Cross sections for neutron capture and other compound reactions from Surrogate measurements

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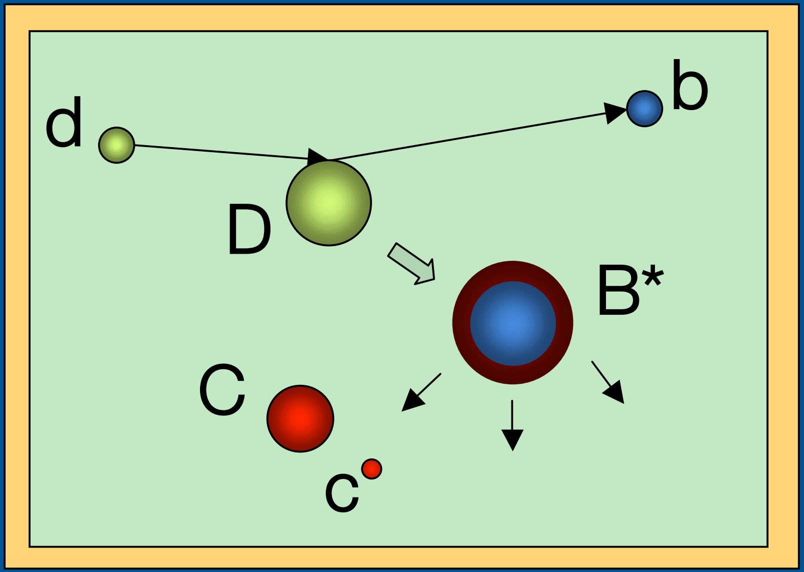

2nd International Workshop on Level Density and Gamma Strength

Oslo, Norway

May 11-15, 2009

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

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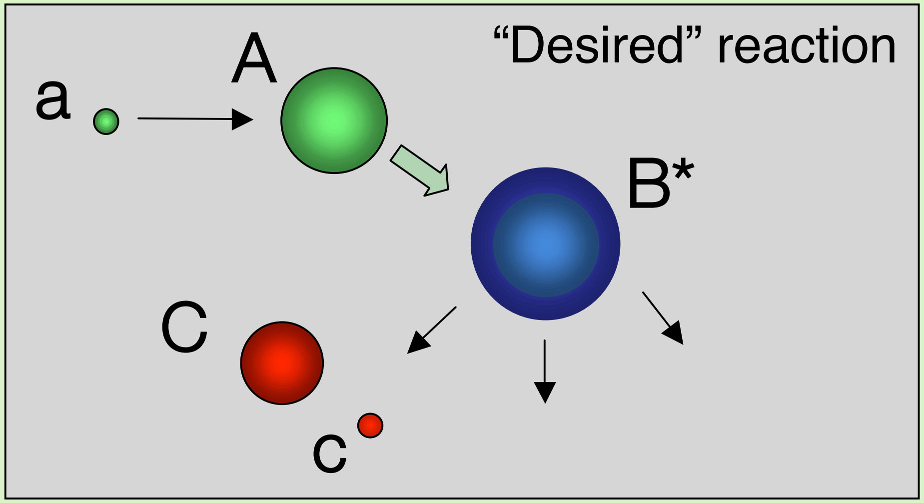
UCRL-PRES-412925

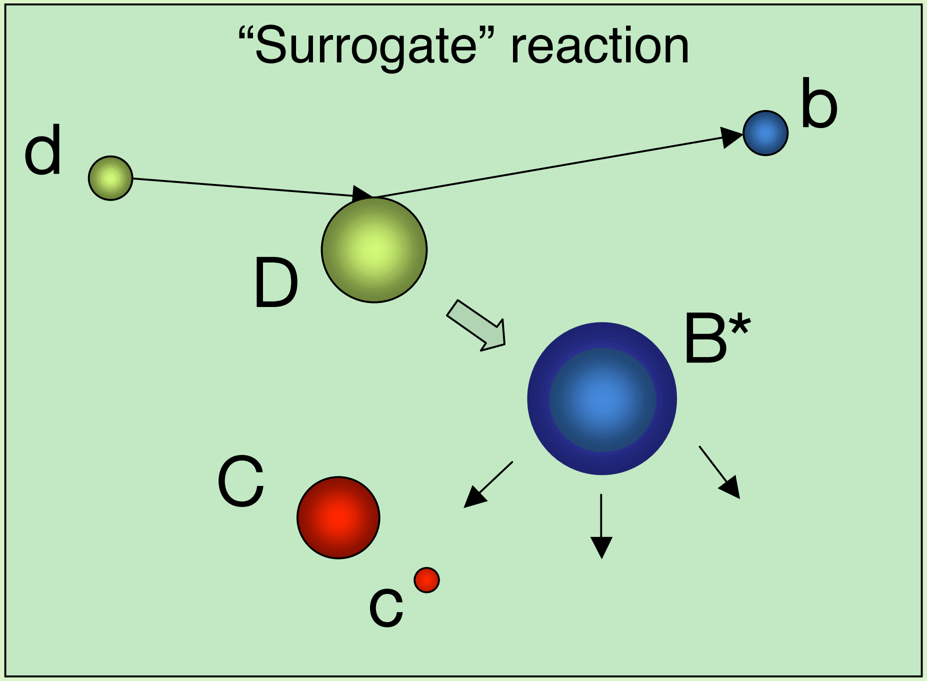
Physics & Advanced Technologies
N Division

The Surrogate Idea

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

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





Prologue

Why Surrogates?

- There are important CN cross sections that will be (almost) impossible to measure
- Calculations of CN cross sections can have very large uncertainties (in particular without constraining data)
- The Surrogate method has shown some success for (n,f) cross sections

This presentation:

- Will summarize insights gained over the past few years from theoretical and experimental work on Surrogates
- Will focus on the prospects for extracting (n,γ) cross sections from Surrogate experiments

Overview

1. Prologue
2. Successful applications of the Surrogate method - (n,f) reactions
3. How about (n,γ)?
4. Notation
5. (n,γ) case studies
   - Zr(n,γ)
   - U(n,γ)
6. CN spin-parity populations and related challenges

7. From case study to data
   - ^{156}Gd(p,p'γ)
8. Insights

Successful applications of the Surrogate method

(n,f) reactions

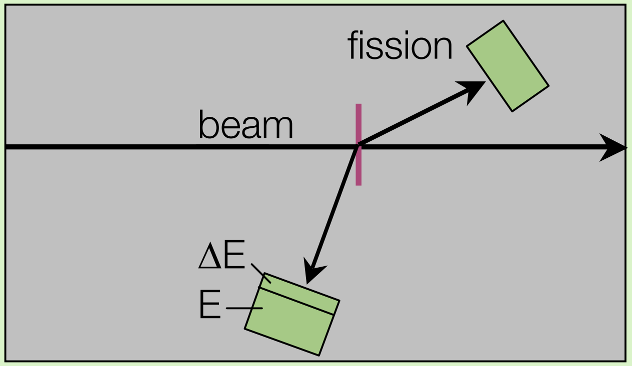
Early Surrogate work in the WE limit

Cramer and Britt

Nucl. Sci. Eng. **41**(1970)177

LANL experiment to study fission barriers:

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



Britt and Wilhelmy

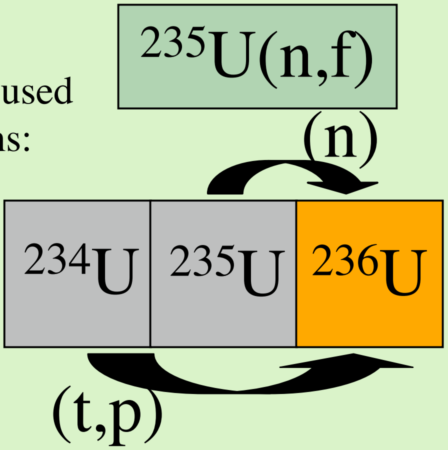
Nucl. Sci. Eng. **72**(1979)222

(^{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

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

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

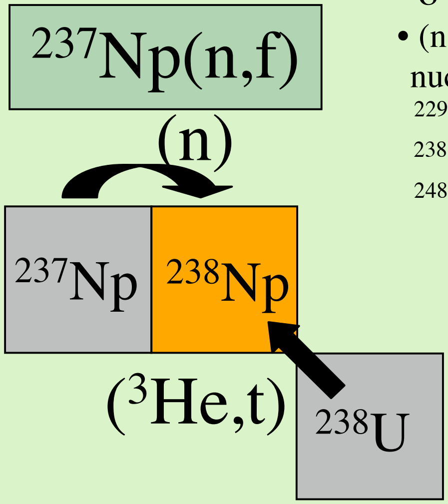


^{235}U(n,f)

(n)

^{234}U ^{235}U ^{236}U

(t,p)



^{237}Np(n,f)

(n)

^{237}Np ^{238}Np

(^{3}He,t)

^{238}U

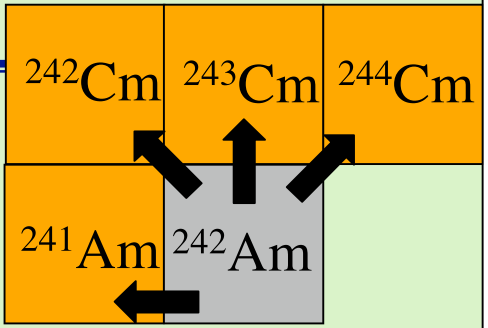
Results

- (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

Results

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

Recent work using the WE approximation

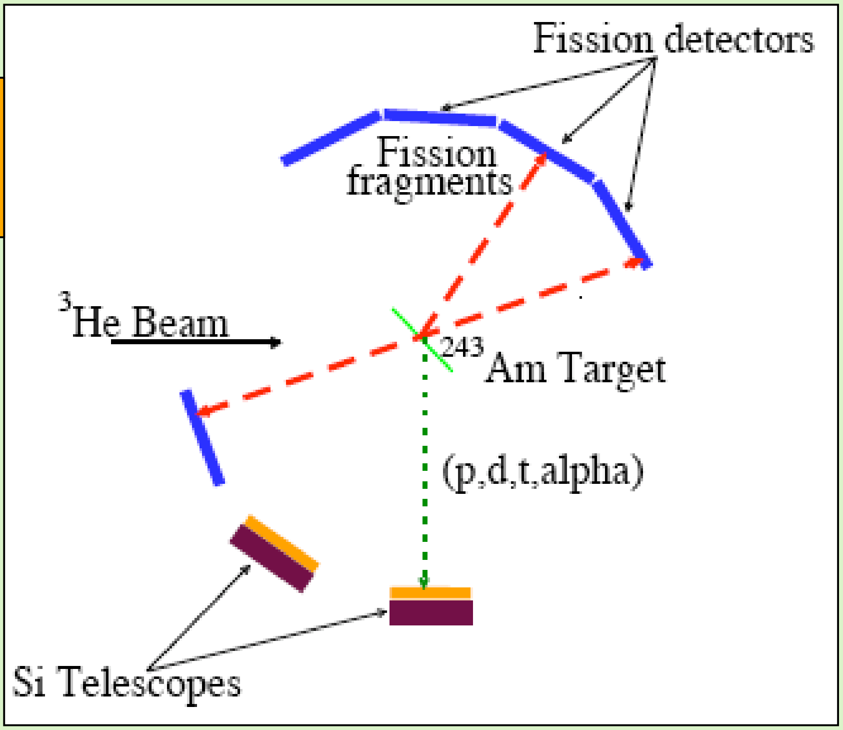


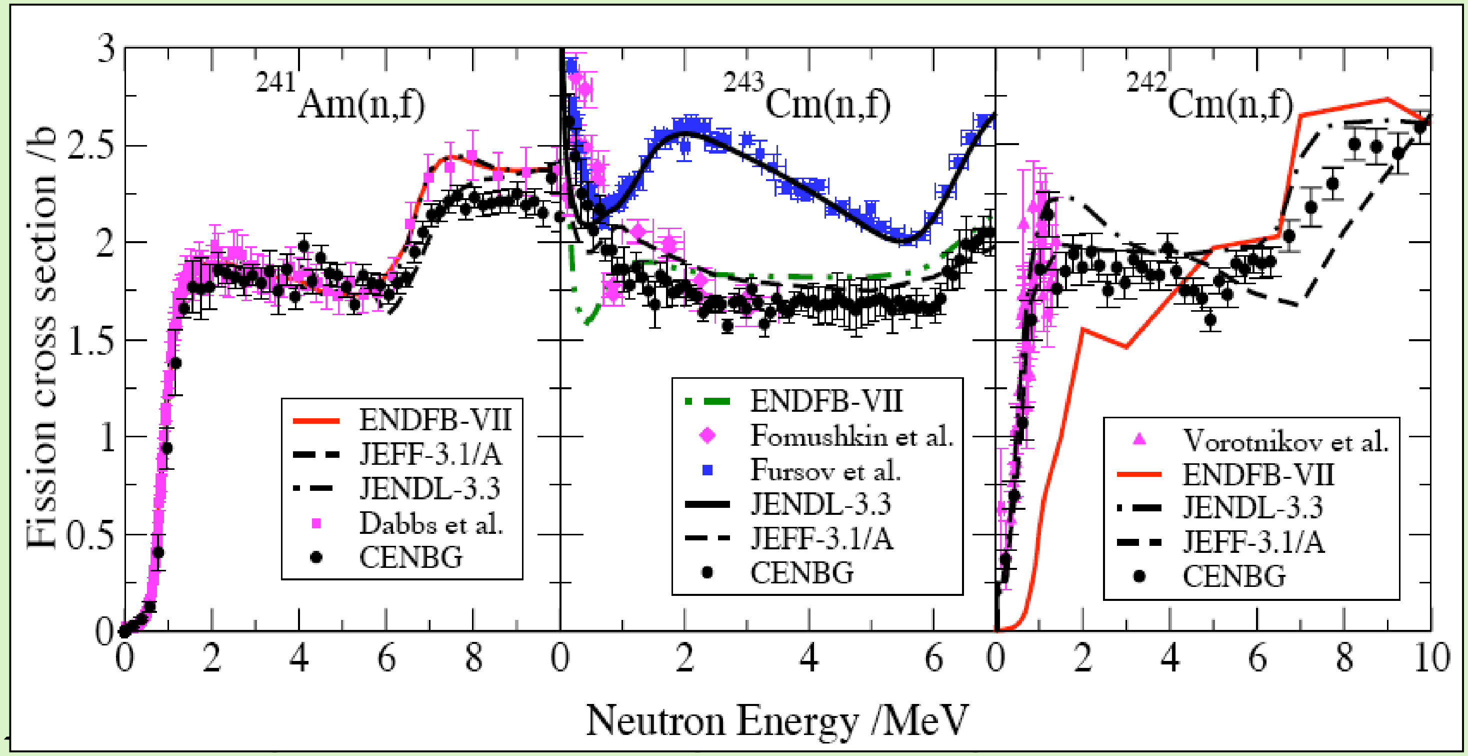
Jurado *et al.*, CENBG Bordeaux

AIP Conf. Proc. **1005**(2008)90

Experiment at IPN Orsay:

- 24-30 MeV ^{3}He beams
- ^{242}Am target on carbon backing
- charged-particle detectors (SI telescopes) at 90° & 130° - back angles!
- 5 fission fragment detectors in reaction plane - forward and back angles! Geometric fission detection efficiency ≈47%
- $P_f(E) = 1/\varepsilon_{eff} \times N_{coinc}(E)/N_{single}(E)$
- corrections applied to account for target impurities



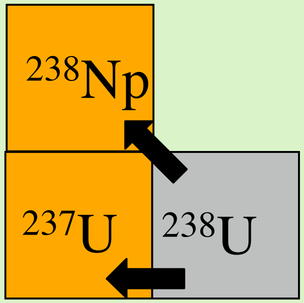


Preliminary results:

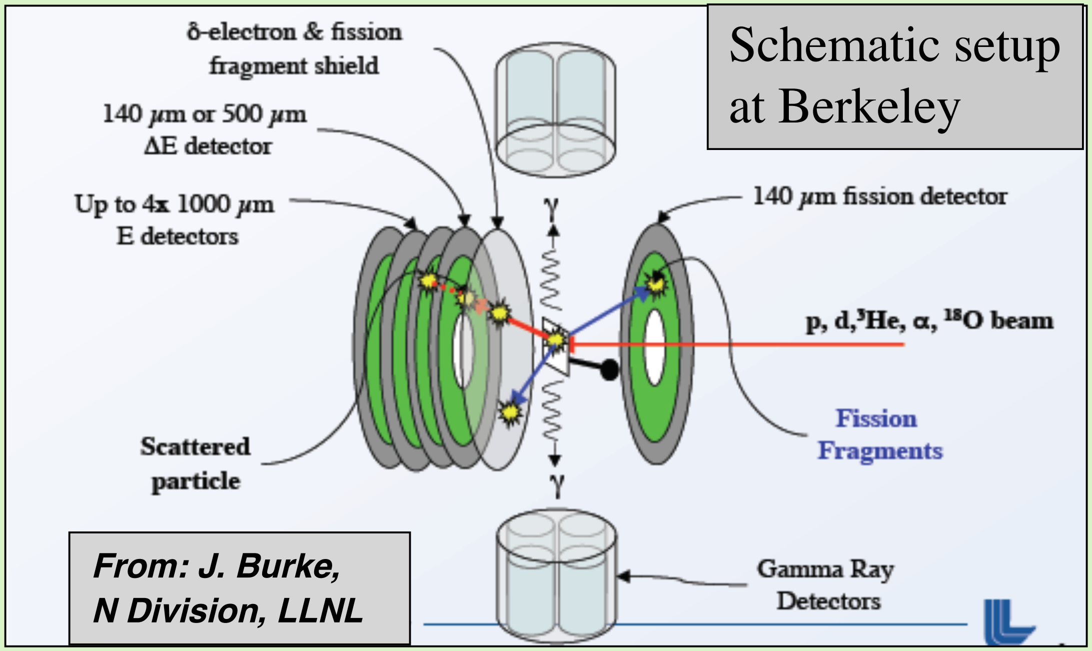
- ^{241}Am(n,f) cross section agrees with direct measurements.
- ^{243}Am(n,f) cross section seems to resolve a discrepancy between two direct measurements.
- ^{242}Cm(n,f) cross section agrees with direct results for low energies and provides new data for higher energies.

J. Escher, LLNL

WE results from the STARS/LiberACE collaboration



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

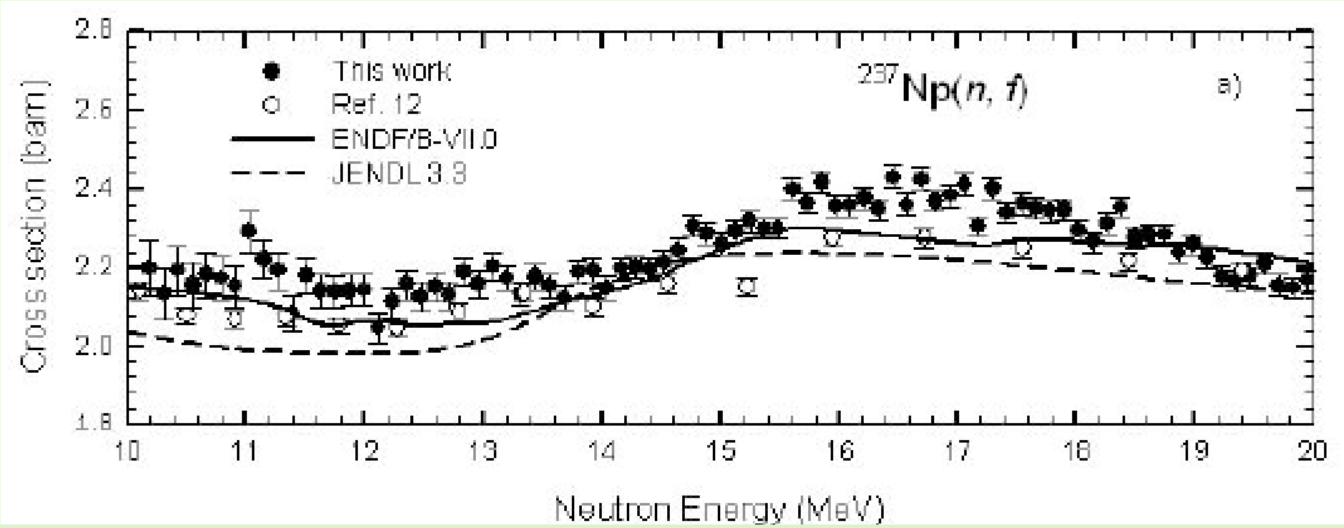

Schematic setup at Berkeley

From: J. Burke, N Division, LLNL

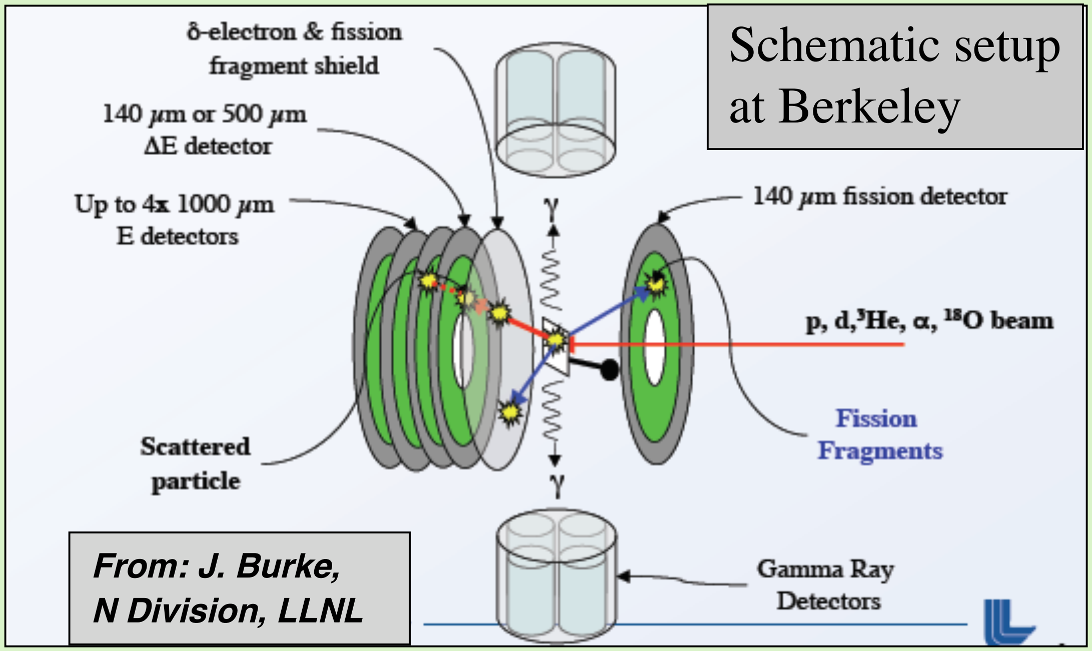
S. Basunia *et al.*
AIP Conf. Proc. **1005**(2008)101

Experiment at LBNL:

- Charge-exchange ^{238}U(^{3}He,t) with 42 MeV ^{3}He beam
- Self-supporting ^{238}U target
- Determined ^{237}Np(n,f) cross section using the WE approx.



Ratio results from the STARS/LiberACE collaboration

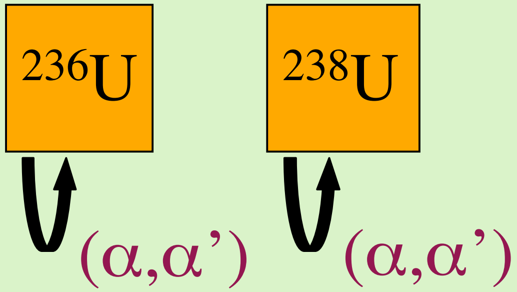


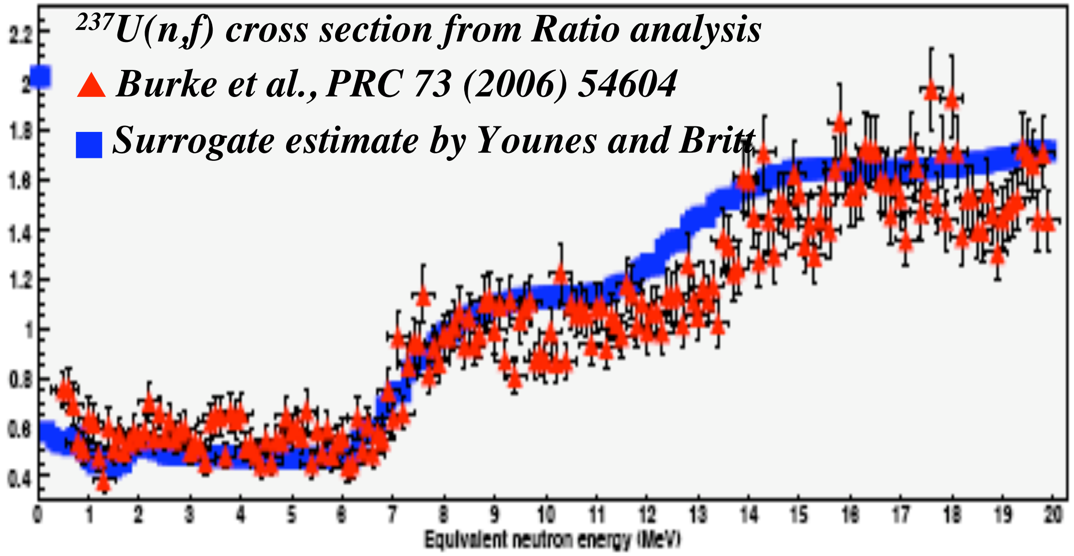
Schematic setup at Berkeley

From: J. Burke, N Division, LLNL

Burke et al., PRC 73 (2006) 054604

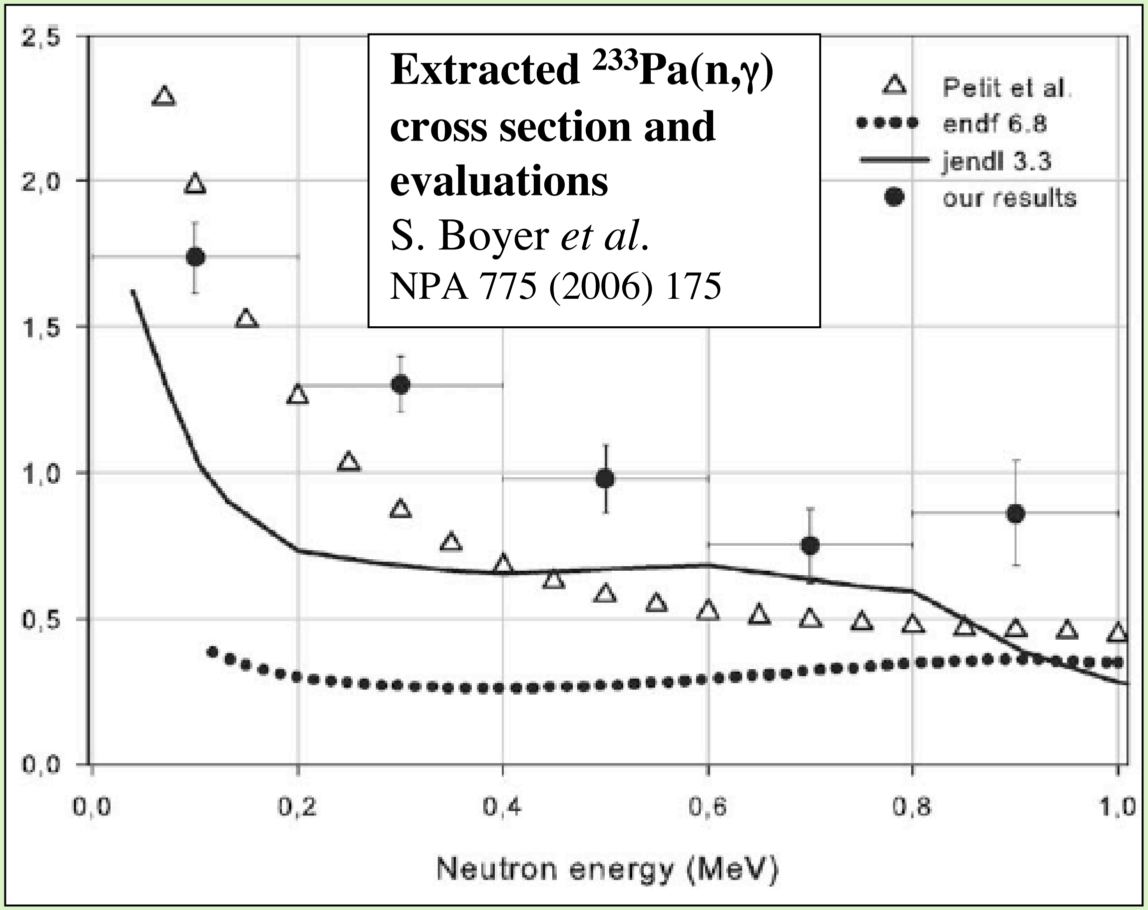
- (α,α’f) on ^{238}U and ^{236}U





How about (n,γ) reactions?

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.*

(AIP Conf. Proc. 1005 (2008) 105)

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.*

(AIP Conf. Proc. 1005 (2008) 109)

Desired: $\sigma[^{153,155,157}$Gd(n,γ)]

Surrogate: P[^{154,156,158}U(p,p’γ)]

The Surrogate approach might work for (n,γ).
There is more uncertainty here than in the (n,f) case.

Notation

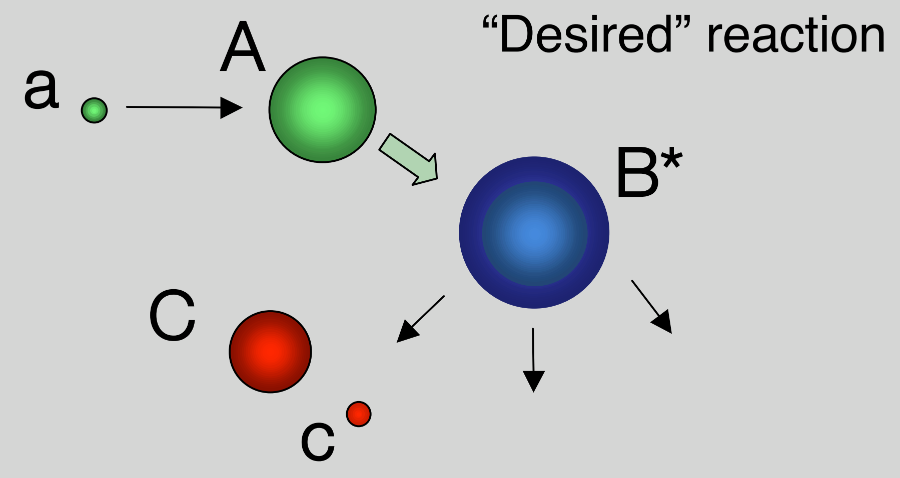
The Surrogate Idea - Formalism

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



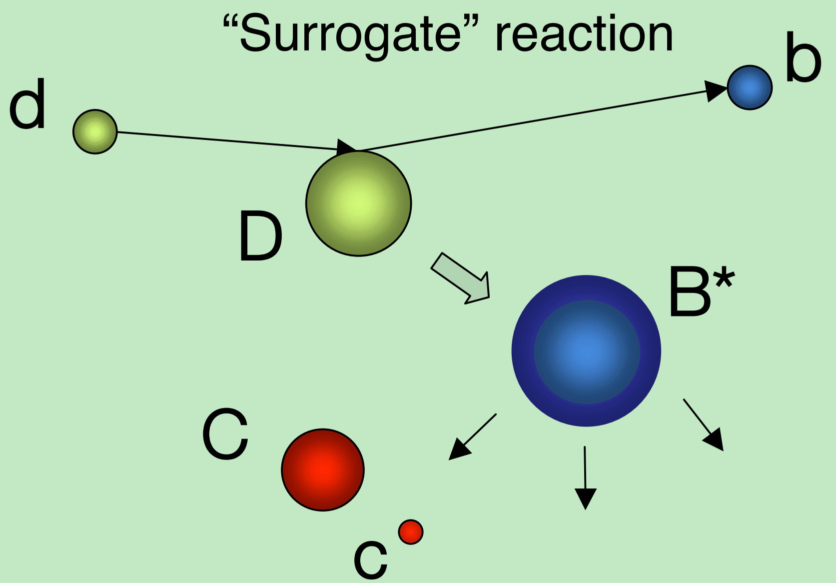
A Surrogate experiment gives

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

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)

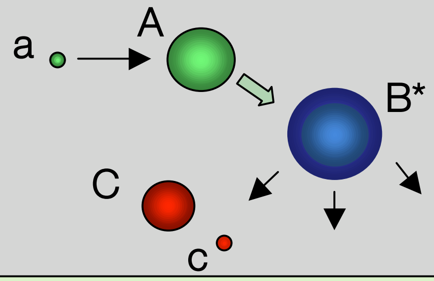


$$P_{\chi} = N_{\delta\chi}/N_{\delta}$$

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:

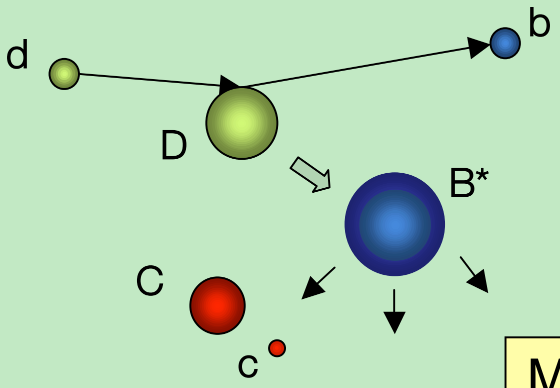
$$G^{CN}_{\chi}(E,J,\pi) \text{ ------> } \mathcal{G}^{CN}_{\chi}(E)$$

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:

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

Most applications to date use the WE approximation!

The Surrogate Ratio approach

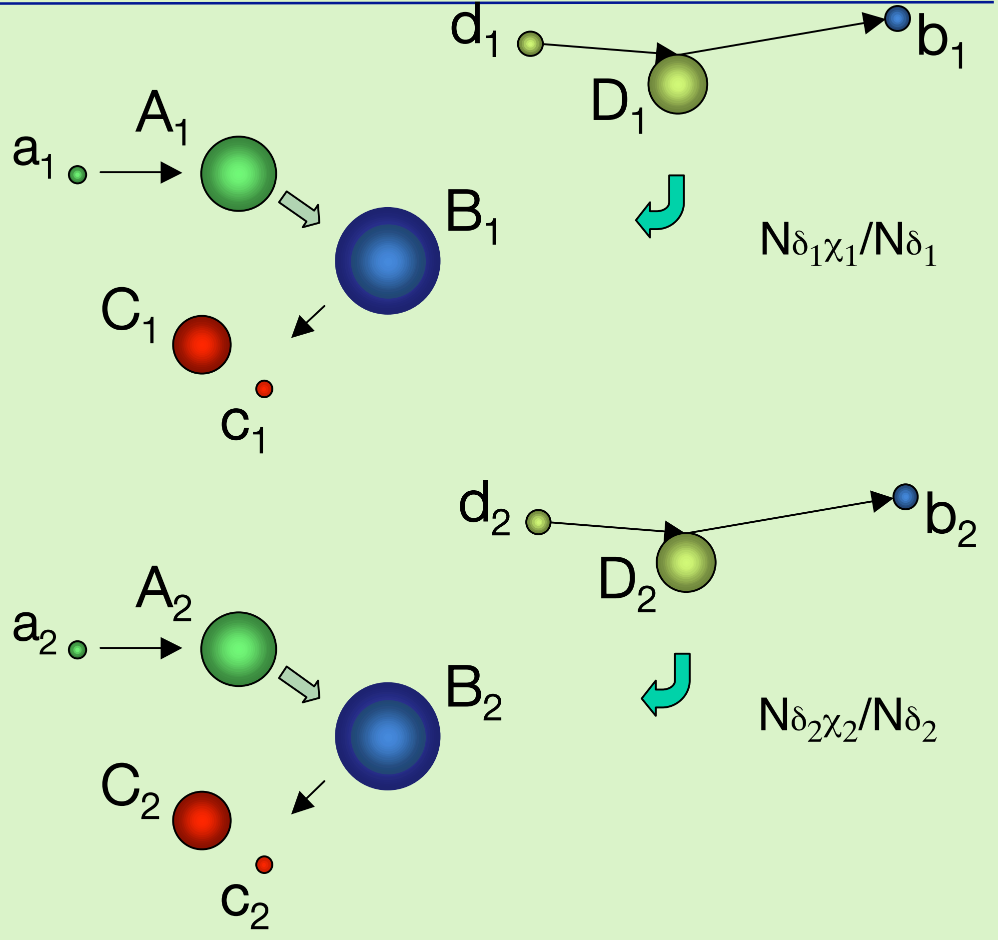
Goal: Determine experimentally

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

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

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

$\times\ N_{\delta_2}/N_{\chi_2 \delta_2}$



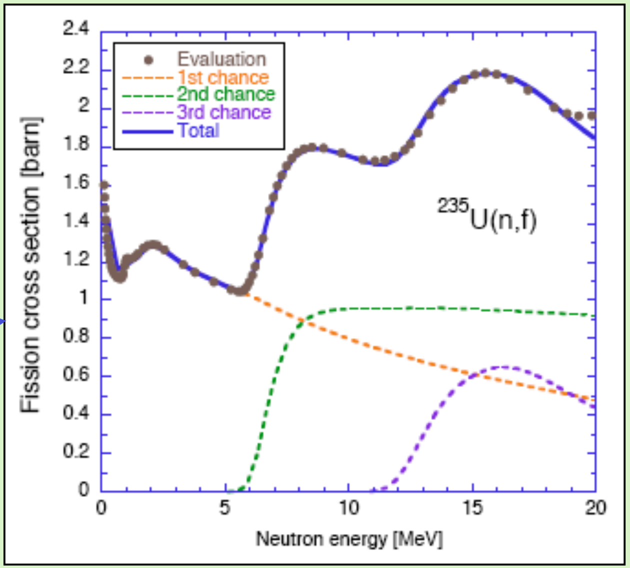
$N_{\delta_2}/N_{\delta_1}$ = const

Investigating decay probabilities, extracted cross sections

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

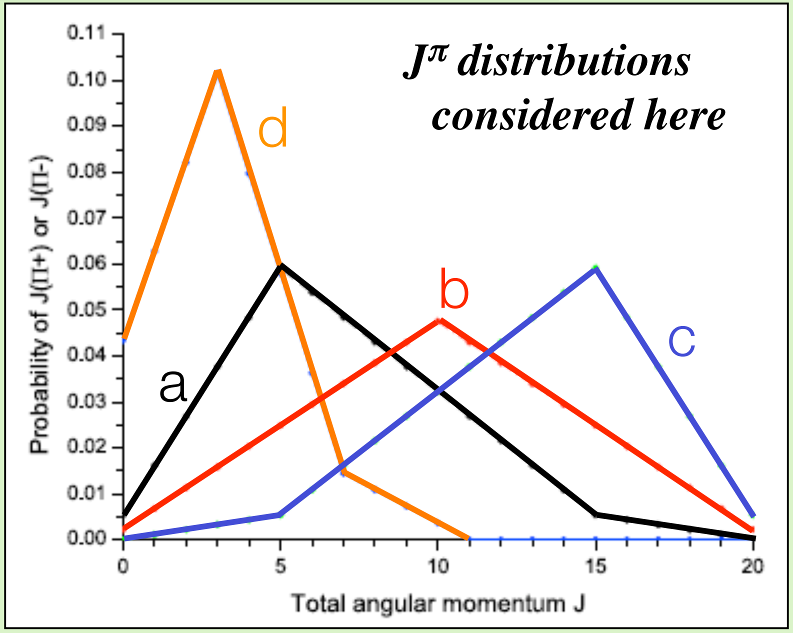
Simulation procedure:

1. Determine “reference cross sections” with a statistical-model calculation.
2. Extract decay 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.



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

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

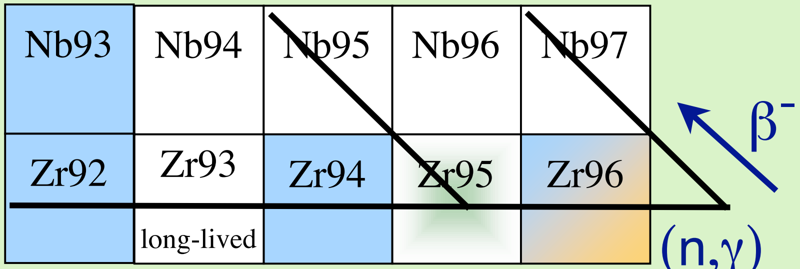


J^{π} distributions considered here

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

(n,γ) case studies

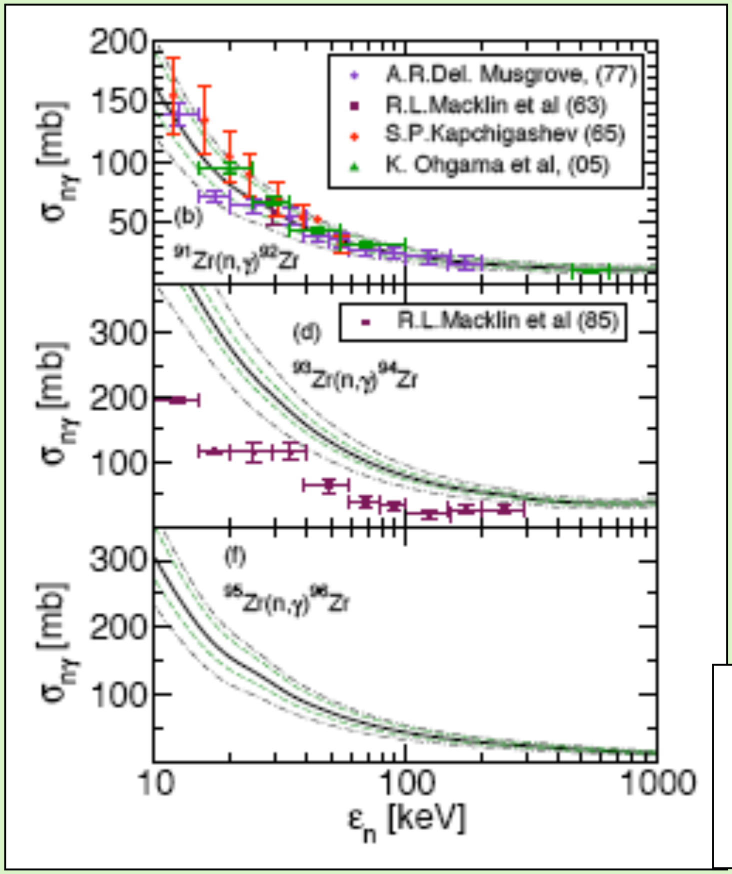
Case study 1: Zr(n,γ) - a near-spherical target



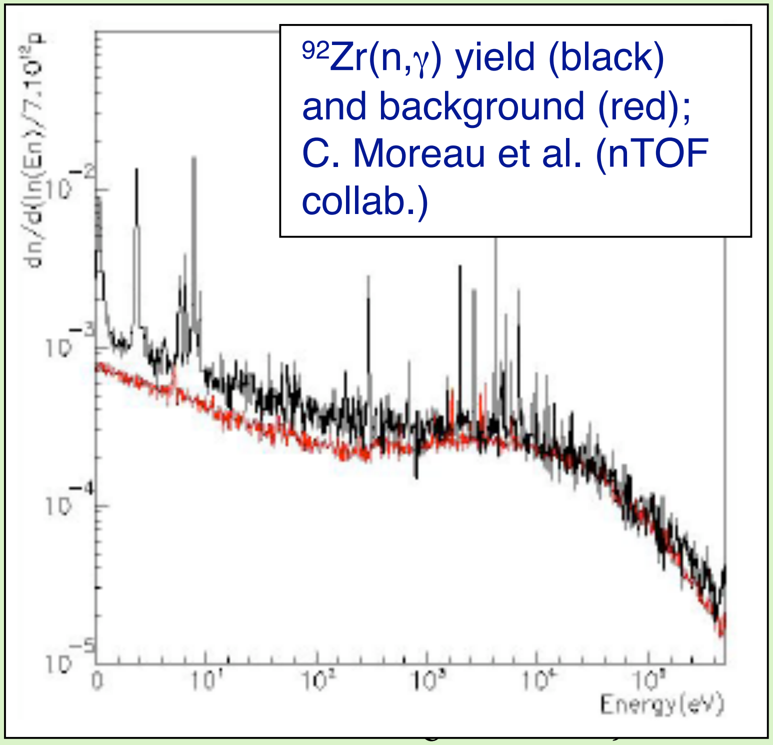
Nb93	Nb94	Nb95	Nb96	Nb97
Zr92	Zr93 long-lived	Zr94	Zr95	Zr96

Surrogate approach for ^{95}Zr(n,γ)

- Of great interest to nuclear astrophysics
- Wanted: Cross section from 300 eV to 200 keV
- Direct measurement presents a challenge: $t_{1/2}(^{95}Zr) = 64$ d
- Calculations have significant uncertainties
- Branch points are close to stable isotopes which can serve as Surrogate targets



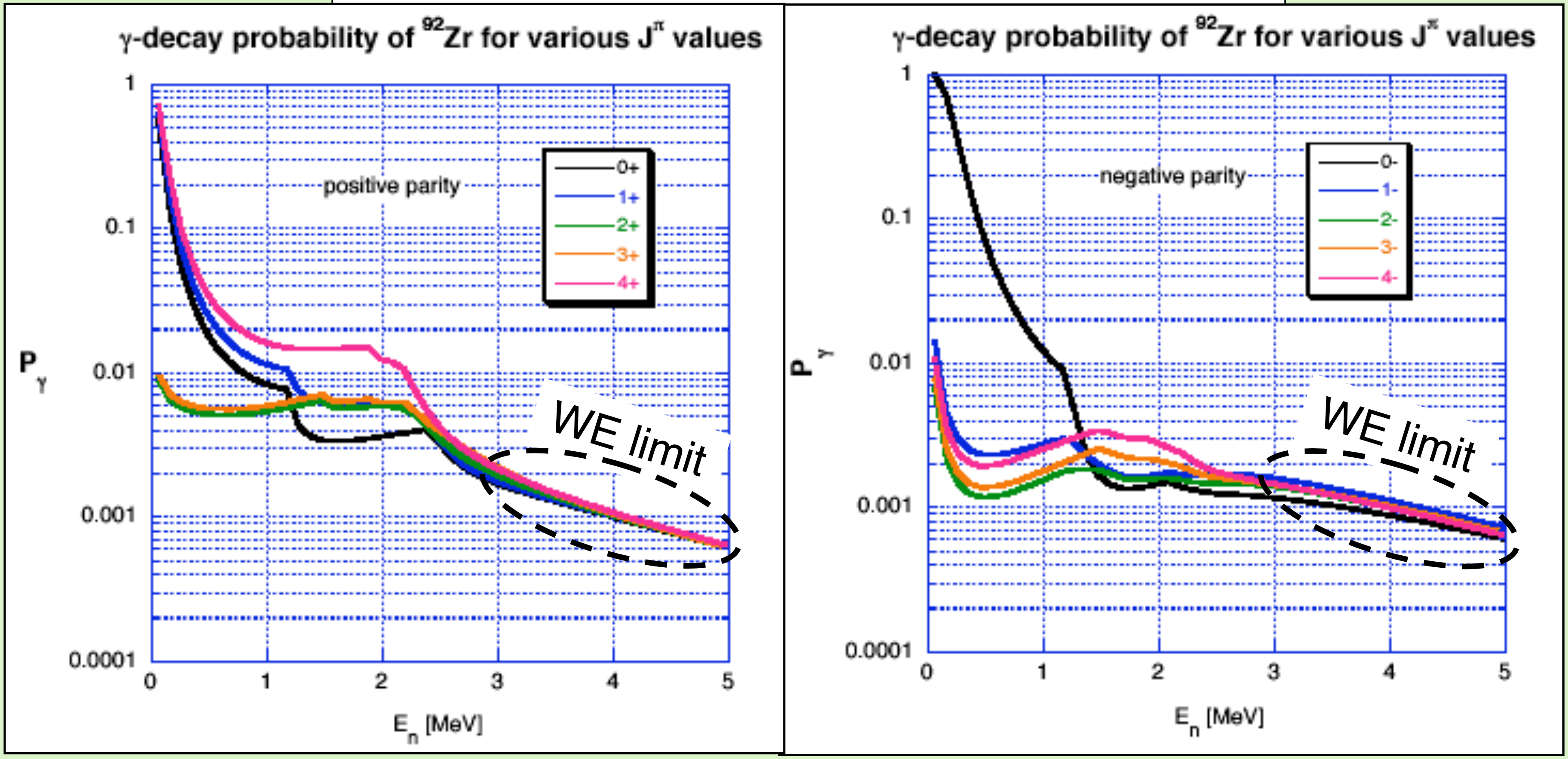
Forssen et al.
Phys. Rev. C 75
(2007) 055807



^{92}Zr(n,γ) yield (black) and background (red); C. Moreau et al. (nTOF collab.)

Case study 1: Zr(n,γ) - a near-spherical target

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



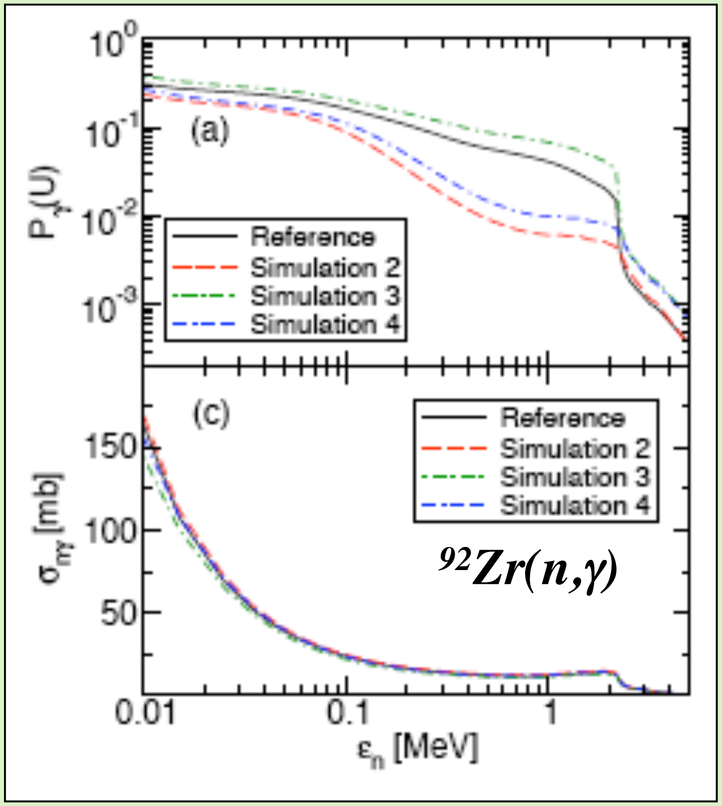
Forssen et al., PRC 75(2007) 055807

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!

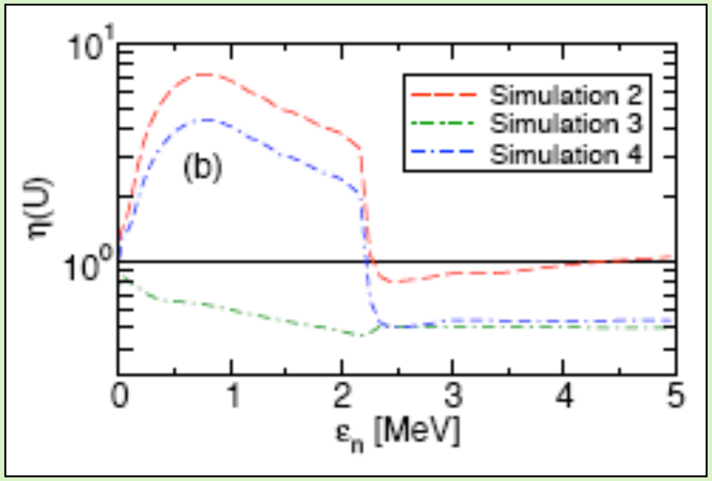
Worst-case scenario!

Case study 1: Zr(n,γ) - a near-spherical target



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

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



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**!

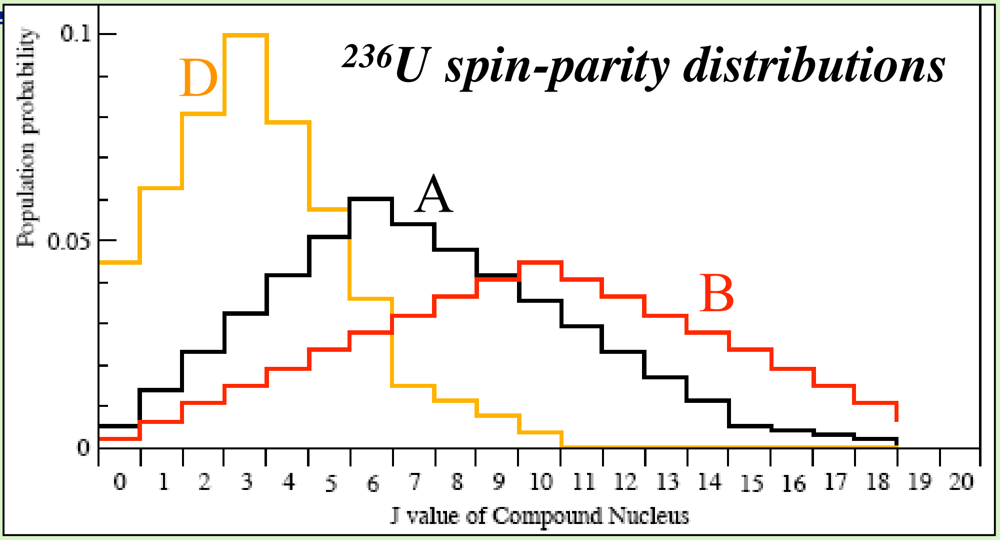
Case study 2: (n,γ) reactions for actinide targets

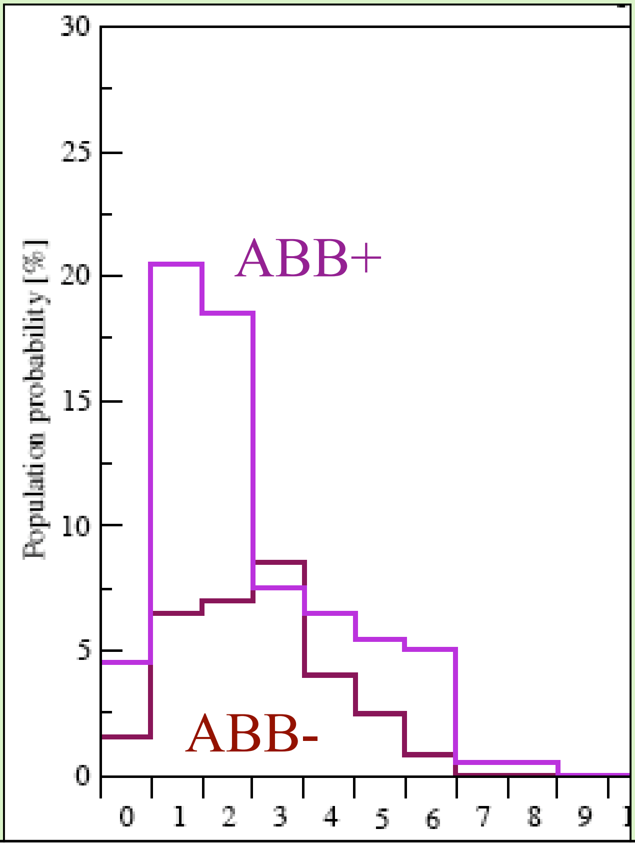
J. Escher and F.S. Dietrich

Simulation procedure:

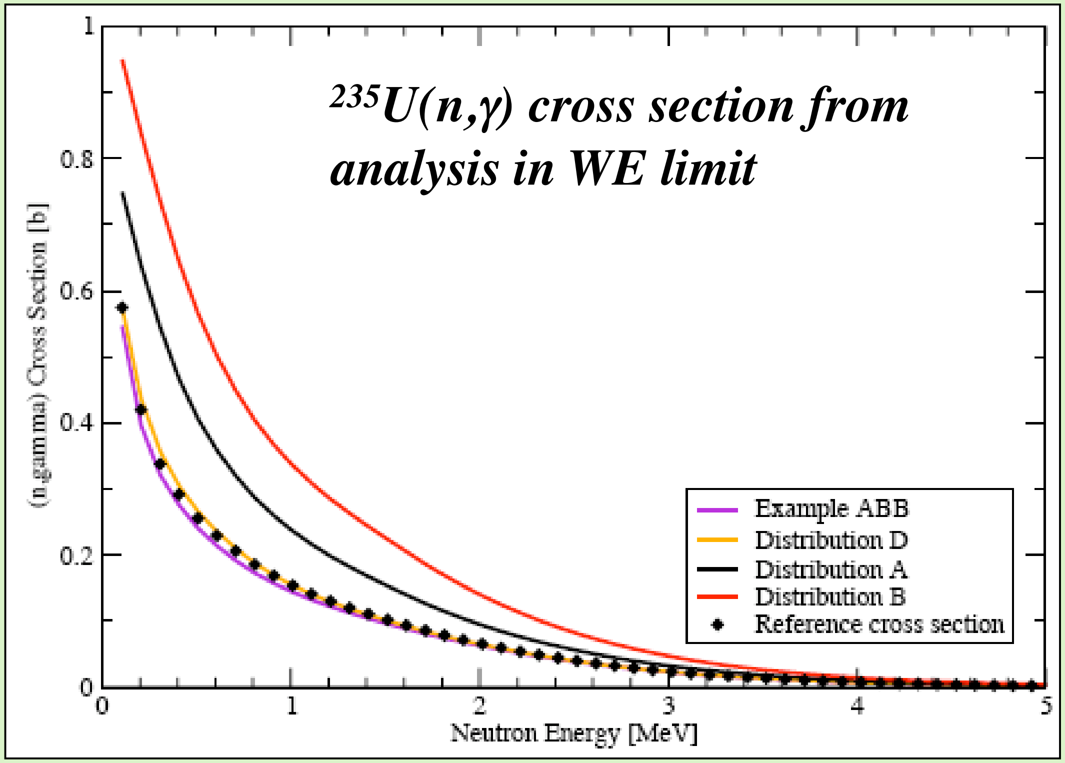
1. Determine “reference cross sections” with a statistical-model calculation.
2. Extract gamma decay probabilities for each (J,π) as function of E_n.
3. Simulate a Surrogate experiment and carry out an analysis in the WE limit.

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



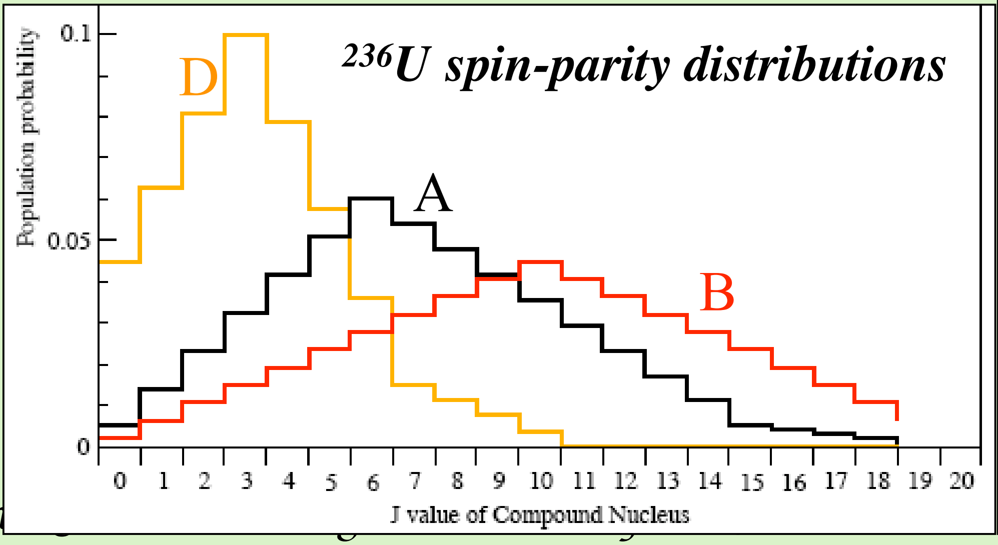


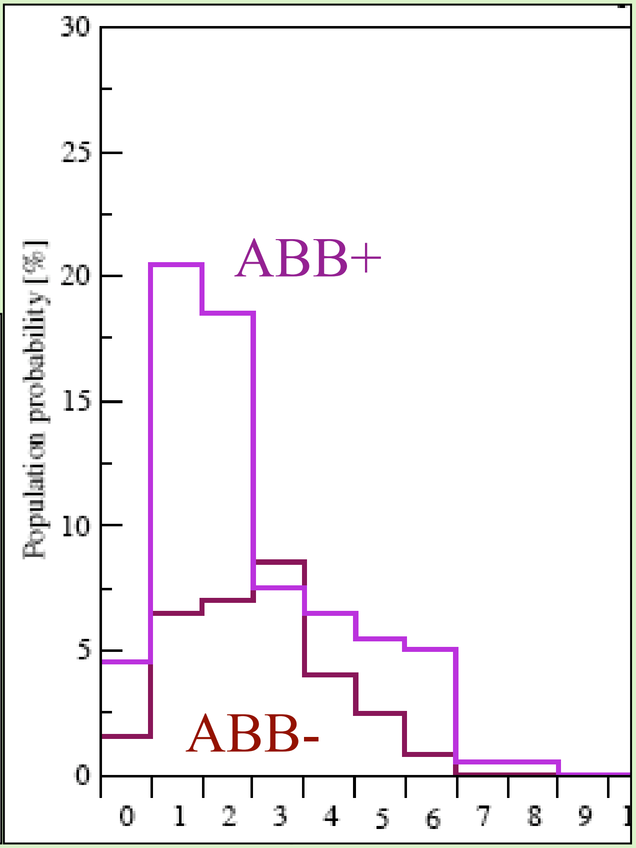
Case study 2: (n,γ) reactions for actinide targets



J. Escher and F.S. Dietrich
To be published

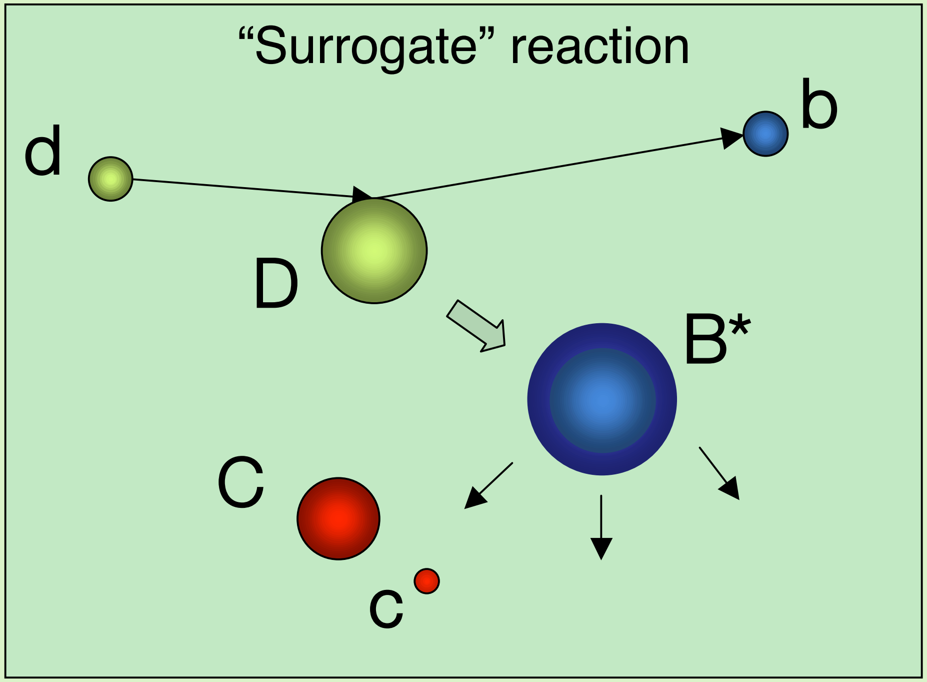
The Surrogate approach might work for (n,γ) cross sections.
Knowledge of J^{π} would be very helpful!





CN spin-parity distributions in Surrogate reactions and related challenges

Challenges for reaction theory



Challenges for reaction theory

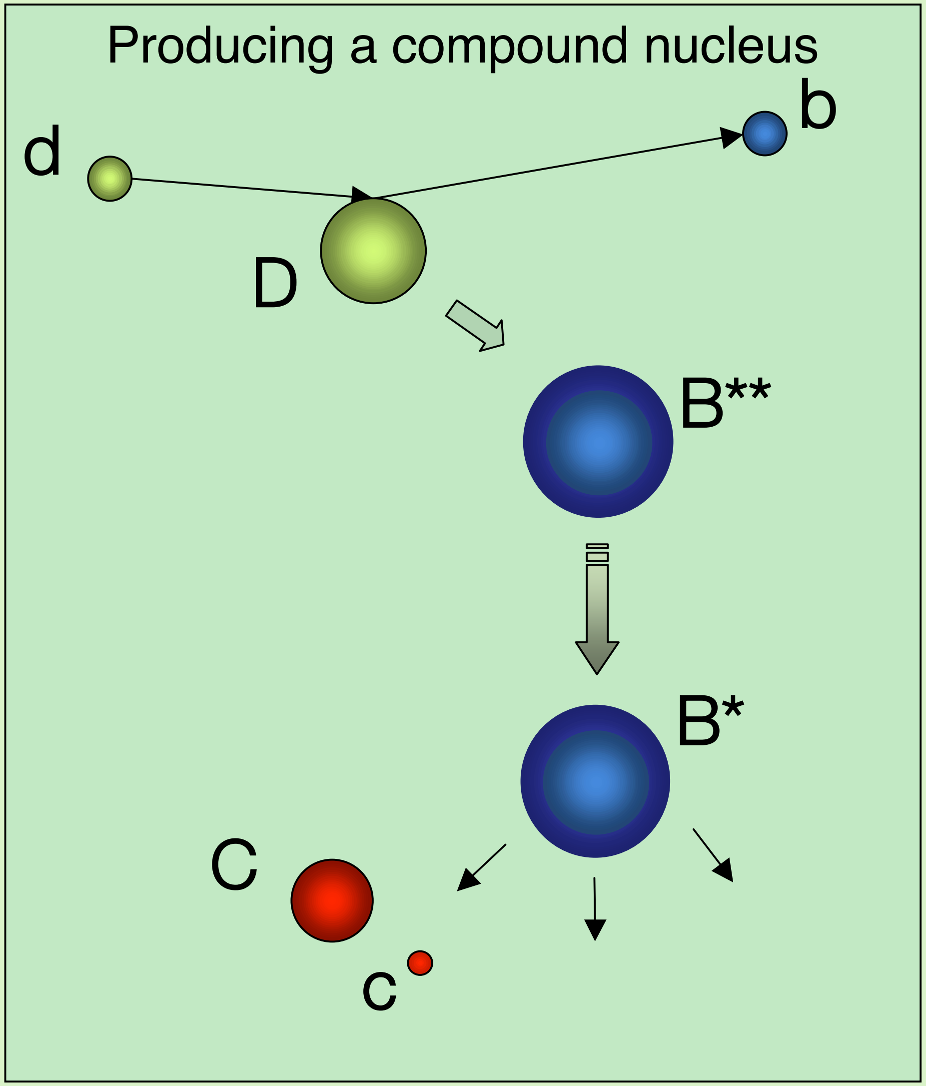
Formation of a highly excited nucleus in a direct reaction

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

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



Addressing the challenges

Formation of a highly excited nucleus in a direct reaction

Damping of the excited states into a compound nucleus

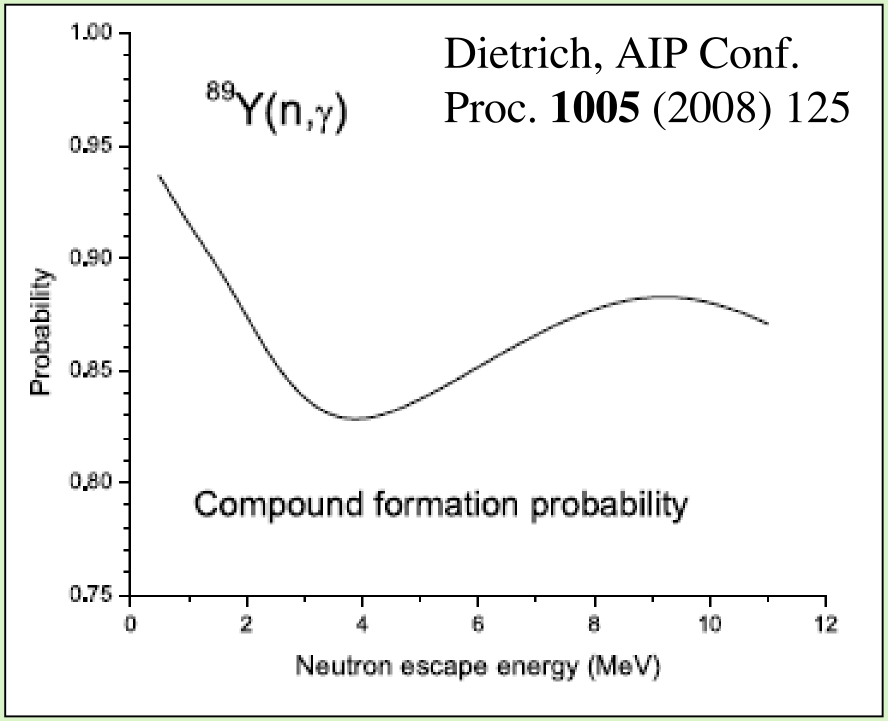
J^{π} calculations for U(^{3}He,α)U* are now possible

Thompson & Escher, UCRL-TR-225985

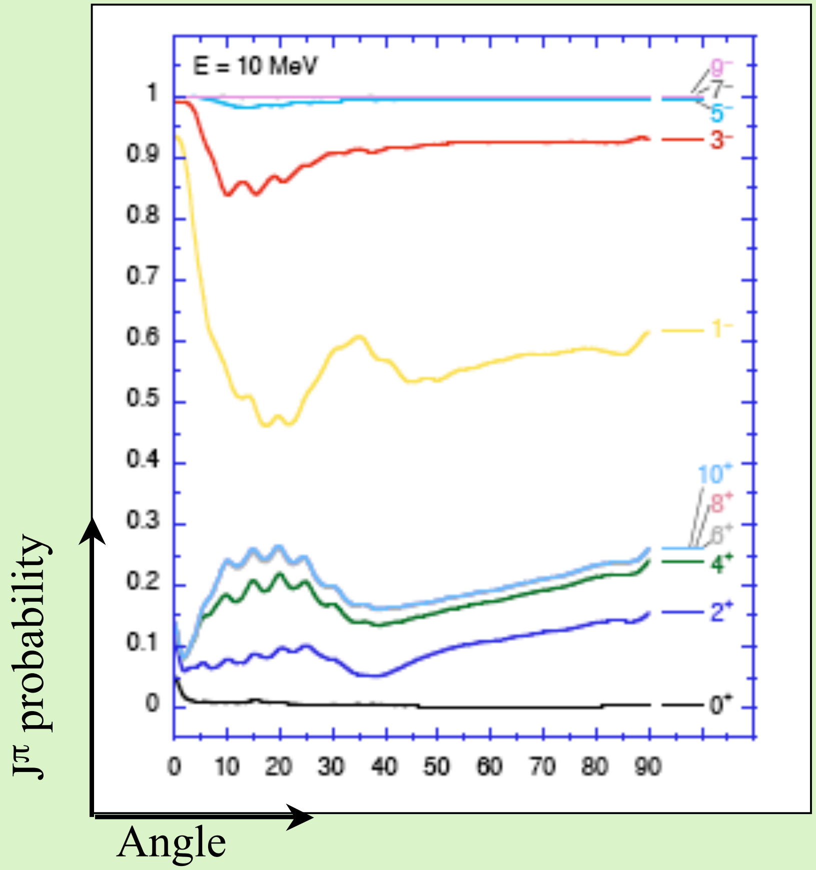
J^{π} distribution for ^{90}Zr(α,α')^{90}Zr*

Escher & Dietrich, UCRL-TR-404300

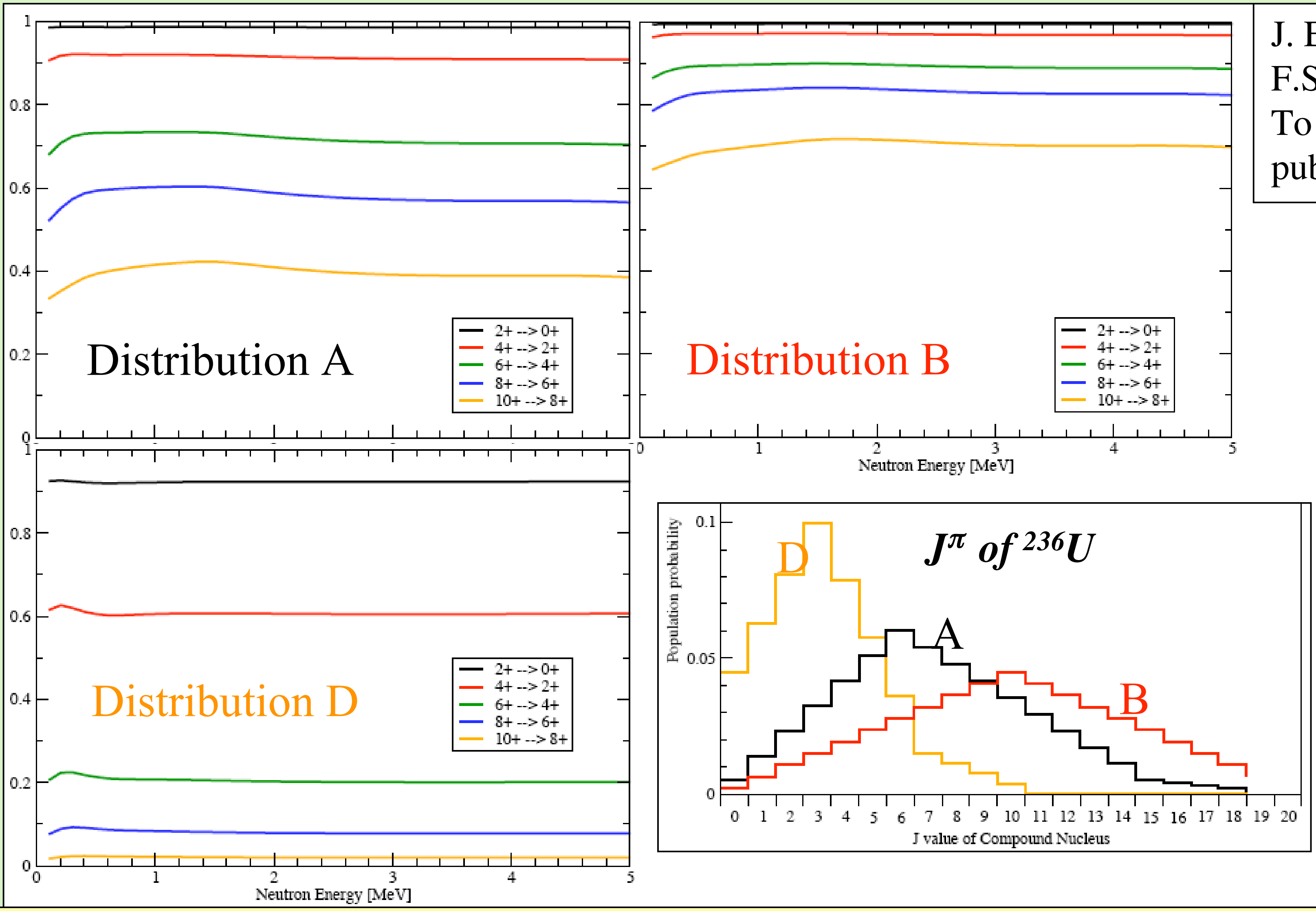
Dietrich studies evolution of a highly-excited nucleus formed by n capture, calculates likelihood that a CN forms.



Dietrich, AIP Conf. Proc. **1005** (2008) 125



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

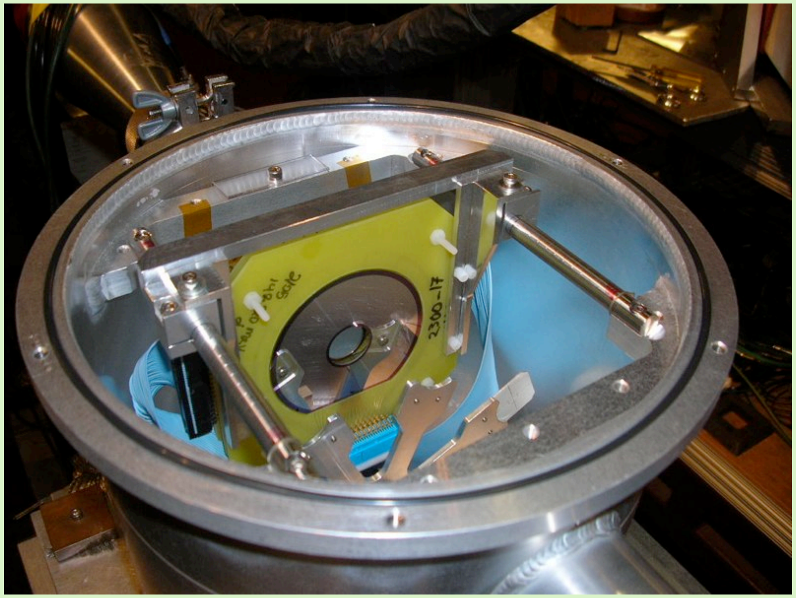


J. Escher and
F.S. Dietrich
To be
published

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.

From case study to data…

From case study to application: inelastic p scattering on ^{154,156,158}Gd



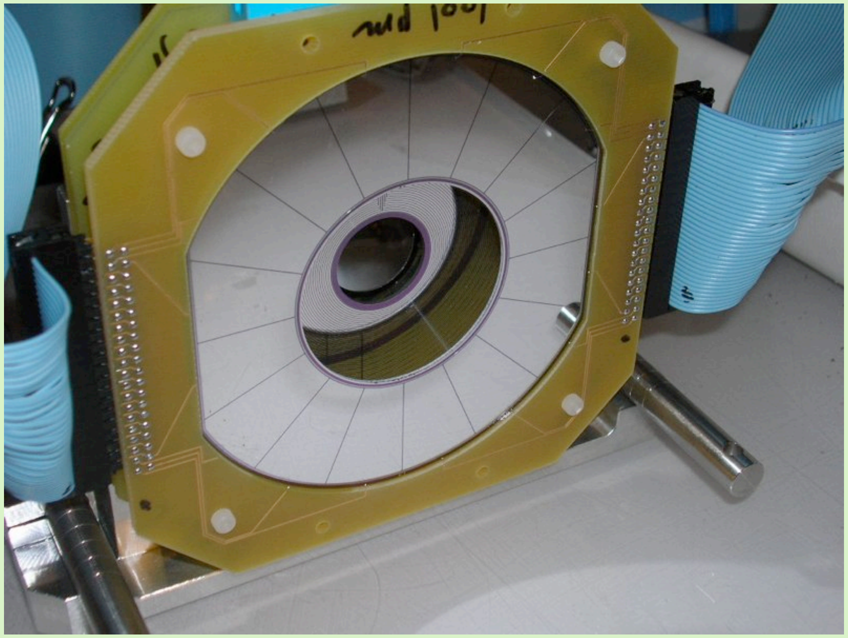
N. Scielzo et al. (analysis completed)

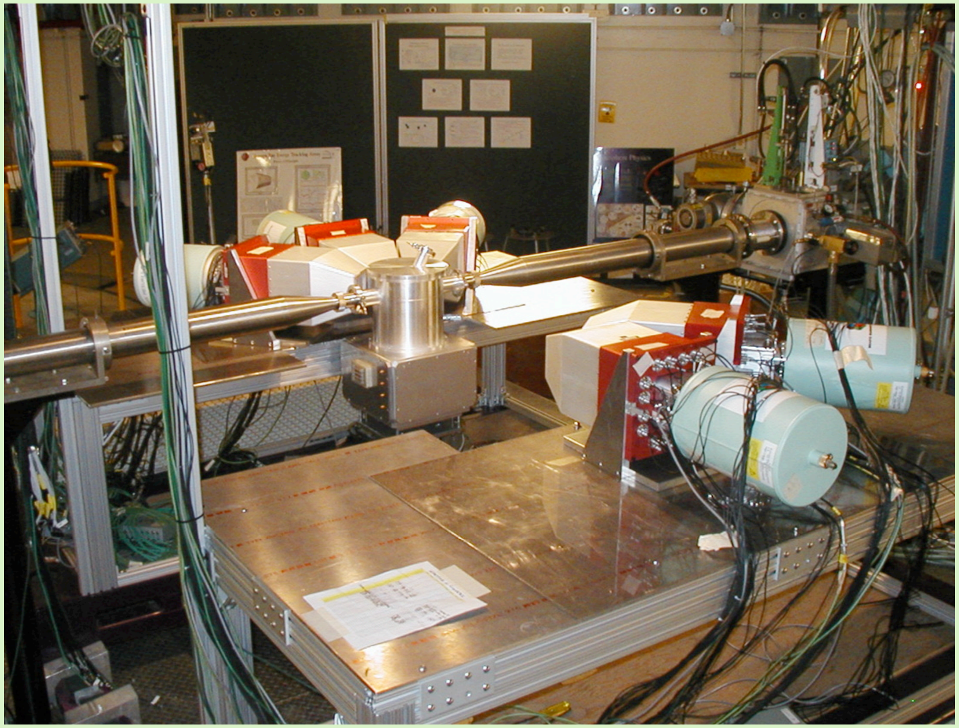
Measurements of ^{154,156,158}Gd(p,p'γ) with with E_p=22 MeV. Goal: determine the ^{153,155,157}Gd(n,γ) cross sections -- two cross sections are known, can provide tests, one is an unknown cross section of interest to astrophysics.

Silicon Telescope Array

Segmentation allows for geometric particle correlations

Target chamber and Ge detectors



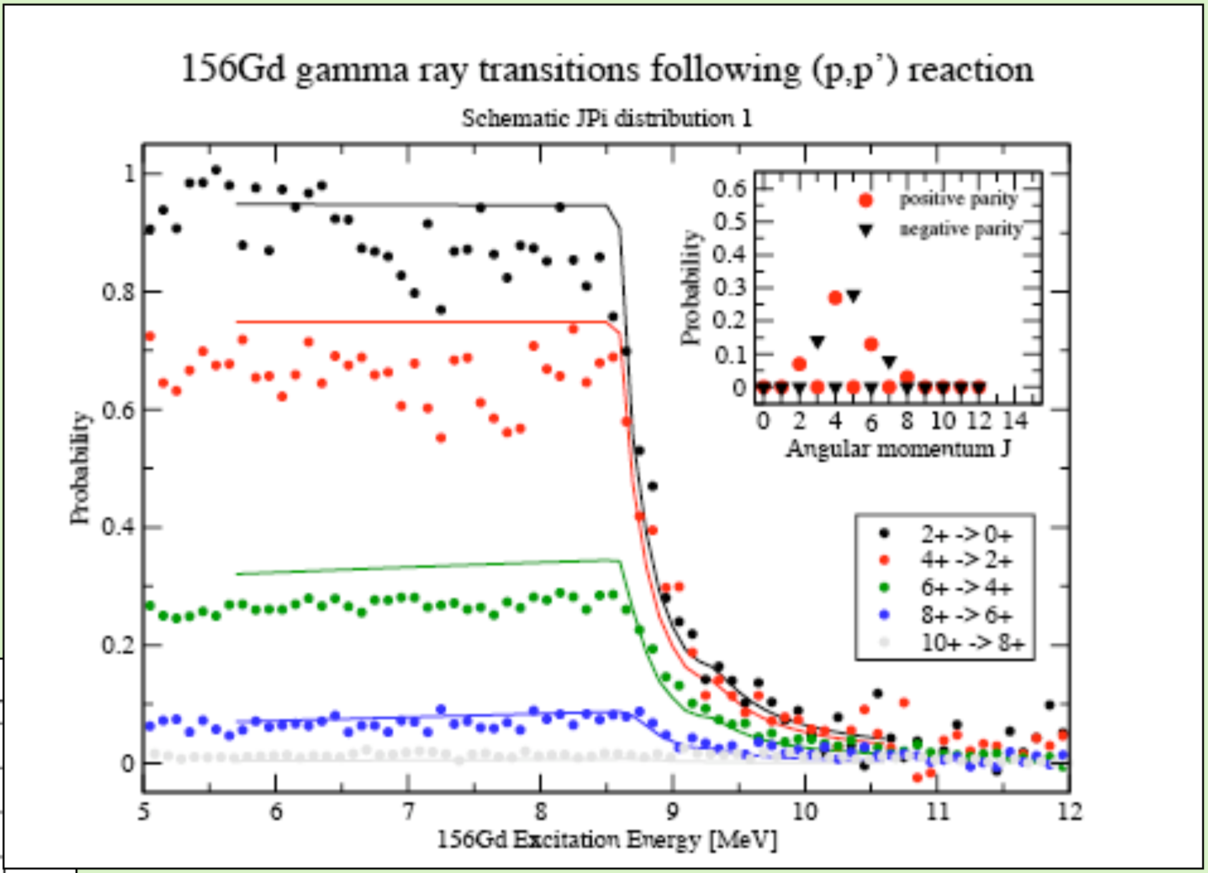


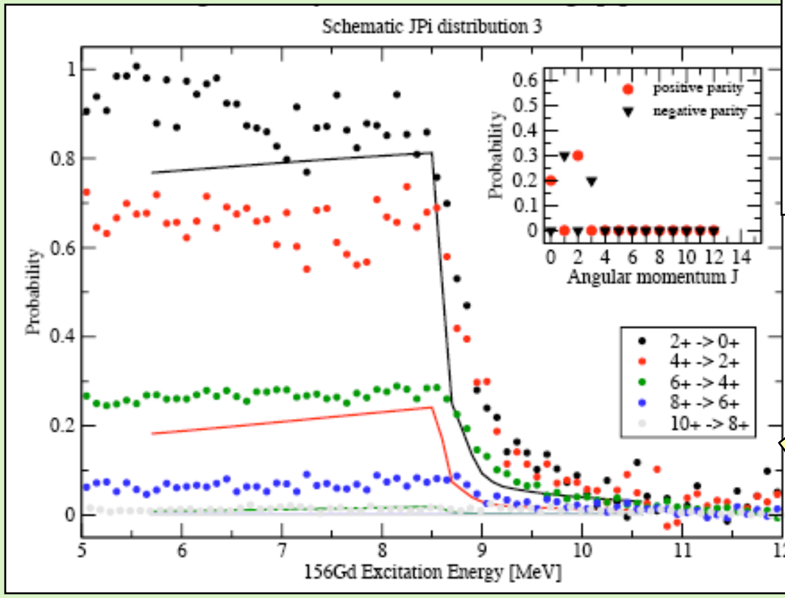
Level Density and Gamma Strength, Oslo, May 2009

J. Escher, LLNL

From case study to application: preliminary results for ^{156}Gd

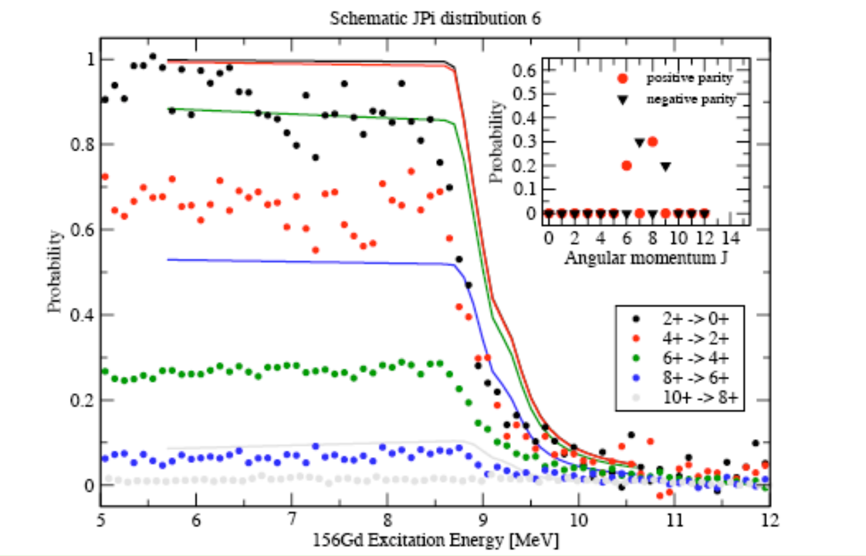
Measured γ-ray probabilities compared to calculated probabilities for various spin distributions (error bars not shown).

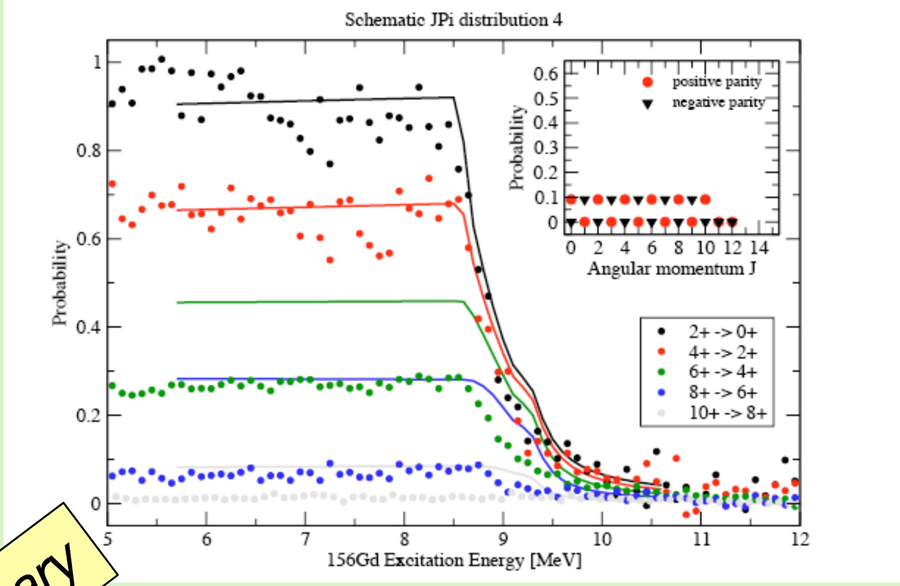




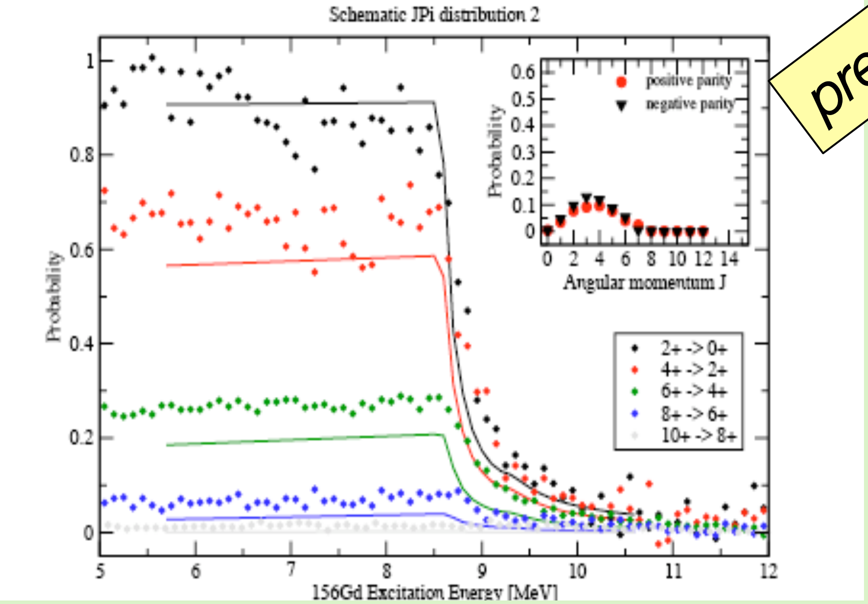
preliminary

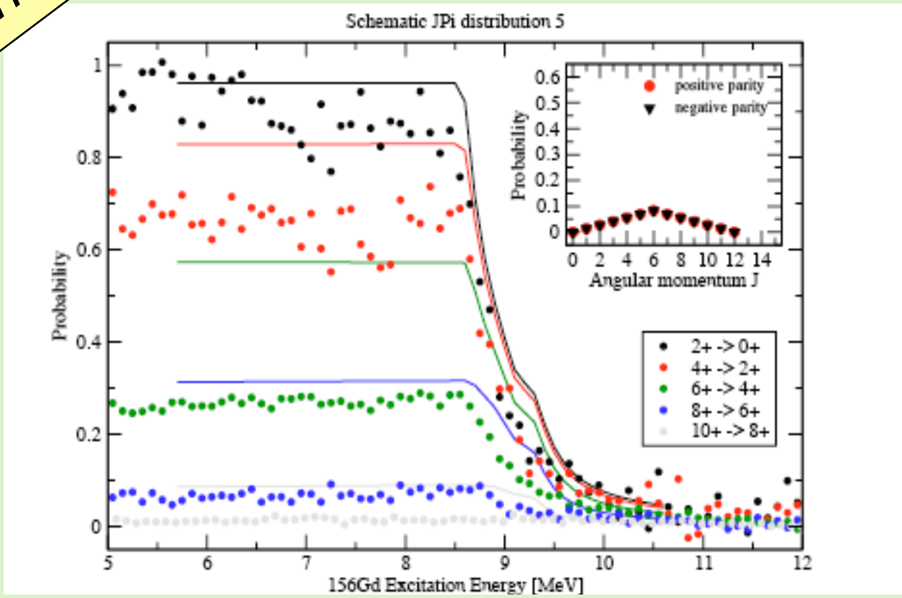
From case study to application: preliminary results for ^{156}Gd





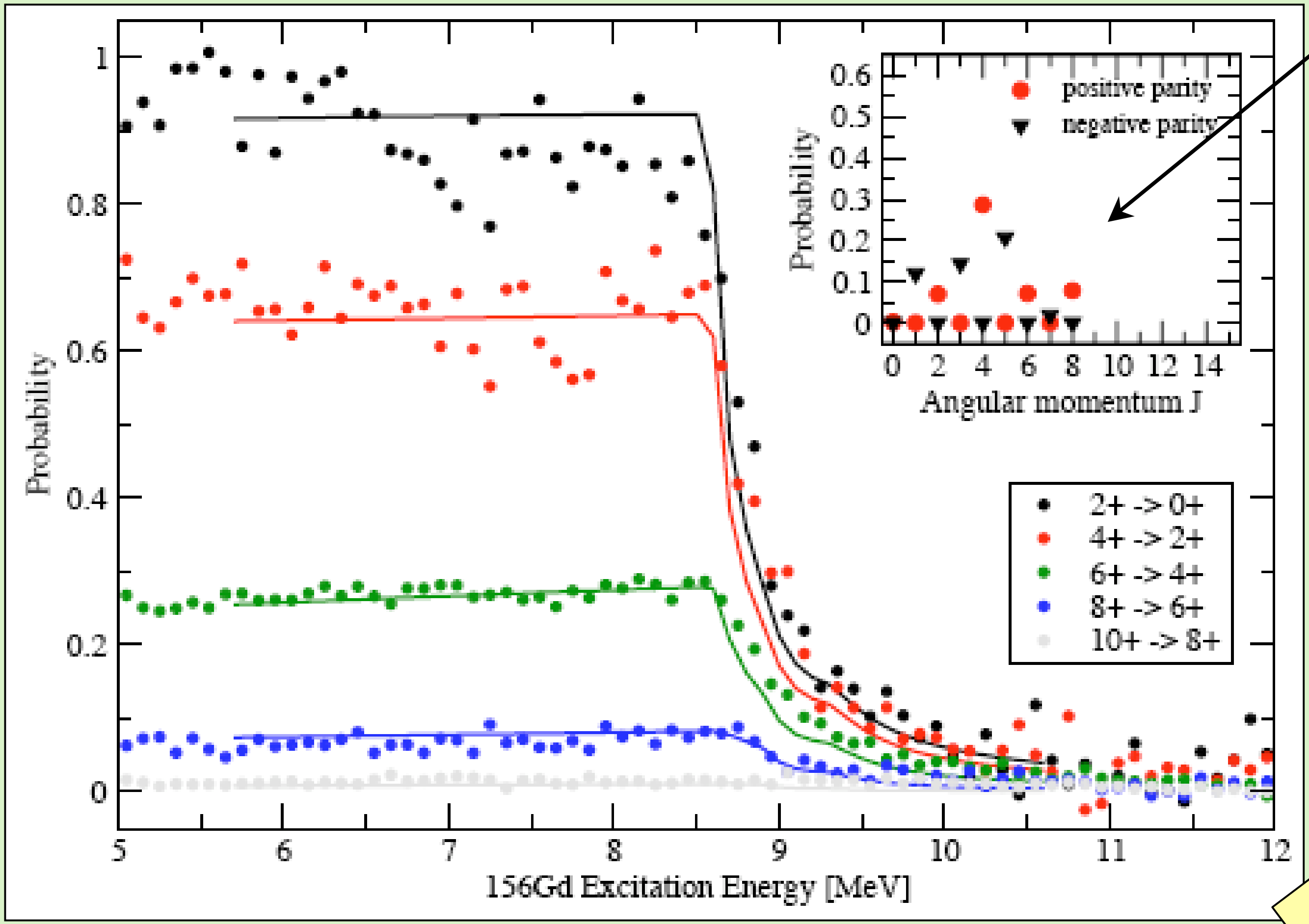
preliminary





From case study to application: preliminary results for ^{156}Gd

Extracting most likely spin-parity distribution from a comparison of data and calculations….

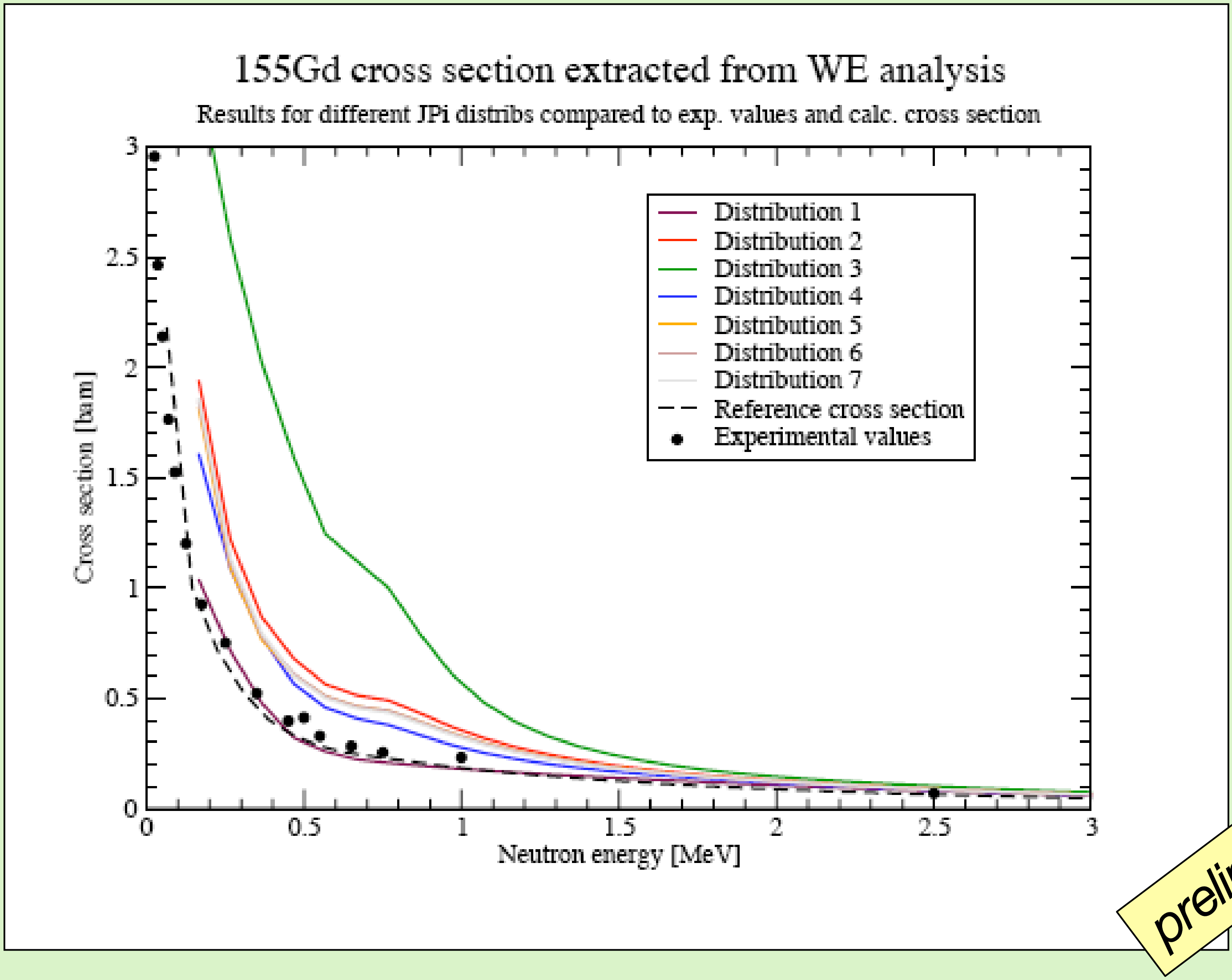


…. study dependence of results on HF parameters.

In progress…

From case study to application: preliminary results for ^{156}Gd

Implications for extracting cross sections using the Weisskopf-Ewing approximation



preliminary

Insights

Some insights

Surrogate measurements of (n,γ) cross sections:

1. Have been attempted in several experimental efforts.
2. Are more difficult to extract reliably than (n,f) cross sections.
3. The measured coincidence probabilities are very sensitive to spin distributions.
4. Theoretical simulations of the reactions shed light on the validity of the approximations and identify limitations.
5. The angular-momentum mismatch between the Surrogate and desired reactions becomes very important. It is not obvious that the WE or Ratio approximations can be used.
6. However: Sensitivity to spin distributions is not only bad….
   …experimental observable sensitive to spin and parity of the CN can be used to place constraints on theory.

Special thanks go to…..

Theory:

F.S. Dietrich, D. Gogny, R. Hoffman, I. Thompson, W. Younes *(LLNL)*
V. Gueorguiev (*UC Merced)*
A.K. Kerman (*MIT/ORNL),* G. Arbanas (*ORNL)*

Experiment:

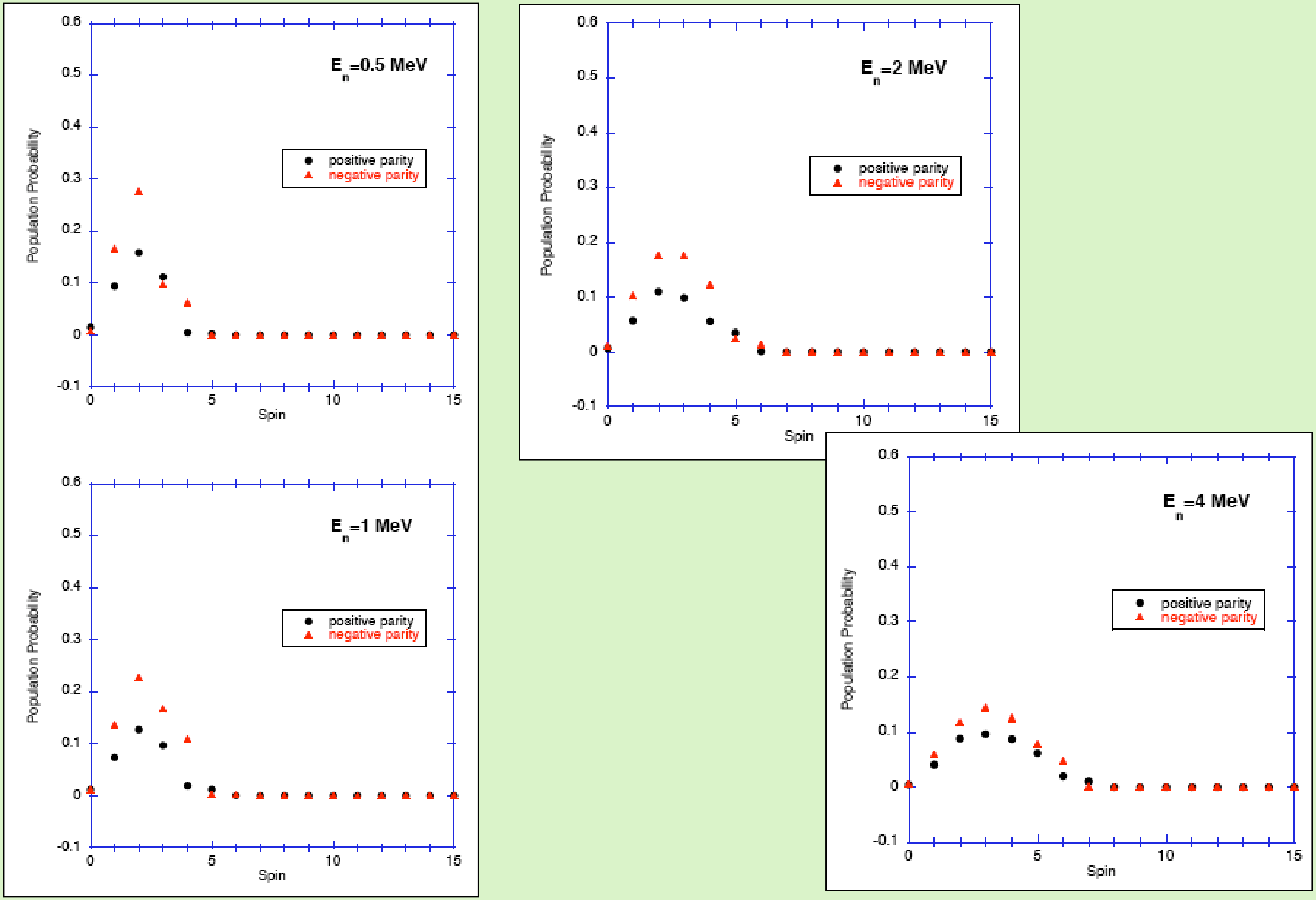
The STARS/LIBERACE collaboration, in particular:
N. Scielzo, L. Ahle, J. Burke, L. Bernstein, J. Church, S. Lesher *(LLNL)*
S. Basunia, R. Clark, L.W. Phair *(LBNL)*
B. Lyles/Goldblum *(LLNL/UC Berkeley)*
J. M. Allmond, C. Beausang *(University of Richmond)*

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

B. Jurardo (CENBG, Bordeaux)

Appendix

Spin-parity distributions in ^{156}Gd following n capture on ^{155}Gd



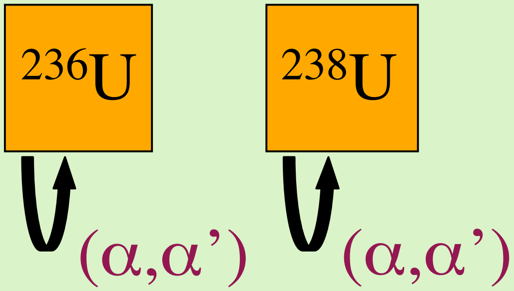
Level Density and Gamma Strength, Oslo, May 2009

J. Escher, LLNL

Ratio results from the STARS/LiberACE collaboration

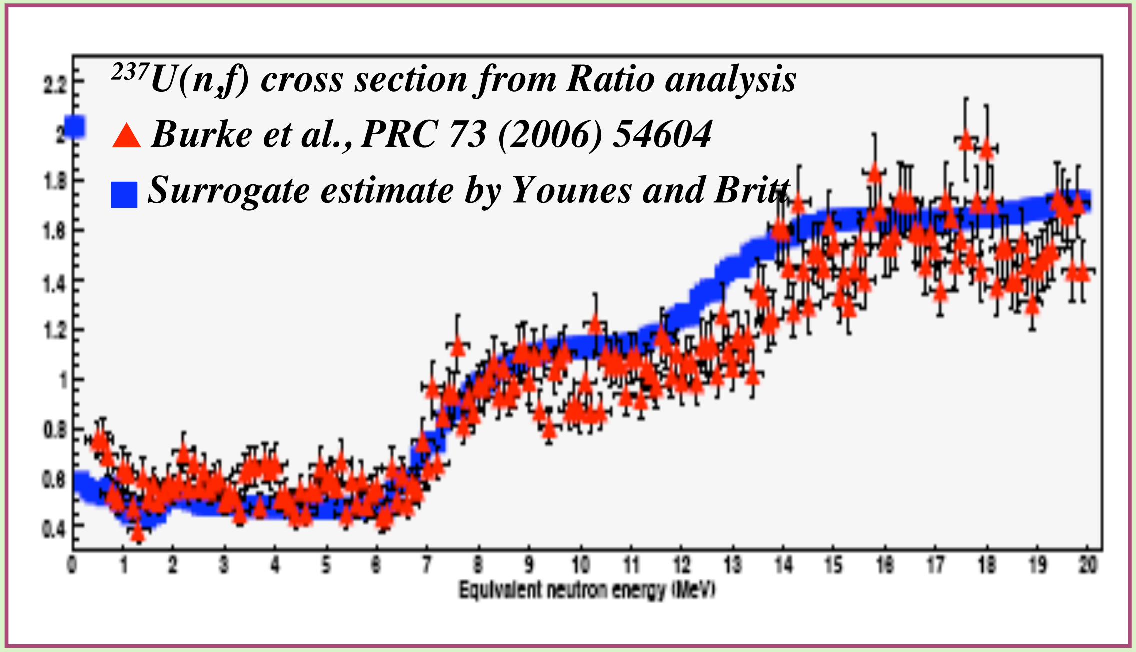
Burke et al., PRC 73 (2006) 054604

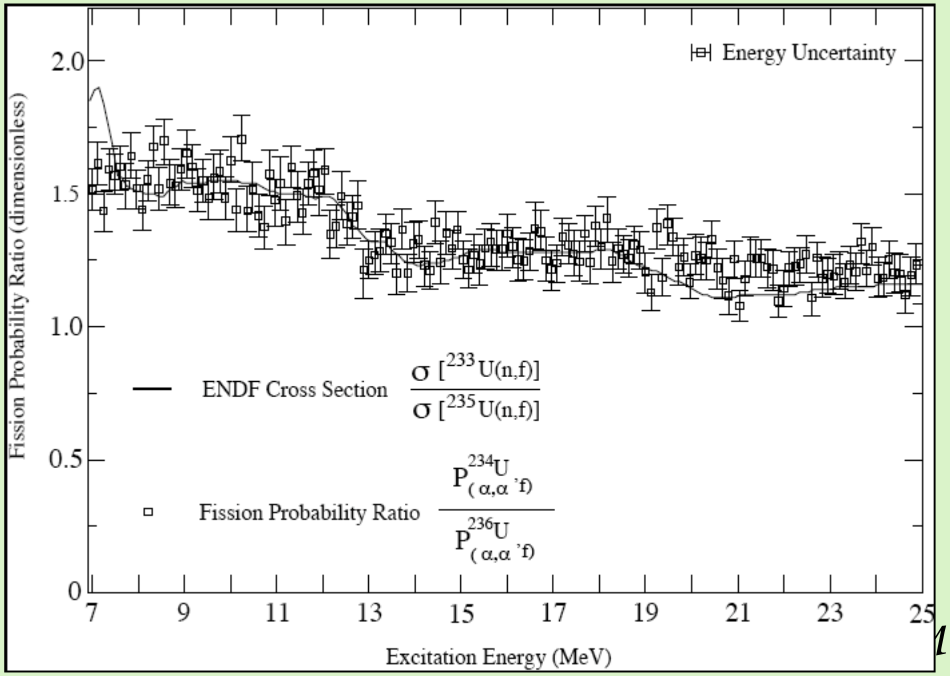
- (α,α'f) on ^{238}U and ^{236}U



^{236}U ^{238}U

(α,α') (α,α')





Lesher et al., PRC 79 (2009) 044609:

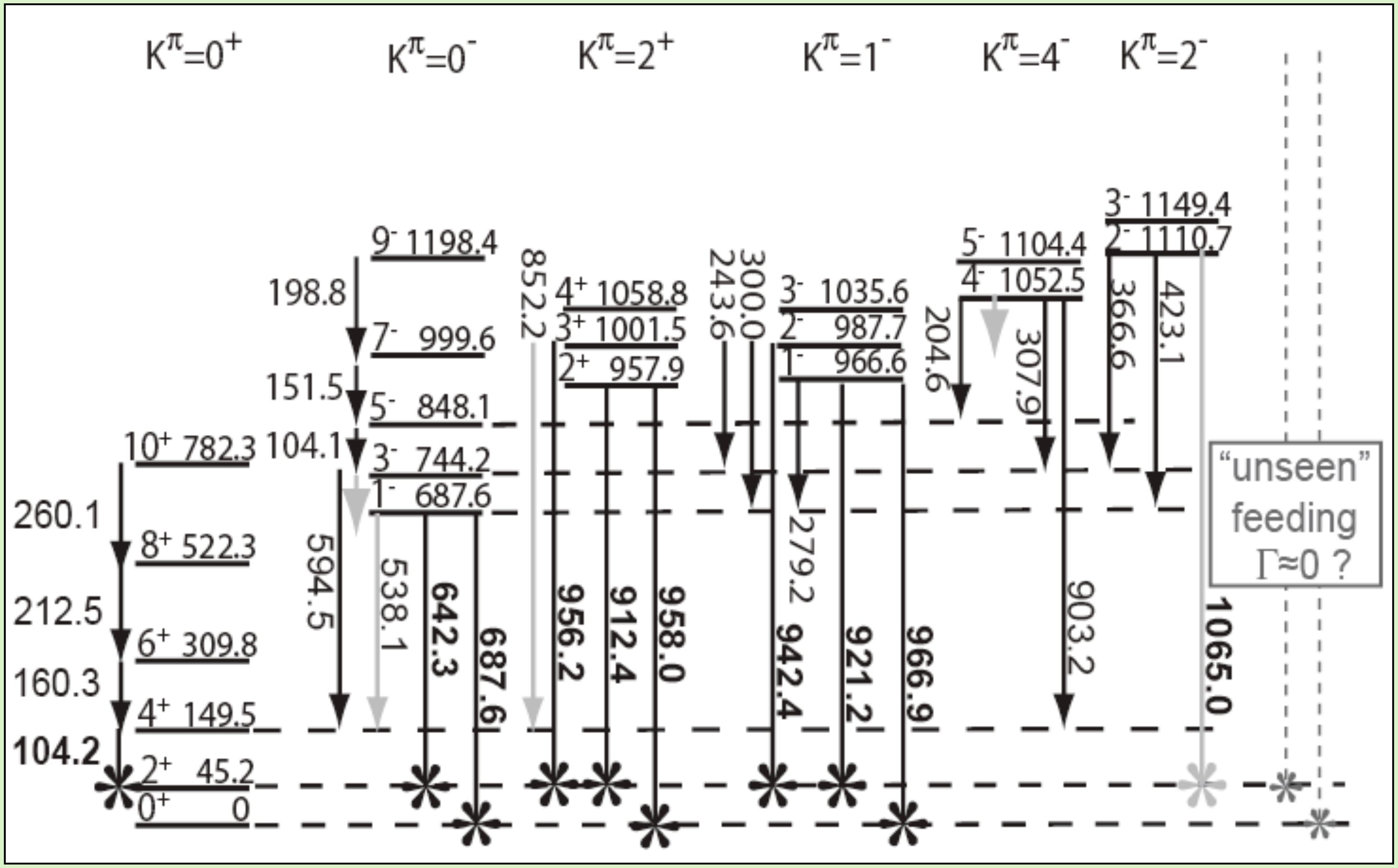
- (α,α'f) on ^{234}U and ^{236}U as a test of the Ratio method

From case study to application: preliminary results for ^{236}U

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

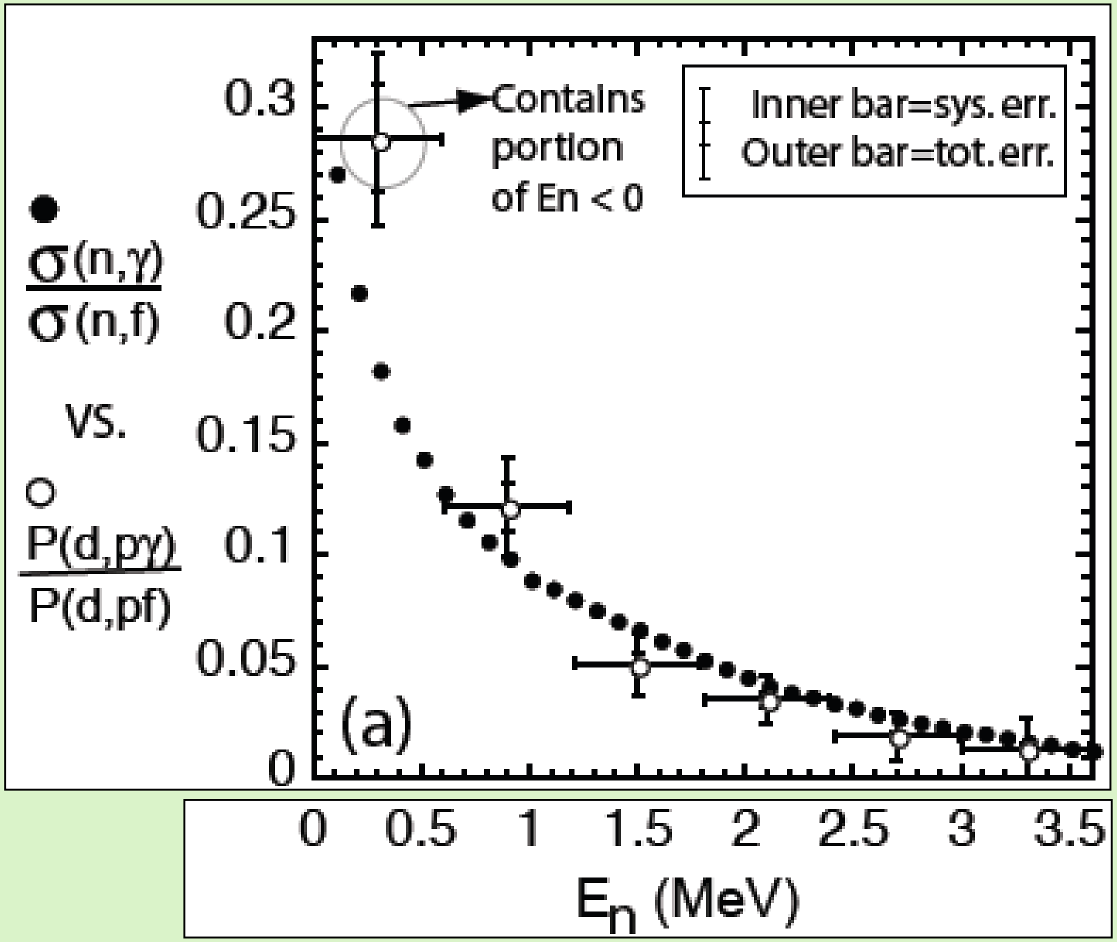
Work makes use of the assumption that 34% of the gamma cascade proceeds through the 2+ -> 0+ (642keV) transition.



From case study to application: preliminary results for ^{236}U

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

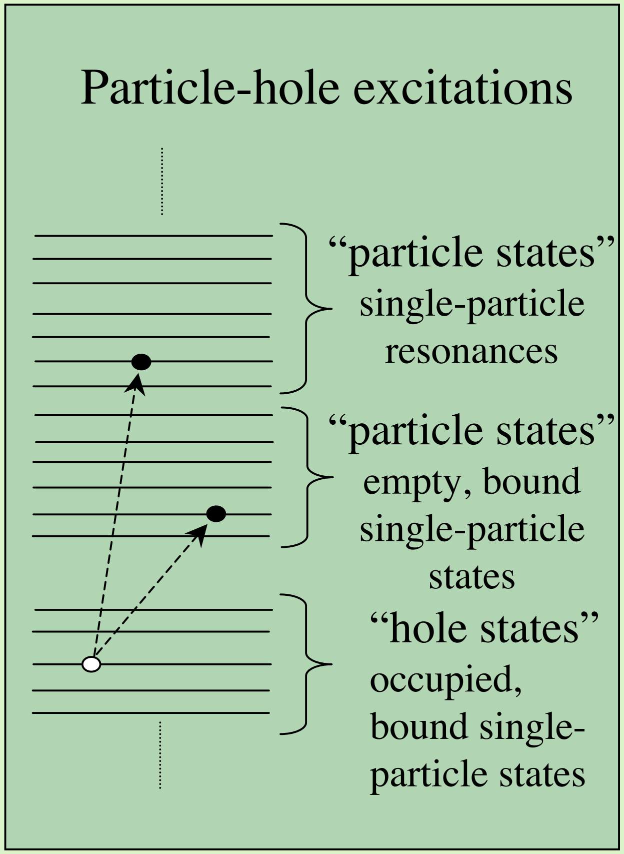
Result (using the Ratio approximation) is in agreement with evaluated cross section.



Predicting J^π for inelastic (α,α') reactions on spherical targets

Calculate cross sections for highly-excited ^{90}Zr states:

- Start with ph description, weak-binding approximation, phenomenological OMPs, schematic treatment of spreading widths
- Systematic investigation of improved nuclear structure input: use Hartree-Fock/RPA approach,…



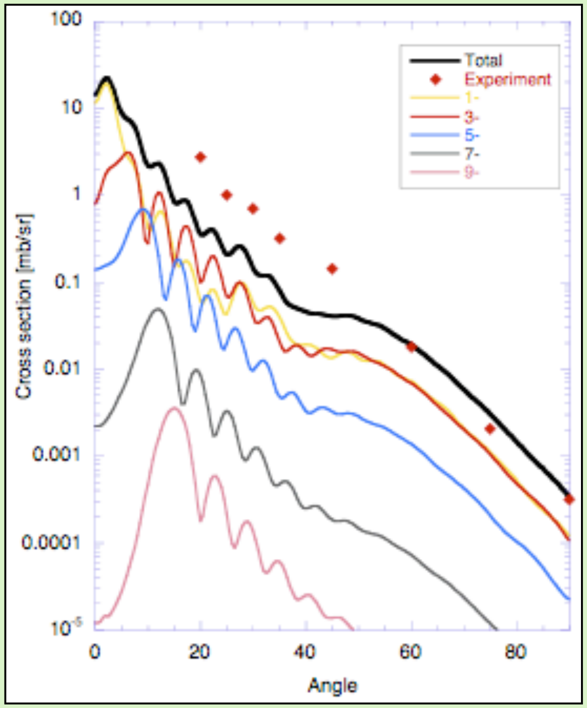
Particle-hole excitations

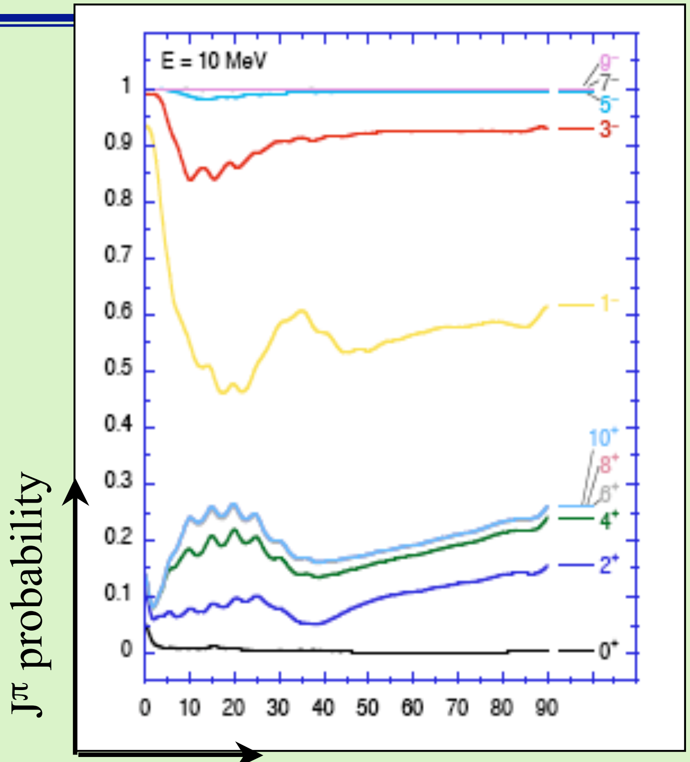
"particle states"
single-particle
resonances

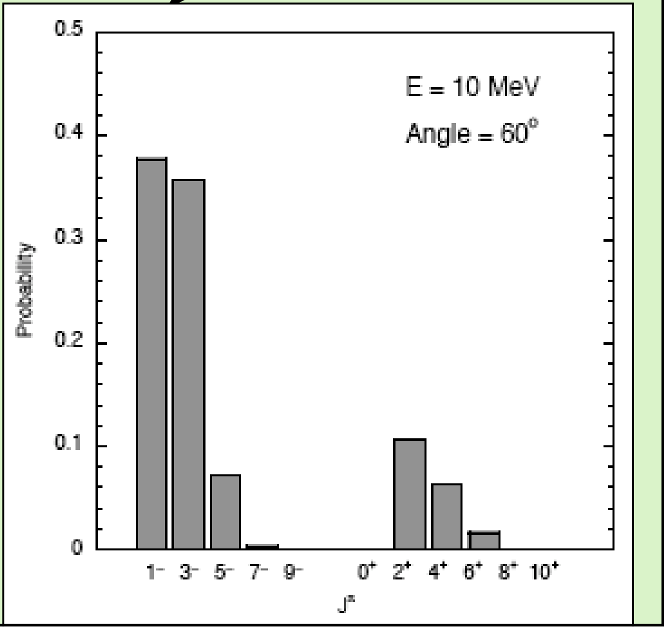
"particle states"
empty, bound
single-particle
states

"hole states"
occupied,
bound single-
particle states

J. Escher & F.S. Dietrich, UCRL-TR-404300





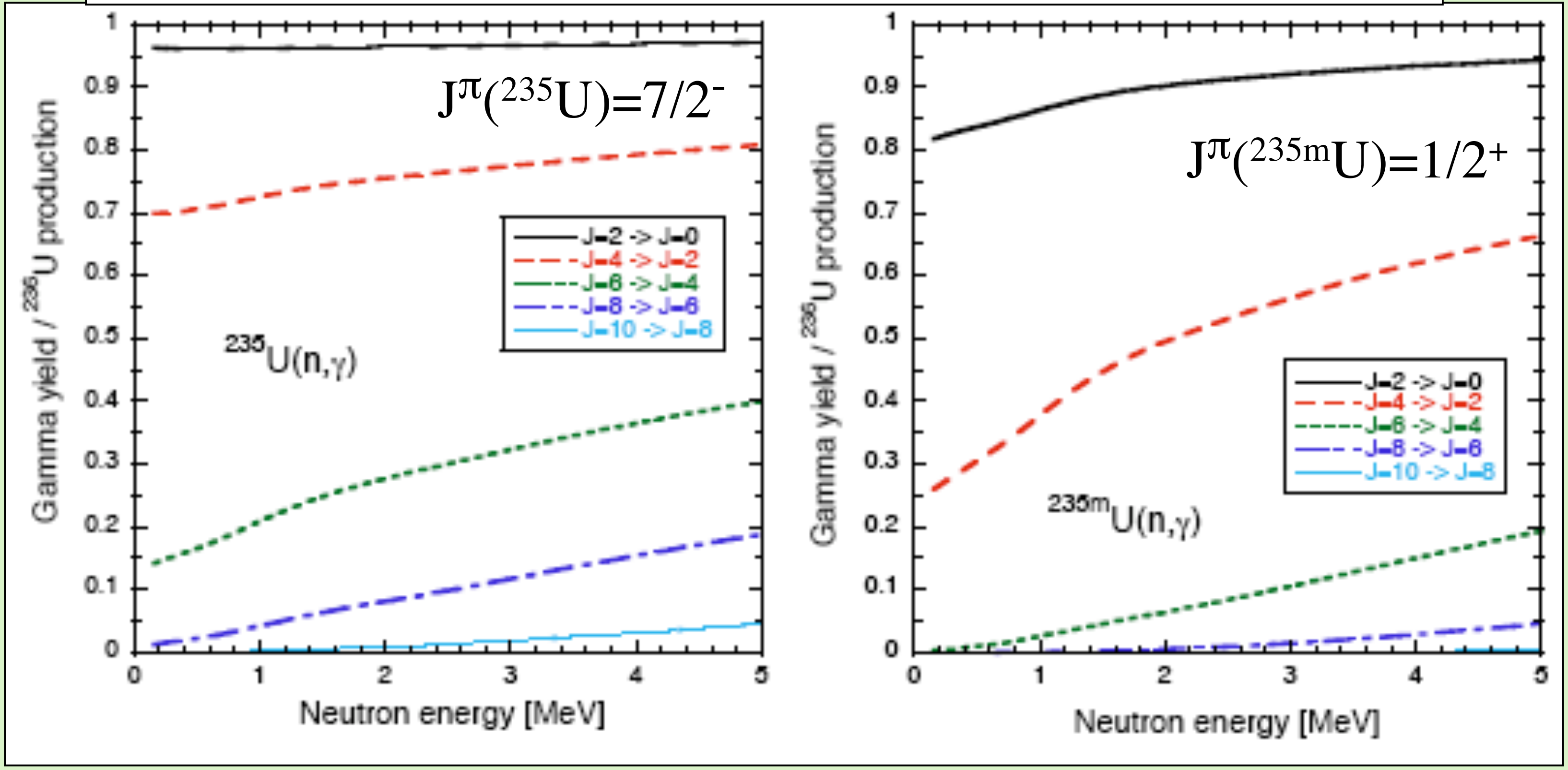


Extensions:

- Improved structure description (RPA transition densities) now available
- (p,p') to be treated analogously
- Consider deformed nuclei

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

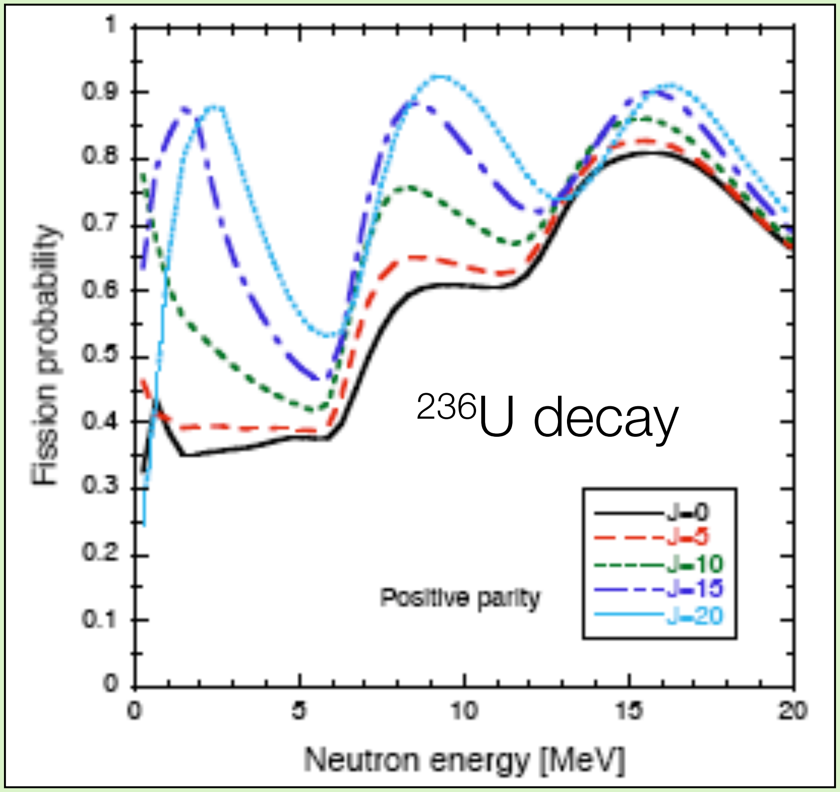
A look at the γ yields for ^{236}U decay with different J^π populations

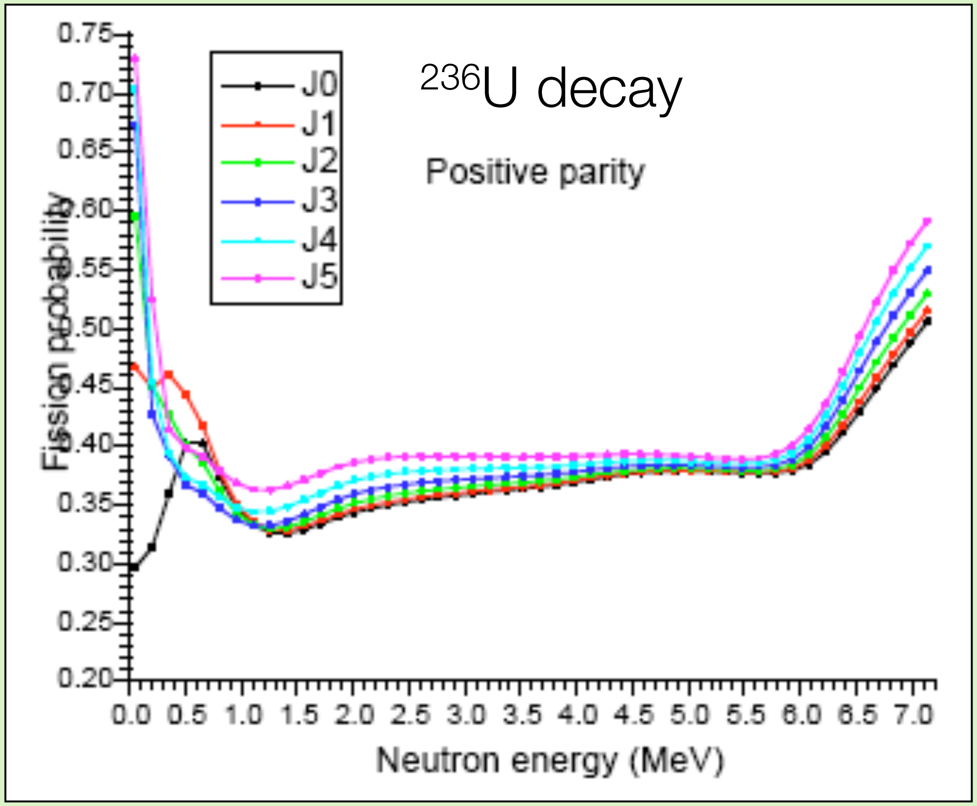


Observation: Relative γ-ray intensities depend sensitively on J^π distribution of the decaying compound nucleus.

Relative γ-ray intensities as function of E for n+^{235m}U and n+^{235}U (not for a Surrogate reaction!)

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





Observations:

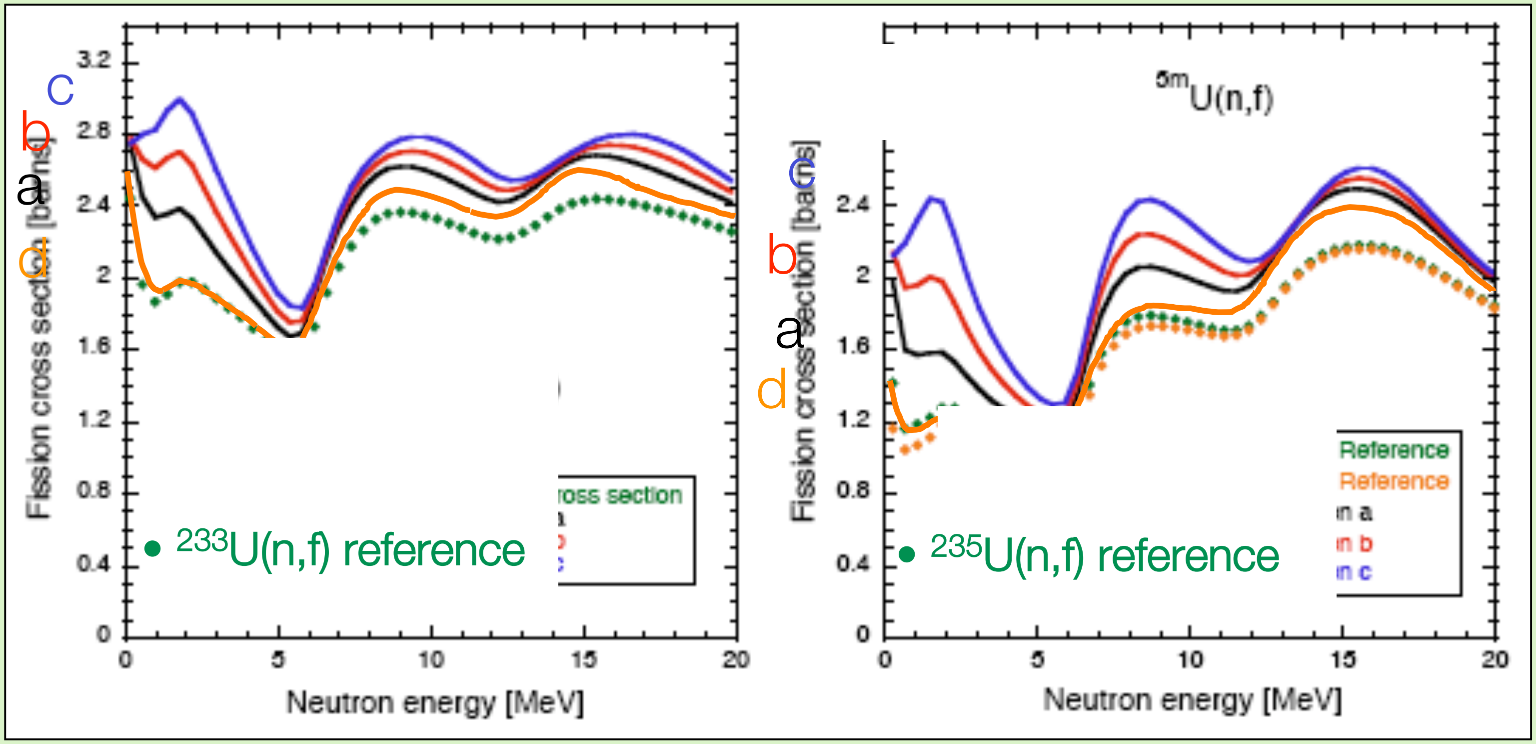
- Fission probabilities show significant J^{π} dependence
- For small energies the WE approximation is not valid
- Differences between fission probabilities increase at onset of 2nd chance fission
- Results depend little on parity (not shown)

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

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 a WE simulation

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



Observations

- The deduced cross sections are clearly dependent on the J^{π} distribution (WE limit not strictly valid)
- The largest uncertainty are below E_n=3 MeV and are due to angular-momentum effects
- Deviations at higher energies are due to preequilibrium effects.

- Identifying a Surrogate reaction that produces a CN similar to that of the desired reaction yields the best result for the extracted cross section
- The Surrogate reaction approach does not account for preequilibrium effects in desired reaction.