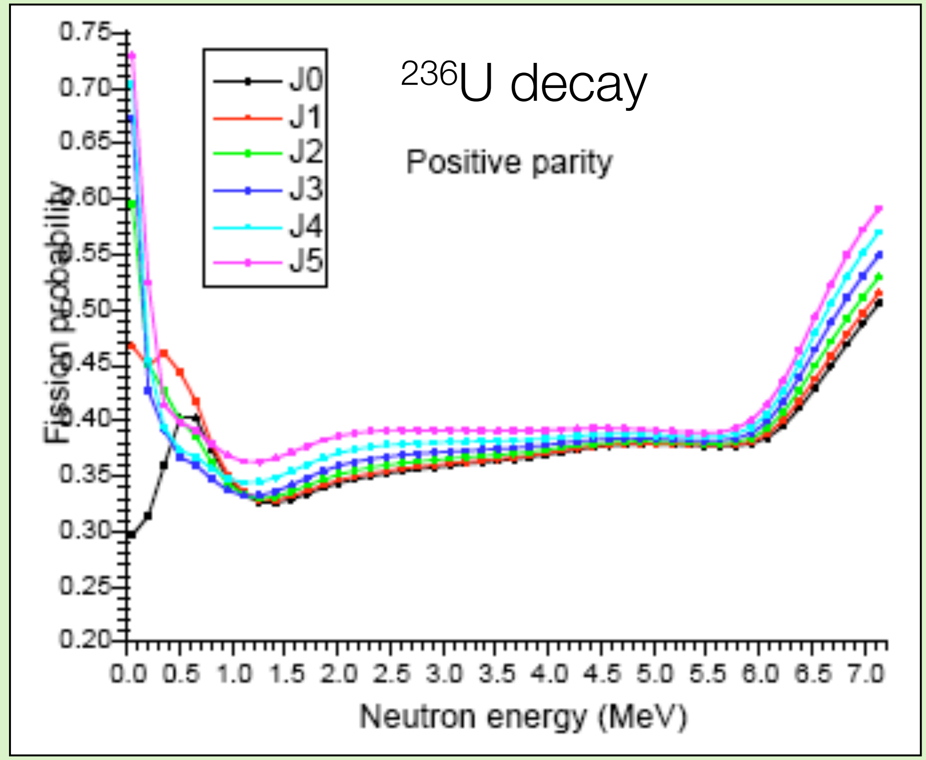
Fit to n + ^{235}U fission cross section



J^π distributions considered here

^{236}U fission probabilities' dependence on J^π



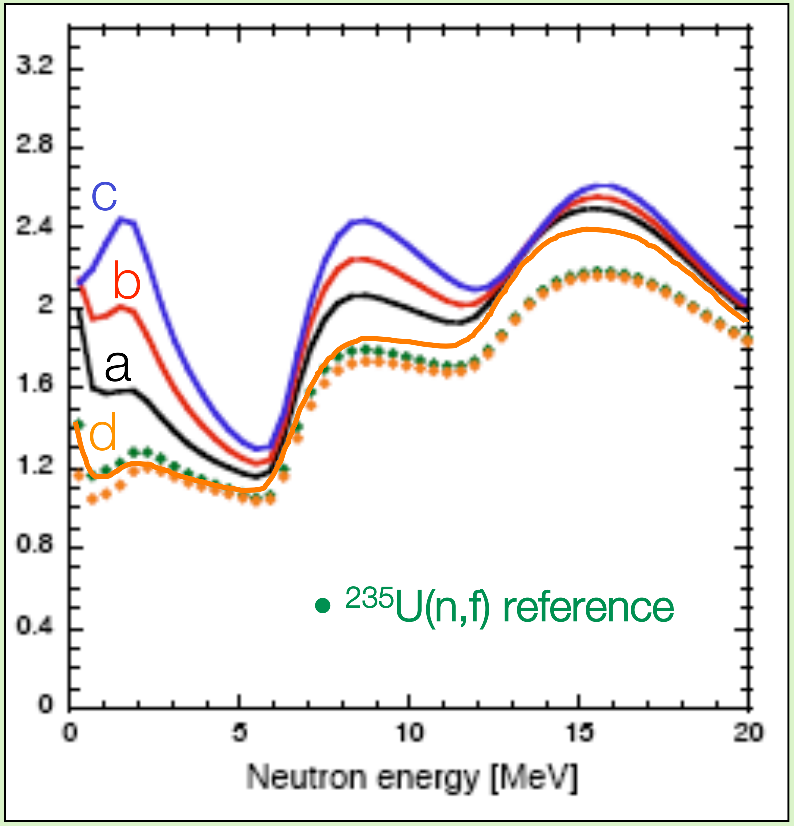


Observations:

- Fission probabilities show significant J^π dependence
- For small energies the WE approx is not valid
- Differences between fission probabilities increase at onset of 2nd chance fission
- Results depend little on parity (not shown)

It is not *a priori* obvious whether the WE limit applies to a particular reaction in a given energy regime. The validity of the WE approximation depends on the relevant J^π and E values.

(n,f) cross sections from our simulation



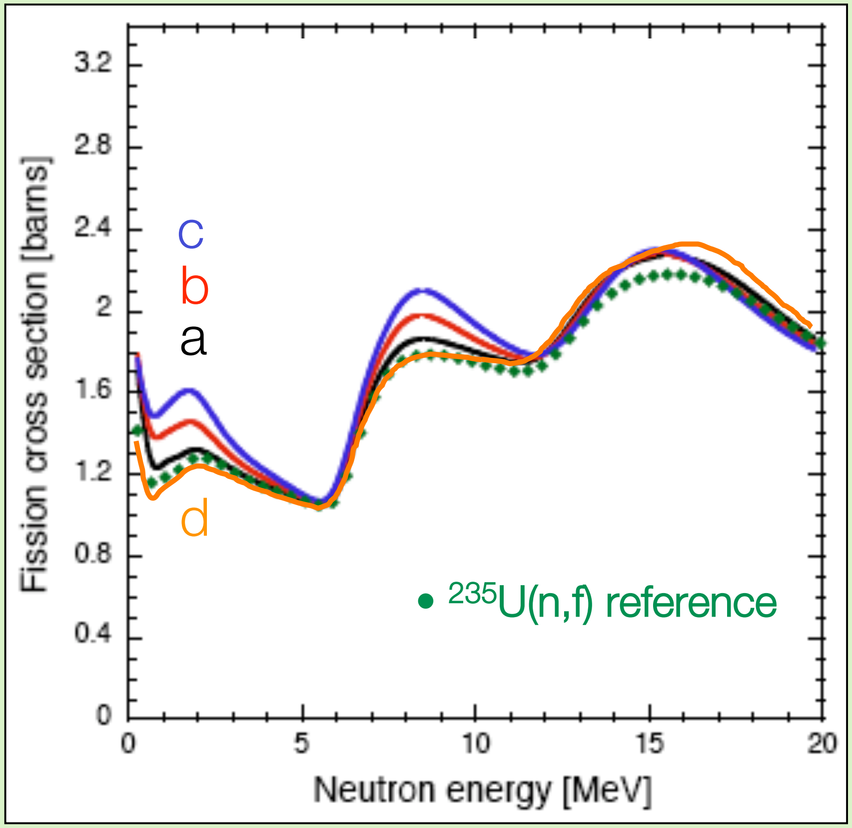
Results from Weisskopf-Ewing analysis

- Cross sections depend on the J^{π} distribution (WE limit not strictly valid)
- Largest uncertainties are below E_n=3 MeV and are due to J^{π} effects
- Deviations at higher energies are due to preequilibrium effects.

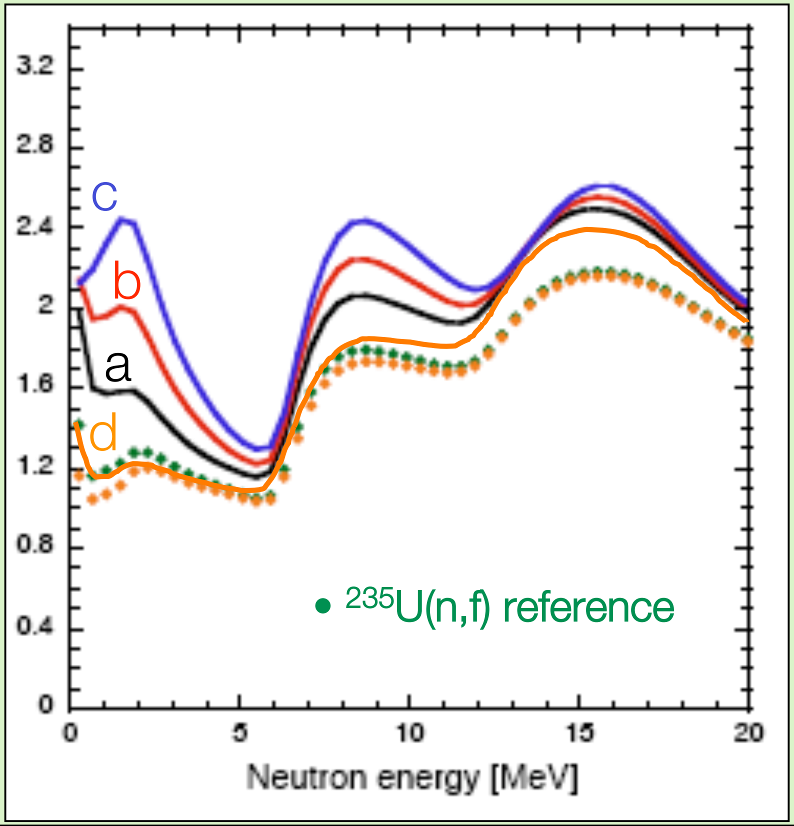
(n,f) cross sections from our simulation

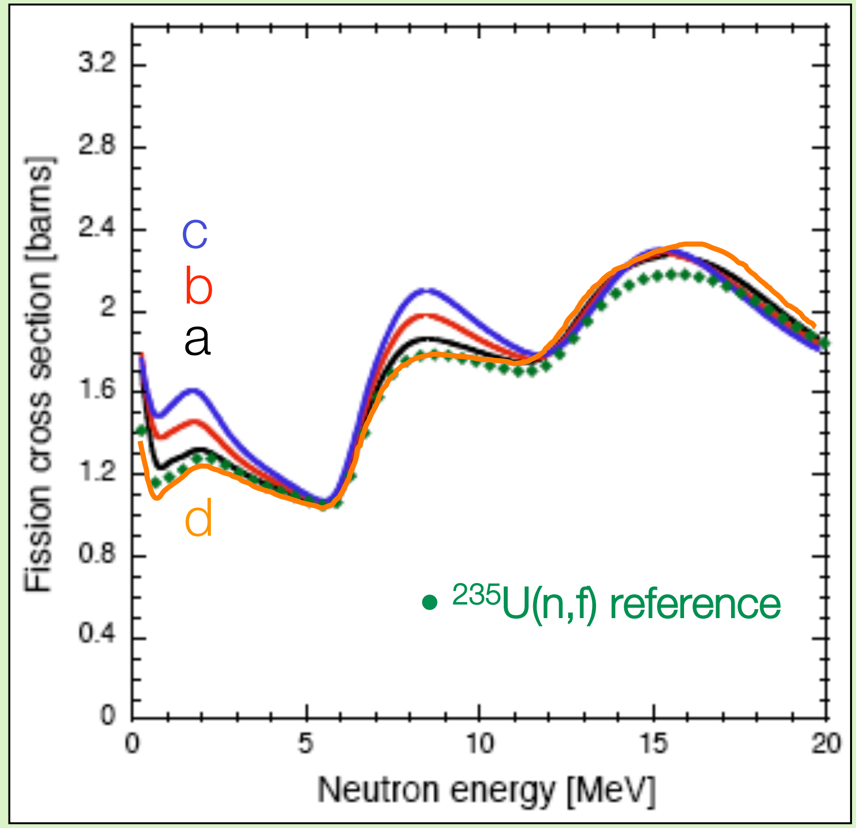
Results from Ratio analysis

- Cross sections show some dependence on J^{π}
- Agreement with expected cross section is very good (except for small energies and at 2nd-chance fission)
- Overall….



(n,f) cross sections from our simulation





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- Cross sections depend on the J^{π} distribution (WE limit not strictly valid)
- Largest uncertainties are below E_n=3 MeV and are due to J^{π} effects
- Deviations at higher energies are due to preequilibrium effects.

Results from Ratio analysis

- Cross sections show some dependence on J^{π}
- Agreement with expected cross section is very good (except for small energies and at 2nd-chance fission)
- **Less J^{π} dependence and better agreement than for the Surrogate WE approach**

Knowledge of J^{π} is important!

J. Escher, LLNL

The importance of spin

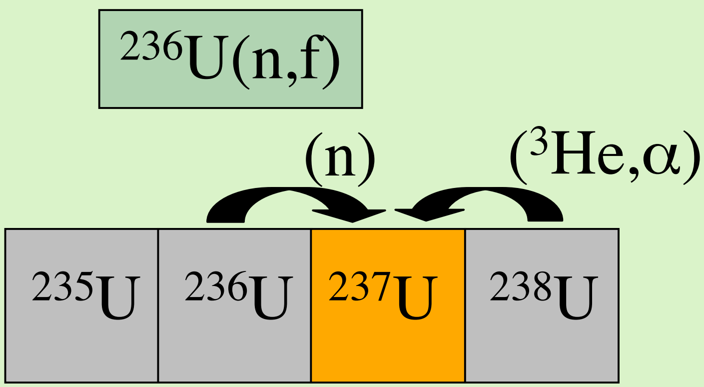
or: the need to move beyond current approximations

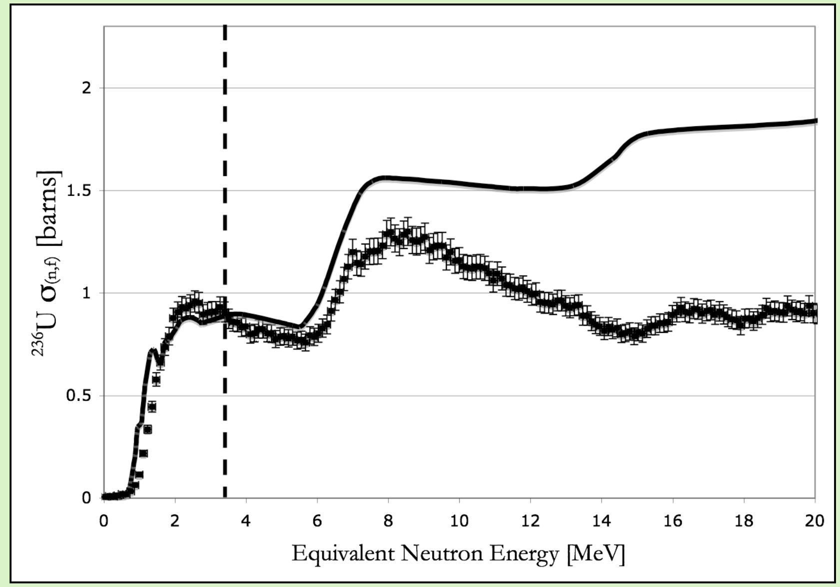
Angular-momentum effects at low energies

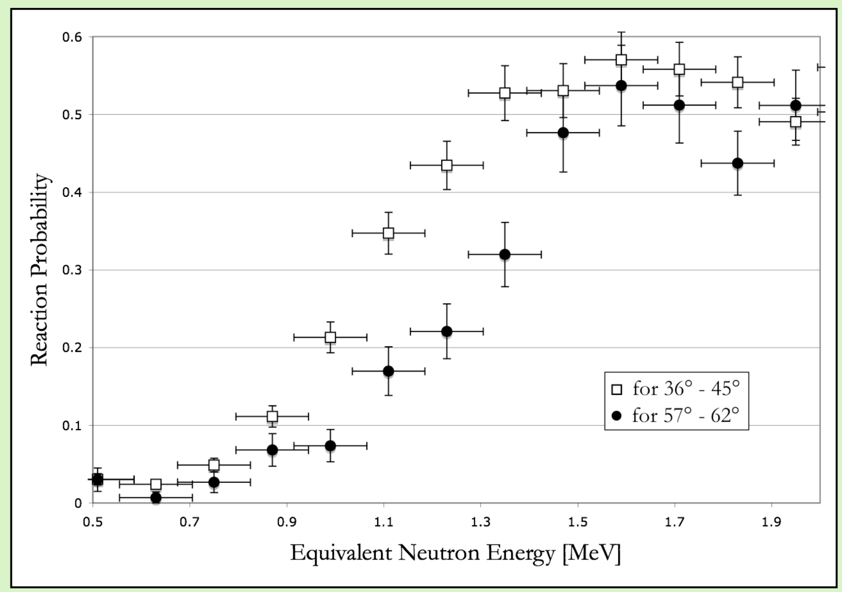
B. Lyles et al.
PRC 76 (2007) 014606

Surrogate (^{3}He,αf) experiments at LBNL:

- Determined the ^{236}U(n,f) cross section using the WE approximation
- Good agreement up to 3-4 MeV
- Deviations at higher energies due to target impurities
- Angular-momentum effects discernable at small energies







Angular-momentum mismatch between Surrogate and desired reactions affects low-energy regime.

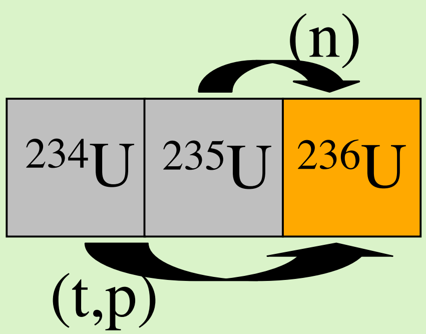
Knowledge of the CN J^π populations is important!

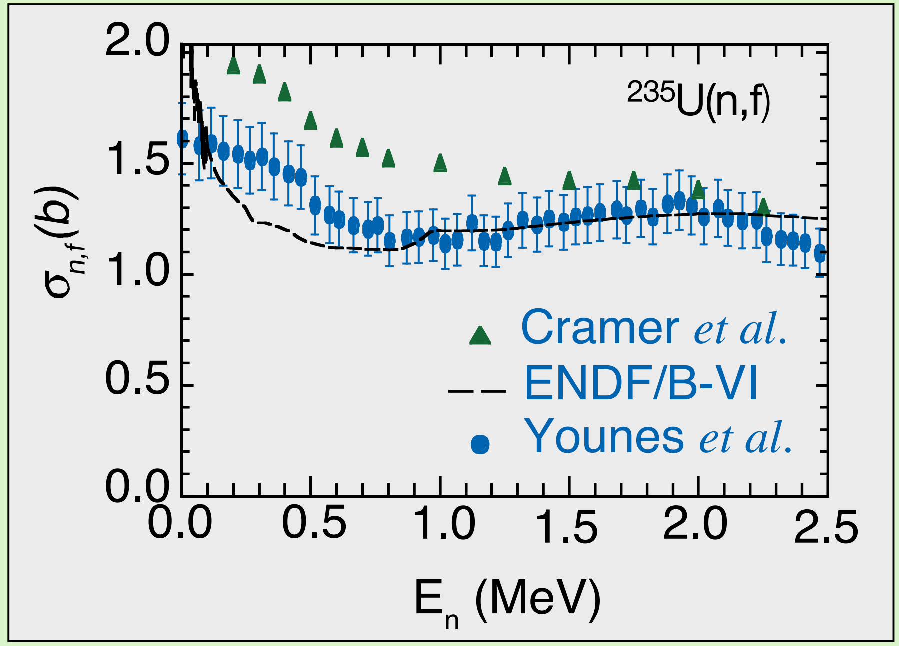
Younes and Britt

Phys. Rev. C **67** (2003) 024610, **68** (2003) 034610

Re-analysis of (t,pf) data from the 1970s:

- **Incorporated effects of J^π population differences**
- Better optical model
- Fit model to experimental fission probabilities
- Added renormalization procedure to improve fit





Improved agreement with the evaluated result!

Need information on CN J^π populations
- To improve extracted cross sections
- To test validity of approximations used
- To extend the method to lower energies

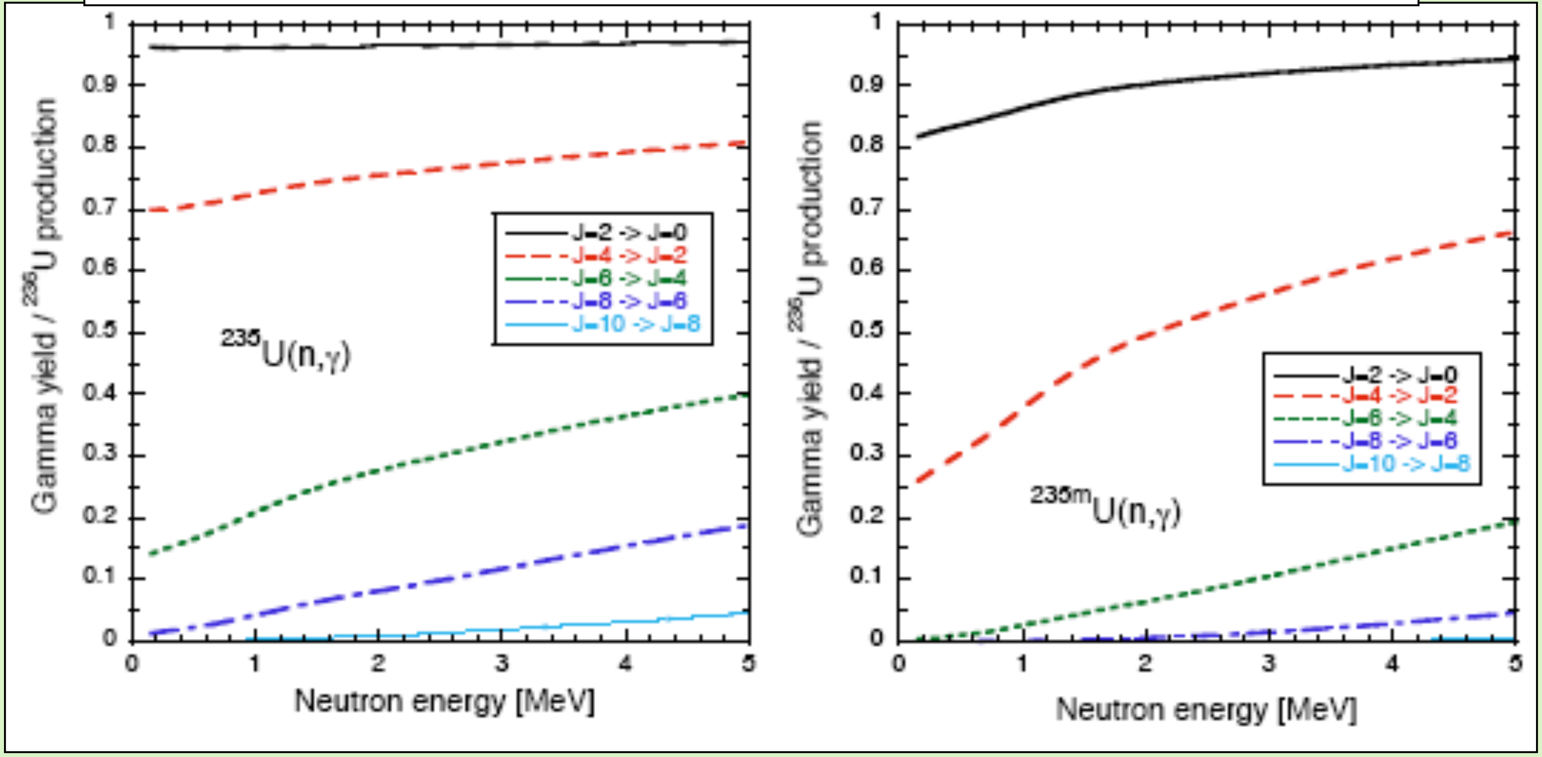
Surrogate approach for (n,γ)?

Actinide targets

Mass-90 targets

Considering (n,γ) reactions for actinides

A look at the γ yields for ^{236}U decay with different J^π populations



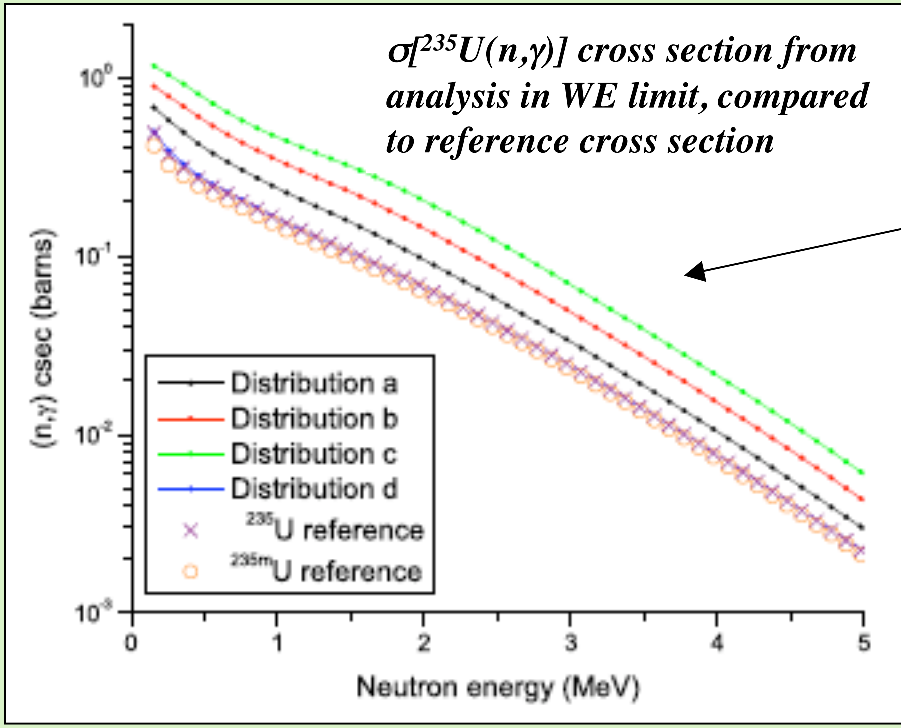
Relative γ-ray intensities as function of E for n+^{235m}U and n+^{235}U

Observation: Relative γ-ray intensities depend sensitively on J^π distribution of the decaying compound nucleus.

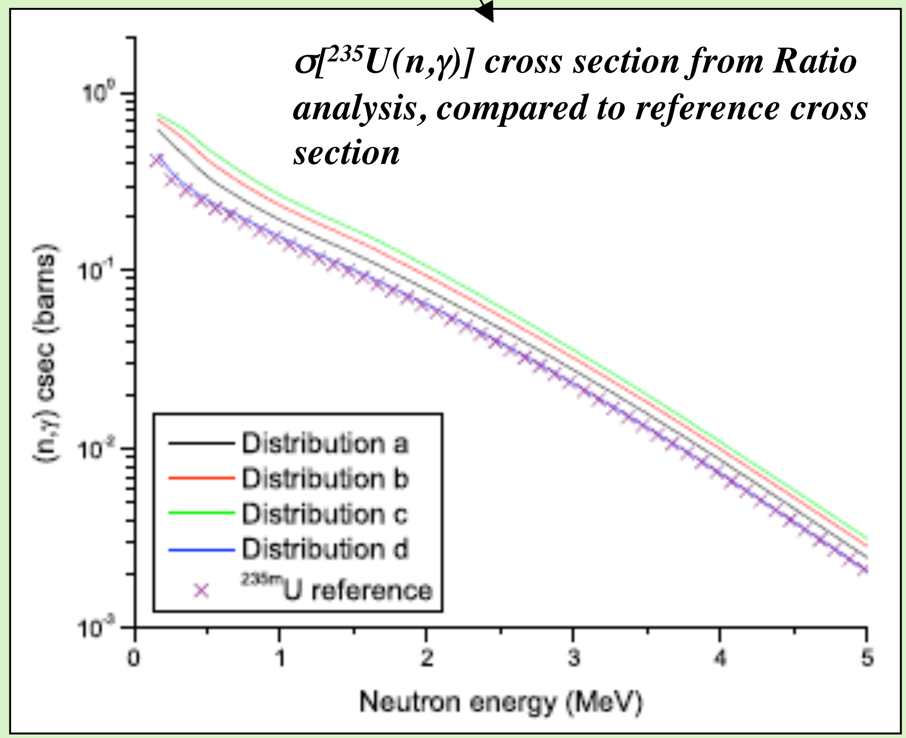
Considering (n,γ) reactions for actinides

Simulating Surrogate experiments for (n,γ)

- Goal: Examine reliability of cross sections determined via Surrogate approach(es)
- Specifically: Study dependence of extracted cross sections on J^{π} population of CN
- Surrogate WE cases studied: ^{235}U(n,γ) and ^{233}U(n,γ)
- Surrogate Ratio case studied: ^{235}U(n,γ) from ^{233}U(n,γ)
- Same procedures as before



σ[^{235}U(n,γ)] cross section from analysis in WE limit, compared to reference cross section

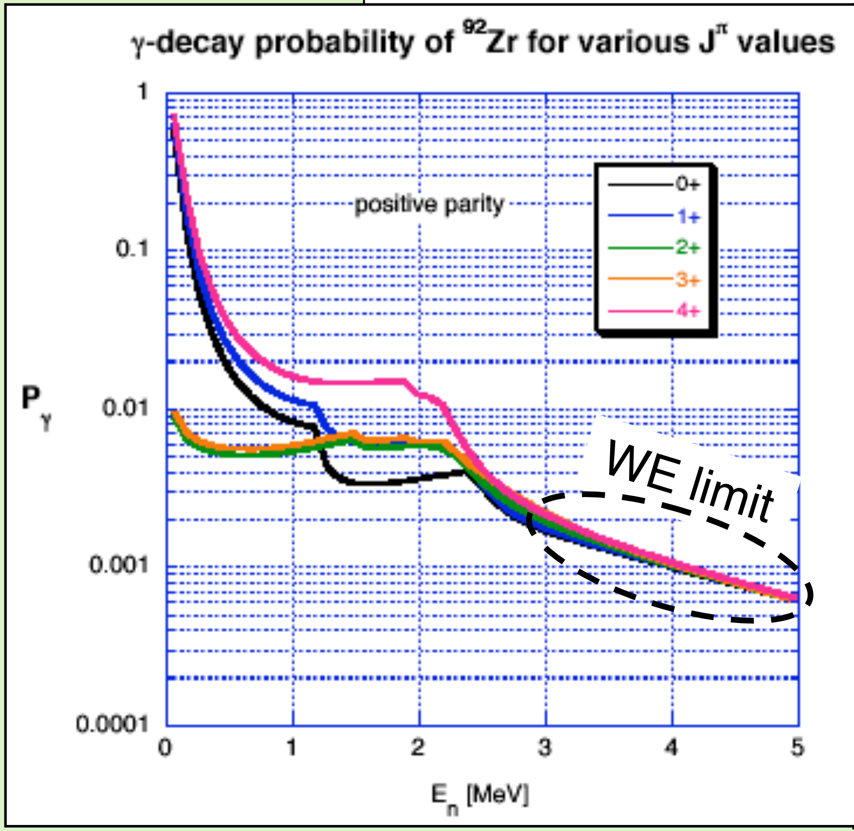


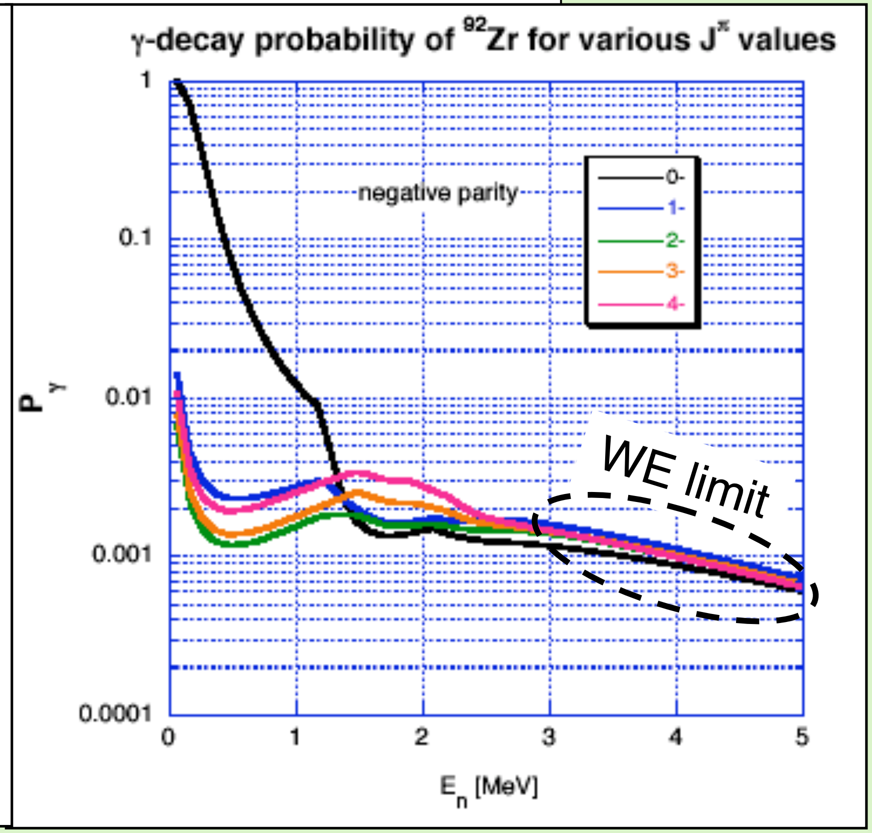
σ[^{235}U(n,γ)] cross section from Ratio analysis, compared to reference cross section

The Surrogate approach might work for (n,γ) cross sections, but knowledge of J^{π} is crucial!

(n,γ) reactions for near-spherical nuclei - a stretch?

Branching ratios for ^{92}Zr decay for various J^π values





Forssen et al., PRC 75(2007) 055807

Shown is the probability (P_γ) that a ^{92}Zr state with excitation energy $E=S_n+E_n$ and given J^π value decays via γ-emission. S_n is the neutron separation energy in ^{92}Zr.

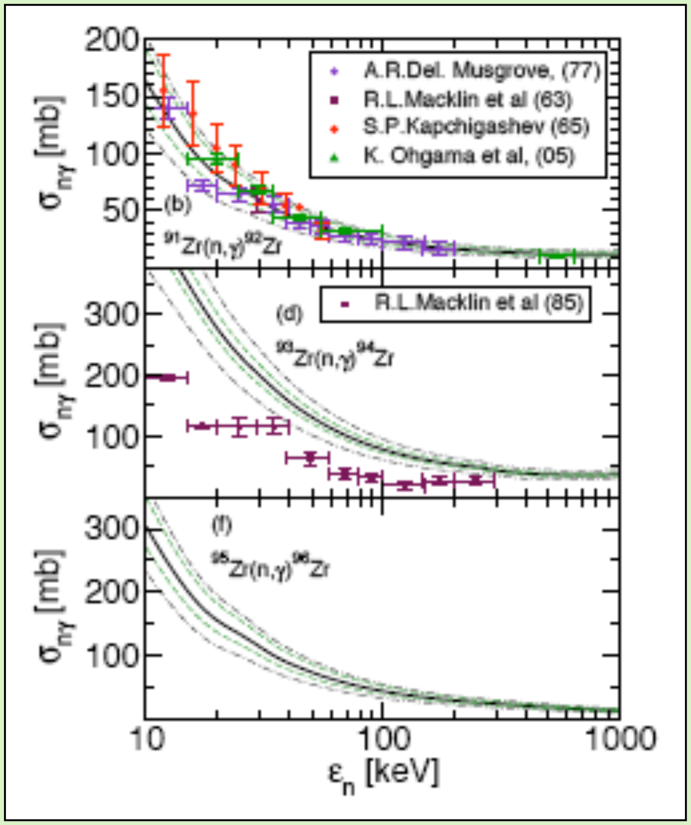
At small energies, the branching ratios are VERY sensitive to CN J^π values!

Worst-case scenario!

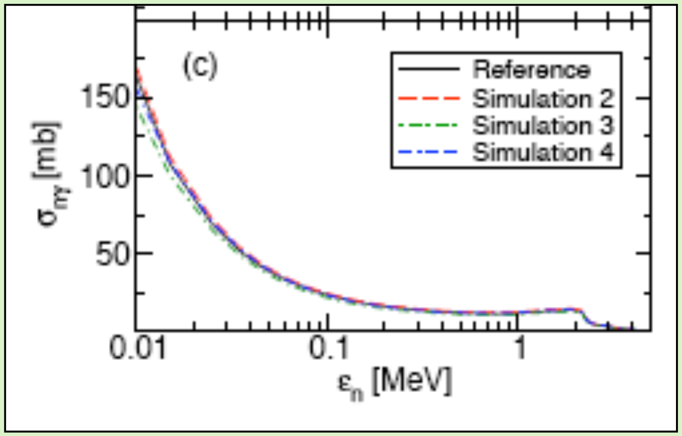
Considering (n,γ) reactions for near-spherical nuclei

Non-negligible uncertainties in calculated cross sections:

Forssen et al.
Phys. Rev. C 75 (2007) 055807



Information from Surrogate experiments at higher neutron energy can constrain calculations:



Surrogate experiments may help constrain models at higher energies and improve calculations in the desired energy range - **even for very challenging cases**!

Challenges for theory

Primarily related to predicting

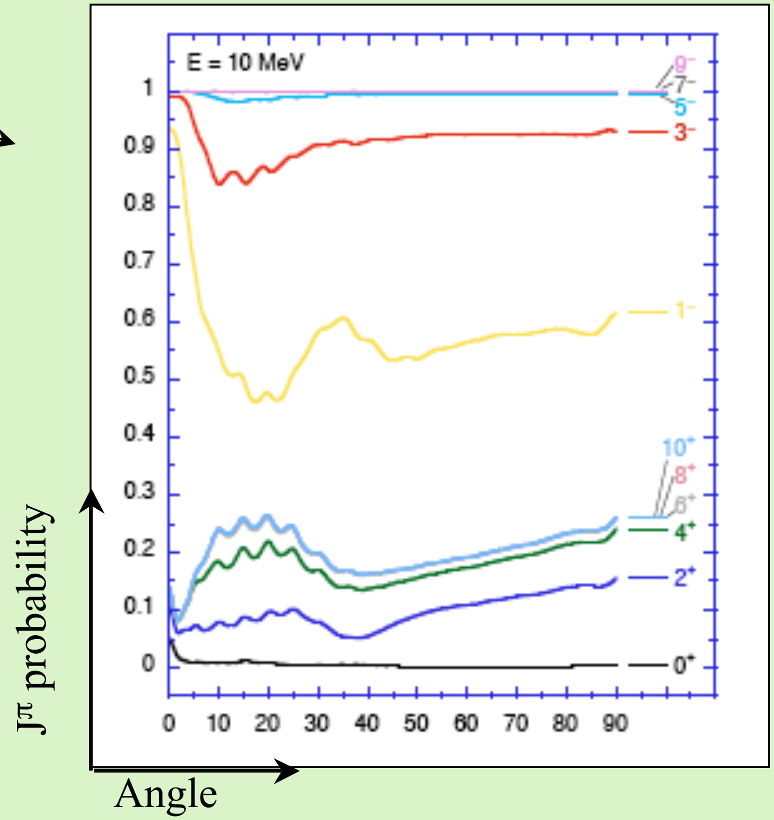
J^{π} distribution for decaying CN

Challenges for reaction theory

Formation of a highly excited nucleus in a direct reaction

- inelastic scattering, pickup, stripping reactions
- various projectile-target combinations
- resonances, quasi-bound states

J^{π} distribution for $^{90}Zr(\alpha,\alpha')^{90}Zr^*$ from a simple model



Damping of the excited states into a compound nucleus

- competition between CN formation and non-equilibrium decay (particle escape)
- dependence on J^{π}

See F.S. Dietrich's talk on Wed

Width fluctuation correlations

Kerman and McVoy (1979)
See G. Arbanas' talk on Wed

Summary

The Surrogate nuclear reaction approach is potentially very valuable. It is the only indirect method for obtaining CN reaction cross sections.

Various approximations to the full Surrogate approach (Weisskopf-Ewing approximation, Surrogate Ratio method) show promising results for (n,f) cross sections for actinides.

Limitations of the method primarily related to differences in the CN spin distributions of the desired and Surrogate reactions.

Challenge to theory: Description of the formation of a CN following a direct reaction.