Surrogate Reactions: Status & Prospects

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Jutta Escher
Nuclear Theory & Modeling Group
Lawrence Livermore National Laboratory

Lawrence Livermore
National Laboratory

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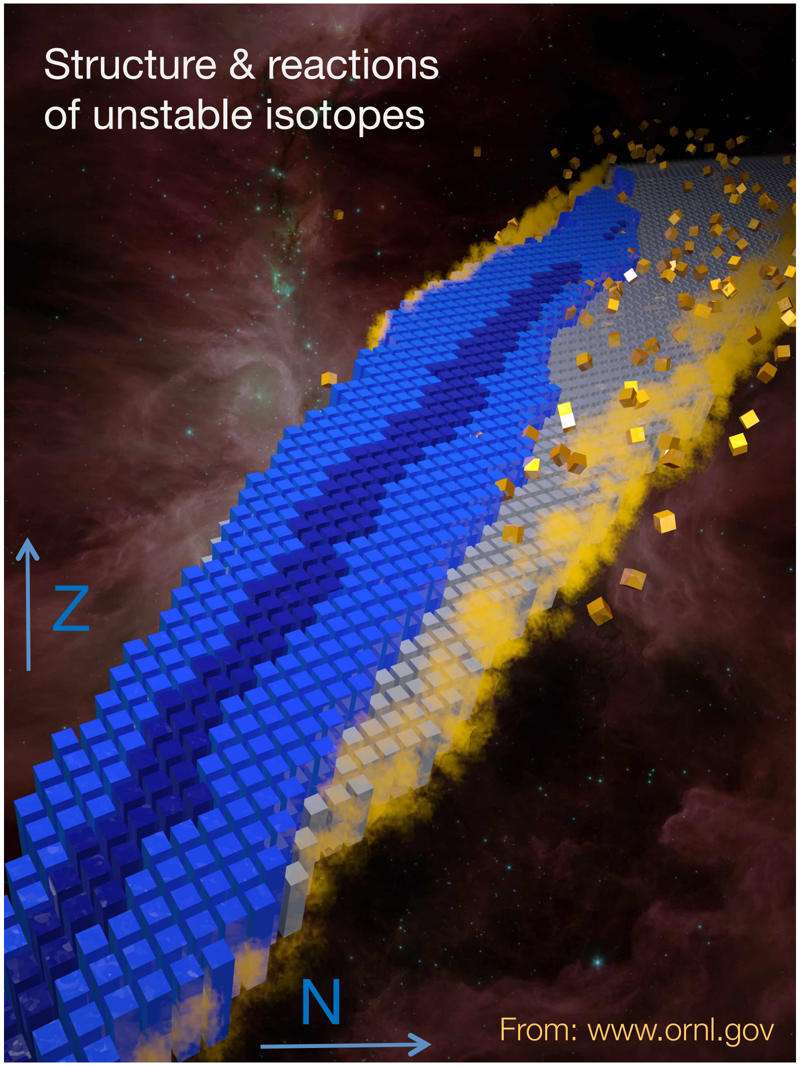
Structure and reaction data for unstable isotopes



… are important for addressing basic science questions and for applications.

Reaction cross sections are important for nuclear astrophysics, nuclear energy, and national security.

Challenge: Many important nuclear reaction cross sections cannot be measured directly

Needed: Indirect methods for determining desired cross sections and/or constraining calculations

This talk: Focus on indirect determination of cross sections for compound-nuclear reactions (mostly n-induced reactions) via the surrogate approach. Propose improvements to make the approach more widely applicable.

Surrogate Reactions 101

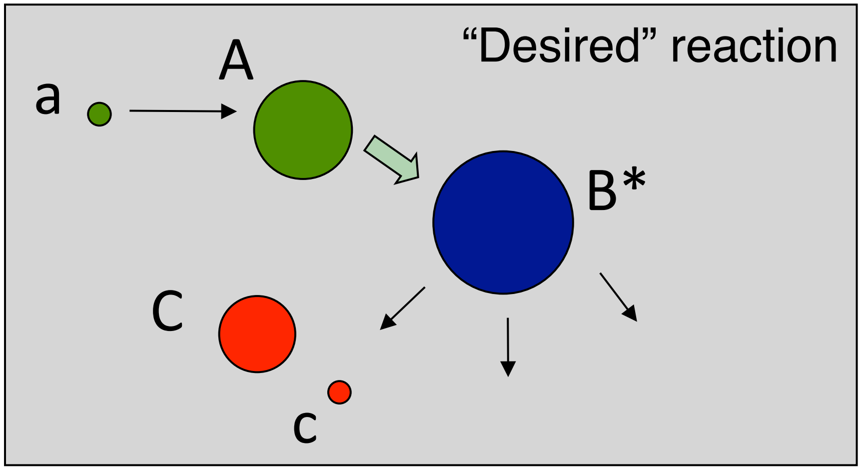
Compound reaction

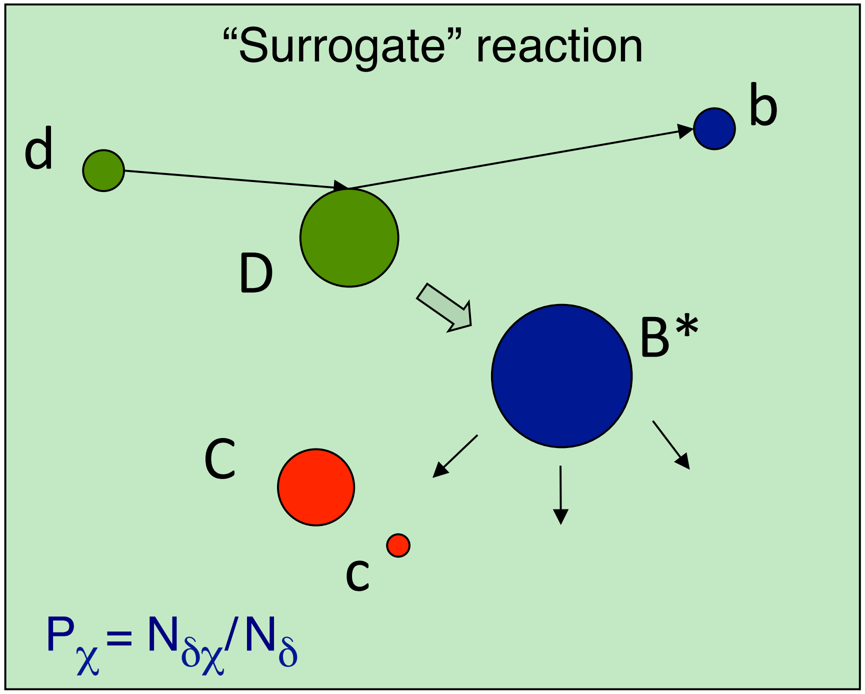
A reaction that proceeds in two stages: formation of a compound-nucleus (CN) and decay

Surrogate approach

An indirect method for obtaining cross sections for compound-nucleus (CN) reactions

Using an intial direct reaction, a CN is formed and its decay is observed. Theory is used to extract the desired reaction.



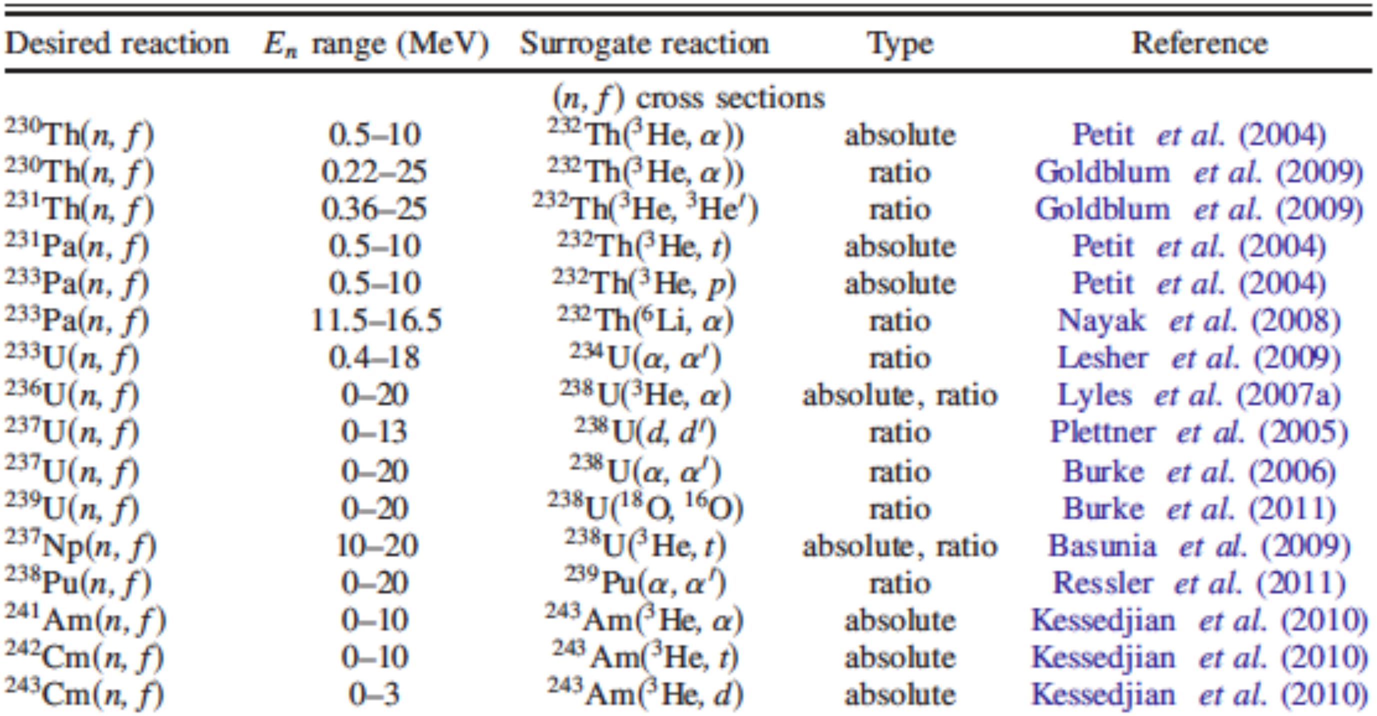


$P_\chi = N_{\delta\chi}/N_\delta$

Surrogate Reactions 101

History

- The surrogate method was introduced in the 1970s by Britt, Cramer, Wilhelmy, *et al*, to determine (n,f) cross sections.
- In the last 10 years, the method has been revived, primarily for (n,f).
- Most applications use approximate treatments, ignoring the difference in the reaction mechanisms that lead to the CN (aka Weisskopf-Ewing approximation)



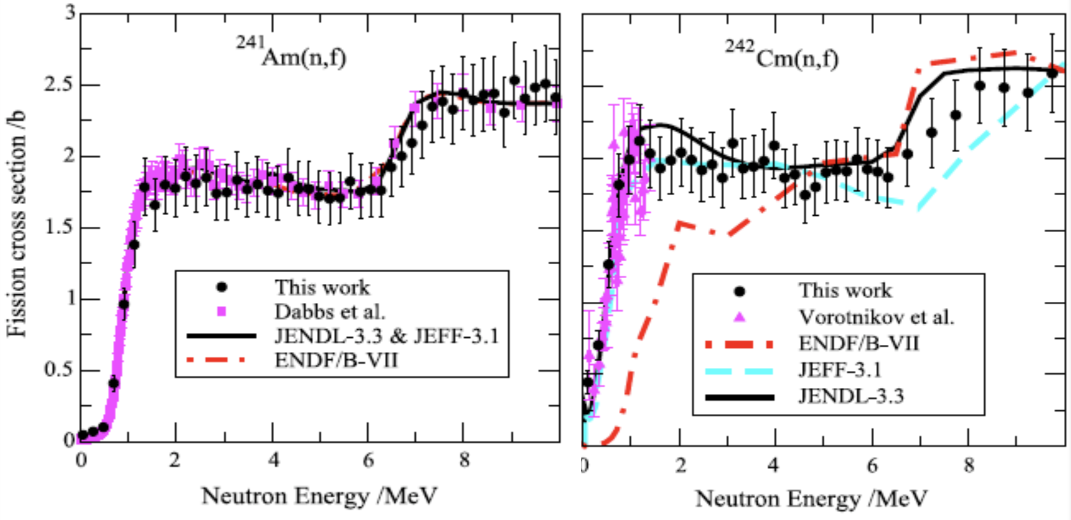
Desired reaction	E_n range (MeV)	Surrogate reaction	Type	Reference
		(n, f) cross sections		
^{230}Th(n, f)	0.5–10	^{232}Th$(^3$He$, \alpha))$	absolute	Petit *et al.* (2004)
^{230}Th(n, f)	0.22–25	^{232}Th$(^3$He$, \alpha))$	ratio	Goldblum *et al.* (2009)
^{231}Th(n, f)	0.36–25	^{232}Th$(^3$He$, ^3$He$')$	ratio	Goldblum *et al.* (2009)
^{231}Pa(n, f)	0.5–10	^{232}Th$(^3$He$, t)$	absolute	Petit *et al.* (2004)
^{233}Pa(n, f)	0.5–10	^{232}Th$(^3$He$, p)$	absolute	Petit *et al.* (2004)
^{233}Pa(n, f)	11.5–16.5	^{232}Th$(^6$Li$, \alpha)$	ratio	Nayak *et al.* (2008)
^{233}U(n, f)	0.4–18	^{234}U(α, α')	ratio	Lesher *et al.* (2009)
^{236}U(n, f)	0–20	^{238}U$(^3$He$, \alpha)$	absolute, ratio	Lyles *et al.* (2007a)
^{237}U(n, f)	0–13	^{238}U(d, d')	ratio	Plettner *et al.* (2005)
^{237}U(n, f)	0–20	^{238}U(α, α')	ratio	Burke *et al.* (2006)
^{239}U(n, f)	0–20	^{238}U$(^{18}$O$, ^{16}$O$)$	ratio	Burke *et al.* (2011)
^{237}Np(n, f)	10–20	^{238}U$(^3$He$, t)$	absolute, ratio	Basunia *et al.* (2009)
^{238}Pu(n, f)	0–20	^{239}Pu(α, α')	ratio	Ressler *et al.* (2011)
^{241}Am(n, f)	0–10	^{243}Am$(^3$He$, \alpha)$	absolute	Kessedjian *et al.* (2010)
^{242}Cm(n, f)	0–10	^{243}Am$(^3$He$, t)$	absolute	Kessedjian *et al.* (2010)
^{243}Cm(n, f)	0–3	^{243}Am$(^3$He$, d)$	absolute	Kessedjian *et al.* (2010)

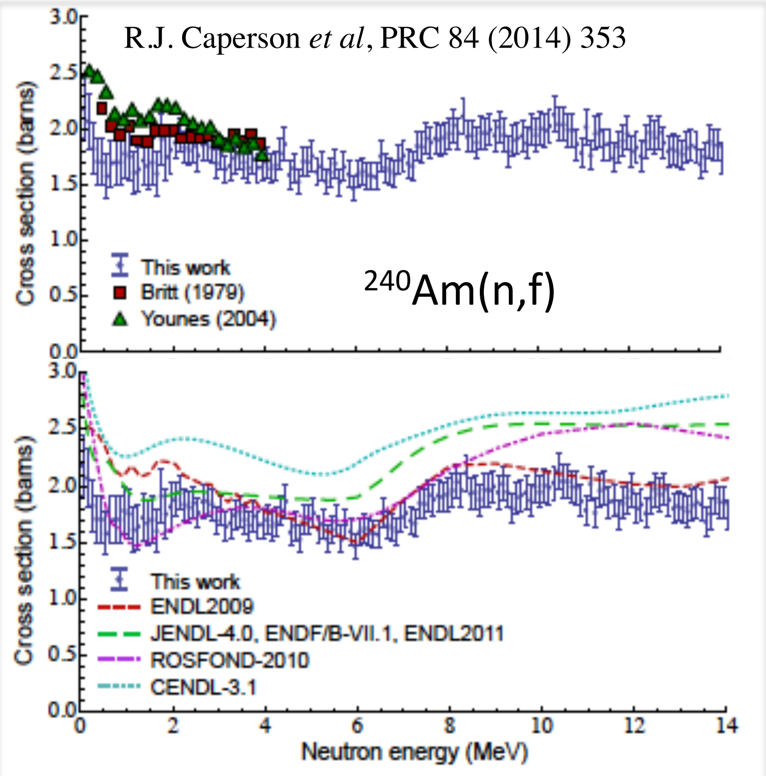
J. Escher *et al*, RMP 84 (2012) 353

(n,f) cross sections from surrogate measurements

- ✓ Complement and extend indirect and direct measurements
- ✓ Typically agree within 10-15% with benchmarks
- ✓ Make use of approximation schemes

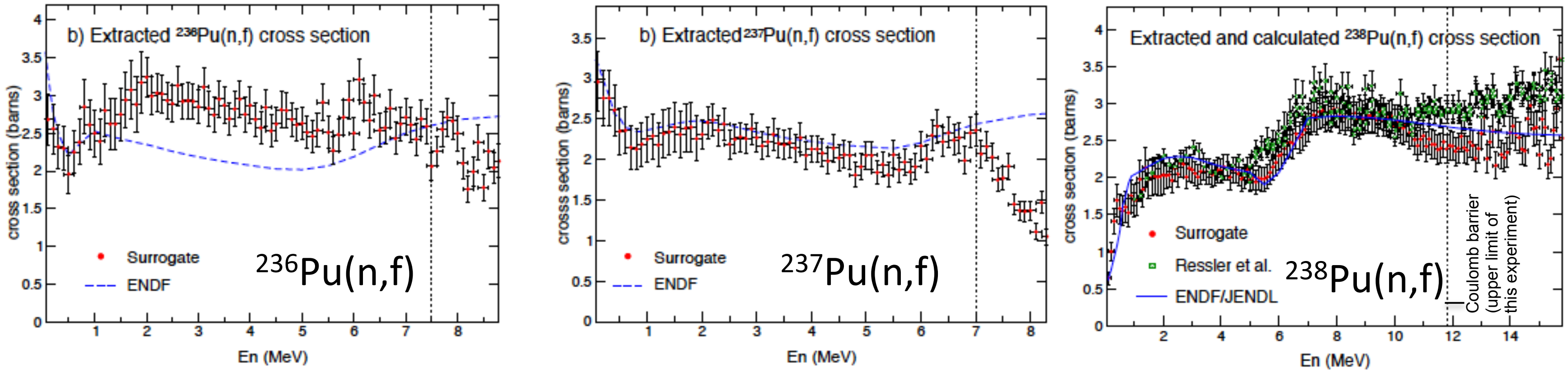
Kessedjian *et al*. (CENBG), PLB 692 (2010) 297





R.J. Caperson *et al*, PRC 84 (2014) 353

R.O. Hughes *et al*, PRC 90 (2014) 014304

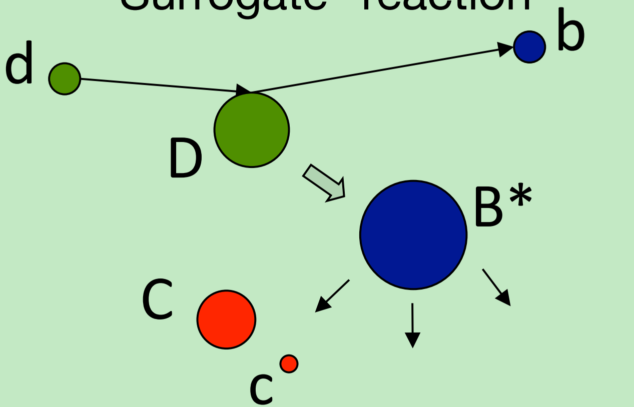


Previous work used a number of approximations

Prevailing assumptions

1. Weisskopf-Ewing approximation valid
2. No ‘pre-equilibrium’ contributions

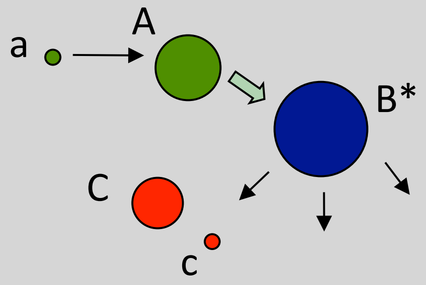
“Surrogate” reaction



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

Weisskopf-Ewing description of the “desired” reaction:

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



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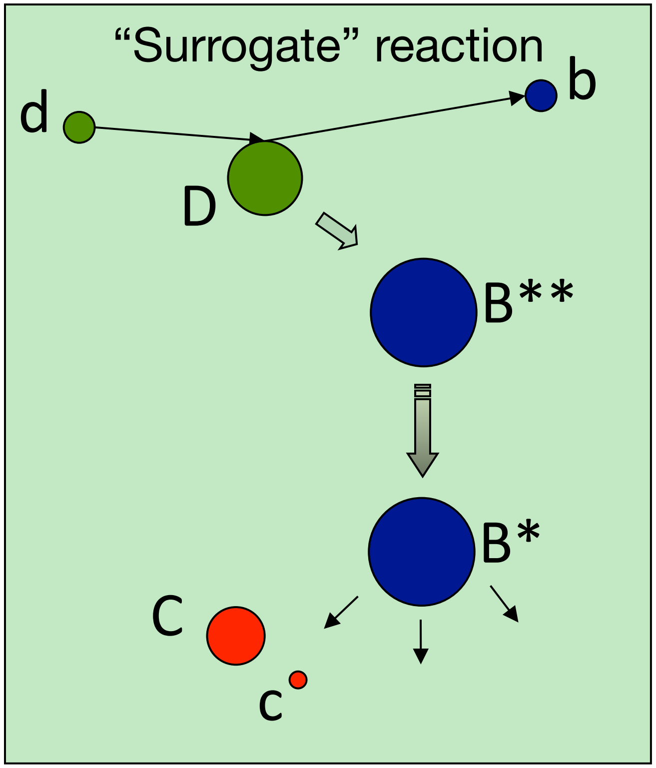

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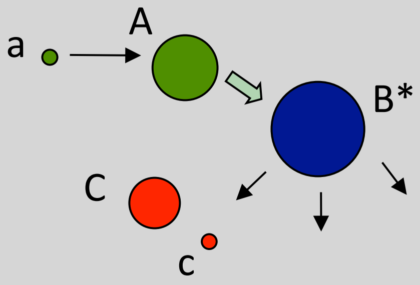
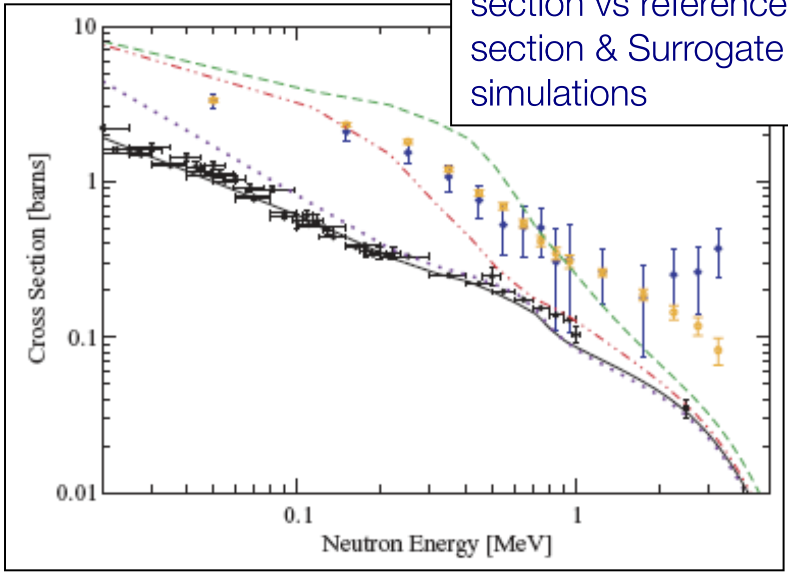


Current implementations of surrogate method are insufficient

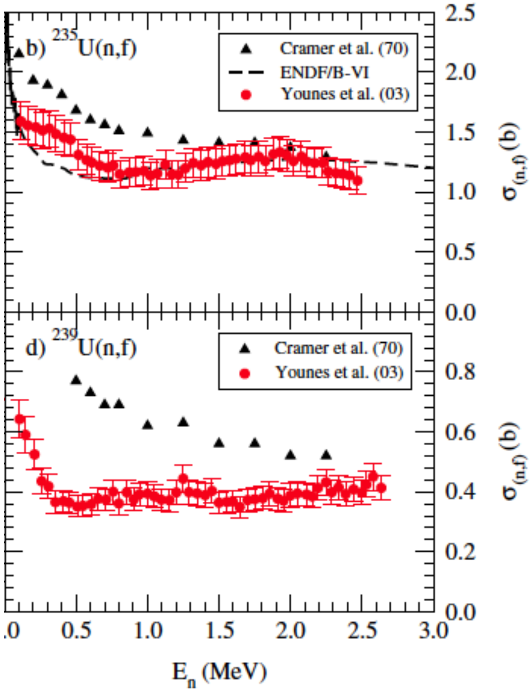
Known limitations

1. WE approximation fails for (n,γ) and (n,p)
2. Limitations visible in low-E regime, e.g. in (n,f) reactions

Extracted ^{157}Gd(n,γ) cross section vs reference cross section & Surrogate simulations



J. Escher and F.S. Dietrich, PRC 81 (2010) 024612
N. Scielzo, J. Escher, et al., PRC 81 (2010) 034608



Younes & Britt, PRC (2003)

Suspect assumption

`Pre-equilibrium effects' are non-existent or can be ignored

Need to move beyond 'Surrogates 101'

Surrogate Reactions – next level….

Objective

Apply the surrogate method to wider range of reactions, such as (n,γ) and (n,2n)

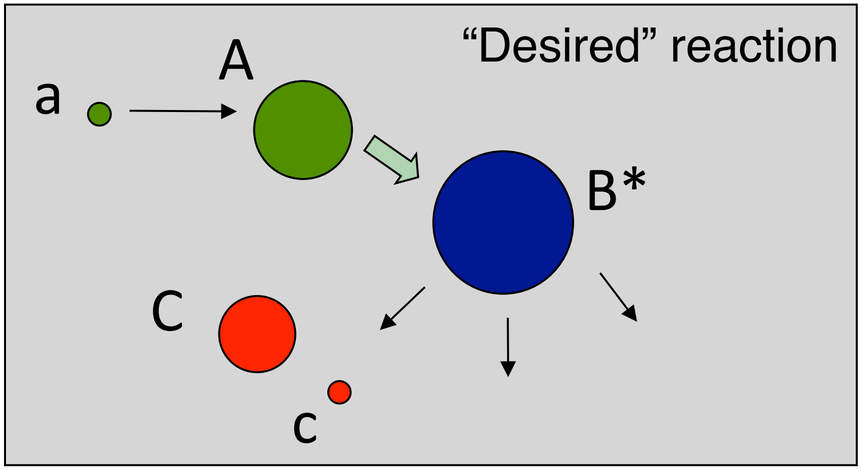
Needed:

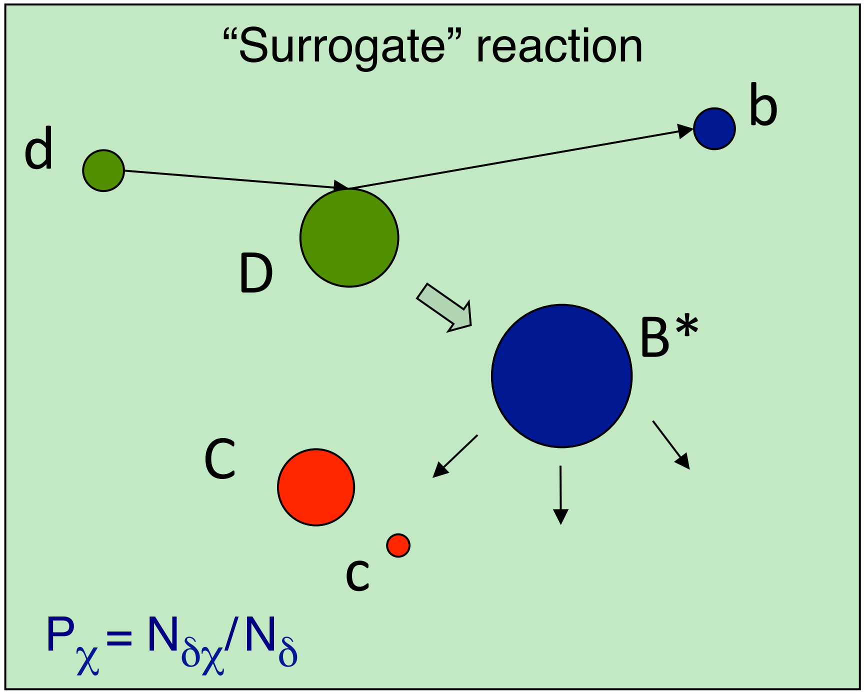
Improved treatment of the reaction mechanisms:

- descriptions of the formation of the CN via transfer or inelastic scattering reactions
- descriptions of the competition between damping and ‘pre-equilibrium’ decay processes.

New strategy for using surrogate data.

Experiments to shed light on the processes.





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

Strategies for constraining HF inputs

I. **Determine ingredients γSF & LD**:

- Theory challenging, not all nuclei covered, but progress is being made
- Experiments need to ‘de-convolute’ γSF & LD, not all nuclei can be reached

II. **Cross section constraints from neighbors**:

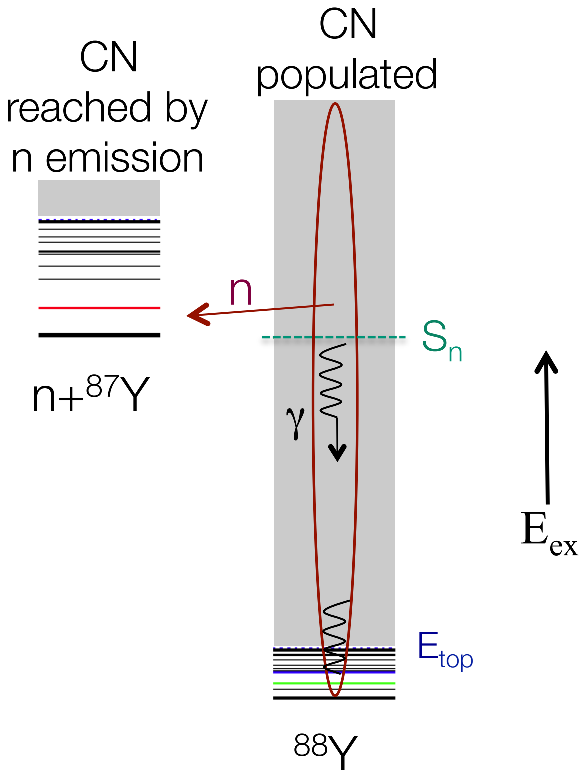
- Measure (n,γ) cross sections in other nuclei & do regional fits
- Extrapolations required

III. **Constraints from surrogate observables**:

- Surrogate approach: use charged-particle transfer or inelastic scatering to create CN of interest and observe decay
- Use measurement to constrain calculation of desired cross section
- Theory needed to relate measurement to desired cross section
- Measure quantities in **actual nuclei of interest**

Implementing a new strategy: Surrogate approach beyond WE

Desired reaction: ^{87}Y(n,g)^{88}Y



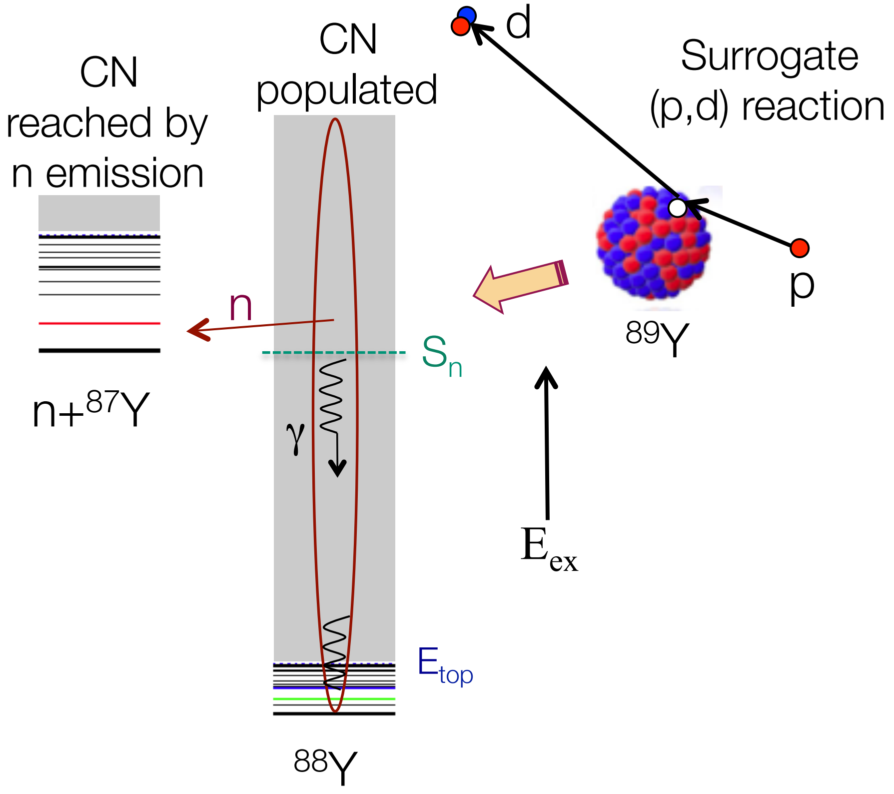
Hauser-Feshbach description of "desired" CN reaction

$$\sigma_{(n,\gamma)} = \sum_{J,\pi} \sigma_{n+target}^{CN}(E,J,\pi) \cdot G^{CN}_{\gamma}(E,J,\pi)$$

Implementing a new strategy: Surrogate approach beyond WE

Surrogate experiment

- Produce CN ^{88}Y via alternative **p + ^{89}Y -> d + ^{88}Y** involving stable ^{89}Y
- Measure outgoing surrogate particle **d** in coincidence with observables indicative of relevant decay channel ➔ $P_{\delta\gamma}(E)$



A Surrogate experiment gives

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

Hauser-Feshbach description of “desired” CN reaction

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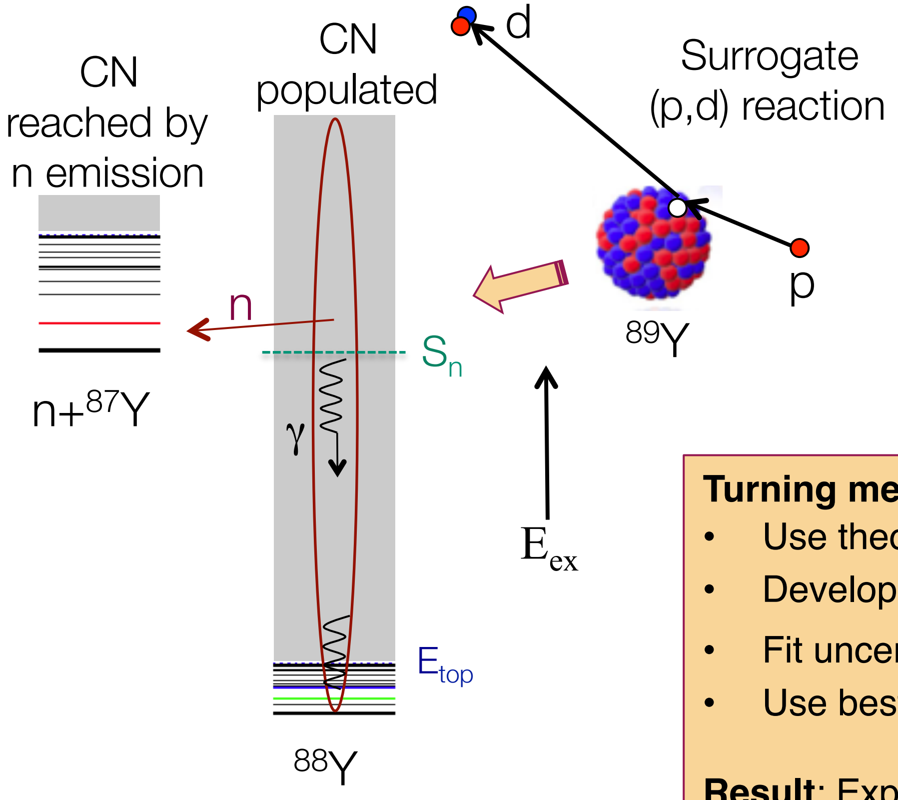

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Turning measurement into cross section

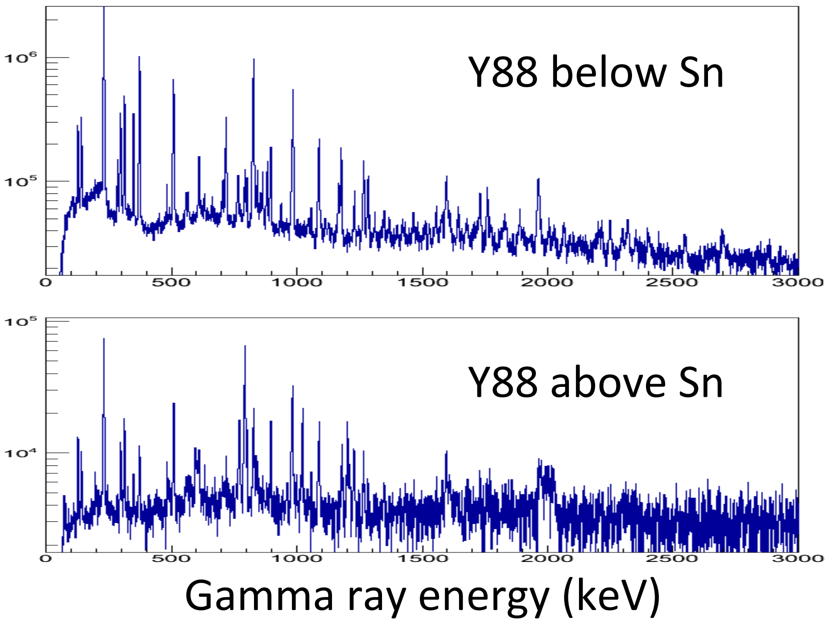
- Use theory to describe Surrogate reaction, predict $F_{(p,d)}^{CN}$
- Develop rough decay model G^{CN}_{γ}
- Fit uncertain parameters in G^{CN}_{γ} to reproduce $P_{(p,d\gamma)}$
- Use best-fit parameters to calculate desired $\sigma_{(n,\gamma)}$

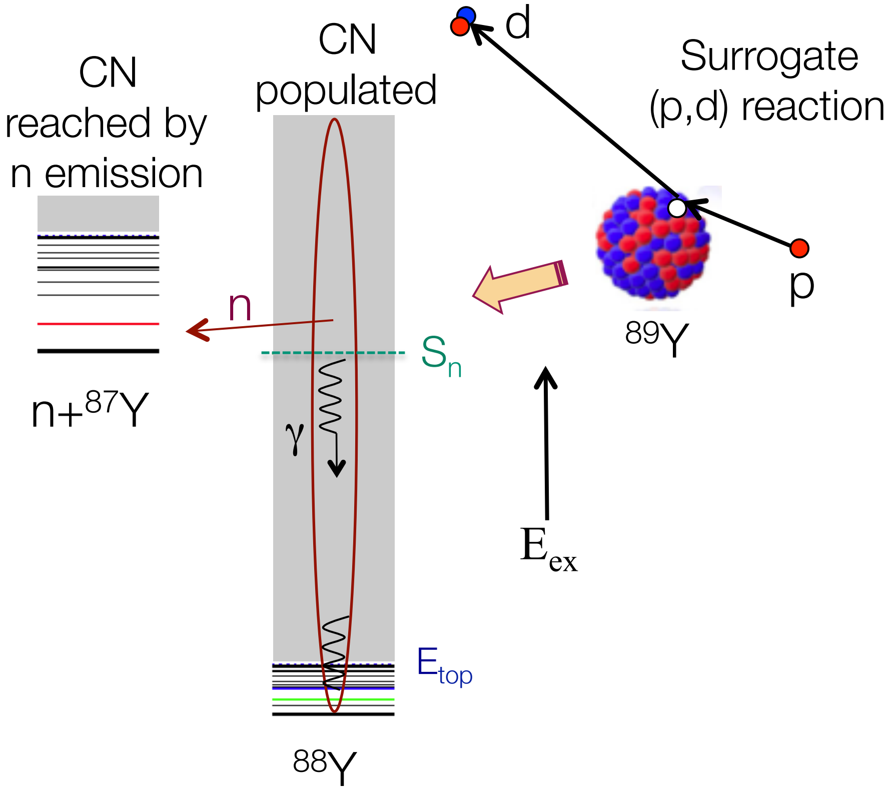
Result: Experimentally constrained cross section calculation.

^{89}Y(p,d)^{88}Y experiment to constrain ^{87}Y(n,γ)

Experiment at Texas A&M Cyclotron
^{89}Y(p,d) and ^{90,91,92}Zr(p,d)

γ-ray cascade in coincidence with outgoing surrogate particle (deuteron)





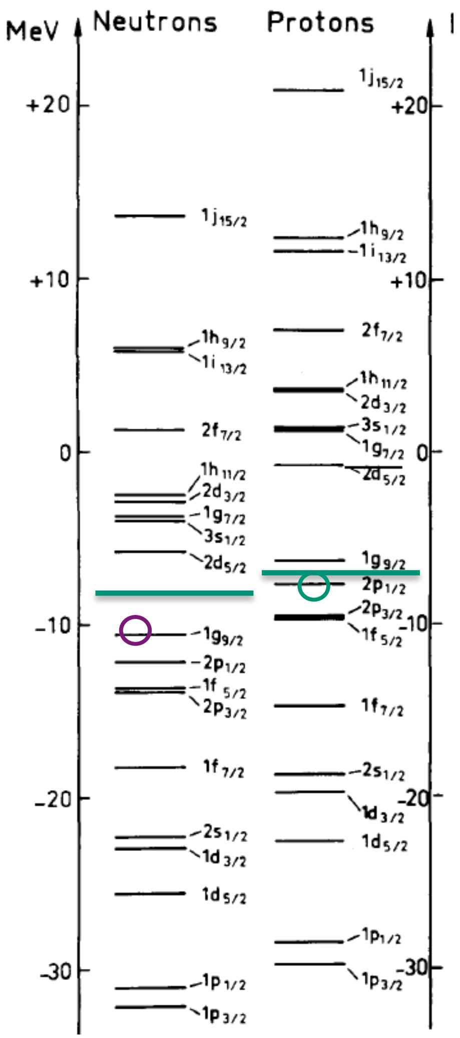
Burke, Casperson, Scielzo et al.

Describing CN formation in ^{89}Y(p,d) reaction

^{89}Y(p,d)^{88}Y:

- Remove neutron from ^{89}Y (n:$J^{\pi}=0^{+}$ × p:$J^{\pi}=1/2^{-}$). Treat proton hole as spectator.

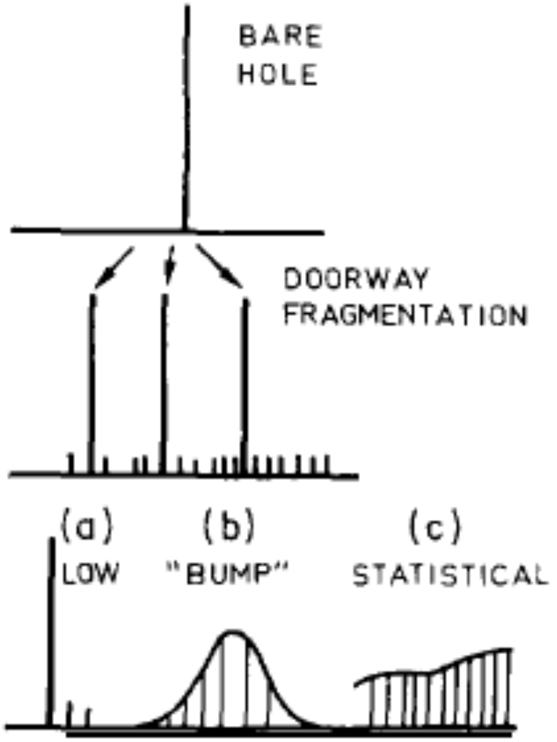
^{89}Y



○ neutron hole
made in reaction

Fragmentation of single-hole states: transfer reaction populates doorway states, which couple to more complex configurations

-> damping to CN occurs



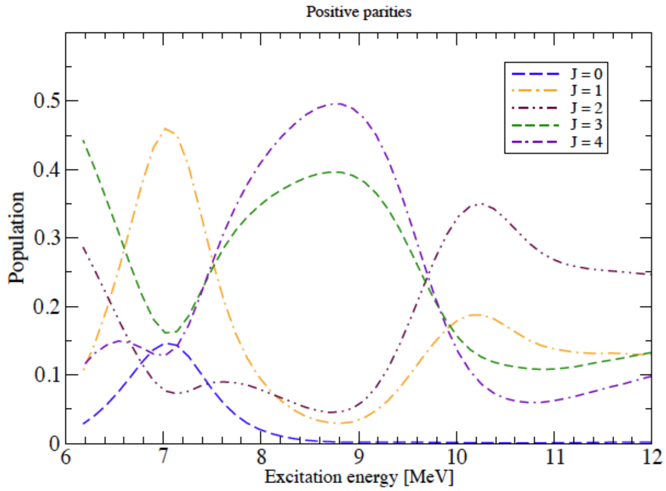
From Gales et al, Phys. Rep. 166 (1988) 125

Describing CN formation in ^{89}Y(p,d) reaction

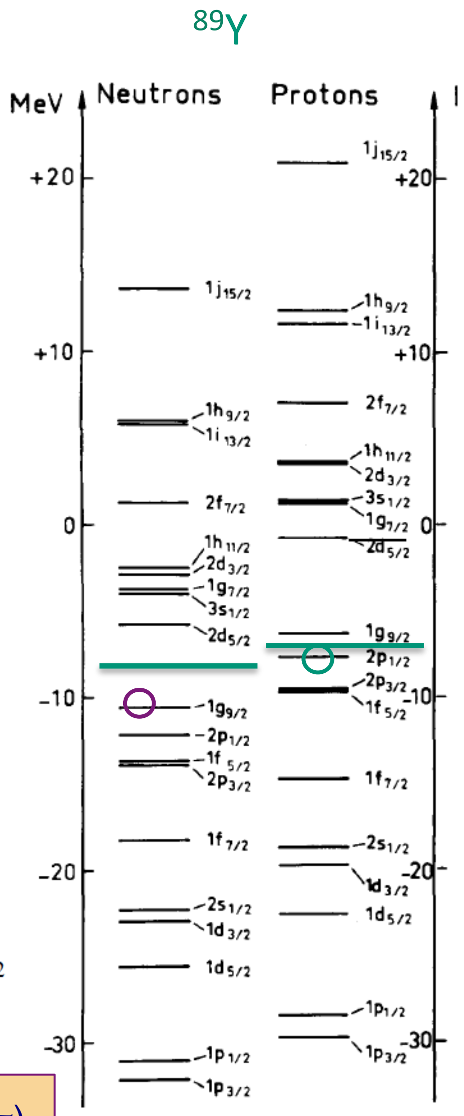
^{89}Y(p,d)^{88}Y:

- Remove neutron from ^{89}Y (n:$J^{\pi}=0^{+}$ × p:$J^{\pi}=1/2^{-}$). Treat proton hole as spectator.
- Apply damping & add all J^{π} contributions
- Extract spins, determine J^{π} distribution of ^{88}Y as function of E.

Spin-parity population $F_{(p,d)}^{CN}(E,J,\pi)$



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



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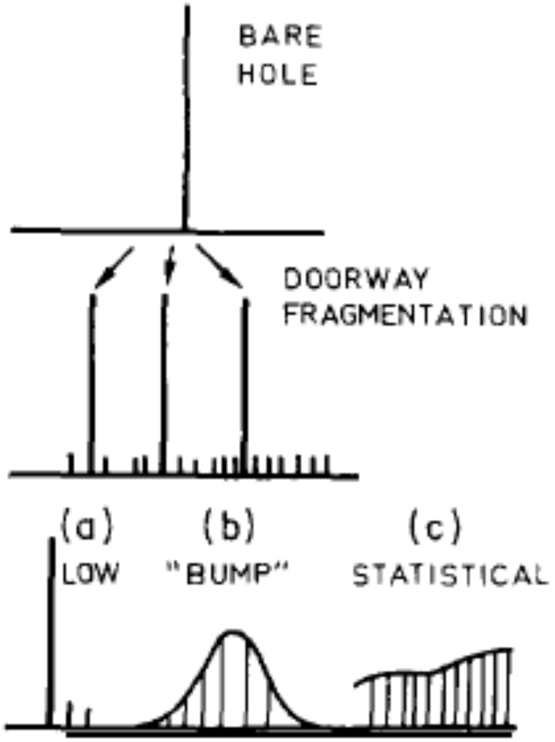

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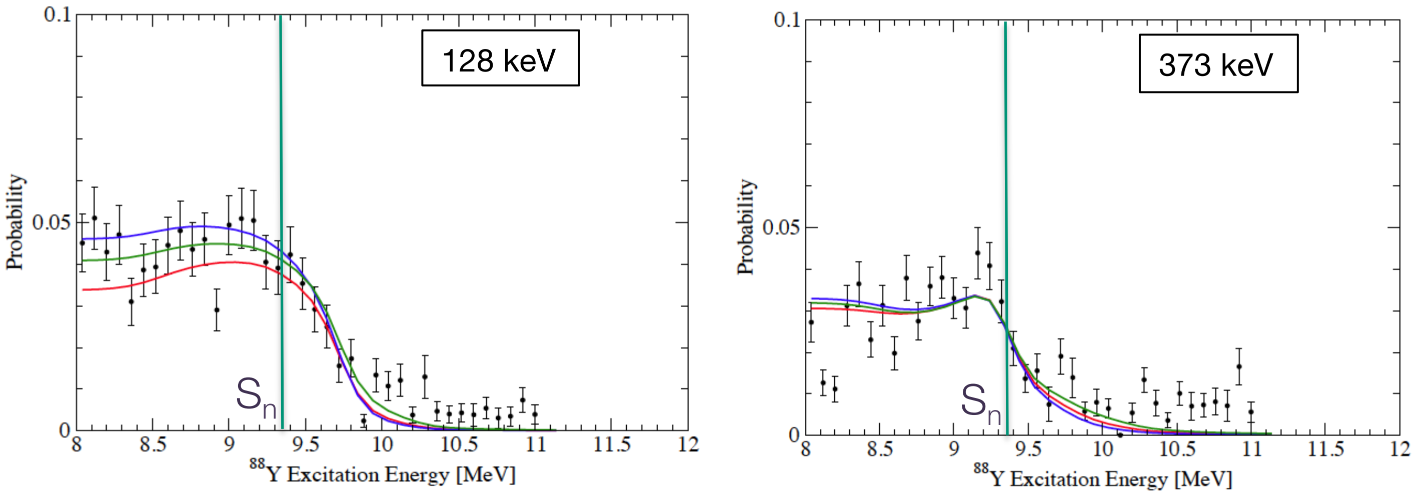
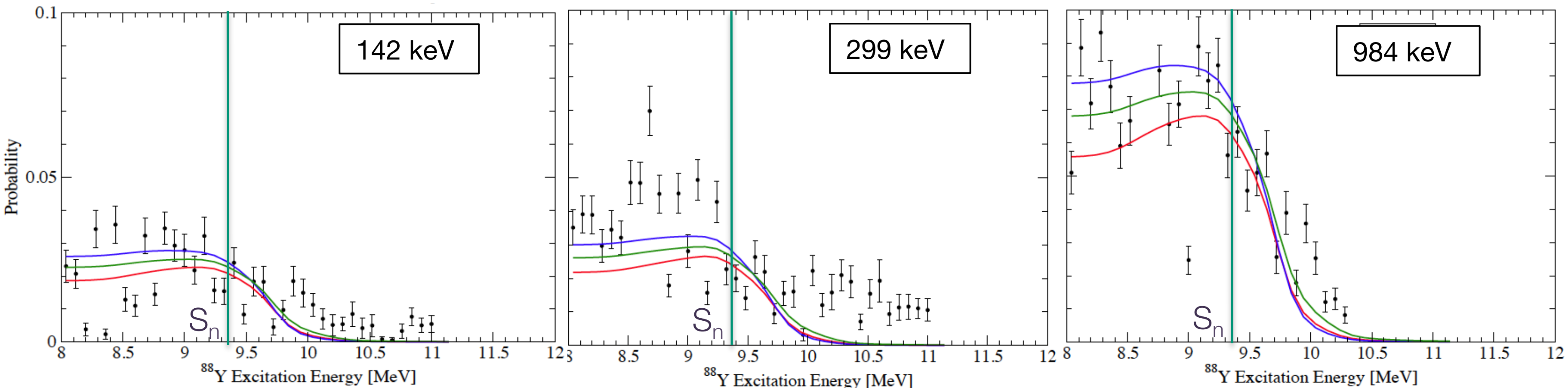
Fitting decay model to surrogate data

Fitting HF inputs to reproduce surrogate observables



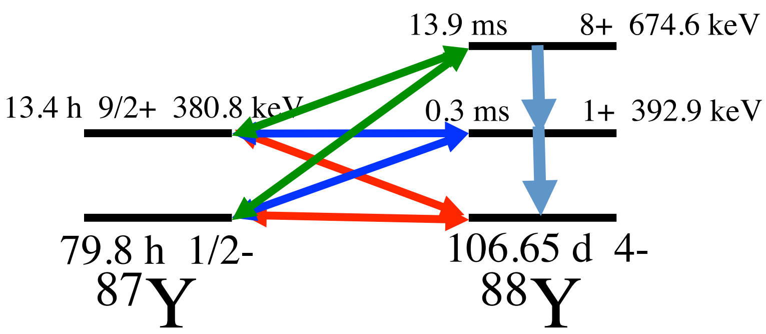
Preliminary

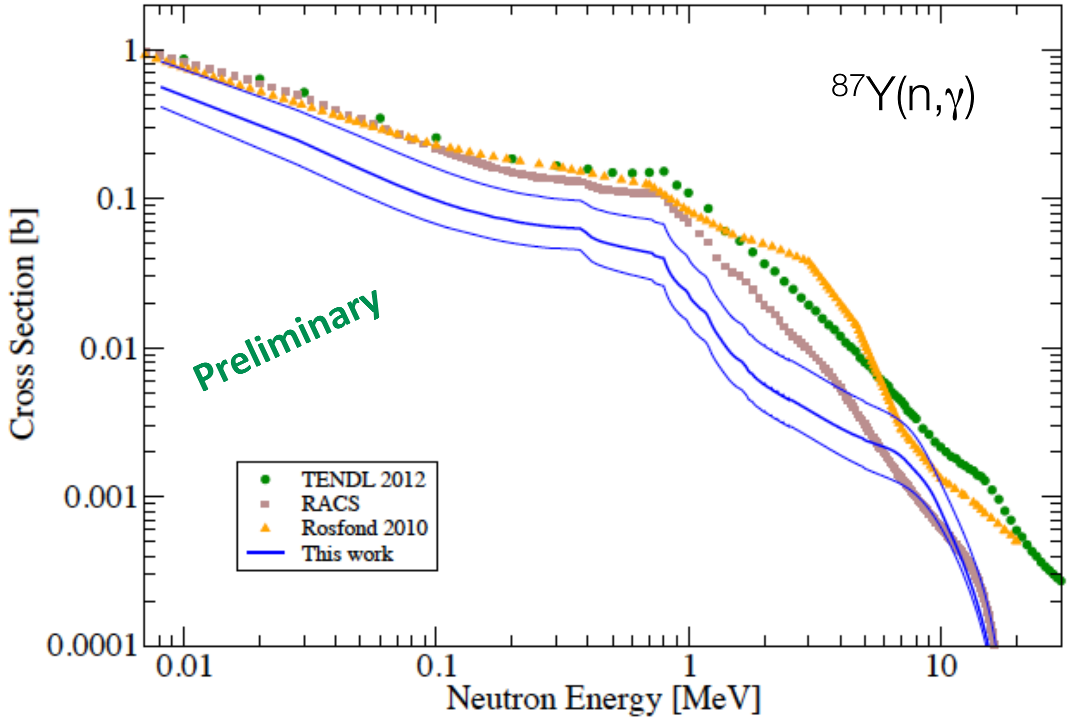


Fit yields best set of parameters & uncertainty estimate.

$$P_{(p,d\gamma)}(E) = \sum_{J,\pi} F_{(p,d)}^{CN}(E,J,\pi)\cdot G^{CN}_{\gamma}(E,J,\pi)$$

Results





Notes

- Cross section lower than previous evaluations
- Theory work underway to improve the J^{π} predictions
- Exp. work underway to reduce data scatter and to provide better constraints for theory
- Approach to be validated with ^{90}Zr(n,γ) benchmark

Using best set of parameters to calculate ^{87}Y(n,γ) and ^{87m}Y(n,γ)

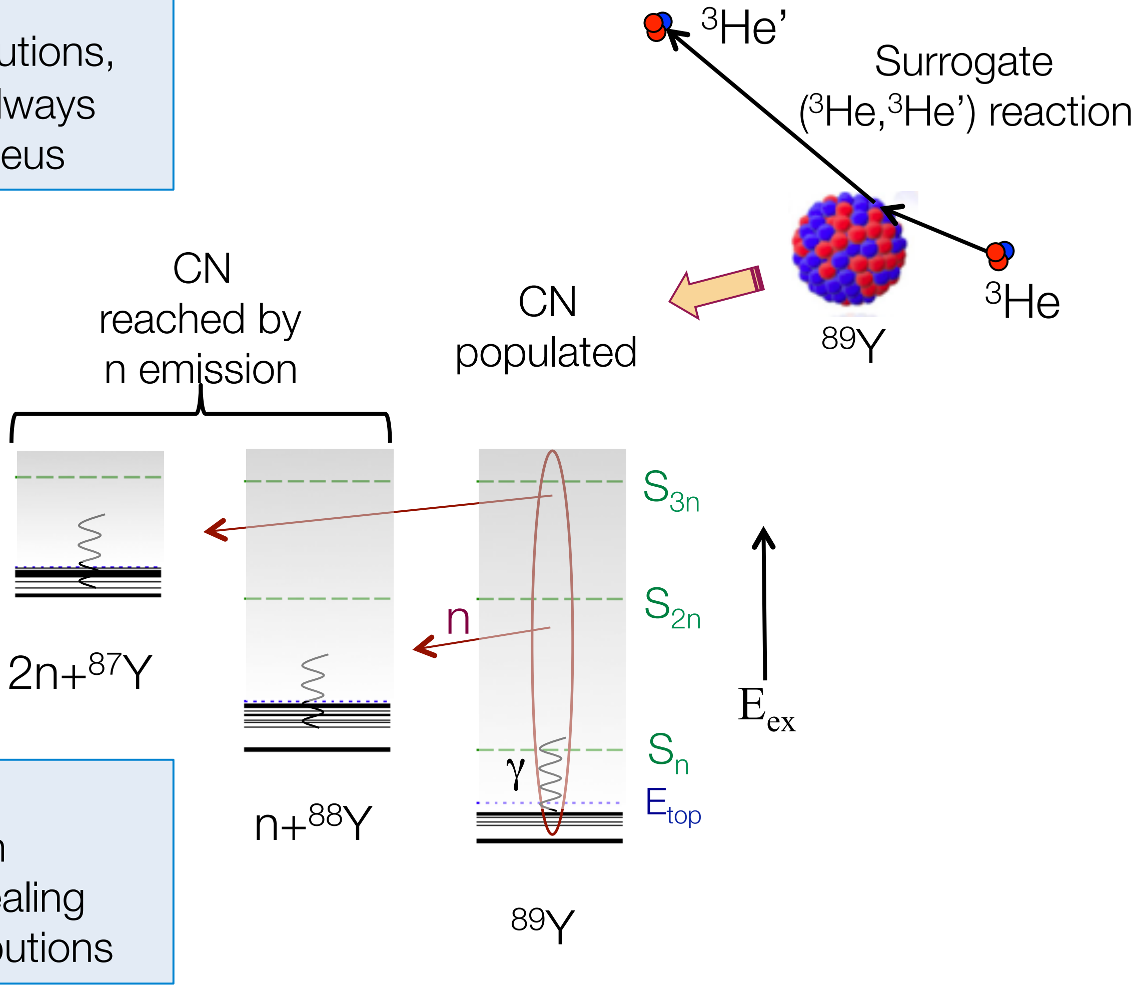
$$\sigma_{(n,\gamma)} = \sum_{J,\pi} \sigma_{n+target}^{CN}(E,J,\pi) \cdot G^{CN}_{\gamma}(E,J,\pi)$$

Is there ‘pre-equilibrium’ decay in surrogate reactions? How can we deal with it?

^{88}Y(n,2n): $t_{1/2}(^{88}Y)$=105d

Prevailing assumption:

No ‘pre-equilibrium’ contributions, i.e. the surrogate reaction always produces a compound nucleus



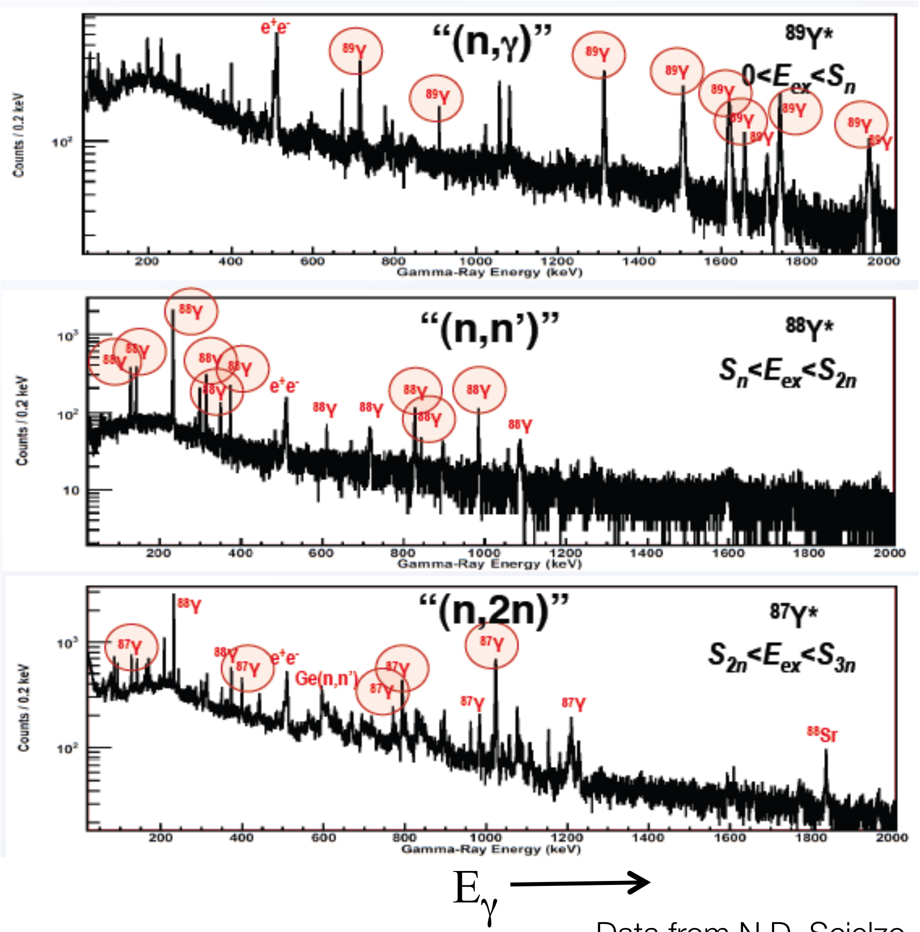
We need to…
1. Question this assumption
2. Develop a strategy for dealing with ‘pre-equilibrium contributions

CN formation via inelastic scattering

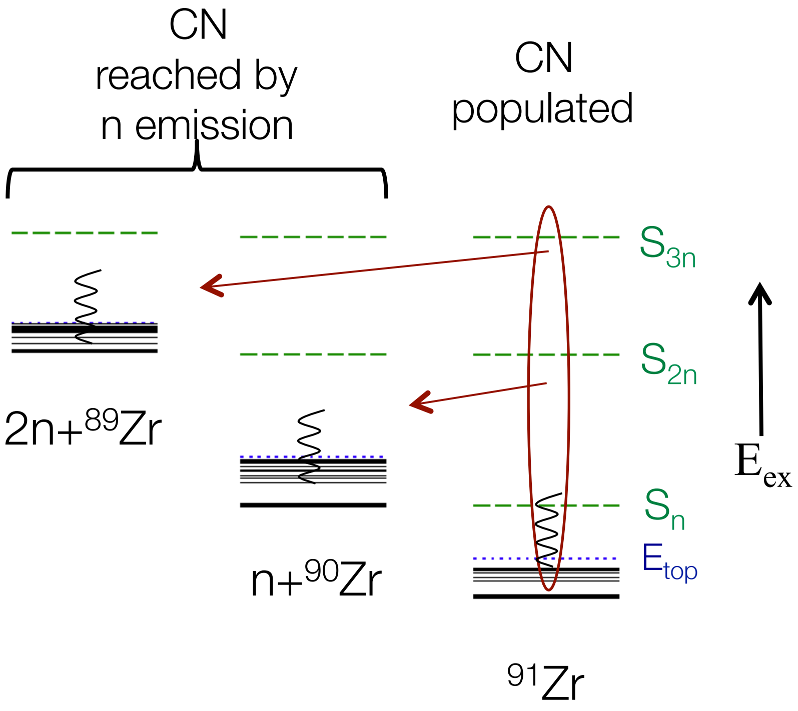
Experiment at LBNL:

- ^{90,91,92}Zr(^{3}He,^{3}He’) and ^{89}Y(^{3}He,^{3}He’)

γ-ray cascade in coincidence with outgoing surrogate particle (^{3}He’)



Data from N.D. Scielzo


CN reached by n emission

CN populated

Describing CN formation via inelastic scattering

Structure theory for ^{90}Zr(^{3}He,^{3}He')

- QRPA with Skyrme SLy4
- (Alternative: RPA with Gogny D1N)
- Description of states to 30 MeV

Reaction theory for ^{90}Zr(^{3}He,^{3}He')

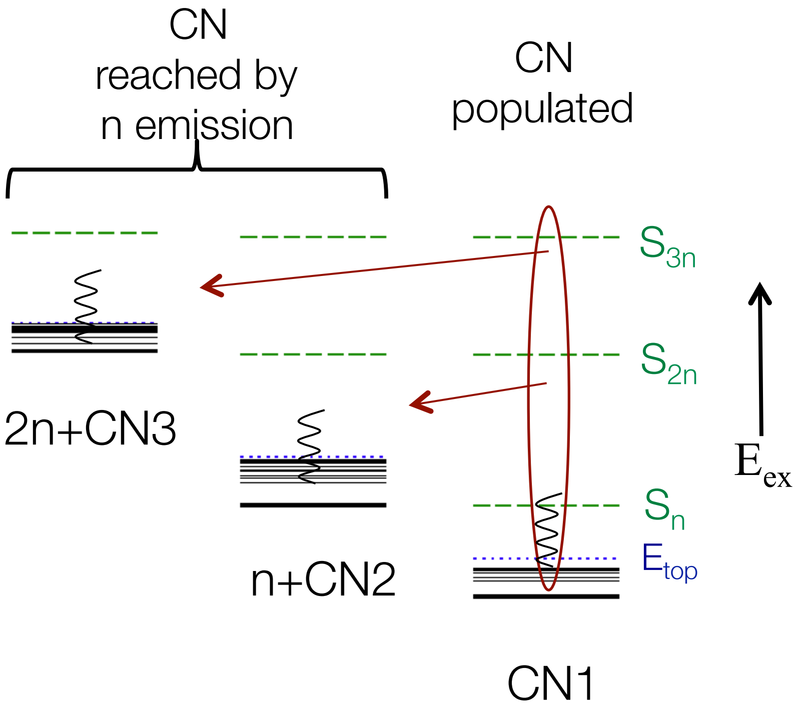
- DWBA description (Fresco code)
- Calculations up to J=9

Treatment of damping (CN formation)

- Phenomenological spreading width
- Accounts for higher-order couplings
- Energy-dependent width

Spin-parity distribution in CN

- Determined from relative contributions of xsecs



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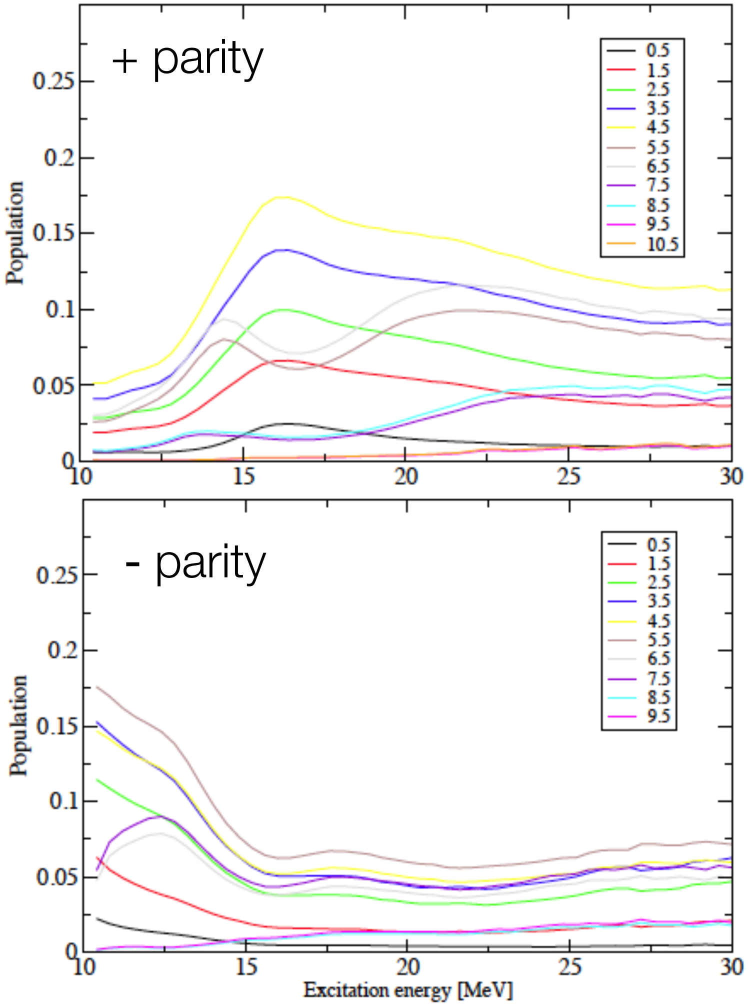


E_{ex} ⟶

Comparison with experiment

Procedure:

- Calculate $F_\delta^{CN}(E,J,\pi)$
- Model CN decay
- Adjust HF parameters to reproduce measured $P_\chi(E)$, here γ-transitions
- Use best-fit HF parameters to obtain G^{CN}_χ
- Calculate desired cross section

A Surrogate experiment gives

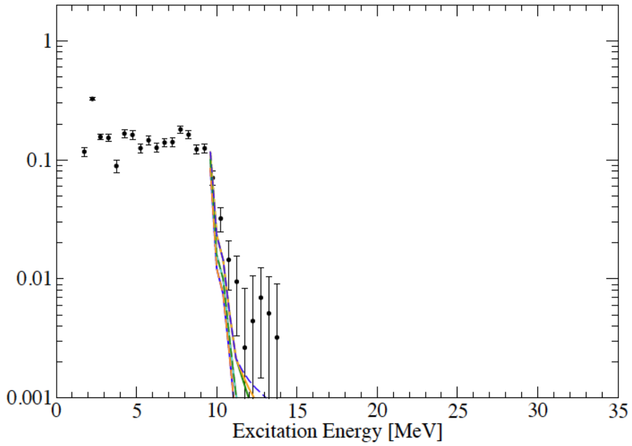
$$P_\chi(E) = \Sigma_{J,\pi} F_\delta^{CN}(E,J,\pi) \cdot G^{CN}_\chi(E,J,\pi)$$

Hauser-Feshbach description of "desired" CN reaction

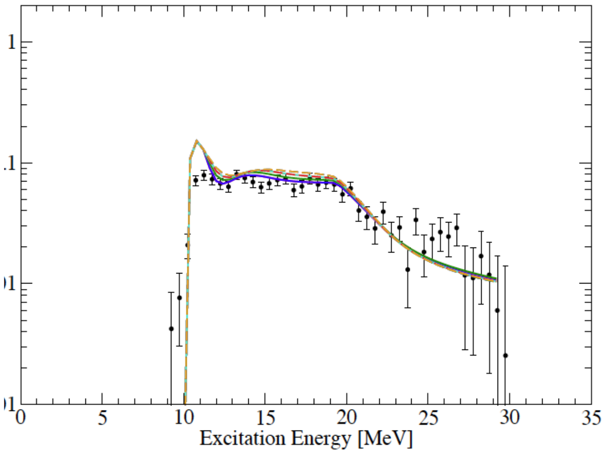
$$\sigma_{\alpha\chi} = \Sigma_{J,\pi} \sigma_\alpha^{CN}(E,J,\pi) \cdot G^{CN}_\chi(E,J,\pi)$$

Preliminary

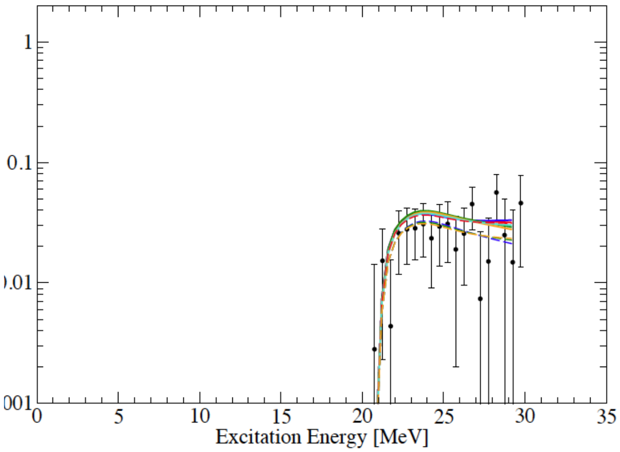
$P_\gamma(E)$ for 2170 keV in ^{91}Zr
Predictions vs. data



$P_\gamma(E)$ for 890 keV in ^{90}Zr
Predictions vs. data

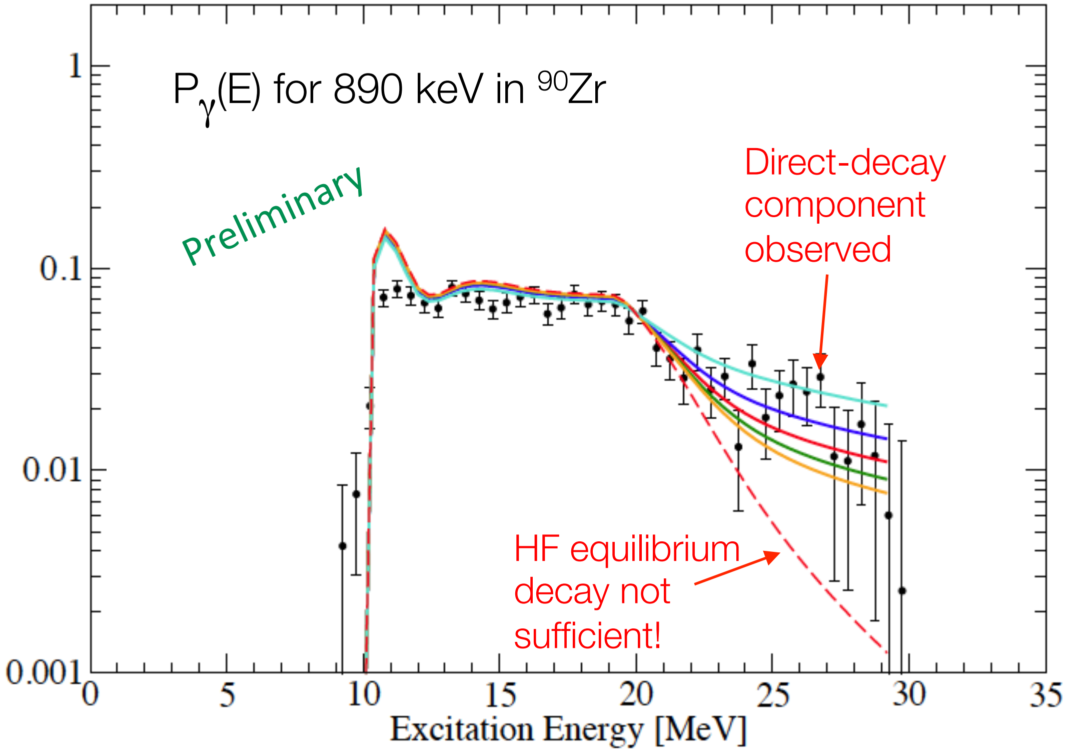


$P_\gamma(E)$ for 1512 keV in ^{89}Zr
Predictions vs. data



…and similarly for Y

Comparison with experiment

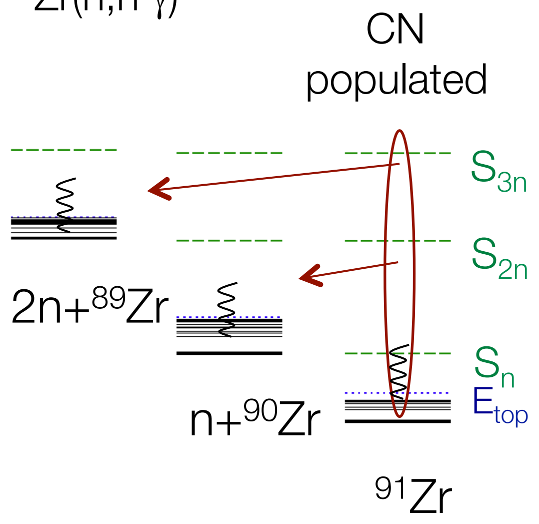

$P_\gamma(E)$ for 890 keV in ^{90}Zr

Preliminary

Direct-decay component observed

HF equilibrium decay not sufficient!

^{91}Zr(^{3}He,^{3}He' n'γ)
~ ^{90}Zr(n,n'γ)


CN populated

S_{3n}

S_{2n}

S_n

E_{top}

2n+^{89}Zr

n+^{90}Zr

^{91}Zr

Insights:

- Reproducing Surrogate coincidence probability requires 'pre-equilibrium' contribution
- Neutron emission prior to equilibration sets in around E_n=7 MeV
- Modeling this contribution is relevant for describing 2n emission
- γ-ray measurements provide useful information

Insights

- Using approximations in surrogate applications to (n,f) reactions generally works well. Limitations visible at low energies (<1-2 MeV)
- Applications to a wider range of n-induced reactions requires more sophisticated implementation of the method -> Need to move beyond ‘Surrogates 101’
- A better understanding of mechanisms that produce CN is needed.
- Successful reproduction of experimental observables. Obtain experimentally constrained cross sections.
- Gaining insights into complex interplay between direct, compound, and pre-equilibrium processes.
- Good experimental data is needed to constrain the theory and to produce cross section results. Comparisons with benchmarks are important for quantitatively assessing the new implementation of the approach.

Outlook

- Approach best suited near valley of stability, adjacent to stable nuclei or a few nucleons away.

- Moving far away from the valley of stability will be practically challenging, as little is known about the structure of n-rich or p-rich nuclei. Difficult to reliably model formation of CN, decay of CN, and to select surrogate observable that uniquely identify exit channel of interest.

- No good alternative indirect methods available. The (d,p) reaction is likely to be intensely used in inverse kinematics.

- Generally, more work needs to be done to understand reactions on isotopes off stability. Low level densities and questions of proper energy averaging will need to be addressed.

Thanks to my Collaborators

Surrogate Reactions

Theory

Frank Dietrich, Daniel Gogny, Ian Thompson, Walid Younes (LLNL)

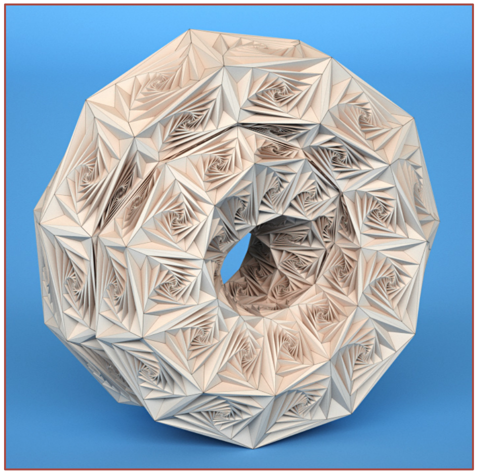
Experiment

J. Burke, R. Casperson, R. Hughes,
J.J. Ressler, N.D. Scielzo (LLNL)
C. Beausang, T. Ross (U Richmond)
J. Cizewski et al (Rutgers)

ReactionTheory.org

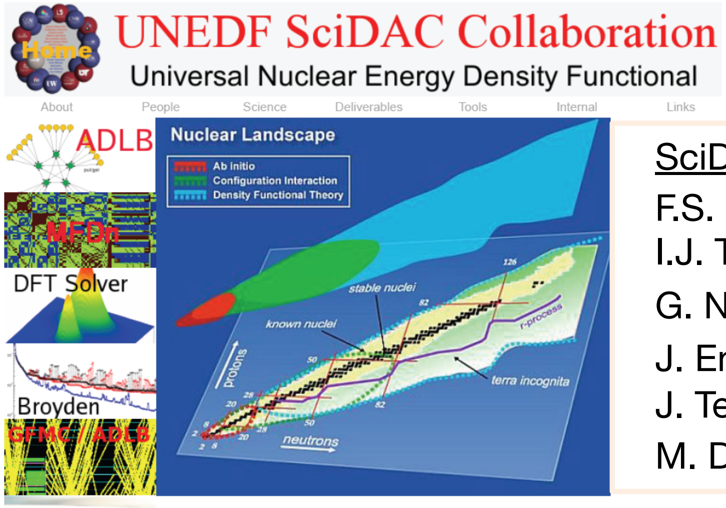
TORUS: Theory of Reactions for Unstable iSotopes
A Topical Collaboration for Nuclear Theory

www.reactiontheory.org



TORUS collaborators

Ian Thompson, LLNL
Jutta Escher, LLNL
Filomena Nunes, MSU
L. Hlophe, OU
V. Eremenko, OU
Charlotte Elster, OU
Goran Arbanas, ORNL



UNEDF SciDAC Collaboration

Universal Nuclear Energy Density Functional

SciDAC collaborators

F.S. Dietrich and
I.J. Thompson (LLNL)
G. Nobre (BNL)
J. Engel and
J. Terasaki (UNC)
M. Dupuis (CEA)

Capture-γ Project

B. Sleaford and N. Summers (LLNL)
R.B. Firestone, A. Hurst, S. Basunia, H. Choi (LBNL)

Surrogate Reactions: Status & Prospects*

Jutta E. Escher
Lawrence Livermore National Laboratory, Livermore, CA 94551, U.S.A.

Providing reliable nuclear cross section data for applications remains a formidable task, and direct measurements have to be complemented by theoretical predictions and indirect methods. Indirect approaches come with their own challenges, as experimental observables have to be related to the quantity of interest. The surrogate method, for instance, aims at determining cross sections for compound-nuclear reactions on unstable targets by producing the compound nucleus via an alternative (transfer or inelastic scattering) reaction and observing the subsequent decay via γ emission, particle evaporation, or fission. A complete theoretical treatment involves integrating descriptions of direct and compound-nucleus reactions, including modeling of compound-nuclear decays. This presentation will give an outline of the surrogate approach and the challenges involved in extracting cross sections from the measurements. Progress made in understanding and describing the nuclear processes involved in a surrogate reaction will be discussed, and applications to neutron-induced fission, neutron capture, and (n,2n) reaction will be presented. Open questions and prospects will be considered.

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