Cross sections for neutron capture from Surrogate measurements

Jutta Escher
Nuclear Theory & Modeling
Lawrence Livermore National Lab

Gamma Strength and Level Density in Nuclear Physics and Nuclear Technology
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UCRL-PRES-452591

Overview

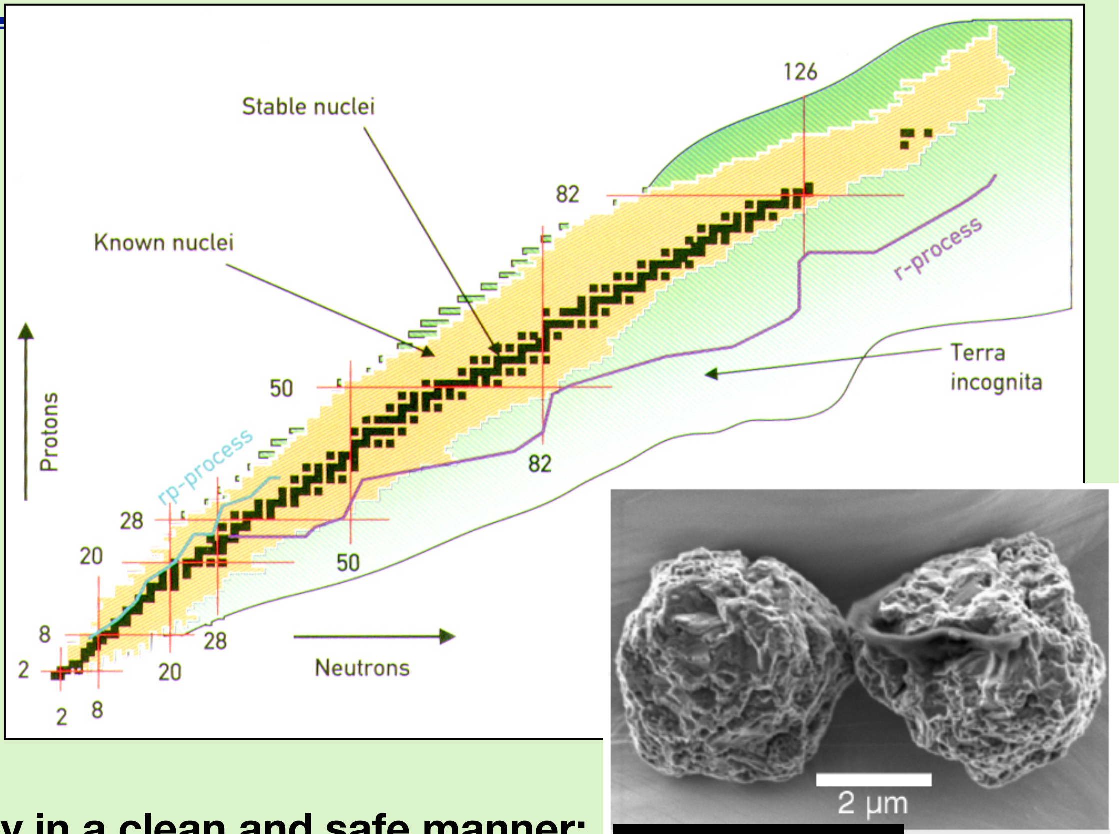
1. Compound-nuclear reactions
2. Surrogate idea
3. Weisskopf-Ewing approximation
4. Challenges specific to (n,γ)
5. Getting better cross section constraints from Surrogate data
6. Summary

Compound-nuclear reactions

Compound-nuclear reactions

Important for understanding astrophysical phenomena and the origin of the elements:

- The s and r processes produce almost all heavy elements
- Processes are linked to stellar evolution
- Abundance patterns predicted by models, require cross section input



Presolar grain

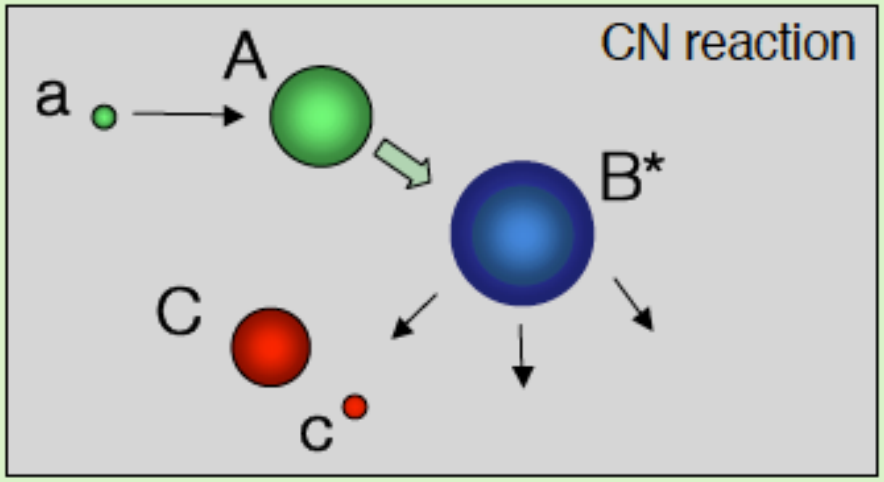
Important for exploiting nuclear energy in a clean and safe manner:

- Goals are to operate safely, reduce toxic waste, ensure availability of U resource, increase efficiency, and contain costs
- Cross sections are needed for investigating waste transmutation scenarios, explore alternative fuel cycles, simulate reactor designs
- Reactions on actinides, minor actinides, fission fragments, structural materials are of interest.

Compound-nuclear (CN) reactions

Simplified description:

- A CN reaction proceeds in *two stages*:
  - Formation of the CN via absorption of the projectile by the target nucleus (a series of nucleon-nucleon interactions leading to equilibration)
  - Decay of the CN via particle emission or fission
- Characteristics:
  - CN reactions are slow: ~10^{-16}s (direct reactions ~10^{-22}s)
  - Evaporated particle spectra exhibit characteristic energy spectra and angular distributions
  - The CN forgets how it was produced (but retains memory of conserved quantities!)



Theoretical formulation:

- Early, simple expression (Weisskopf-Ewing):

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

- Accounting for conservation of angular momentum (Hauser-Feshbach):

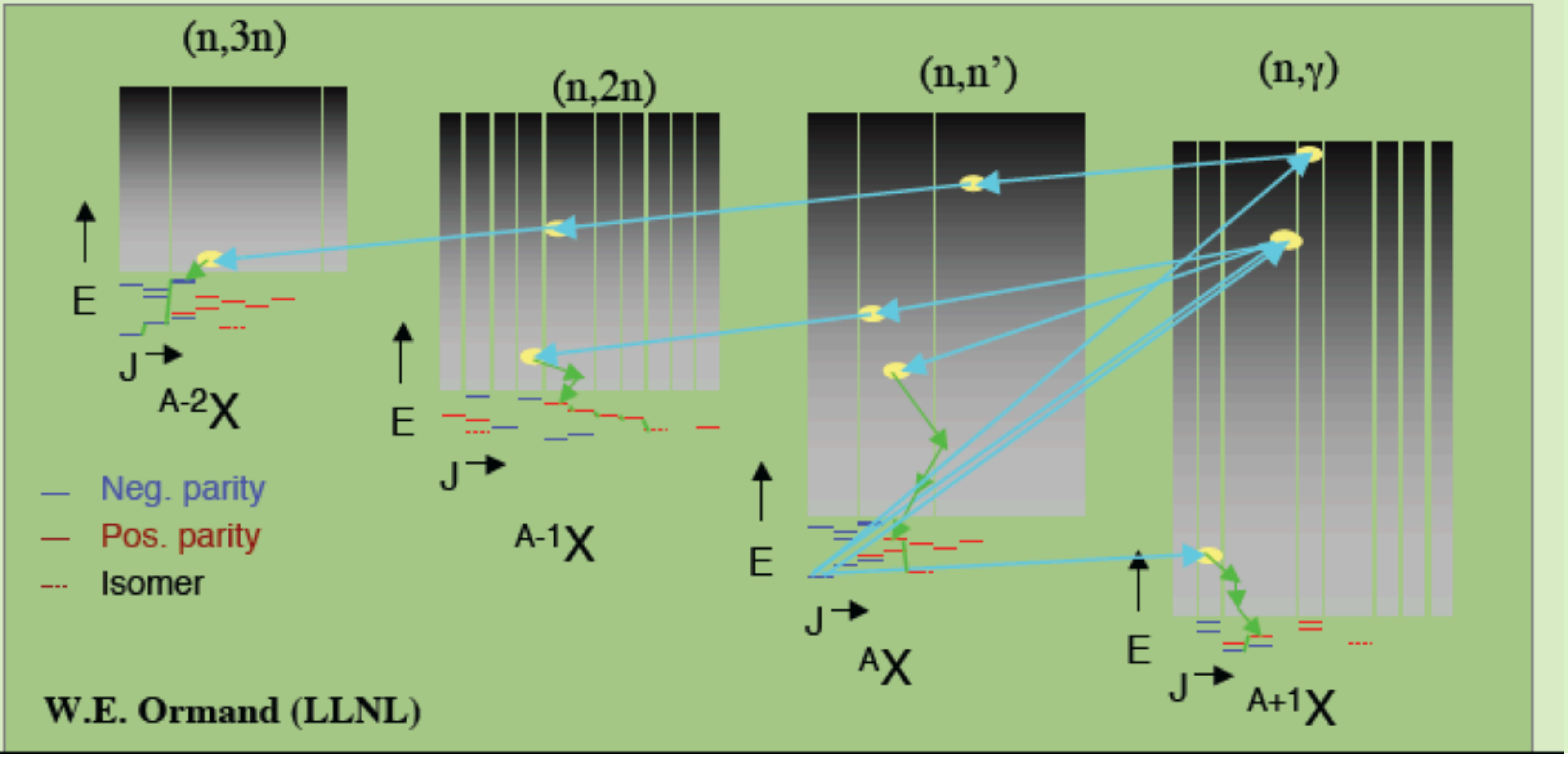
  $\sigma_{\alpha\chi} = \Sigma_{J,\pi}\, \sigma_{\alpha}{}^{CN}(E,J,\pi) \cdot G^{CN}{}_{\chi}(E,J,\pi)$

State-of-the-art: powerful tool to calculate cross sections

Average cross section per unit energy in the outgoing channel:

$$\frac{d\sigma_{\alpha\chi}^{HF}}{dE_{\chi}} = \pi\lambda_{\alpha}^{2}\sum_{J\pi}\omega_{\alpha}^{J}\sum_{lsl's'I'}\frac{T_{\alpha ls}^{J}T_{xl's'}^{J}\rho_{I'}(U)}{\sum'_{x''l''s''}T_{x''l''s''}^{J}+\sum_{x''l''s''}\int T_{x''l''s''}^{J}(E_{\chi''})\rho_{I''}(U'')dE_{\chi''}}$$

Evaluating this expression requires knowledge of optical potentials and the structure of the nuclei that can be reached in the decay of the CN:

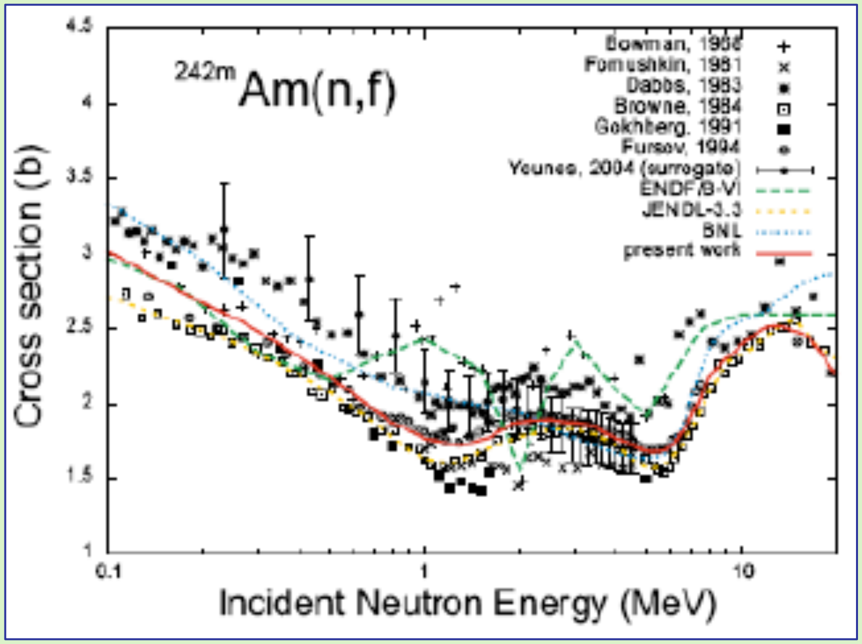


W.E. Ormand (LLNL)

State-of-the-art: powerful tool to calculate cross sections

Practice:

- STAPRE, TALYS, EMPIRE, MCNASH, COH, etc. allow one to calculate cross sections.
- Nuclear physics input is provided by data bases or by the user; input parameters are not unique (art *and* science)



Chadwick *et al*, Nucl. Data Sheets 107 (2006) 2931

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Nuclear Data Sheets

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RIPL – Reference Input Parameter Library for Calculation of Nuclear Reactions and Nuclear Data Evaluations

R. Capote,[1*] M. Herman,[1,2] P. Obložinský,[1,2] P.G. Young,[3] S. Goriely,[4] T. Belgya,[5] A.V. Ignatyuk,[6]
A.J. Koning,[7] S. Hilaire,[8] V.A. Plujko,[9] M. Avrigeanu,[10] O. Bersillon,[8] M.B. Chadwick,[3] T. Fukahori,[11]
Zhigang Ge,[12] Yinlu Han,[12] S. Kailas,[13] J. Kopecky,[14]
V.M. Maslov,[15] G. Reffo,[16] M. Sin,[17] E.Sh. Soukhovitskii,[15] P. Talou[3]
[1] *NAPC–Nuclear Data Section, International Atomic Energy Agency, A-1400 Vienna, Austria*
[2] *National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[3] *Los Alamos National Laboratory, Los Alamos, NM 87544, USA*
[4] *Université Libre de Bruxelles, BE 1050 Brussels, Belgium*
[5] *Institute of Isotope and Surface Chemistry, Chemical Research Center, H-1525 Budapest, Hungary*
[6] *Institute of Physics and Power Engineering, 249033 Obninsk, Russia*
[7] *Fuels Actinides and Isotopes NRG Nuclear Research and Consultance Group, NL-1755 Petten, The Netherlands*
[8] *CEA, DAM, DIF, F-91297 Arpajon, France*
[9] *Taras Shevchenko National University, 03022 Kiev, Ukraine*
[10] *National Institute of Physics and Nuclear Engineering "Horia Hulubei", 077125 Bucharest-Magurele, Romania*
[11] *Japan Atomic Energy Agency, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195 Japan*
[12] *China Institute of Atomic Energy, Beijing 102413 China*
[13] *Bhabha Atomic Research Center, Trombay, 400085 Mumbai, India*
[14] *JUKO Research, NL-1817 Alkmaar, The Netherlands*
[15] *Joint Institute for Power and Nuclear Research – Sosny, BY-220109 Minsk, Belarus*
[16] *Retired in 1998, Ente Nuove Tecnologie, Energia e Ambiente (ENEA), 40129 Bologna, Italy and*
[17] *Nuclear Physics Department, Bucharest University, 077125 Bucharest-Magurele, Romania*

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We describe the physics and data included in the Reference Input Parameter Library, which is devoted to input parameters needed in calculations of nuclear reactions and nuclear data evaluations. Advanced modelling codes require substantial numerical input, therefore the International Atomic Energy Agency (IAEA) has worked extensively since 1993 on a library of validated nuclear-model input parameters, referred to as the Reference Input Parameter Library (RIPL). A final RIPL coordinated research project (RIPL-3) was brought to a successful conclusion in December 2008, after 15 years of challenging work carried out through three consecutive IAEA projects. The RIPL-3 library was released in January 2009, and is available on the Web through *http://www-nds.iaea.org/RIPL-3/*. This work and the resulting database are extremely important to theoreticians involved in the development and use of nuclear reaction modelling (ALICE, EMPIRE, GNASH, UNF, TALYS) both for theoretical research and nuclear data evaluations.

The numerical data and computer codes included in RIPL-3 are arranged in seven segments: **MASSES** contains ground-state properties of nuclei for about 9000 nuclei, including three theoretical predictions of masses and the evaluated experimental masses of Audi *et al.* (2003). **DISCRETE LEVELS** contains 117 datasets (one for each element) with all known level schemes, electromagnetic and γ-ray decay probabilities available from ENSDF in October 2007. **NEUTRON RESONANCES** contains average resonance parameters prepared on the basis of the evaluations performed by Ignatyuk and Mughabghab. **OPTICAL MODEL** contains 495 sets of phenomenological optical model parameters defined in a wide energy range. When there are insufficient experimental data, the evaluator has to resort to either global parameterizations or microscopic approaches. Radial density distributions to be used as input for microscopic calculations are stored in the MASSES segment. **LEVEL DENSITIES** contains phenomenological parameterizations based on the modified Fermi gas and superfluid models and microscopic calculations which are based on a realistic microscopic single-particle level scheme. Partial level densities formulae are also recommended. All tabulated total level densities are consistent with both the recommended average neutron resonance parameters and discrete levels. **GAMMA** contains parameters that quantify giant resonances, experimental gamma-ray strength functions and methods for calculating gamma emission in statistical model codes. The experimental GDR parameters are represented by Lorentzian fits to the photo-absorption cross sections for 102 nuclides ranging from ^{51}V to ^{239}Pu. **FISSION** includes global prescriptions for fission barriers and nuclear level densities at fission saddle points based on microscopic HFB calculations constrained by experimental fission cross sections.

*) Corresponding author, electronic address: r.capotenoy@iaea.org; roberto.capote@yahoo.com

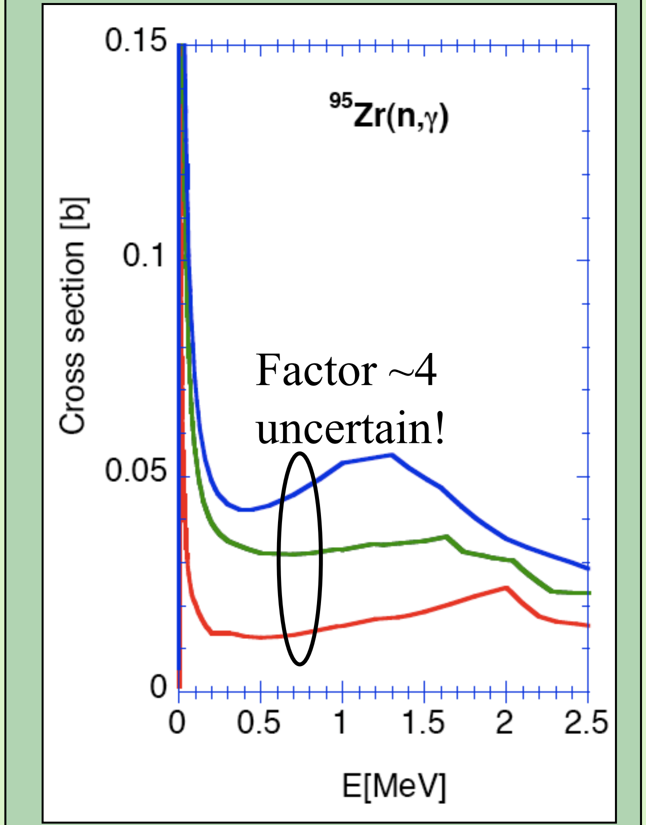
Capote *et al*, Nuclear Data Sheets 110 (2009) 3107
23 authors, 108 pages, many years…

Constraining the input

Constraints for models and parameters:

- γSF: total radiative width,...
- Level densities: discrete low-lying levels, neutron resonance spacings at S_n,…
- Microscopic calculations for γSF and LDs
- Global systematics
- Local systematics
- Complementary/competing cross sections
- Measured cross sections of the reaction of interest, possibly near the energy of interest

$^{95}Zr(n,\gamma)^{96}Zr$ cross section



From: www.nndc.bnl.gov

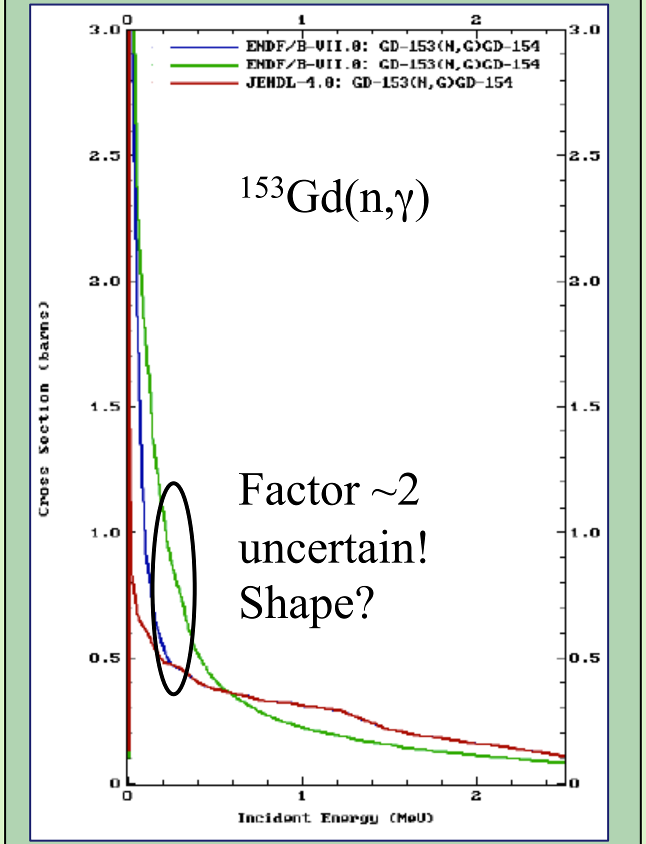
Lack of cross section constraints can lead to large differences between evaluations

Constraining the input

Constraints for models and parameters:

- γSF: total radiative width,..
- Level densities: discrete low-lying levels, neutron resonance spacings at S_n,…
- Microscopic calculations for γSF and LDs
- Global systematics
- Local systematics
- Complementary/competing cross sections
- Measured cross sections of the reaction of interest, possibly near the energy of interest

^{153}Gd(n,γ)^{154}Gd cross section

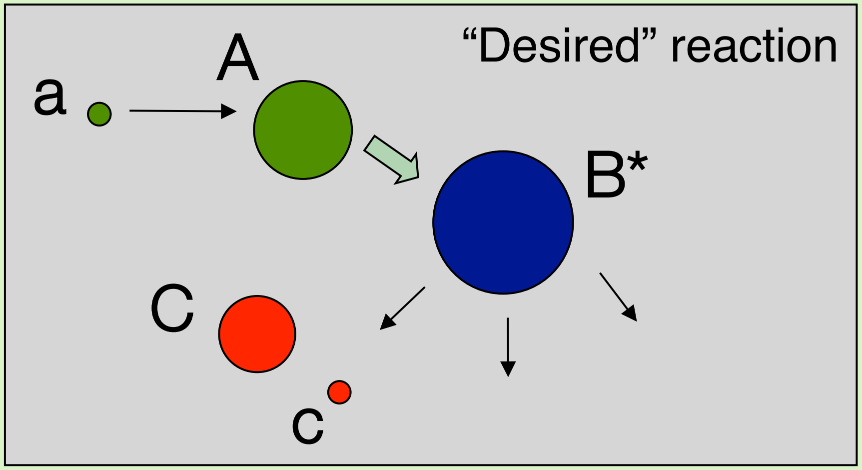


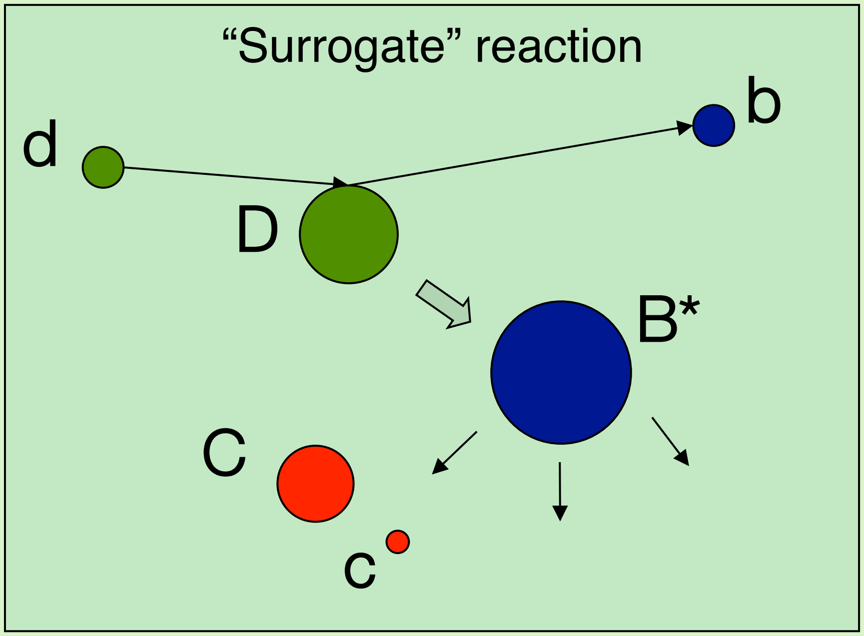
From: www.nndc.bnl.gov

Measurements of cross sections are very important to constrain calculations. Where these are not feasible, we explore using Surrogate reactions to determine meaningful constraints.

The Surrogate Idea

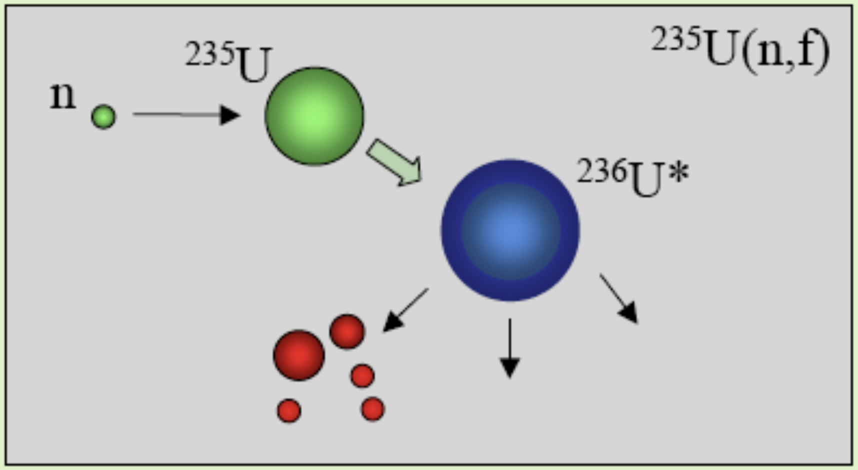
The Surrogate Idea - schematically



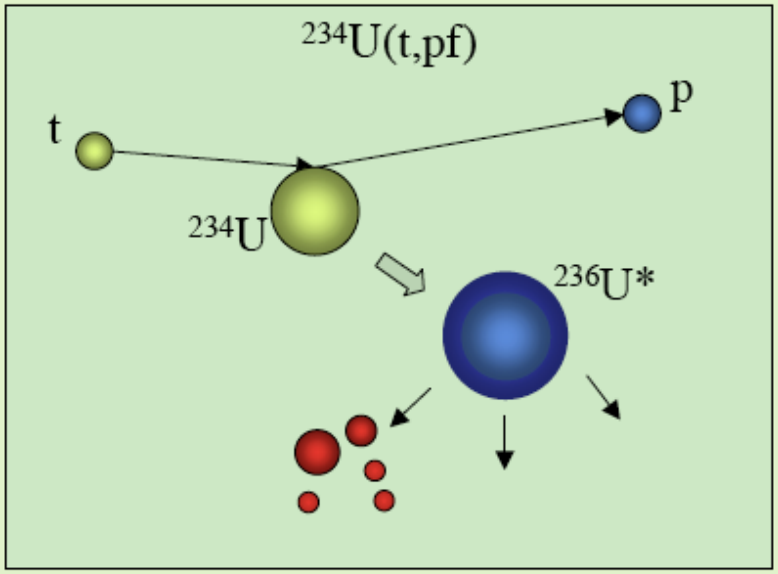


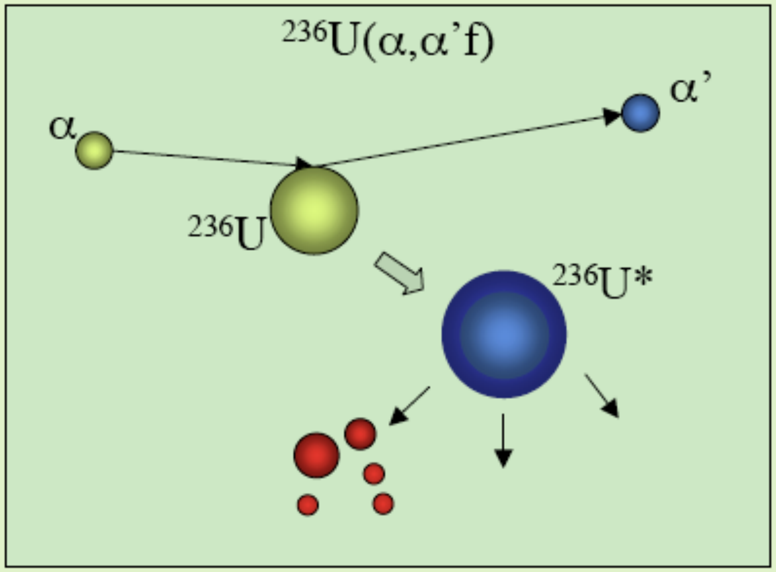
The Surrogate Nuclear Reactions approach combines theory and measurements to determine cross sections of compound-nuclear reactions that are difficult/ impossible to measure directly.

The Surrogate Idea - examples



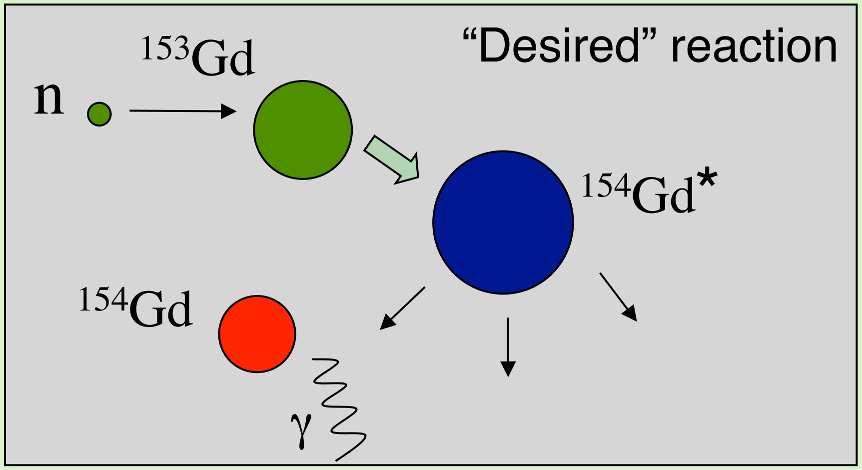
Various direct-reaction mechanisms can be employed to create the compound nucleus of interest.

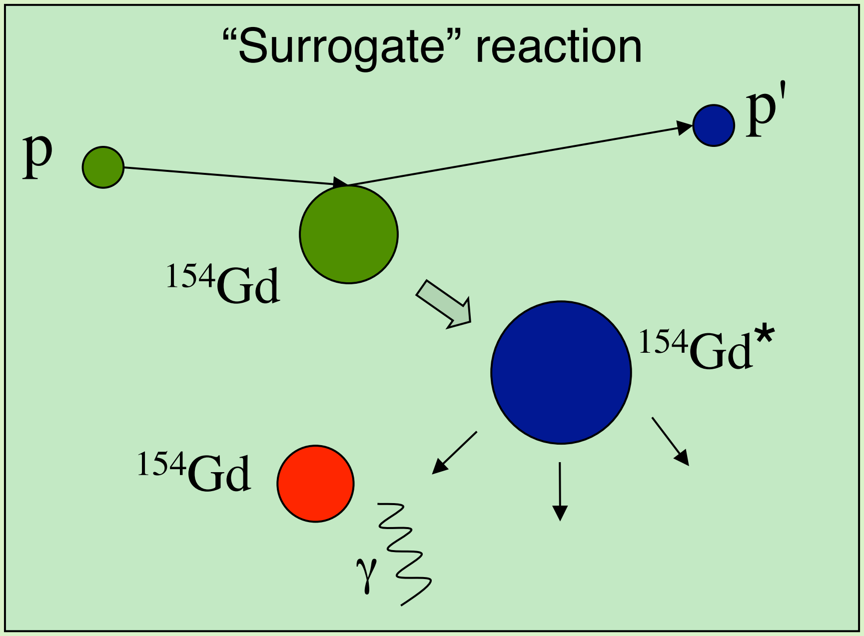




The Surrogate Idea - examples

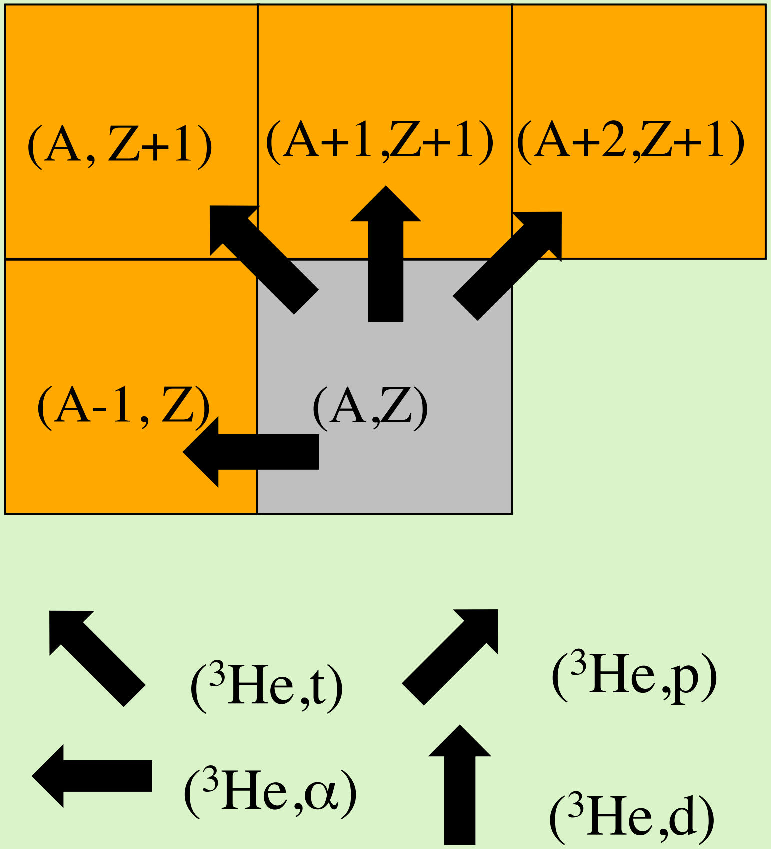
Different types of compound-nuclear decays can be considered.





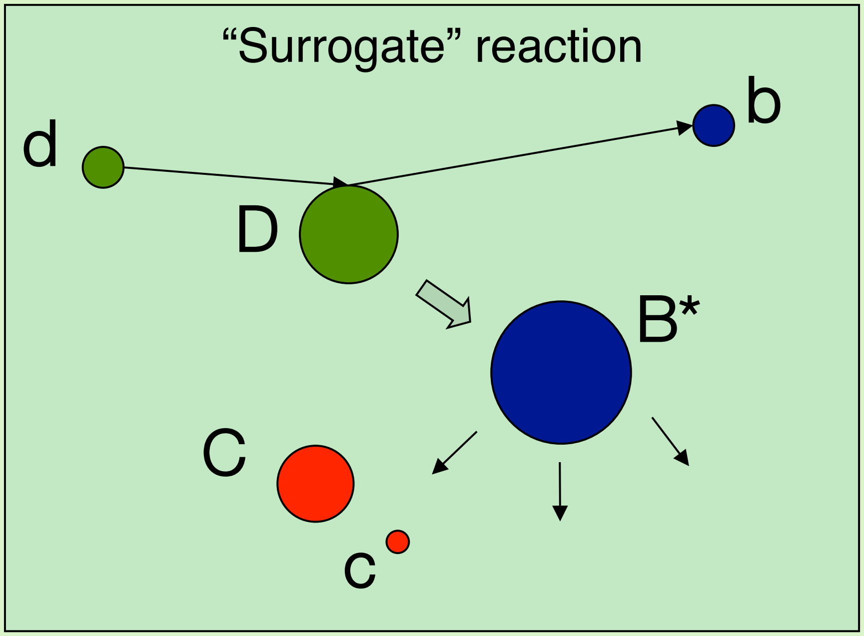
The Surrogate Idea

One experiment can be used to determine several cross sections:



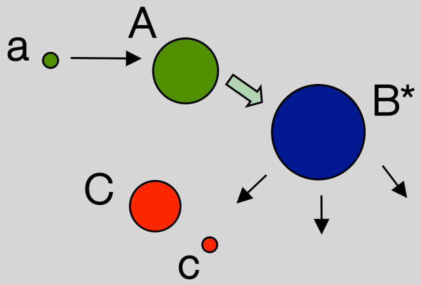
A Surrogate measurement with fixed beam energy can be used to probe the desired cross section for a range of energies:

For fixed beam energy E_d, the CN can be produced at various excitation energies



Simple Weisskopf-Ewing (WE) description

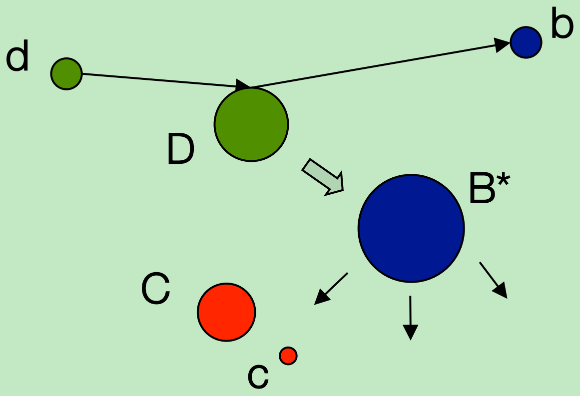
"Desired" reaction:



Weisskopf-Ewing description of the "desired" reaction:

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

"Surrogate" measurement:



Weisskopf-Ewing expression for the "Surrogate" measurement:

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

Cross section for the desired reaction:

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

WE applications to (n,f) reactions

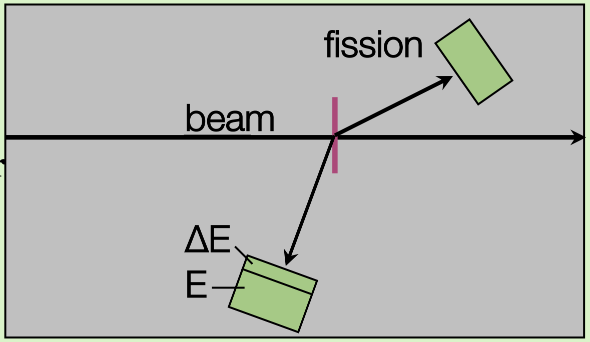
Early Surrogate work in the WE limit

Cramer and Britt

Nucl. Sci. Eng. 41(1970)177

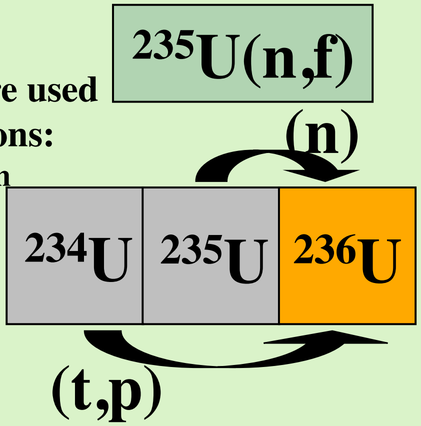
LANL experiment to study fission barrier

- 18 MeV triton beam
- charged-particle detector at 140°, $\Delta E \approx 120$keV
- 8 fission detectors in the reaction plane
- $P_f = 2\pi/\Delta\Omega$ x N(t,pf)/N(t,p)



Fission probabilities P_f were used to estimate (n,f) cross sections:

- $\sigma^{CN}_{(n+A)}(E)$ was obtained from an optical-model calculation
- $\sigma_{(n,f)}(E) = \sigma^{CN}_{(n+A)}(E) \cdot P_f(E)$



Results

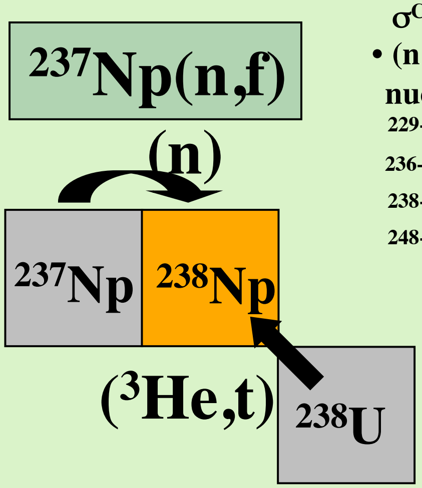
- (n,f) cross section estimates for 7 nuclei: ^{231}Th, ^{233}Th, ^{235}U, ^{237}U, ^{239}U, ^{241}Pu, ^{243}Pu
- Comparison with available direct measurements for ^{235}U and ^{241}Pu showed reasonable agreement above $E_n \approx 1$ MeV
- Uncertainties: 10% for P_f, 5-20% for $\sigma^{CN}_{(n+A}$, 5-20% for angular-momentum differences between the desired and Surrogate reactions

Britt and Wilhelmy

Nucl. Sci. Eng. 72(1979)222

(^{3}He,d) and (^{3}He,t) experiments:

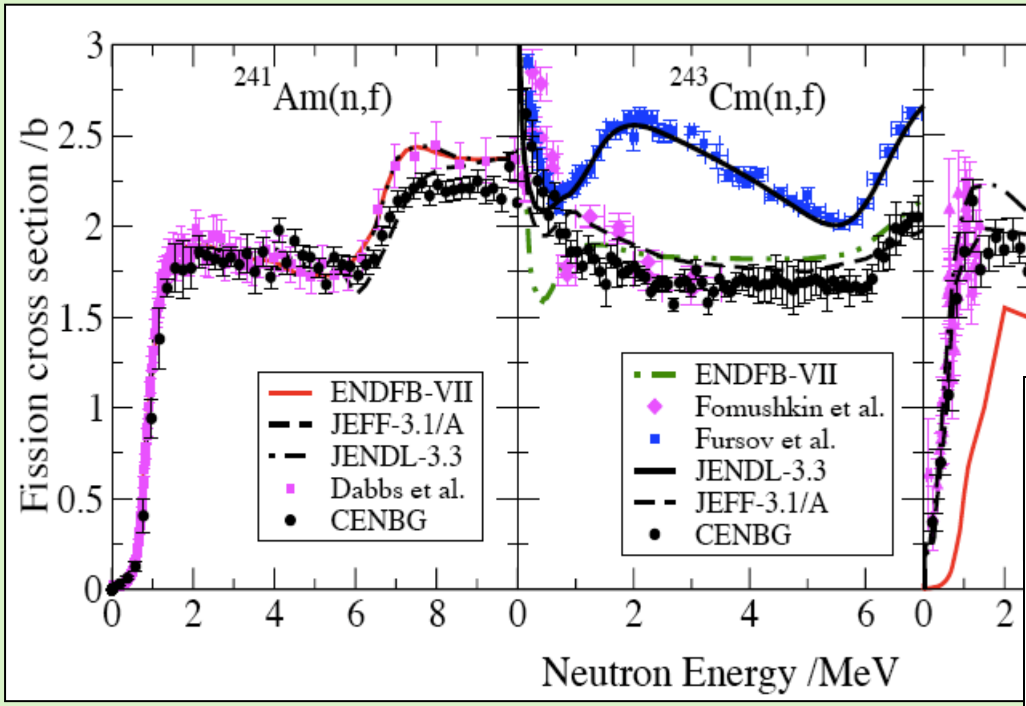
- various actinide targets
- same procedure as before
- additional simplification: $\sigma^{CN}_{(n+A)}(E) = 3.1$ b = const
- (n,f) cross section estimates for 34 nuclei for $E_n \approx 0.5$-6 MeV: $^{229\text{-}232}$Pa, ^{230,231}U, $^{232\text{-}238}$Np, $^{236\text{-}237}$Pu, $^{238\text{-}244}$Am, $^{240\text{-}243}$Cm, $^{244\text{-}248}$Bk, $^{248\text{-}250}$Es

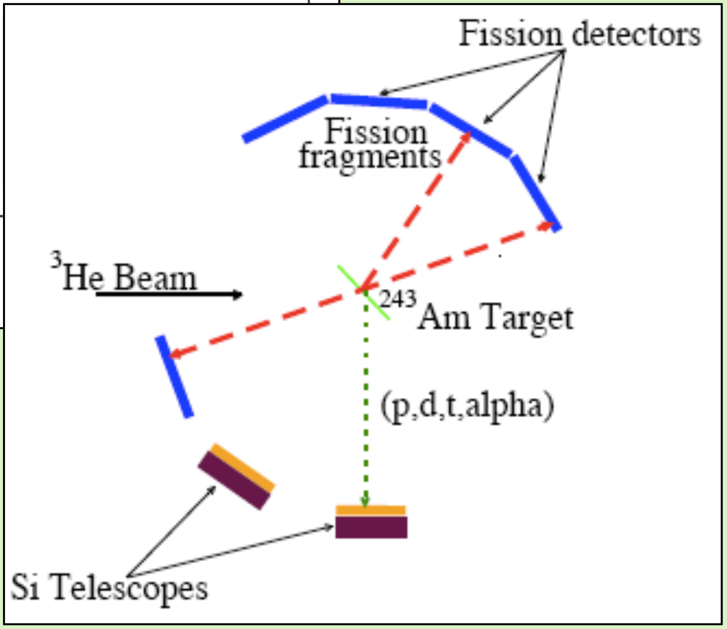


Results

- Essentially reasonable agreement with directly measured cross sections, where available
- Uncertainties similar to those of the earlier work

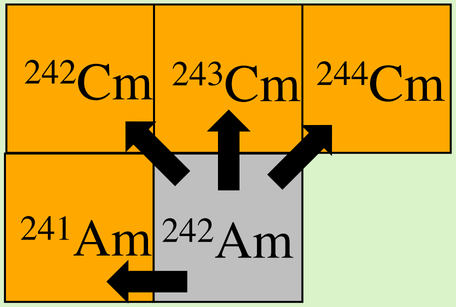
Results from CENBG collaboration





Jurado *et al.*, CENBG
AIP Conf. Proc. **1005**(2008)90

Experiment at IPN Orsay



^{242}Cm ^{243}Cm ^{244}Cm

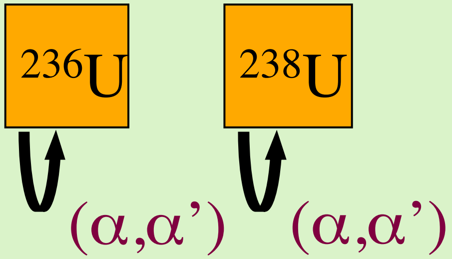
^{241}Am ^{242}Am

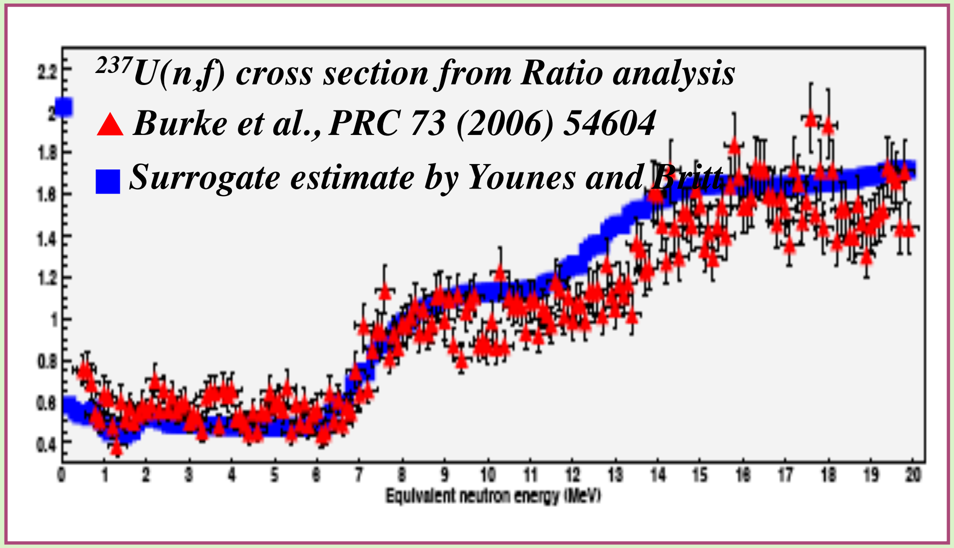
(n,f) cross sections extracted in Weisskopf-Ewing approximation are consistent with direct measurement, able to resolve controversies and extend range of data.

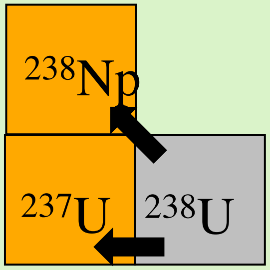
Results from the STARS/LiberACE collaboration

Burke et al., PRC 73 (2006) 054604

- (α,α'f) on ^{238}U and ^{236}U



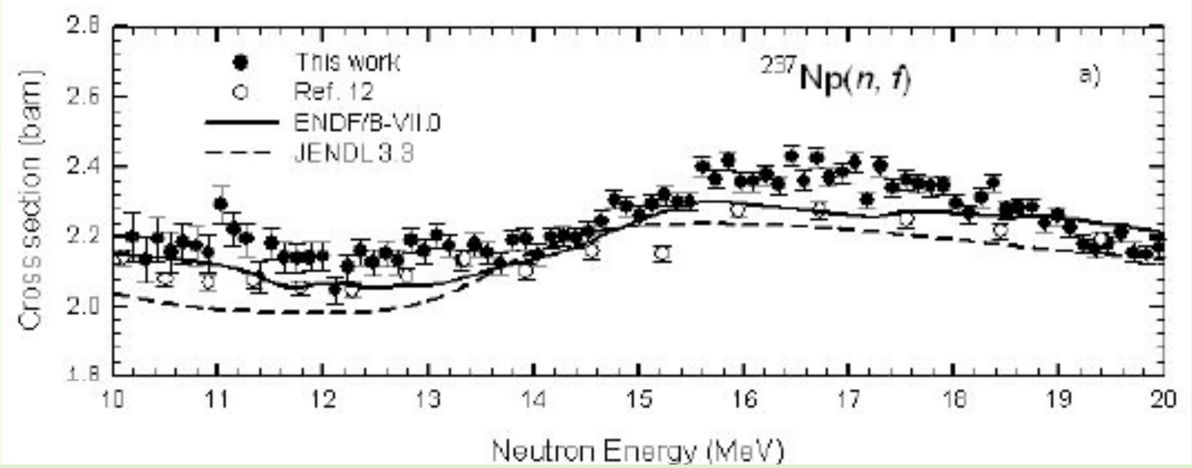




$$\sigma_{(n,f)} = \sigma^{CN}_{(n+A)} \cdot P_f$$

S. Basunia *et al.*
NIMB **267** (2009) 1899

- Charge-exchange ^{238}U(^{3}He,t)



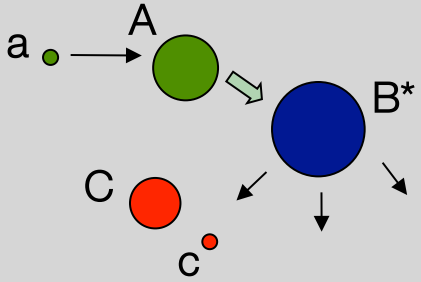
(n,f) cross sections extracted in Weisskopf-Ewing and Ratio approximations are consistent with each other and with direct measurements

Weisskopf-Ewing Approximation: Ignoring spin effects

The Weisskopf-Ewing (WE) 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:

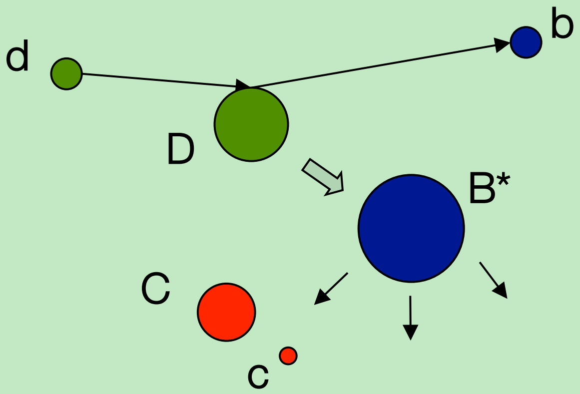
$$G^{CN}_{\chi}(E,J,\pi) \text{ ------> } \mathcal{G}^{CN}_{\chi}(E)$$

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:

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

Reduction of Hauser-Feshbach to Weisskopf-Ewing

$$\frac{d\sigma_{\alpha\chi}^{HF}}{dE_{\chi}} = \pi\lambda_{\alpha}^{2}\sum_{J\pi}\omega_{\alpha}^{J}\sum_{lsl's'I'}\frac{T_{\alpha ls}^{J}T_{xl's'}^{J}\rho_{I'}(U)}{\sum'_{x''l''s''}T_{x''l''s''}^{J} + \sum_{x''l''s''}\int T_{x''l''s''}^{J}(E_{\chi''})\rho_{I''}(U'')dE_{\chi''}}$$

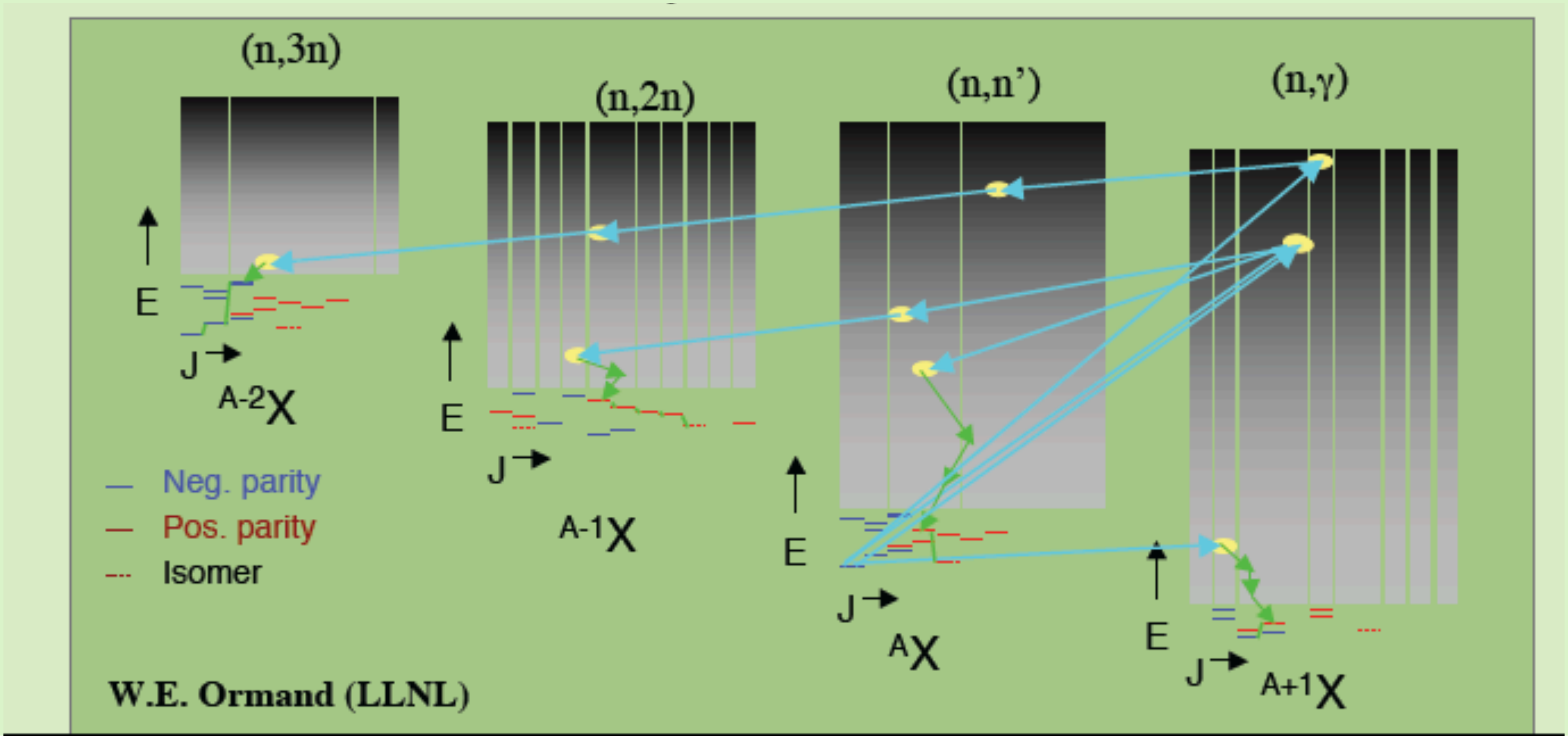
WE limit valid when:

- Decay channels are dominated by integrals over the level density.
- Width fluctuations are negligible.
- Transmission coefficients T associated with available exit channels are independent of spin of states reached.
- Level densities in available channels are independent of parity and dependence on spin I has the form ~(2I+1)

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

Reduction of Hauser-Feshbach to Weisskopf-Ewing

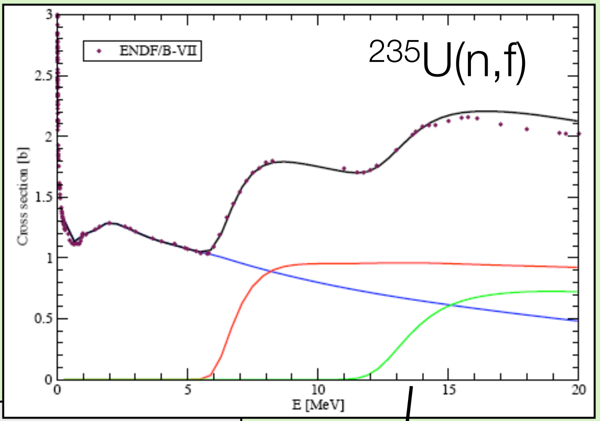
$$\frac{d\sigma^{HF}_{\alpha\chi}}{dE_{\chi}} = \pi\lambda^2_{\alpha}\sum_{J\pi}\omega^J_{\alpha}\sum_{lsl's'I'}\frac{T^J_{\alpha ls}T^J_{\chi l's'}\rho_{I'}(U)}{\sum'_{x''l''s''}T^J_{x''l''s''}+\sum_{x''l''s''}\int T^J_{x''l''s''}(E_{\chi''})\rho_{I''}(U'')dE_{\chi''}}$$

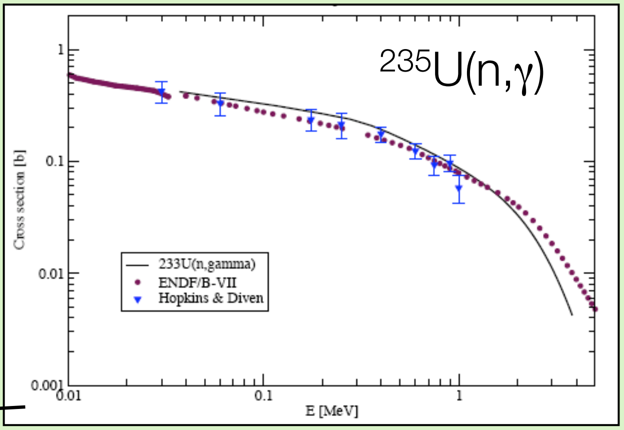


Testing the WE approximation for (n,γ)

Testing the WE approximation….

J. Escher and F.S. Dietrich,
PRC 74 (2006) 054601
PRC 81 (2010) 024612





Simulation procedure:

1. Determine "reference cross sections" with a statistical-model calculation.

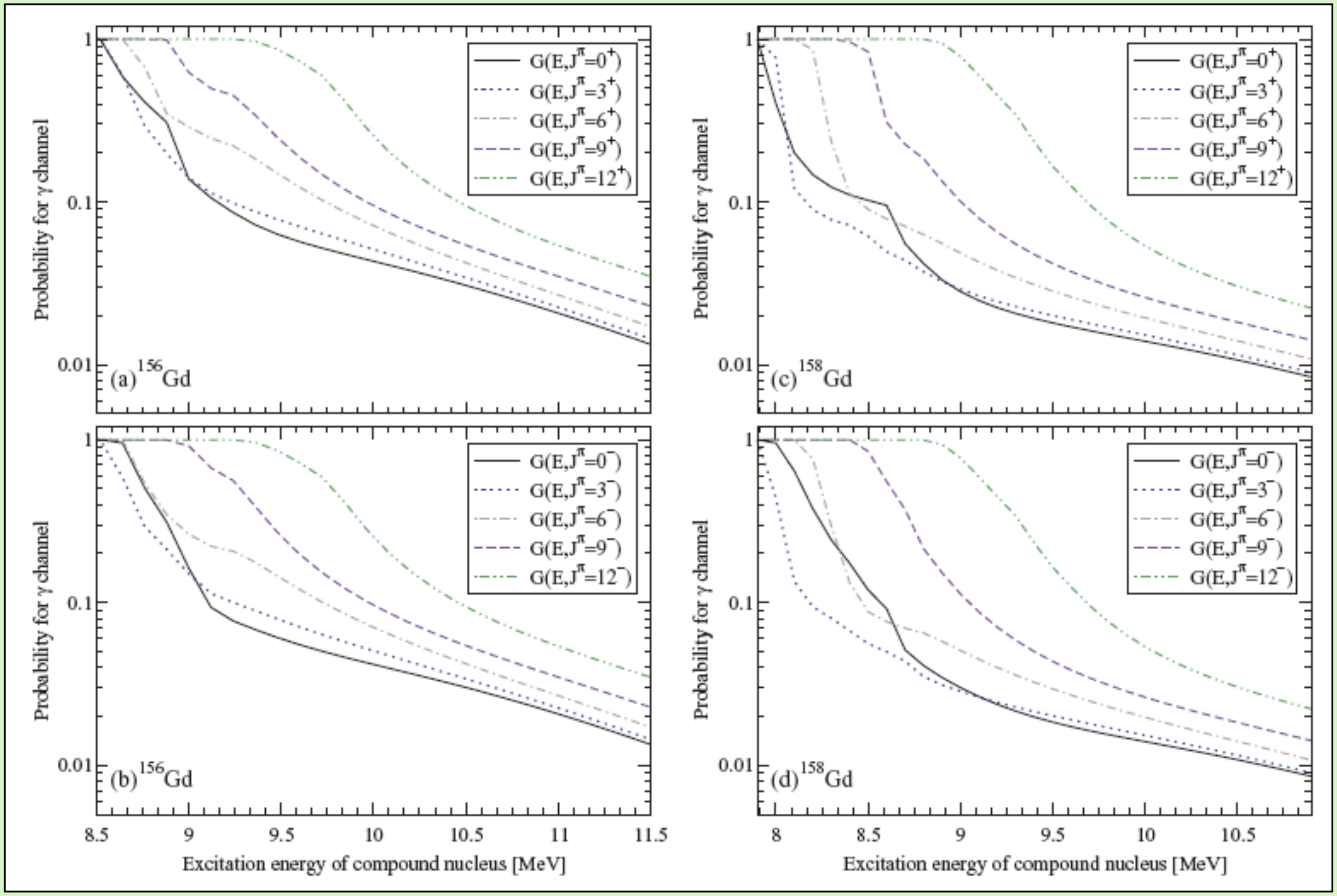
2. Extract gamma decay probabilities for each (J,π) as function of E_n.

$G^{CN}_{\gamma}(E,J,\pi)$ or $G^{CN}_{f}(E,J,\pi)$

Case 3: (n,γ) reactions for rare-earth targets

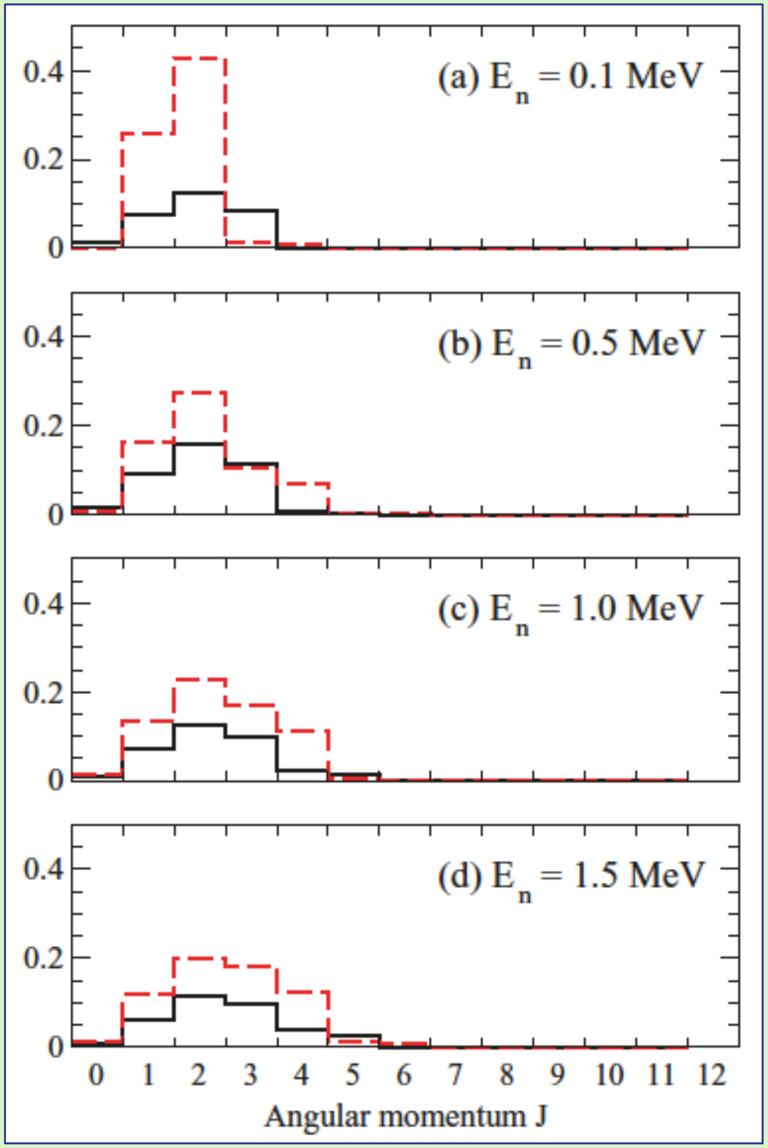
Probability G(E,J,π) that a ^{156}Gd state with excitation energy E=S_n+E_n and given J^π value decays via γ-emission

J. Escher and F.S. Dietrich, PRC 81 (2010) 024612



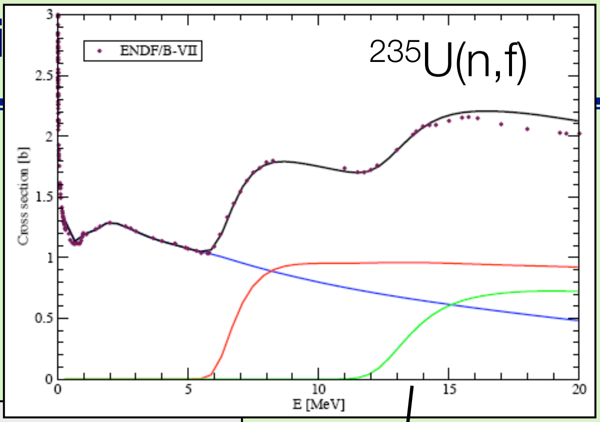
Case 3: (n,γ) reactions for rare-earth targets

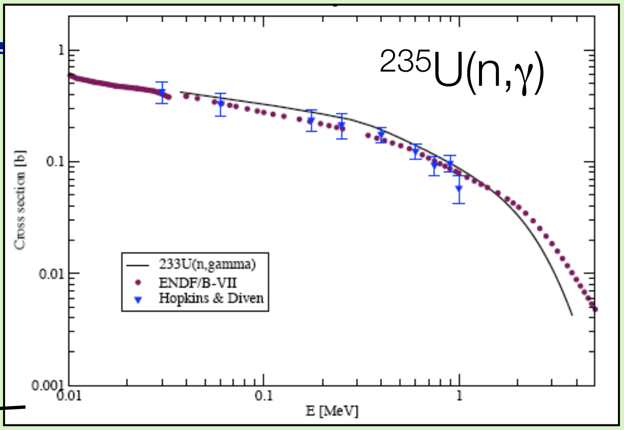
Neutron-induced spin-parity distributions n+^{155}Gd



Testing the WE approxi

J. Escher and F.S. Dietrich,
PRC 74 (2006) 054601
PRC 81 (2010) 024612



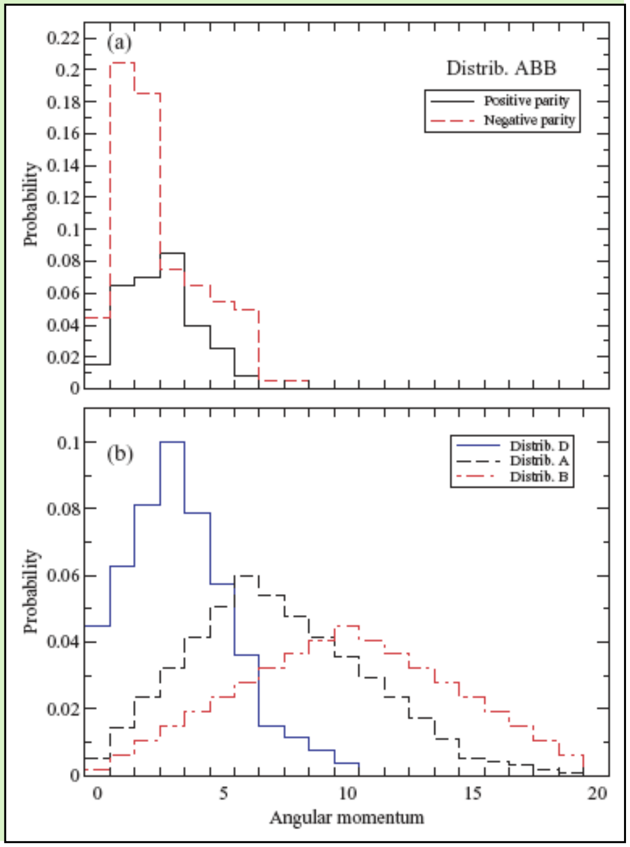


Simulation procedure:

1. Determine “reference cross sections” with a statistical-model calculation.
2. Extract gamma decay probabilities for each (J,π) as function of E_n.
3. Simulate a Surrogate experiment and carry out an analysis in the WE limit.
4. Repeat 1-3 to carry out Ratio analysis.

$G^{CN}_{\gamma}(E,J,\pi)$

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

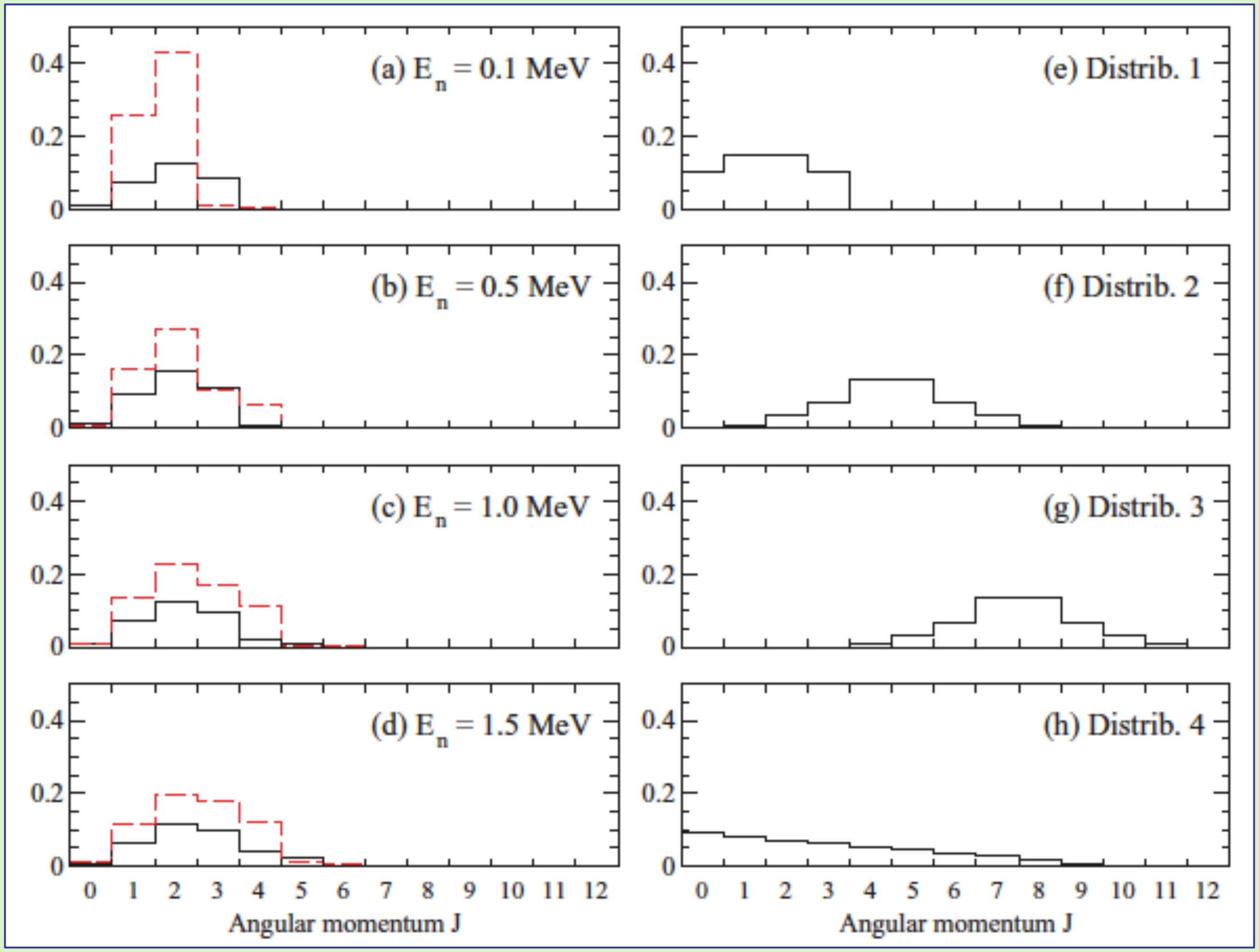


Case 3: (n,γ) reactions for rare-earth targets

Neutron-induced spin-parity distributions n+^{155}Gd

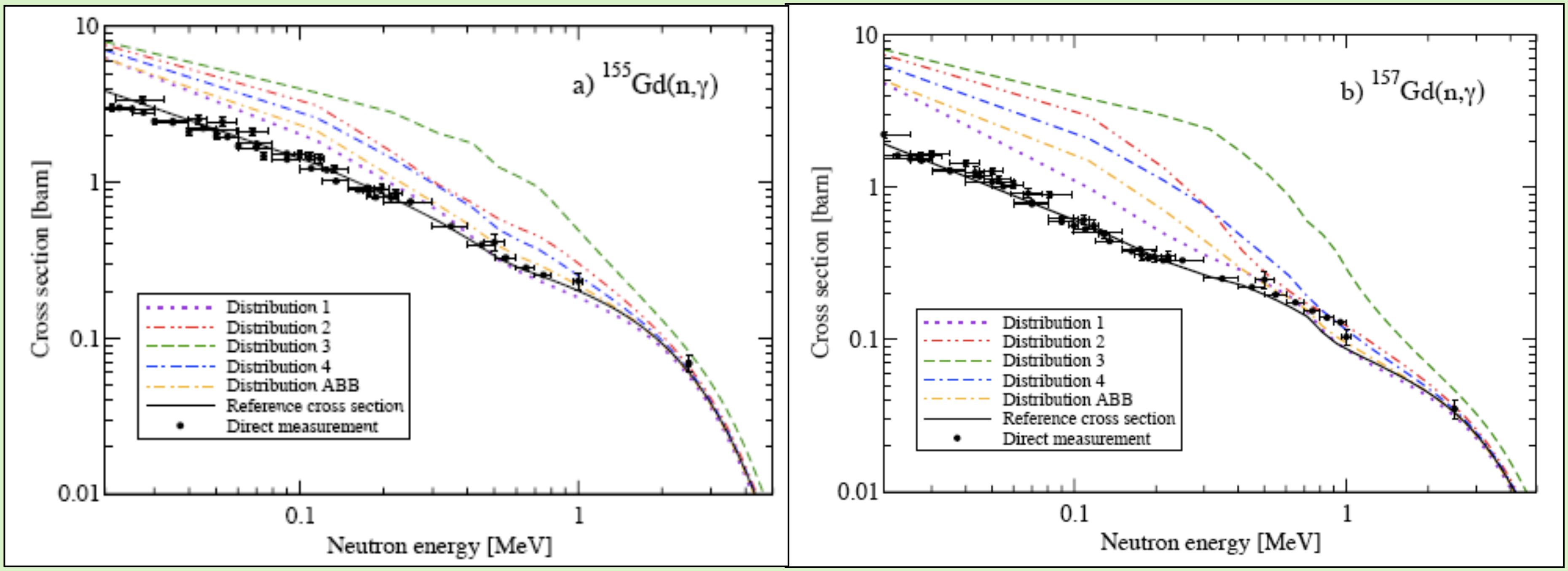
Schematic spin-parity distributions for simulations

J. Escher and F.S. Dietrich, PRC 81 (2010) 024612



(n,γ) reactions for rare-earth targets

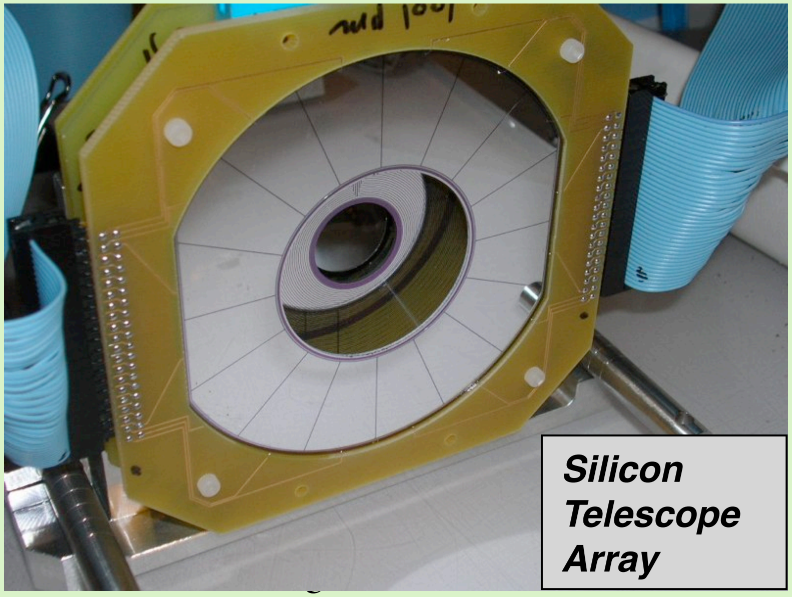
Cross sections extracted from simulated Surrogate observables



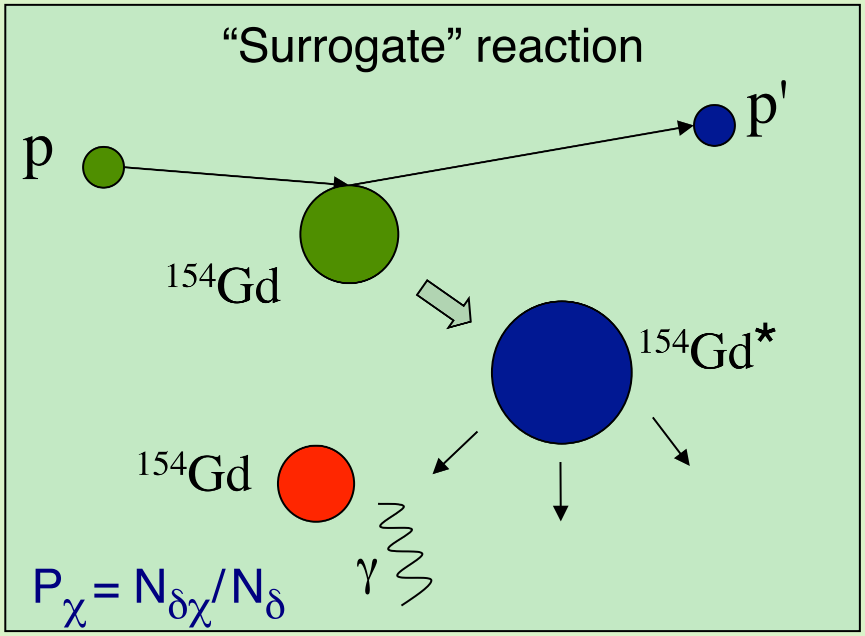
J. Escher and F.S. Dietrich, PRC 81 (2010) 024612

Inelastic p scattering on ^{154,156,158}Gd at STARS/LiBerACE

Target chamber and Ge detectors



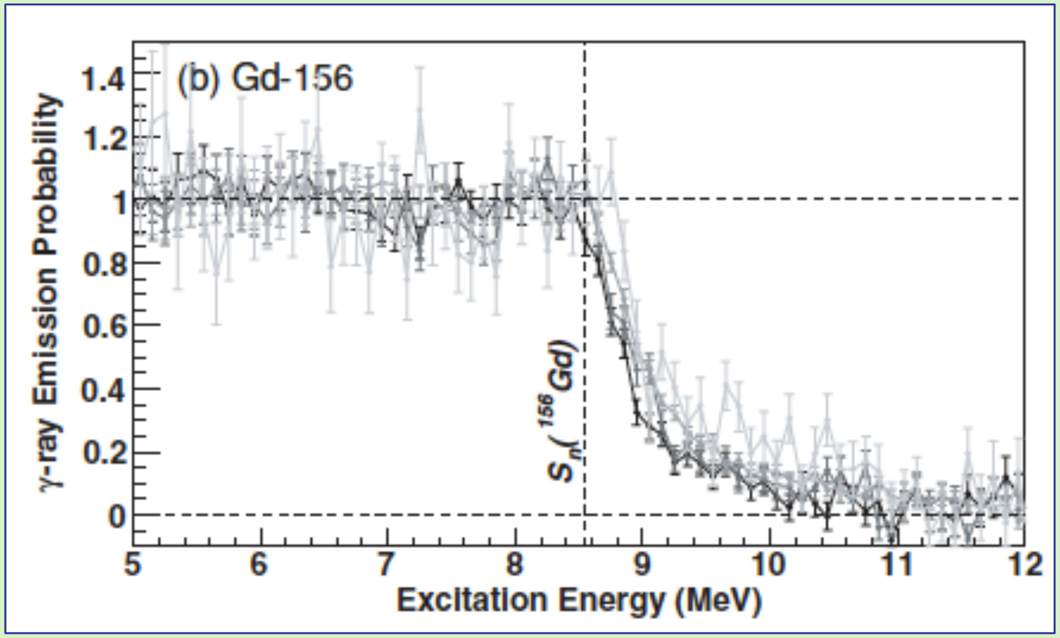
Silicon Telescope Array



N. Scielzo et al., PRC 81 (2010) 034608

Measurements of ^{154,156,158}Gd(p,p'γ) with with E_p=22 MeV. Goal: determine the ^{153,155,157}Gd(n,γ) cross sections -- two cross sections are known, can provide tests, one is an unknown cross section of interest to astrophysics.

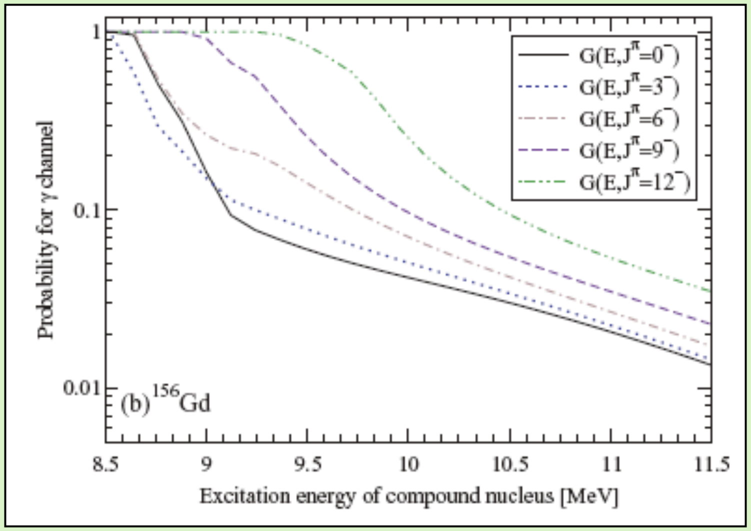
^{156}Gd decay following excitation by inelastic p scattering



Measured γ-ray emission probability for lowest 4 γ-rays in ^{156}Gd Normalized to 1 below S_n

N. Scielzo et al., PRC 81 (2010) 034608

J. Escher and F.S. Dietrich, PRC 81 (2010) 024612

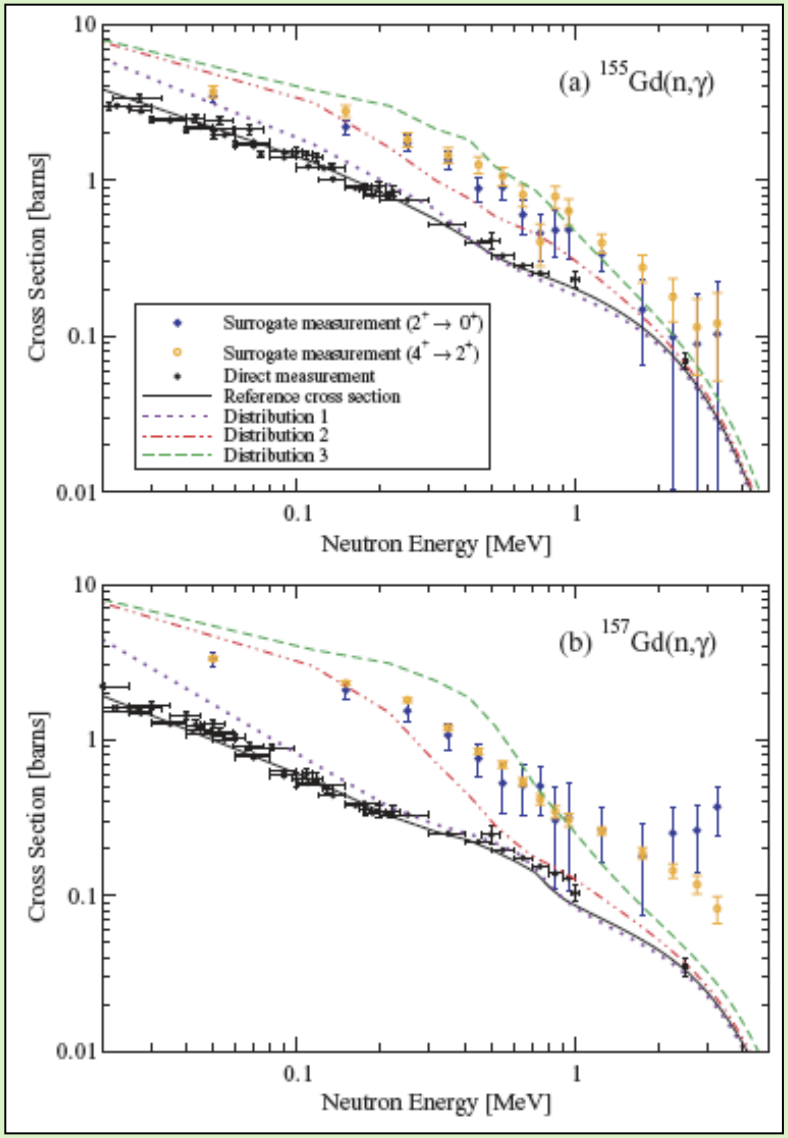


Calculated probability G(E,J,π) that a ^{156}Gd state with excitation energy $E=S_n+E_n$ and given J^π decays via γ-emission

Indication that different transitions sample different parts of the cascade.

^{155,157}Gd(n,γ) cross sections from WE analysis

Extracted ^{155}Gd(n,γ) cross section compared to reference cross section and Surrogate simulations



The WE approximation gives results roughly within a factor of 2-5 of the expected cross section.

More work is needed to obtain cross sections to better than a factor of two.

N. Scielzo et al., PRC 81 (2010) 034608

The Surrogate Ratio approach

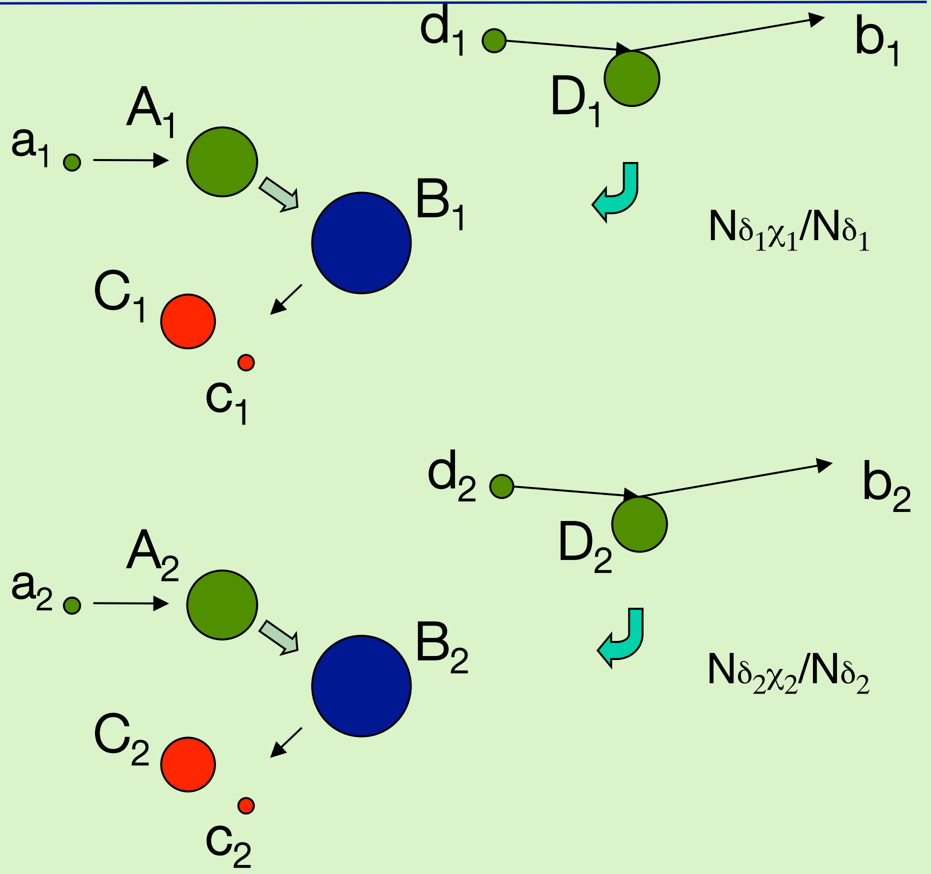
Goal: Determine experimentally

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

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

$= N_{\delta_1\chi_1}/N_{\delta_1}$

$\text{x } N_{\delta_2}/N_{\chi_2\delta_2}$



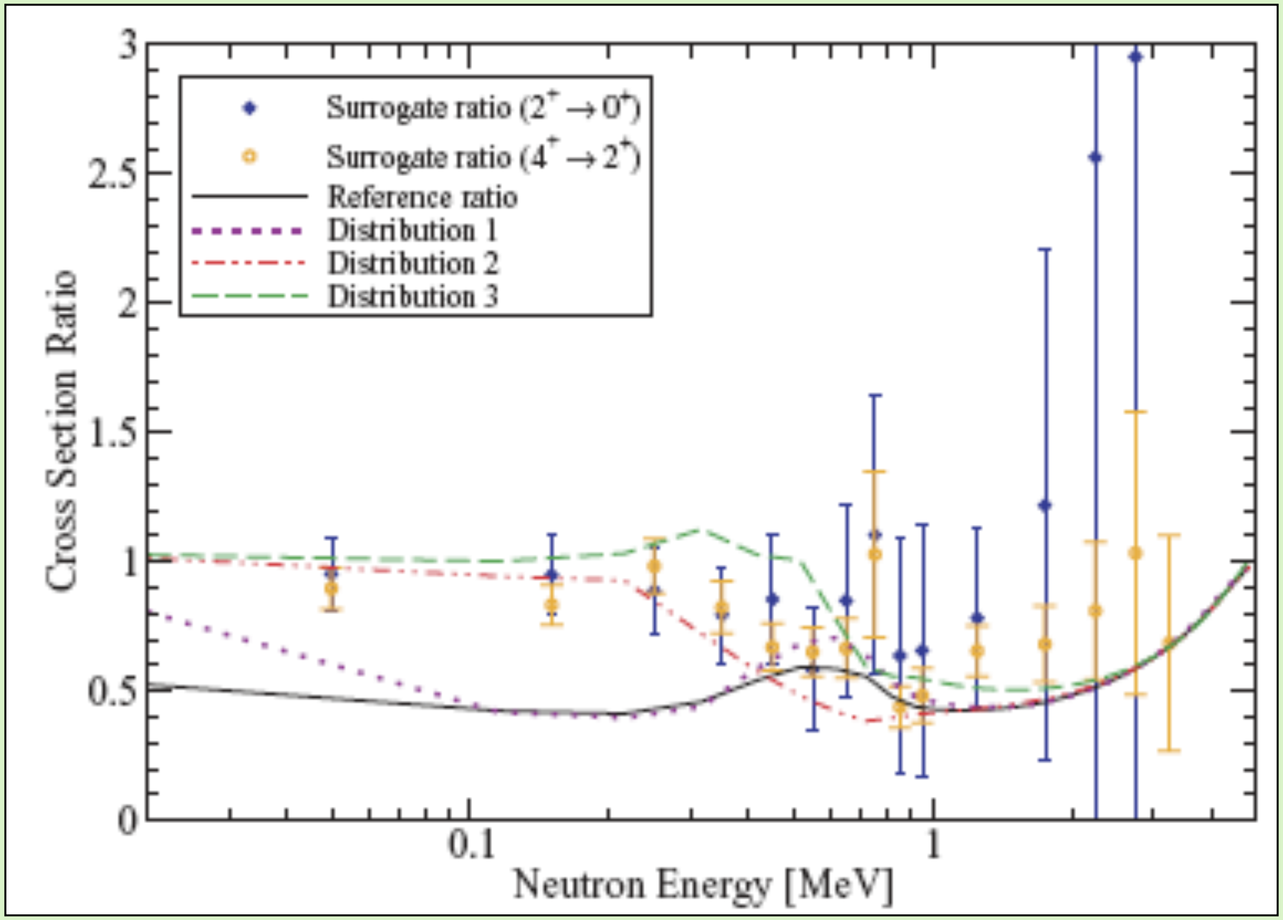
$N_{\delta_2}/N_{\delta_1}$ = const

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

Ratio method for ^{157}Gd(n,γ) / ^{155}Gd(n,γ)

Comparing ratio of extracted cross sections to ratios of reference cross sections and ratios of Surrogate simulations:



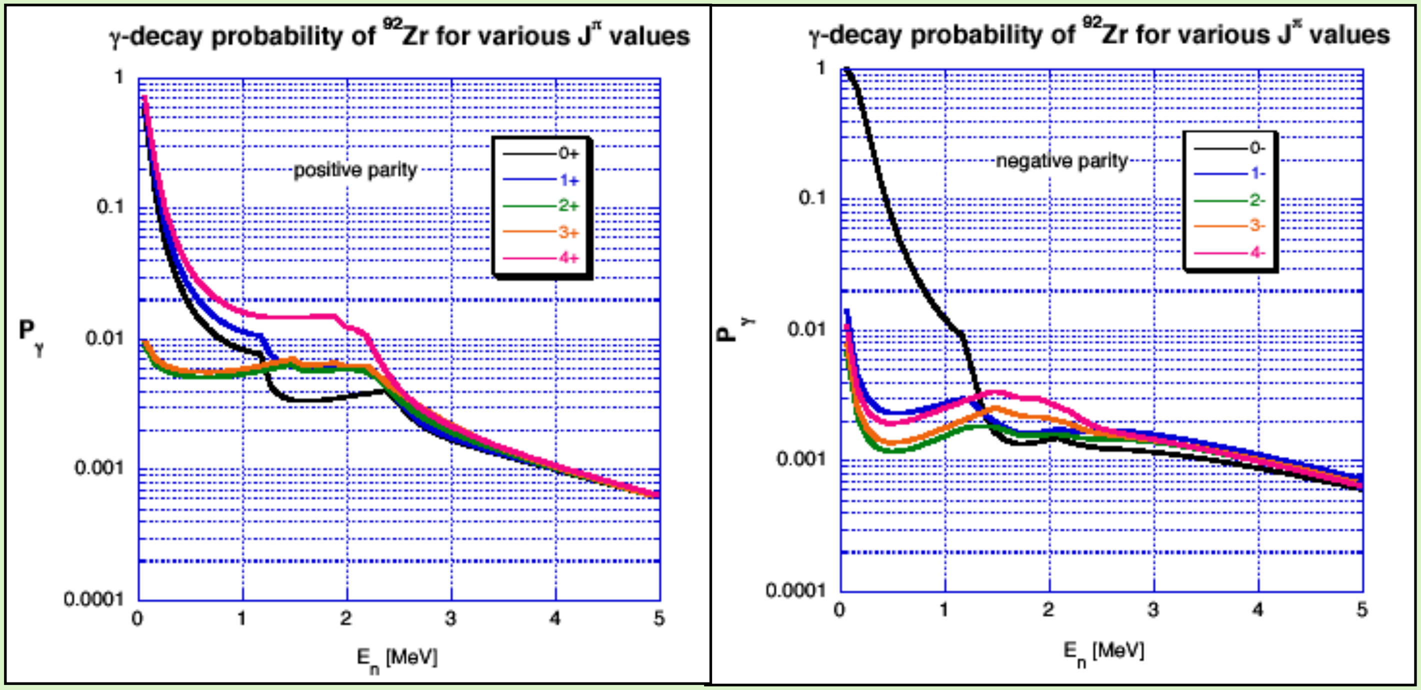
N. Scielzo et al.,
PRC 81 (2010)
034608

The Ratio approach reduces, but does not remove the discrepancies!

Other mass regions

Case 1: WE for (n,γ) reactions for near-spherical nuclei?

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

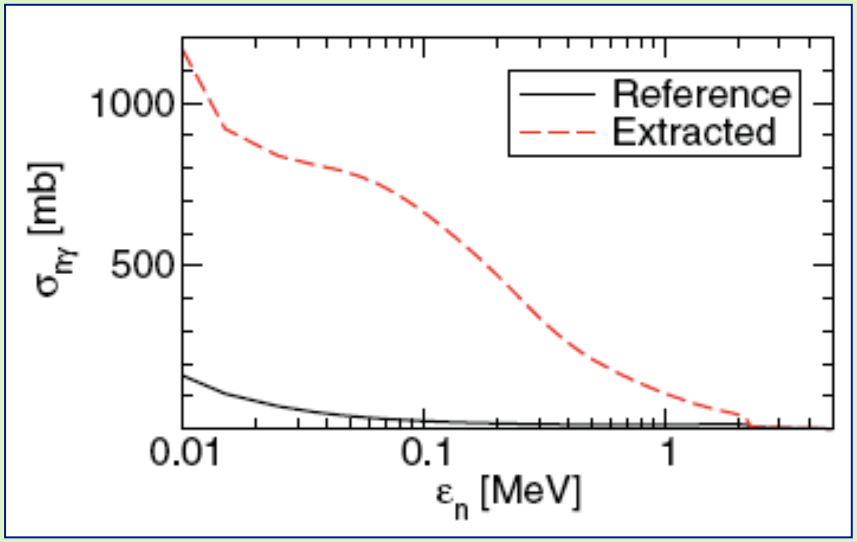


Shown is the probability (P_{γ}) that a ^{92}Zr state with excitation energy $E=S_n+E_n$ and given J^{π} value decays via γ-emission. S_n is the neutron separation energy in ^{92}Zr.

Forssen et al., PRC 75 (2007) 055807

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

WE is worse for (n,γ) reactions for near-spherical nuclei



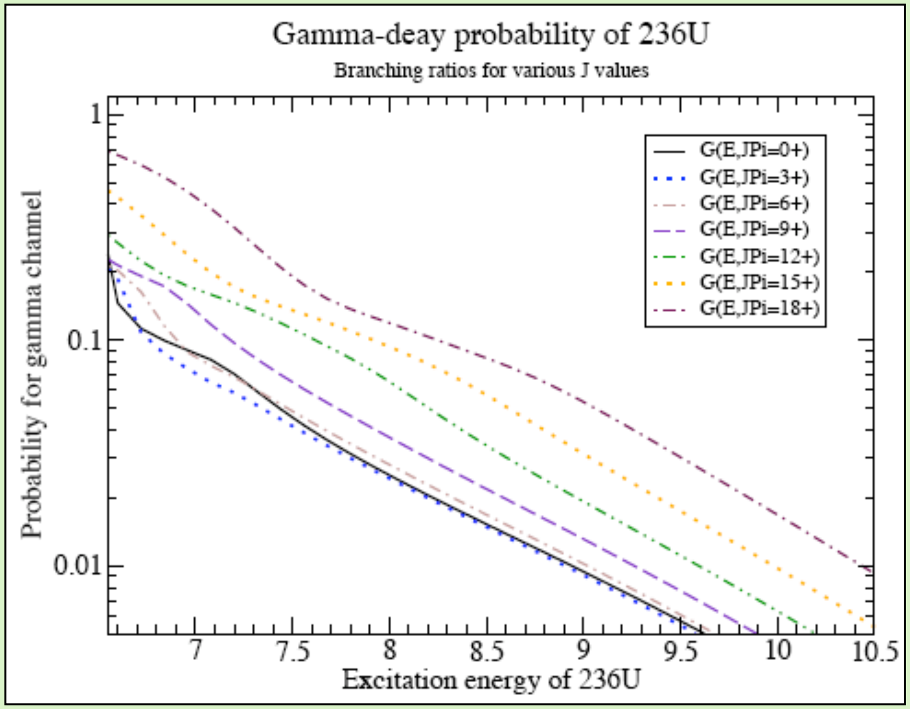
Forssen et al., PRC 75 (2007) 055807

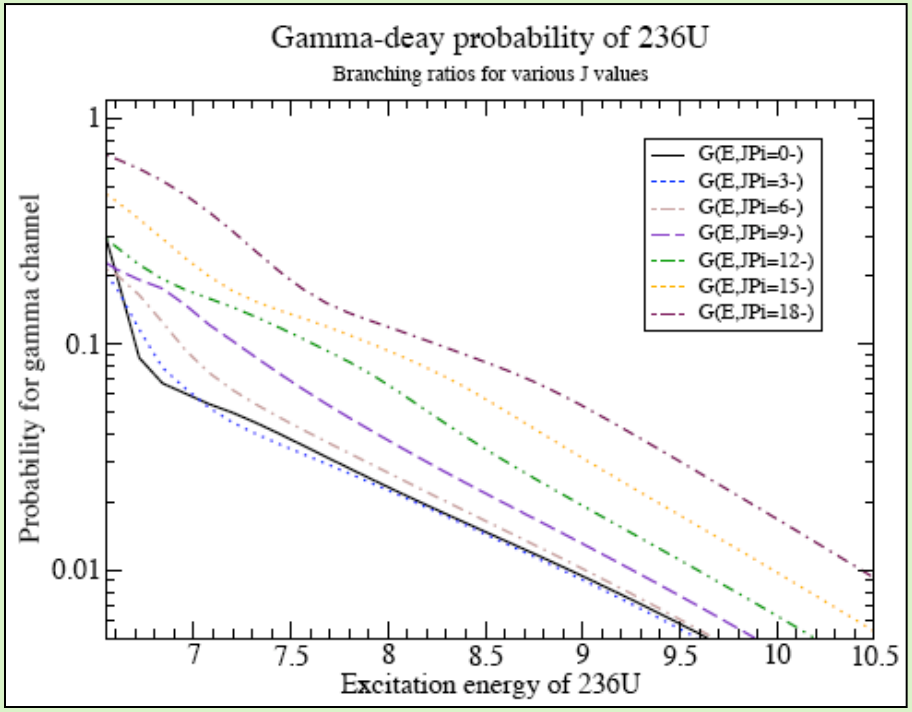
Simulated Surrogate WE analysis compared to ^{91}Zr(n,γ) reference cross section

Weisskopf-Ewing analysis does not work here!

Case 2: (n,γ) reactions for actinide targets

J. Escher and F.S. Dietrich, PRC 81 (2010) 024612



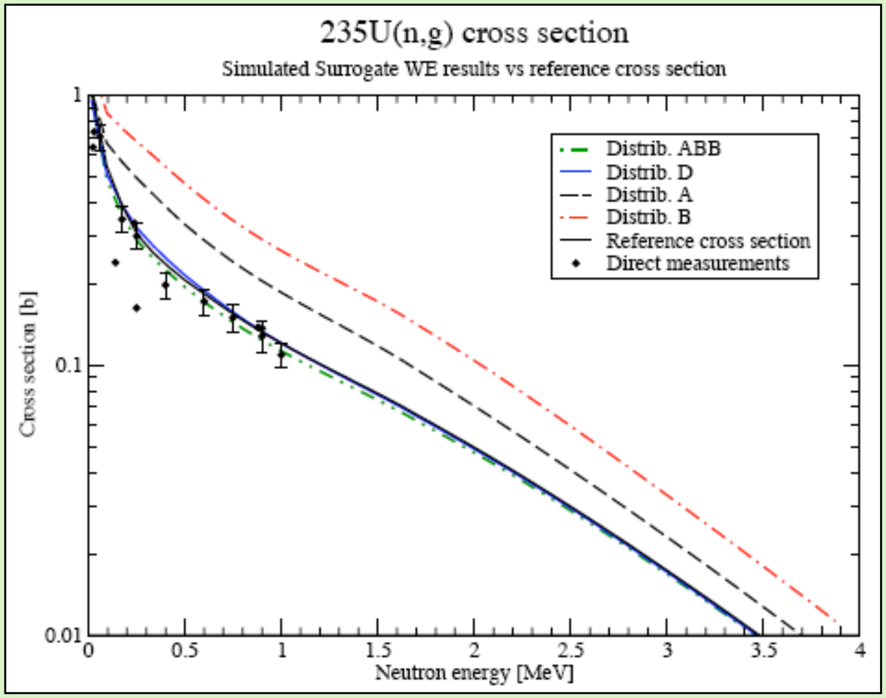


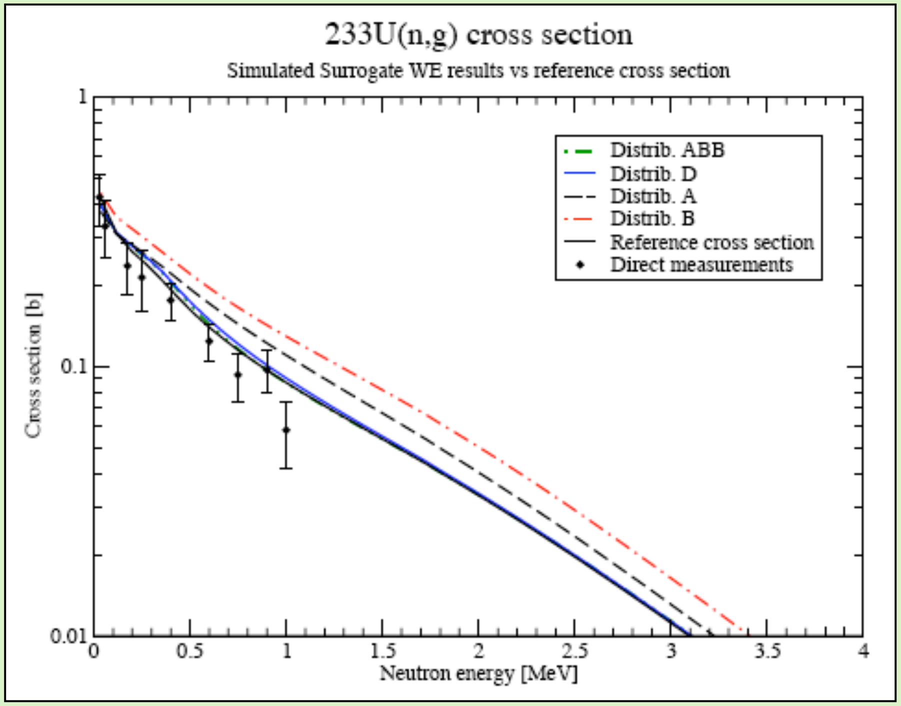
Probability G(E,J,π) that a ^{236}U state with excitation energy $E=S_n+E_n$ and given J^π value decays via γ-emission.

Case 2: (n,γ) reactions for actinides - Weisskopf-Ewing limit

Cross sections extracted from simulated Surrogate observables

J. Escher and F.S. Dietrich
PRC 81 (2010) 024612

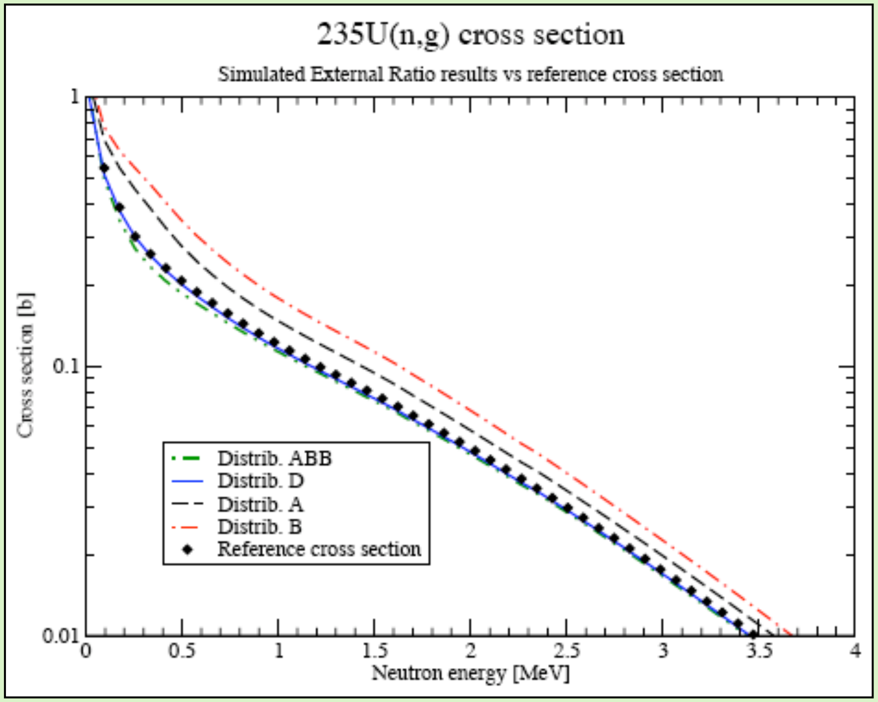


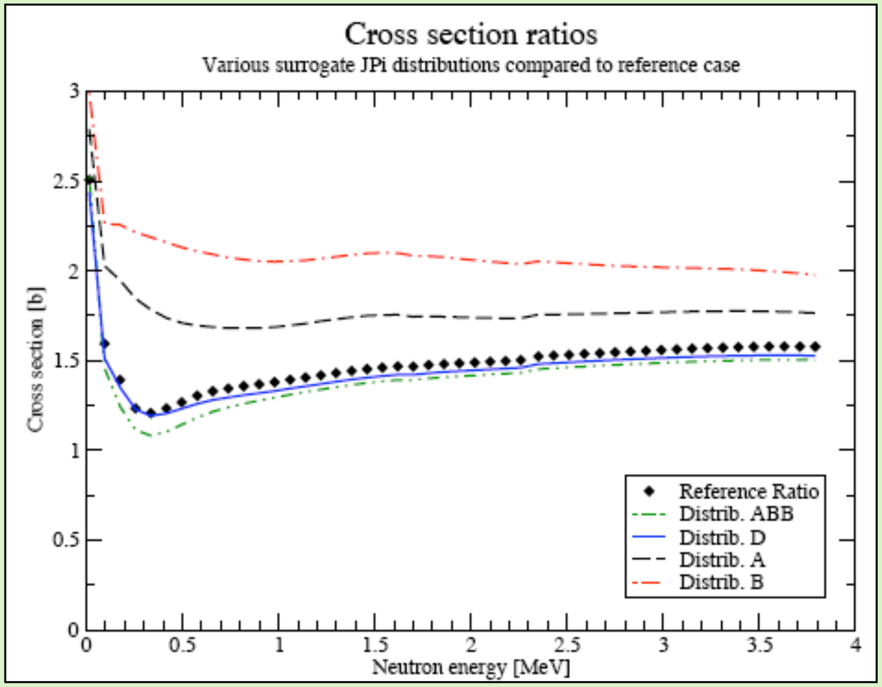


The WE limit may or may not work for (n,γ) cross sections.
Knowledge of J^{π} would be very helpful!

Case 2: (n,γ) reactions for actinides - External Surrogate Ratio

Cross section and cross section ratio extracted from simulated Surrogate observables





J. Escher and F.S. Dietrich
PRC 81 (2010) 024612

The Ratio approach yields some improvements.

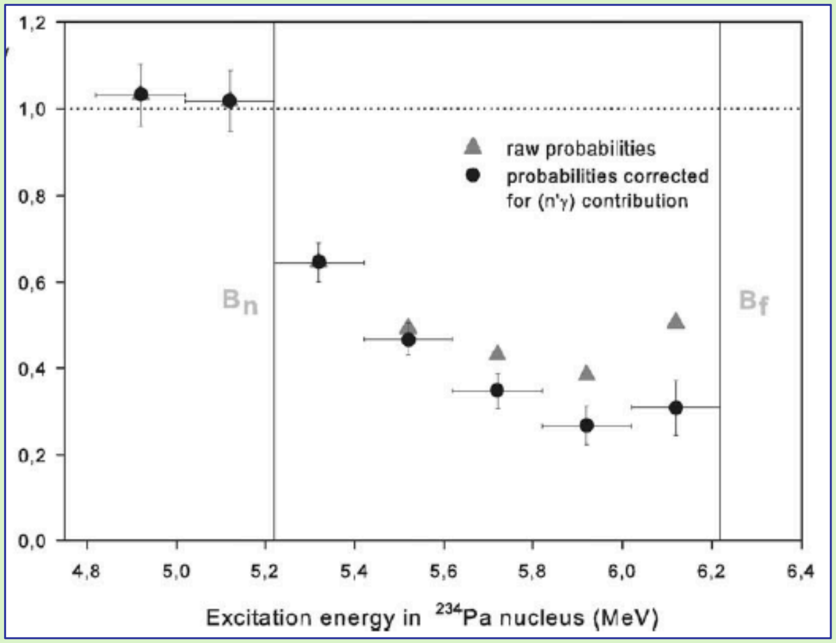
Challenges specific to (n,γ)

Detecting the γ channel

Considering some options:

- Most experiments gate on individual γ rays in the residual nucleus instead of determining the appropriate sum of γ rays
  -> need to account for portion of gamma cascade not seen
  -> correction depends on the CN spin distribution
  Additional spin dependence!

- Alternative: detecting the complete gamma cascade:
  -> better statistics
  -> 'contamination' from other γ sources, such
  as γ following n evaporation require corrections
  -> does not resolve the spin mismatch issue



Gamma probability for decay of ^{234}Pa following (3He,p)
S. Boyer *et al*.
NPA 775 (2006) 175

(n,γ) cross sections pose new challenges

Getting better cross section constraints from Surrogate data

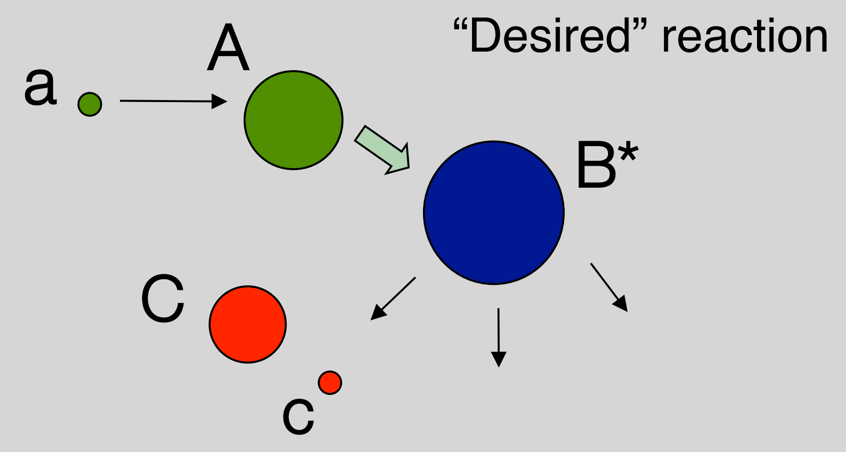
The Surrogate Idea - Formalism

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

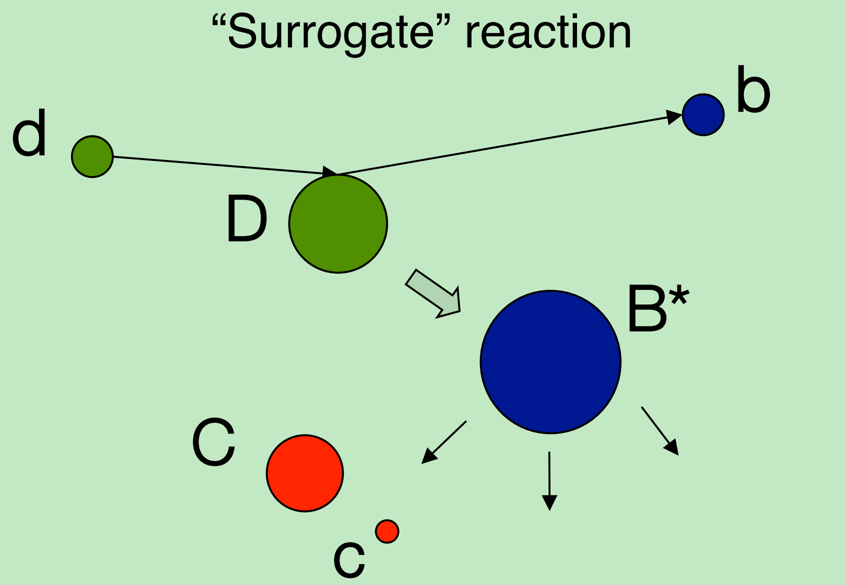


A Surrogate experiment gives

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

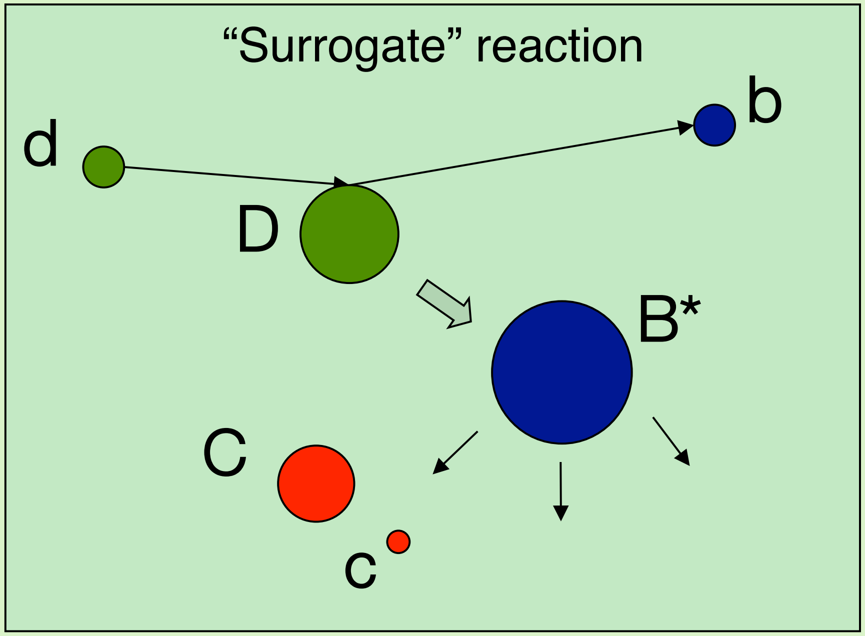
Preferred approach: calculate $F_{\delta}^{CN}(E,J,\pi)$, model CN decay, adjust HF parameters to reproduce measured $P_{\chi}(E)$, obtain G^{CN}_{χ}

Typical approach so far - *approximations:* assume (J,π)-independent G^{CN} and employ simplified formulae ("Weisskopf-Ewing" and "Surrogate Ratio" approaches)



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

Predicting compound-nuclear spin-parity distributions



Predicting compound-nuclear spin-parity distributions

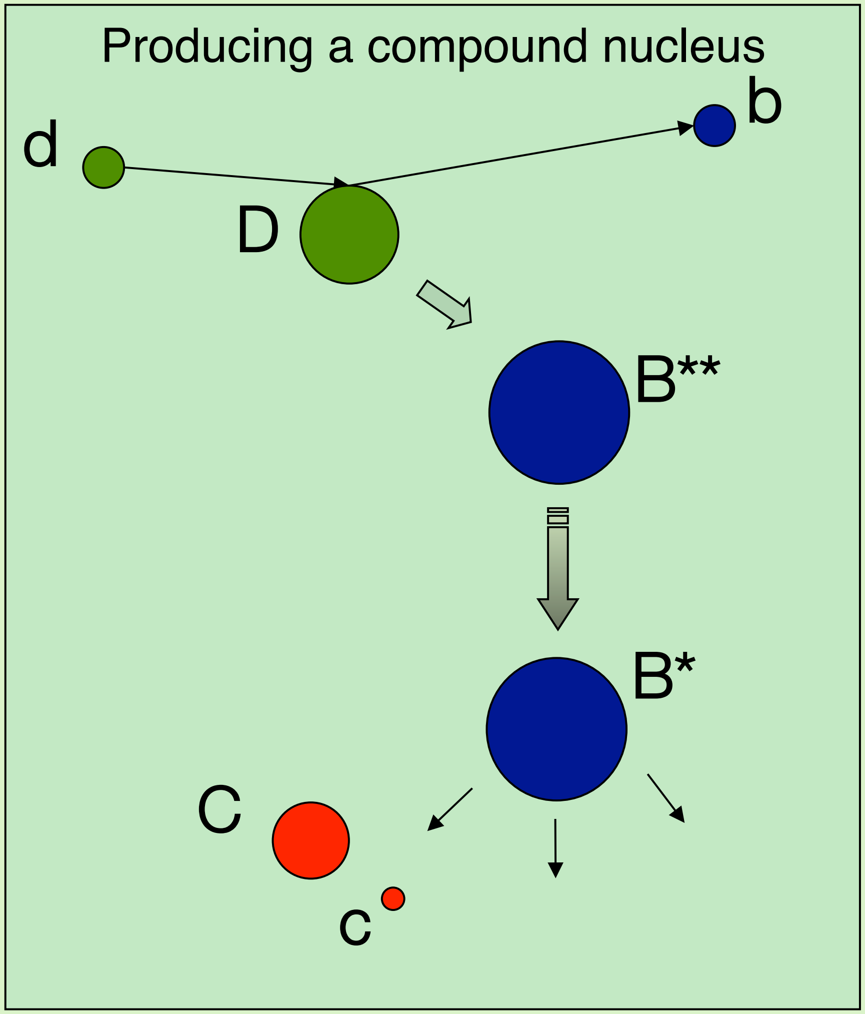
Formation of a highly excited nucleus in a direct reaction

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

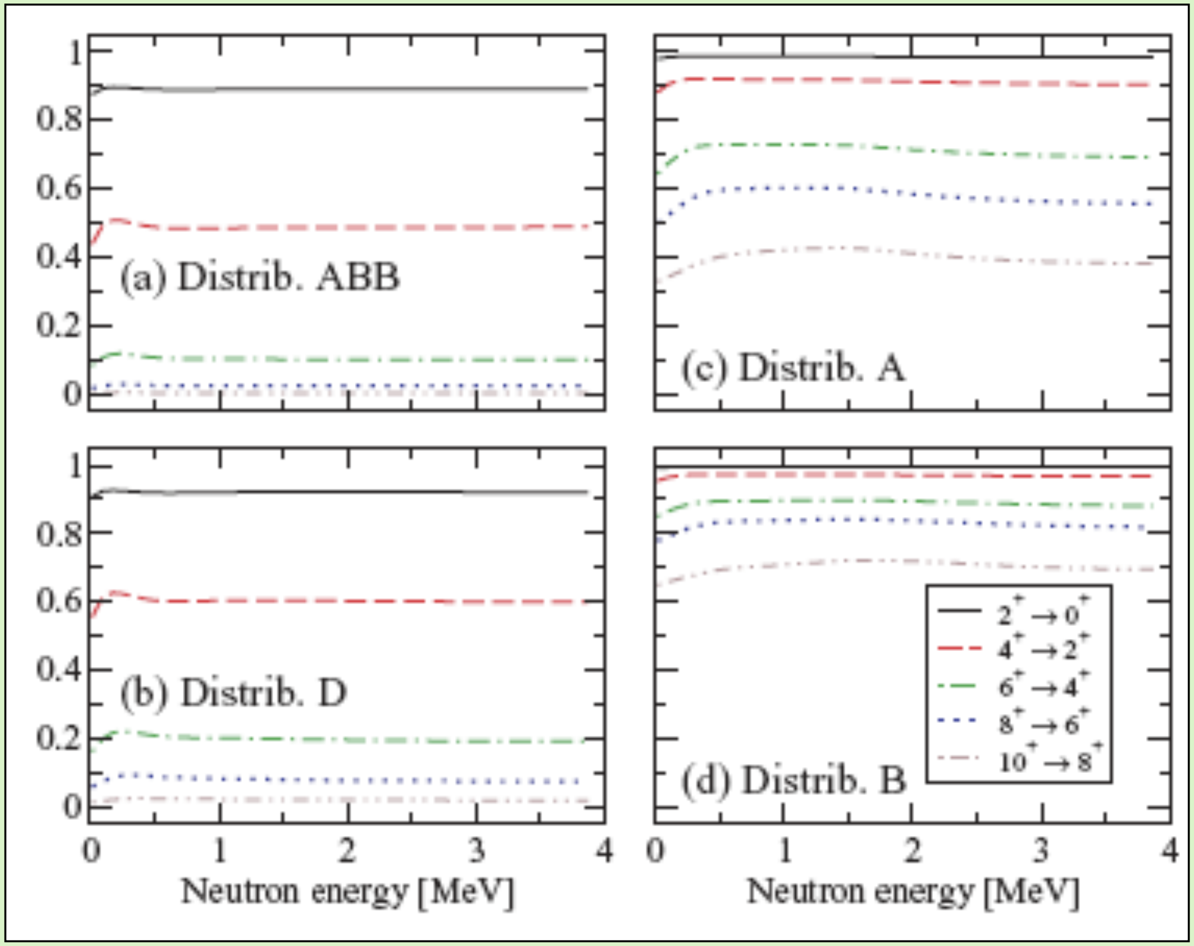
Damping of the excited states into a compound nucleus

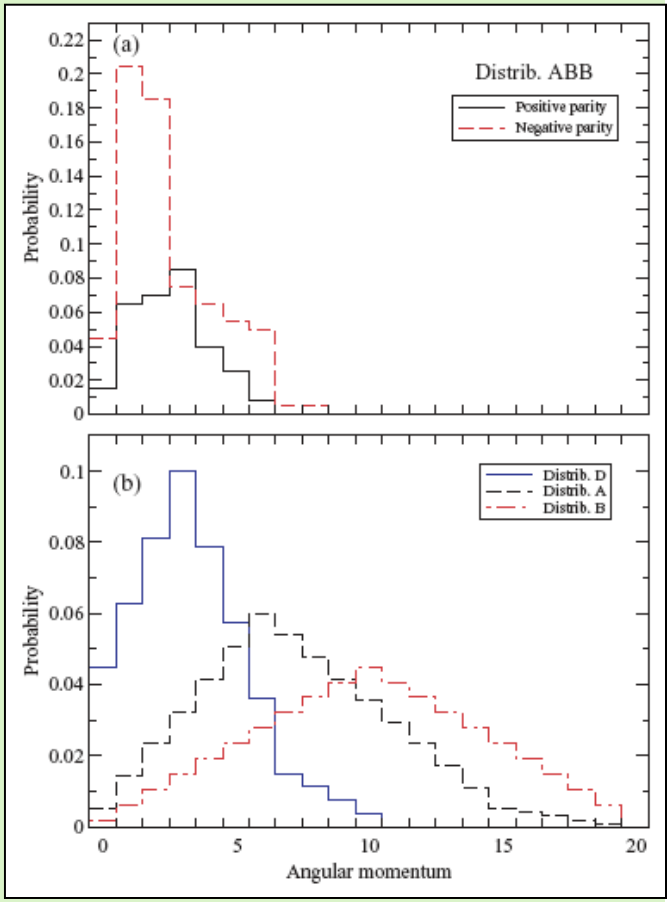
- competition between CN formation and non-equilibrium decay (particle escape)
- dependence on J^{π}

Width fluctuation correlations


Producing a compound nucleus

γ-rays as a signature of the CN spin-parity distributions: actinide case





γ-ray intensities are sensitive to the J^π distribution of the decaying CN nucleus.
The 'collector' transition (2^+->0^+) accounts for 90-100% of the intensity.

Summary

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

We have observed:

- (n,γ) reactions are very sensitive to angular-momentum effects
- Cross sections extracted from Surrogate experiments in the WE approximation do, in general, not give satisfactory results. Conclusion is based on theoretical considerations, calculations, and Gd experiments.
- Nuclei near closed shells present a special challenge due to the low level densities, actinides seem somewhat less sensitive to spin effect.
- Individual γ transitions contain valuable information. A combination with measurements of the complete γ-cascade is potentially very useful.

Collaborators

Theory:

F.S. Dietrich, D. Gogny, R. Hoffman, I.J. Thompson, W. Younes *(LLNL)*
C. Forssén (*Chalmers University)*
A.K. Kerman (*MIT/ORNL)*

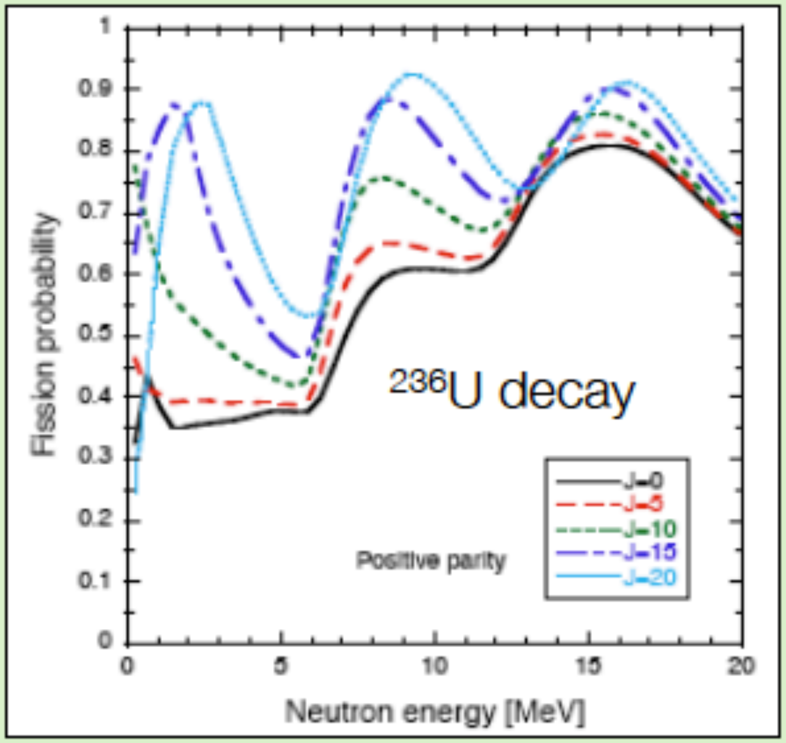
Experiment:

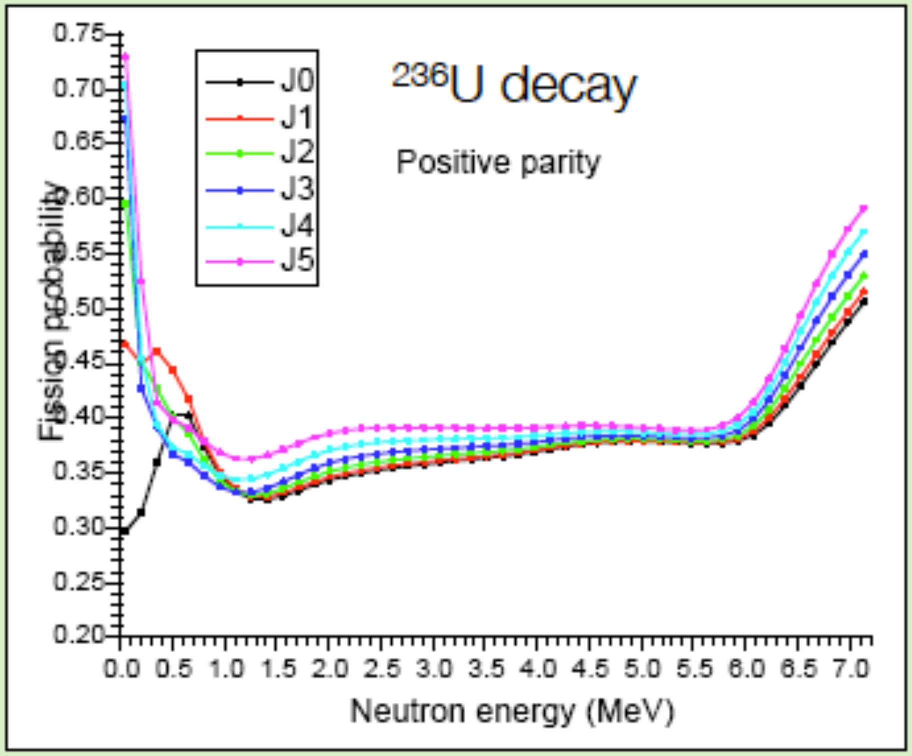
The STARS/LIBERACE collaboration, in particular:
J. Burke, L. Bernstein, S. Lesher, J.J. Ressler, **N. Scielzo** *(LLNL)*
R. Hatarik, S. Basunia, L.W. Phair *(LBNL)*
B. Lyles/Goldblum *(LLNL/UC Berkeley)*
C. Beausang *(University of Richmond)*

J. Cizewski, W. Peters *(Rutgers/ORNL)*

Appendix

^{236}U fission probabilities: dependence on J$^{\pi}$



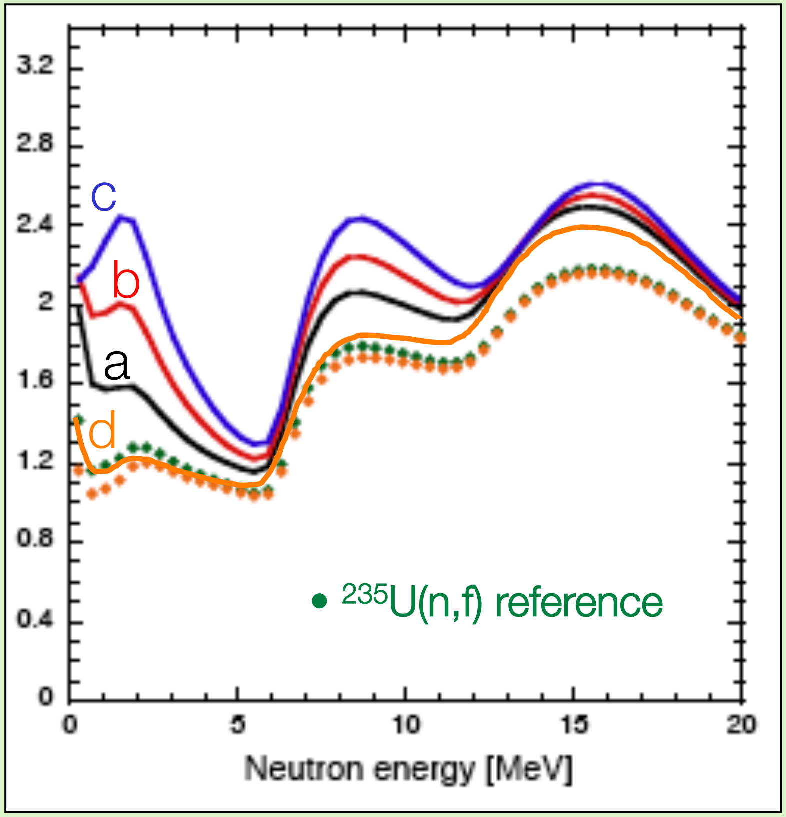


Insights:

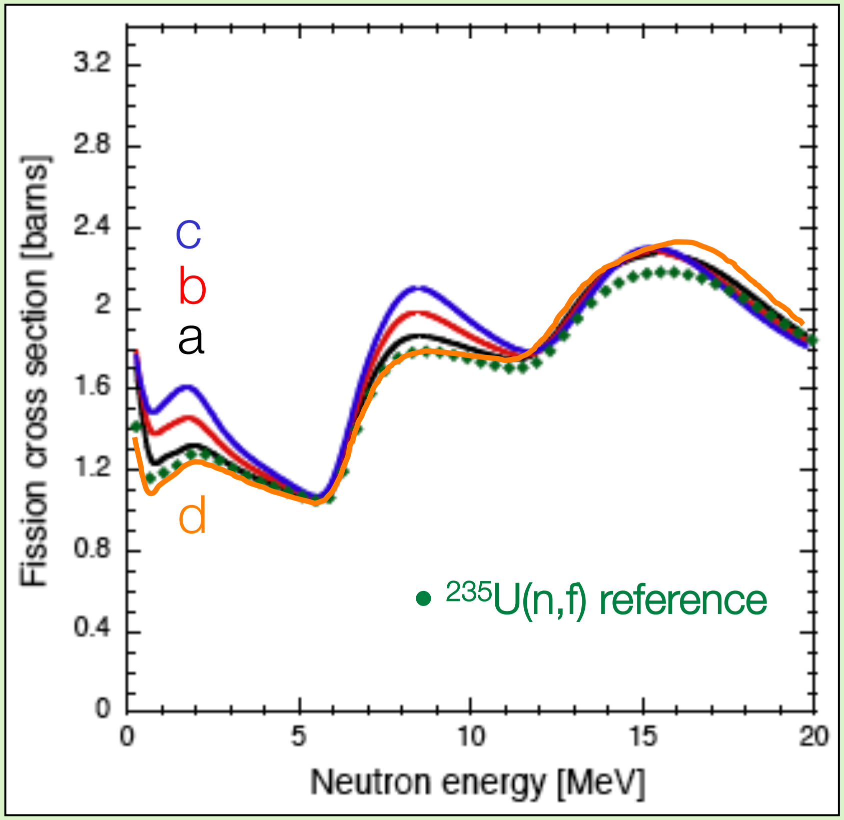
- It is not a priori obvious whether the WE approximation applies. The validity of the approximation depends on the energy and the range of J$^{\pi}$ populated.
- Note the range of spins and the linear scale.

Theory tests of WE and Ratio approximations

Simulations of Surrogate results for different spin distributions



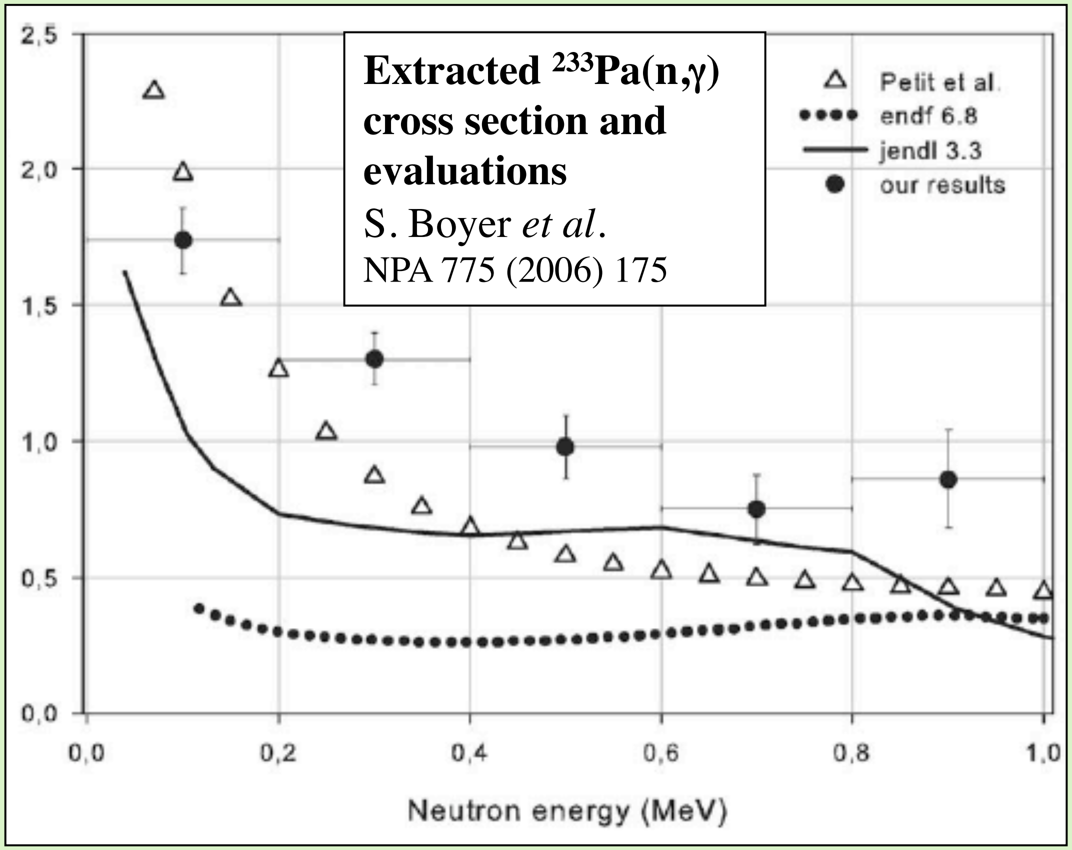
Results from Weisskopf-Ewing analysis



Results from Ratio analysis

Calculations illustrate the level of agreement that can be expected from (n,f) cross sections extracted in Weisskopf-Ewing and Ratio approximations.

Surrogate approach for (n,γ) cross sections



Extracted ^{233}Pa(n,γ) cross section and evaluations

S. Boyer *et al.*

NPA 775 (2006) 175

△ ^{232}Th(^{3}He,p)^{234}Pa Surrogate measurement for fission, used to adjust HF calculation of (n,γ) cross section

● ^{232}Th(^{3}He,p)^{234}Pa Surrogate measurement for γ exit channel, analyzed in WE approximation

Hatarik *et al.*
(PRC 81 (2010) 011602(R))
Desired: $\sigma[^{171}$Yb(n,γ)]/$\sigma[^{173}$Yb(n,γ)]
Surrogate: P[^{171}Yb(d,pγ)]/P[^{171}Yb(d,pγ)]

Goldblum *et al.(PRC 78 2008)064606)*
Desired: ^{171}Yb(n,γ)
Surrogates:
P[^{171}Yb(^{3}He,^{3}He')]/P[^{161}Dy(^{3}He,^{3}He')]
P[^{172}Yb(^{3}He,α)]/P[^{162}Dy(^{3}He,α)]

Allmond *et al. (PRC 79 (2009) 054610)*
Desired: $\sigma[^{235}$U(n,γ)]/$\sigma[^{235}$U(n,f)]
Surrogate: P[^{235}U(d,pγ)]/P[^{235}U(d,pf)]

Scielzo *et al.*
(PRC 81 (2010) 034608)
Desired: $\sigma[^{153,155,157}$Gd(n,γ)]
Surrogate: P[^{154,156,158}Gd(p,p'γ)]

Surrogate measurements for (n,γ) are now being considered.

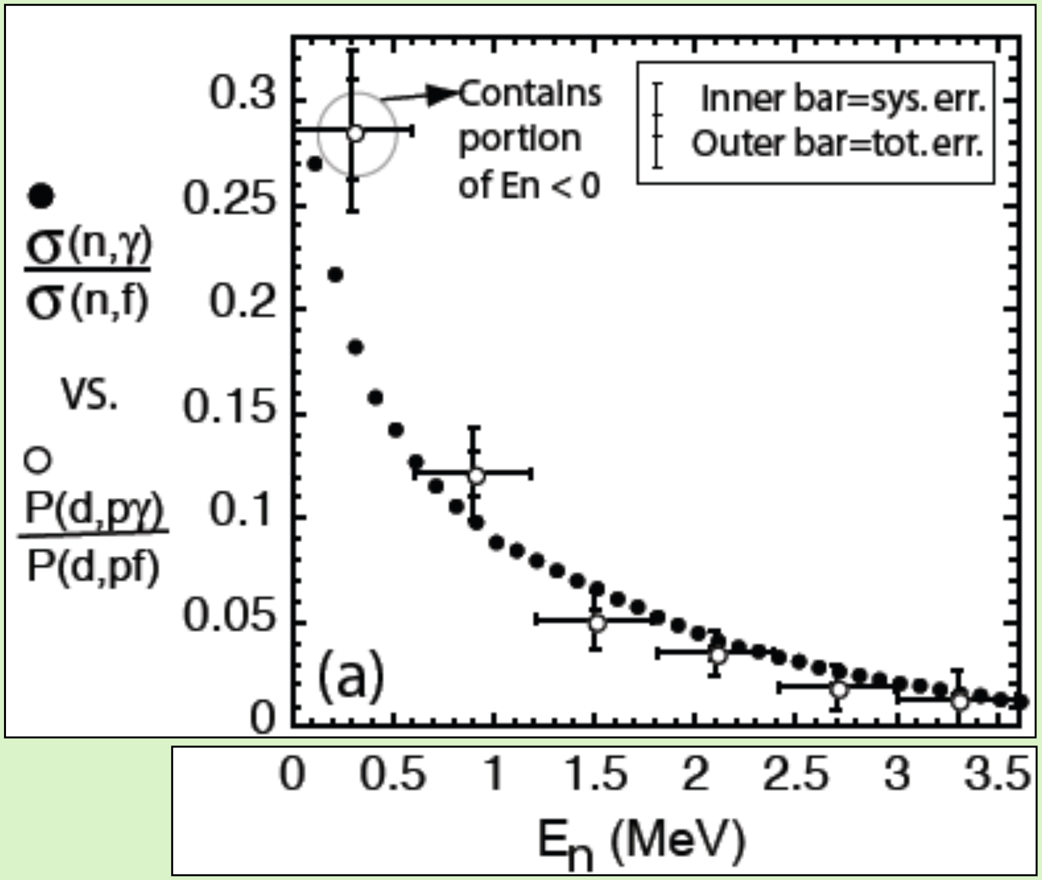
Minimizing effects of the spin-parity mismatch: ratio results for ^{235}U(n,γ)

J.M Allmond et al. (PRC 79 (2009) 054610)

Deduced the ^{235}U(n,γ) cross section from a Surrogate Internal Ratio, using ^{235}U(d,pγ) and ^{235}U(d,pf) with E_d=21MeV

Work assumes that 34% of the gamma cascade proceeds through the 1- -> 2+ (642keV) transition.

Result is in agreement with evaluated cross section.



Dresden, August 2010

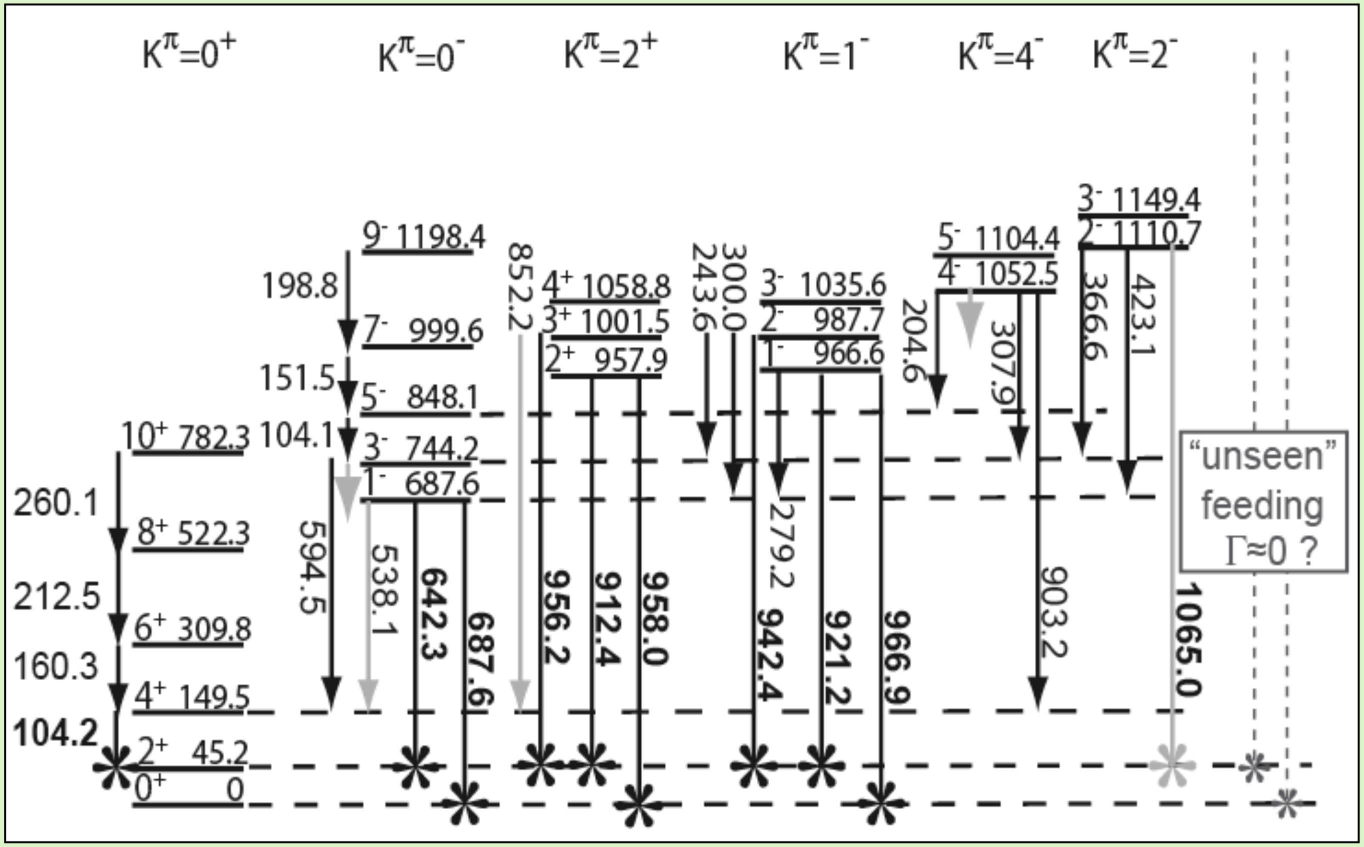
J. Escher, LLNL

Minimizing effects of the spin-parity mismatch: ratio results for ^{235}U(n,γ)

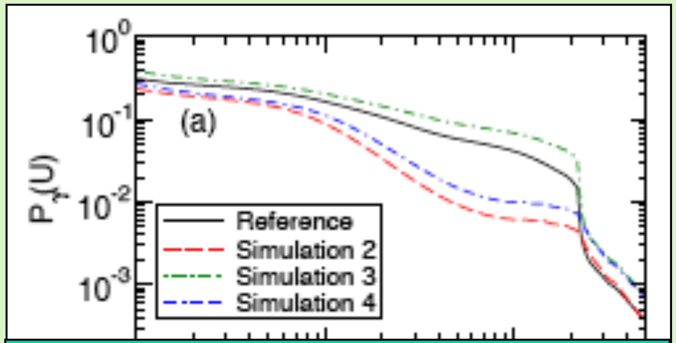
J.M Allmond et al. (PRC 79 (2009) 054610)

Goal: deduce the ^{235}U(n,γ) cross section from a Surrogate Internal Ratio, using ^{235}U(d,pγ) and ^{235}U(d,pf) with E_d=21MeV

Work makes use of the assumption that 34% of the gamma cascade proceeds through the 1- -> 2+ (642keV) transition.



Normalizing calculated cross sections with Surrogate data



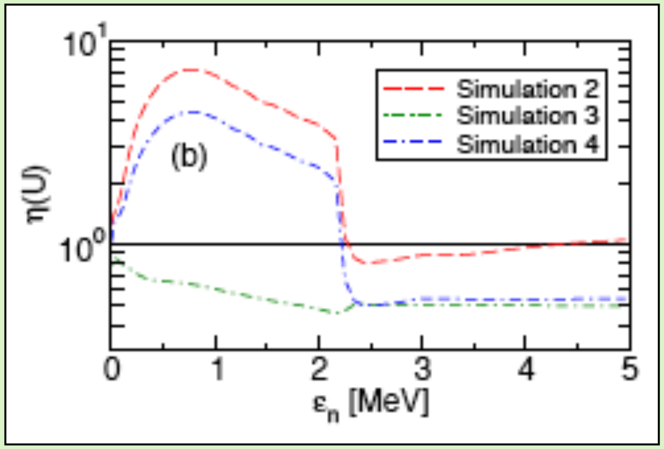
Curves 2,3,4 simulate the effect of

i) incomplete knowledge of the Surrogate CN spin distributions, and
ii) uncertainties in describing the decay of the CN nucleus

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

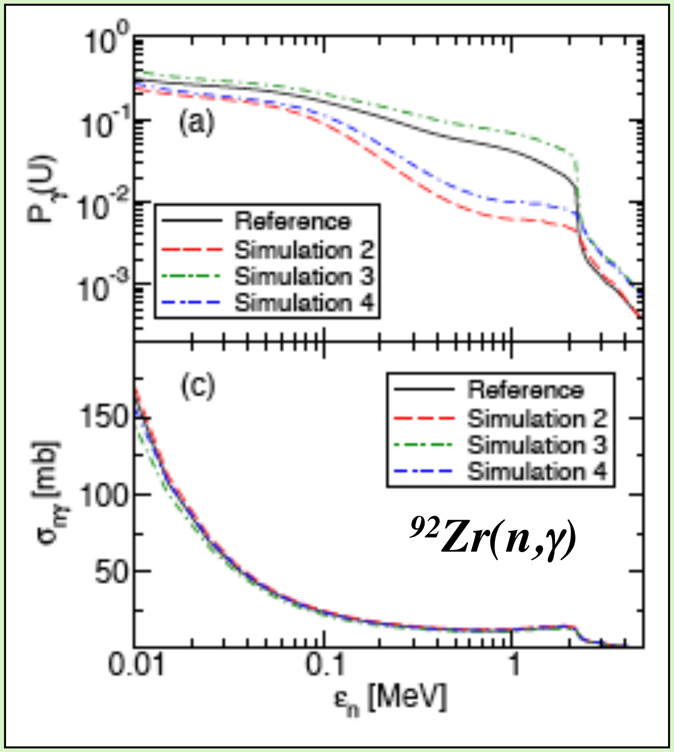
$$P_\chi^{th}(E) = \Sigma_{J,\pi}\, F_\delta^{CN,th}(E,J,\pi)\cdot G^{CN,th}_\chi(E,J,\pi)$$

$$\eta(E) = P_\chi^{exp}(E) / P_\chi^{th}(E)$$



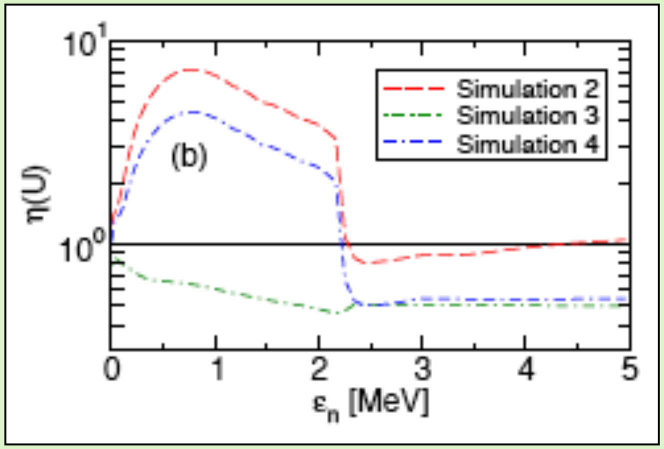
$$\sigma_{n\gamma}^{extr}(E) = \eta(E_s)\, \Sigma_{J,\pi}\, \sigma_n^{CN,th}(E,J,\pi)\cdot G^{CN,th}_\chi(E,J,\pi)$$

Normalizing calculated cross sections with Surrogate data



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

$$\eta(E) = P_\chi^{exp}(E) / P_\chi^{th}(E)$$



Forssen et al.

Phys. Rev. C 75 (2007) 055807

$$\sigma_{n\gamma}^{extr}(E) = \eta(E_s)\,\Sigma_{J,\pi}\, \sigma_n^{CN,th}(E,J,\pi)\cdot G^{CN,th}_\chi(E,J,\pi)$$

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