Surrogate nuclear reactions: An indirect approach to determine cross sections for compound reactions

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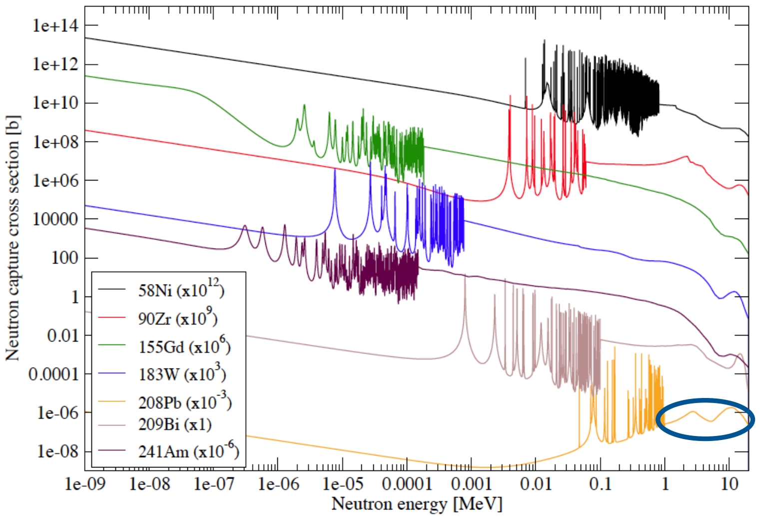
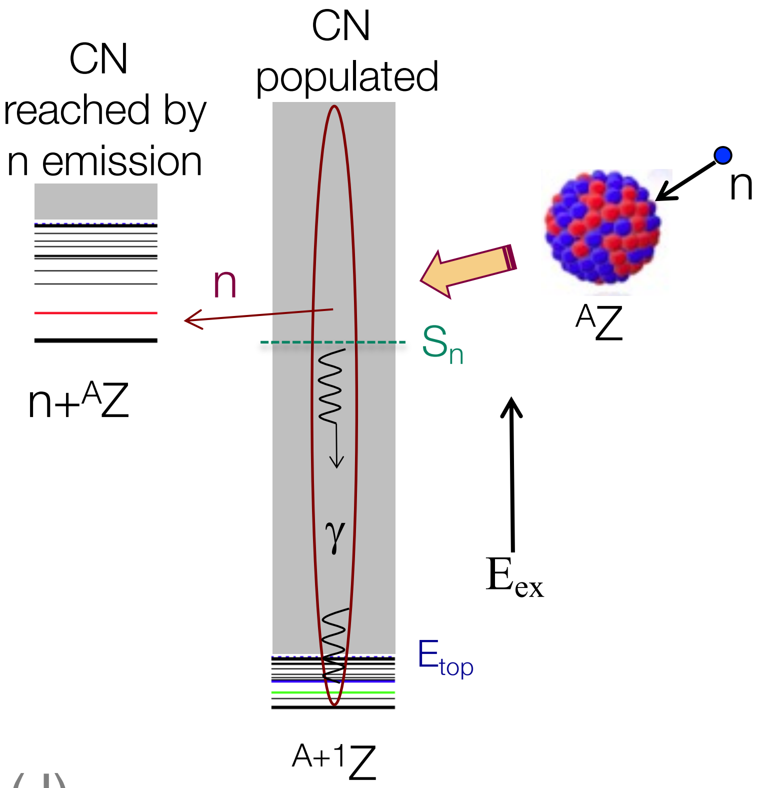
Statistical reactions and Hauser-Feshbach calculations

- Hauser-Feshbach (HF) theory describes compound-nuclear reactions that involve statistical averages over overlapping resonances
- HF calculations are essential component of nuclear data evaluations
- Applications rely on cross sections calculated with HF, e.g. neutron capture



(n,γ) evaluations for select stable isotopes (ENDF/B-VII)

Strongly overlapping resonances



Hauser-Feshbach formalism:

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

Known for nuclei near stability

Highly Uncertain w/o constraints

Well-studied corrections

Jutta Escher, escher1@llnl.gov

Predictive power of HF reaction calculations is limited… … this provides an opportunity for more sophisticated theory and indirect reaction methods

- Challenges:
  - Ambiguous model combinations, large parameter uncertainties, and multiple reaction channels
  - Away from stability there are few/no known constraints
- Needed – a multipronged approach:
  - development of predictive microscopic structure and reaction theories
  - direct measurements (where possible) to validate theory
  - indirect measurements to constrain theory

$$\sigma_{\alpha\chi}(E) = \sum_{J\pi} \sigma_{\alpha}^{CN}(E,J,\pi)\, G_{\chi}^{CN}(E,J,\pi) \cdot W_{\alpha\gamma}(J)$$

Width fluctuation corrections

Formation of CN

$$\sigma_{\alpha}^{CN}(E,J,\pi) = \pi\lambda_{\alpha}\omega_{\alpha}^{J} \sum_{ls} T_{\alpha ls}^{J}$$

Probability for decay of CN

$$G_{\chi}^{CN}(E,J,\pi) = \frac{\sum_{l's'} T_{\chi l's'}^{J}\, \rho_{I'}(U')}{\sum_{\chi''l''s''} \int T_{\chi''l''s''}^{J}\, \rho_{I''}(U')\, dE_{\chi''}}$$

Indirect measurements using the Surrogate Reactions Method

- Concept
- (p,d) as a surrogate reaction mechanism
- (d,p) as a surrogate reaction mechanism
- Inelastic scattering as a surrogate reaction mechanism

Surrogate reactions method combines theory and experiment to constrain cross section calculations for compound reactions

Escher et al, RMP 84, 353 (2012)

Producing a CN in a surrogate reaction:

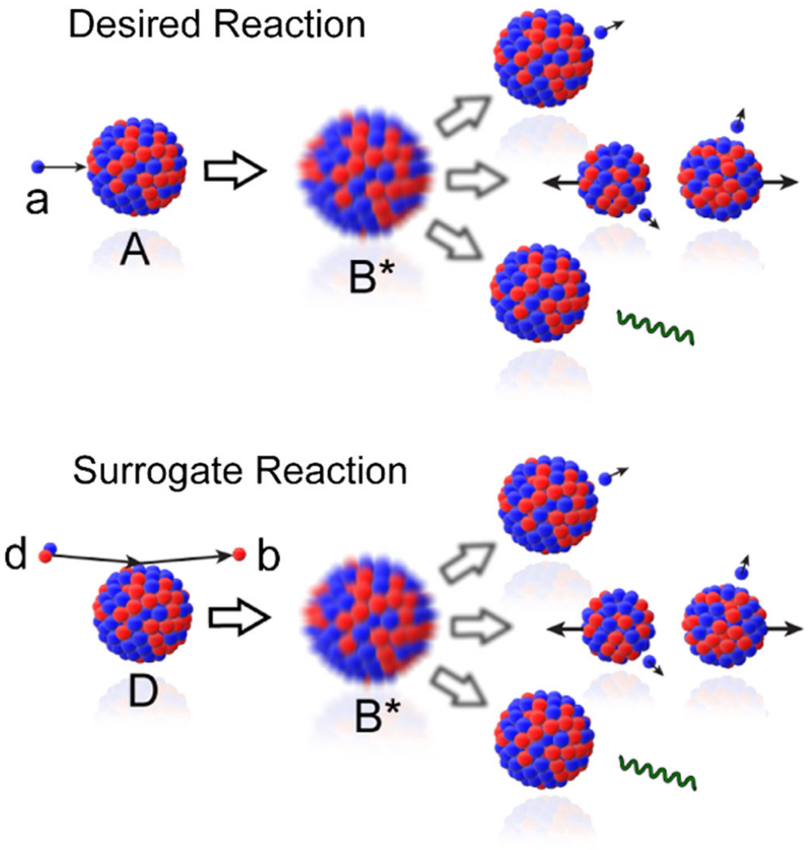
- Starts with a ‘direct’ reaction to produce a ‘doorway state’ at E_{ex} > several MeV
- Doorway evolves into a CN
- Spin population of doorway state = spin population of the CN

Observe the decay of the CN:

- Measure coincidence probability of outgoing surrogate particle with decay into channel of interest
- Model HF decay and fit parameters to measured surrogate probability

Obtain desired cross section:

- Calculate desired reaction cross section using inferred parameters



- Concept
- **(p,d) as a surrogate reaction mechanism**
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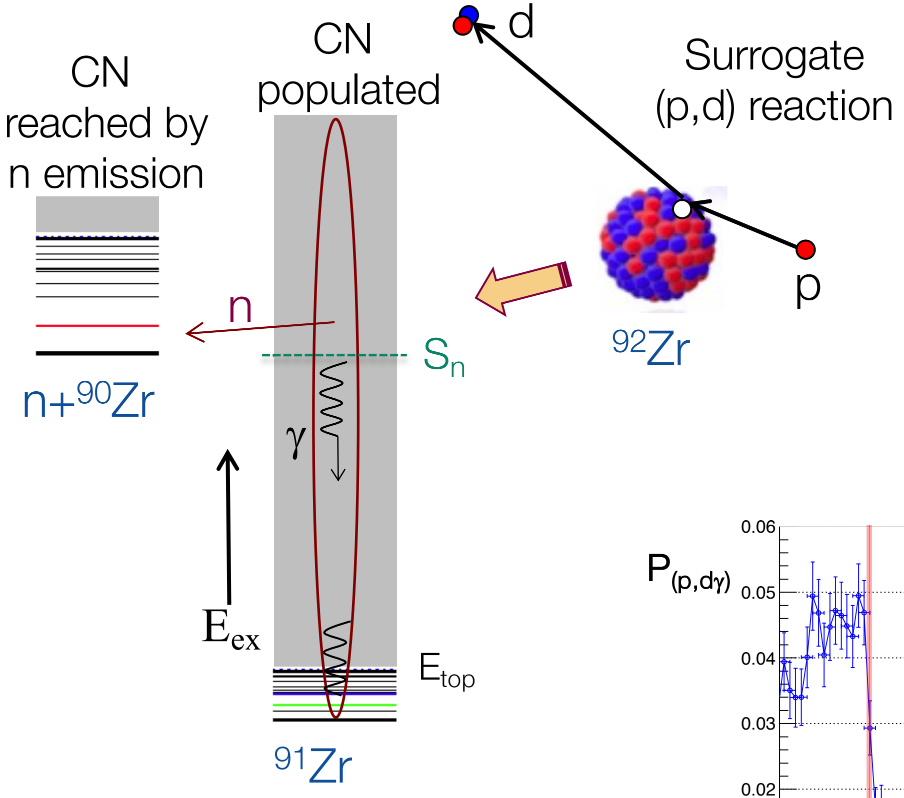
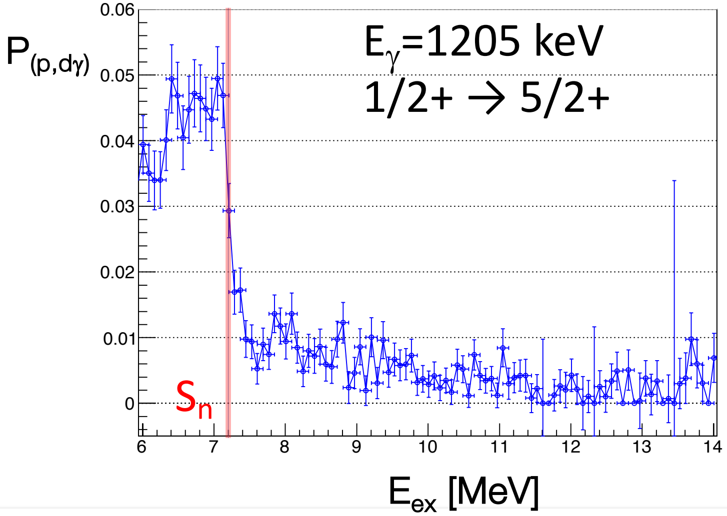
- Inelastic scattering as a surrogate reaction mechanism

Surrogate reactions method for neutron capture

Escher et al, PRL 121, 052501 (2018)





From theory

To be determined

A Surrogate experiment gives

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

^{90}Zr(n,γ) cross section*:

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

From experiment

The new cross section we want

Well modelled from nuclear theory

*Width fluctuation corrections are omitted here, but accounted for in applications.

Theory for surrogate reactions:
Parameter constraints from Bayesian fit to decay observables

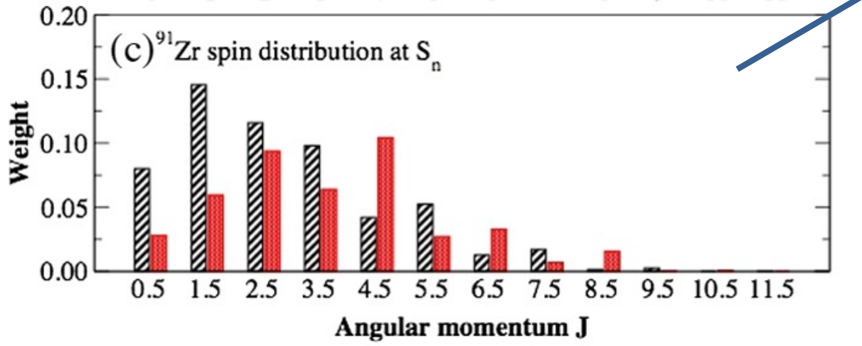
Escher et al, PRL 121, 052501 (2018)

Coincidence probabilities from surrogate experiment

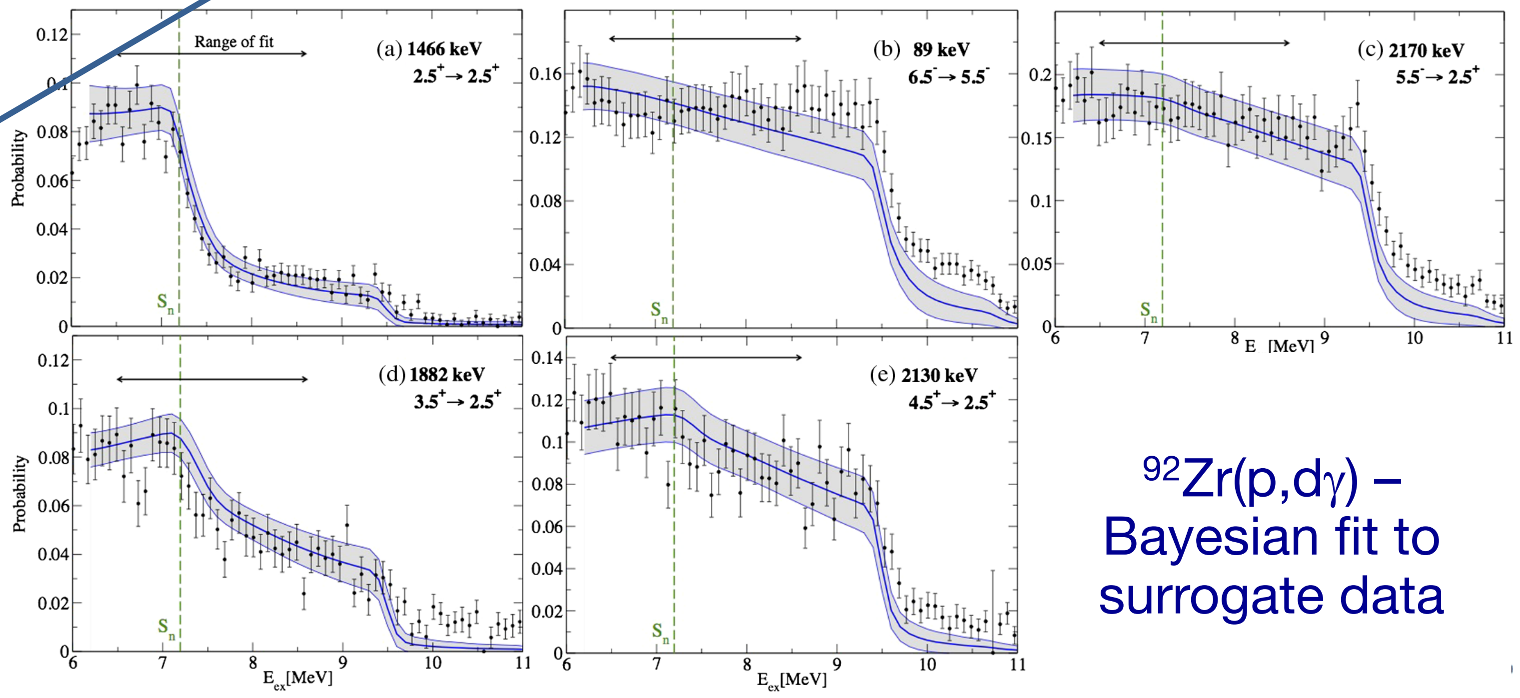
Surrogate coincidence probabilities

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

Spin-parity population from direct-reaction theory



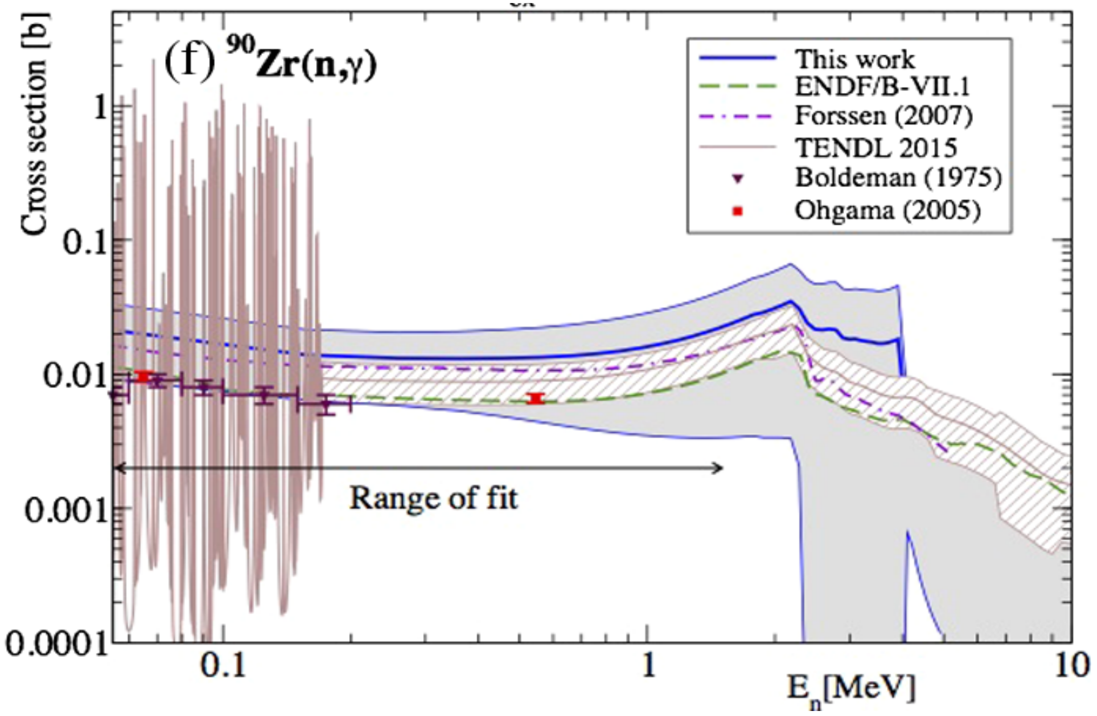
PHYSICAL REVIEW LETTERS **121,** 052501 (2018)



^{92}Zr(p,dγ) – Bayesian fit to surrogate data

Surrogate (p,d) transfer reactions enable determination of unknown (n,γ) cross sections - benchmark ^{90}Zr(n,γ)

Escher et al, PRL 121, 052501 (2018)



Surrogate method does not use D_0 or $\langle\Gamma_\gamma\rangle$

Procedure

- ➢ Measure the surrogate reaction coincidence probability
- ➢ Calculate the spin-parity population of the doorway state = spin-parity of the CN
- ➢ Model CN decay and perform Bayesian parameter fit to surrogate coincidence probabilities
- ➢ Sample posterior HF parameter distributions to obtain neutron-capture cross section

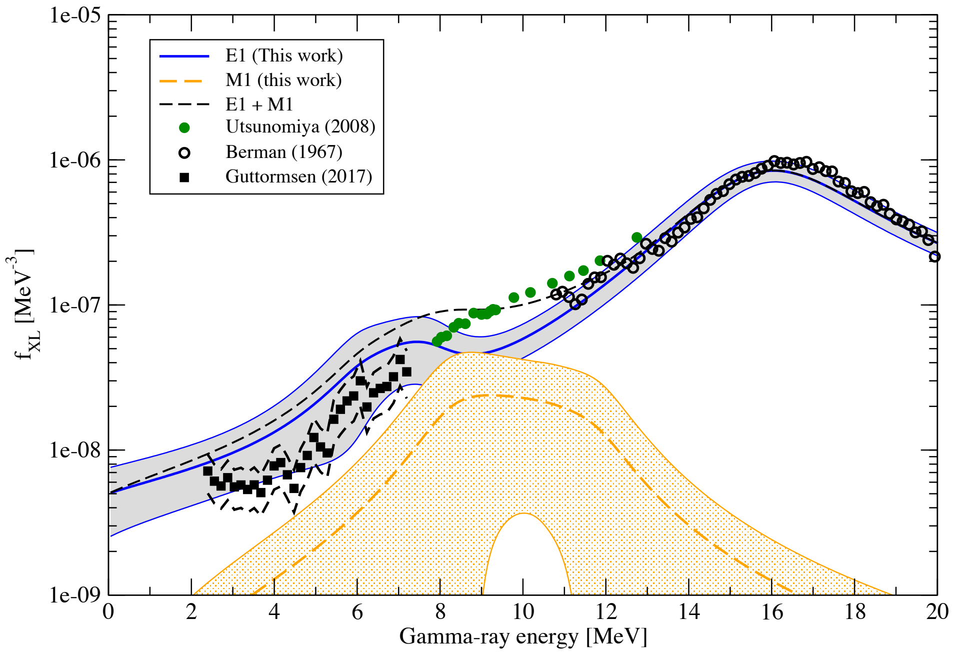
The surrogate reactions method also yields experimentally-constrained level densities and γ-ray strength functions

Extracted D_0 and $<\Gamma_\gamma>$ values

D_0 [keV]	Reference
10	This work
6.89 (0.53)	Mughabghab, 2006
6.00 (1.40)	RIPL-3
7.18 (23)	Guttormsen, PRC 2017

$<\Gamma\gamma>$ [meV]	Reference
185	This work
170 (20)	Mughabghab, 2006
130 (40)	RIPL-3
180 (137) 130 (40)	Guttormsen, PRC 2017

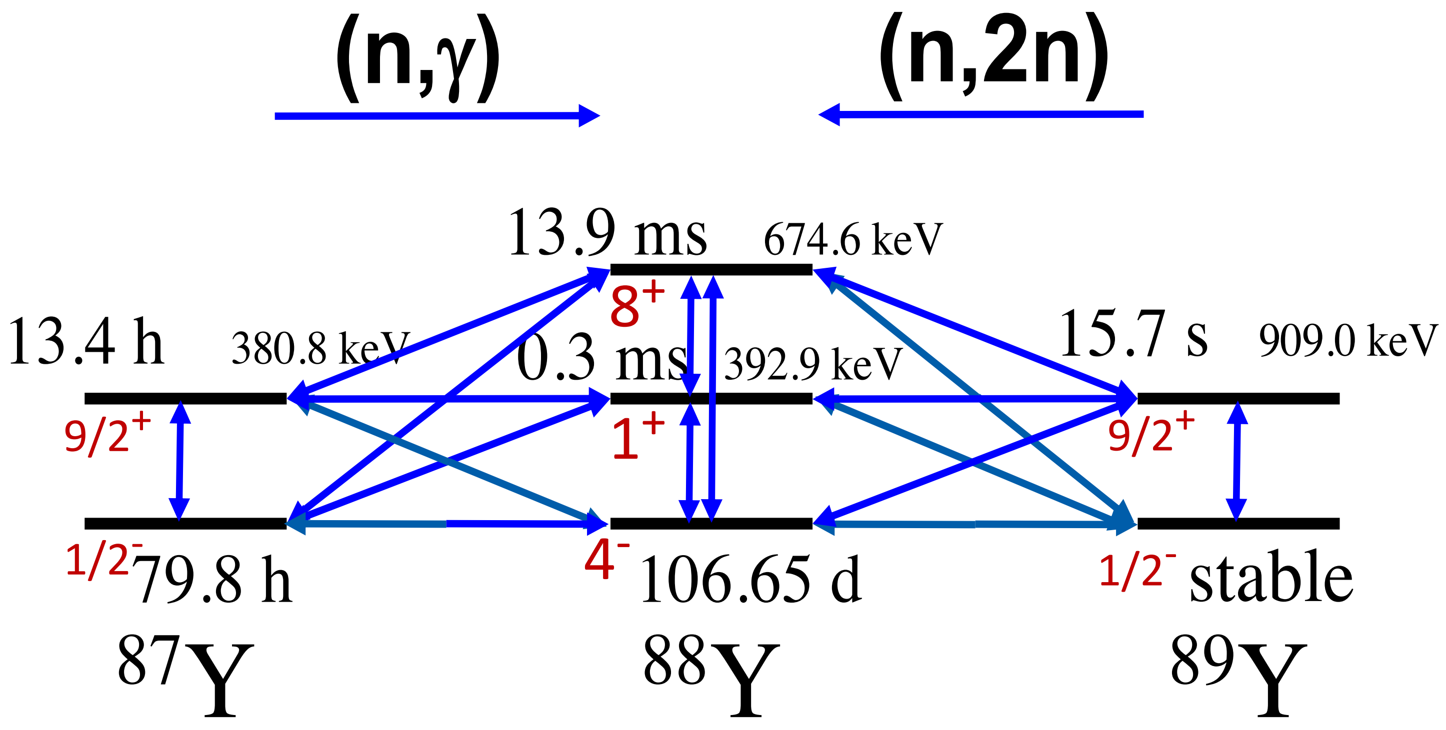
Extracted E1, M1 strengths



Oslo data from:
Guttormsen et al, PRC 96, 024313 (2017)

Surrogate method does not use D_0 or $<\Gamma_\gamma>$

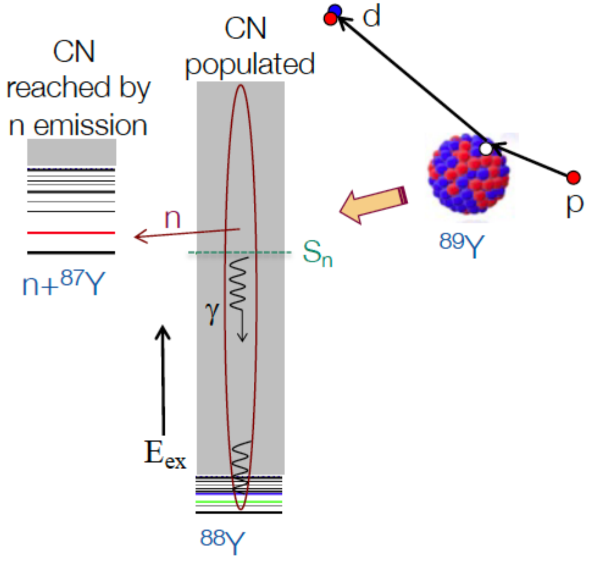
Surrogate (p,d) transfer reactions enable determination of unknown (n,γ) reaction cross sections involving isomers

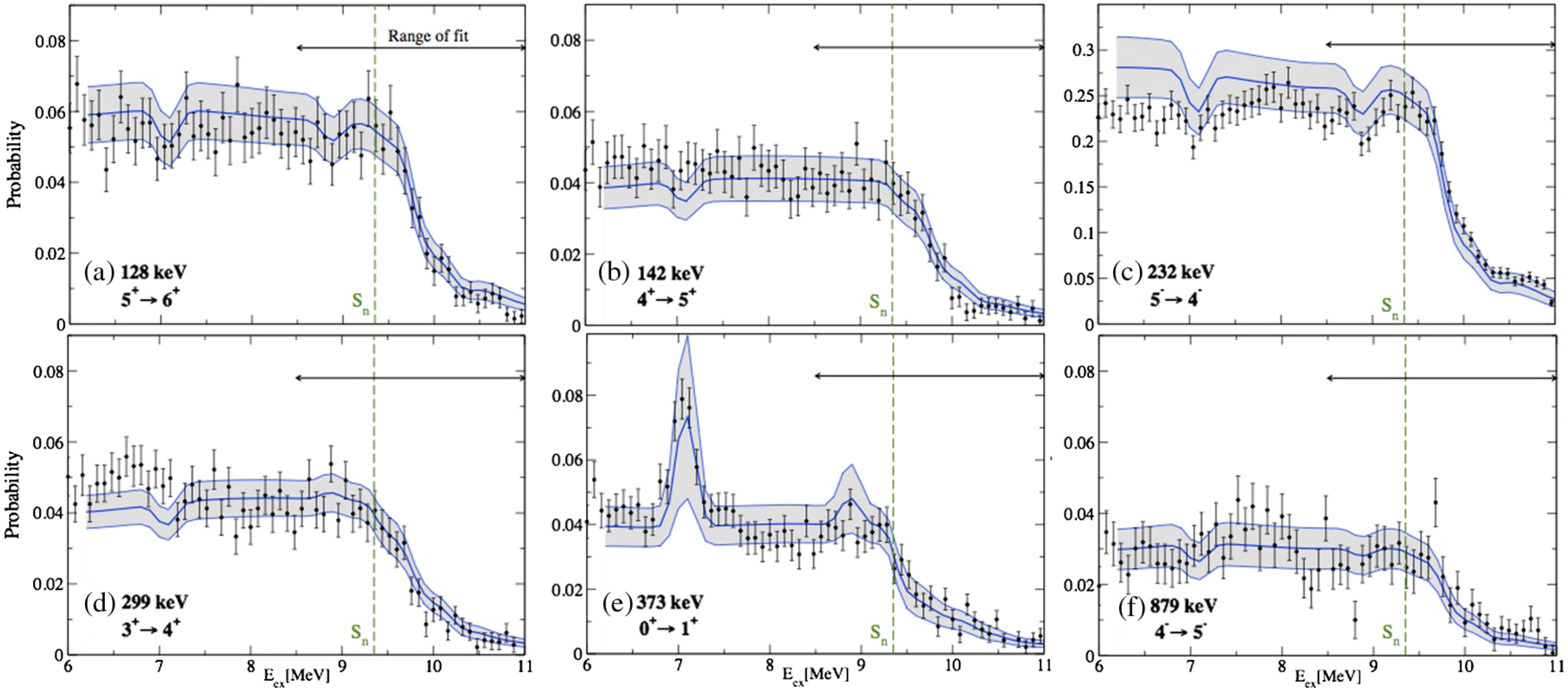


Multiple isomers occur in the unstable Y isotopes

^{87}Y(n,γ) cross sections from ^{89}Y(p,dγ) surrogate reaction data

Escher et al, PRL 121, 052501 (2018)



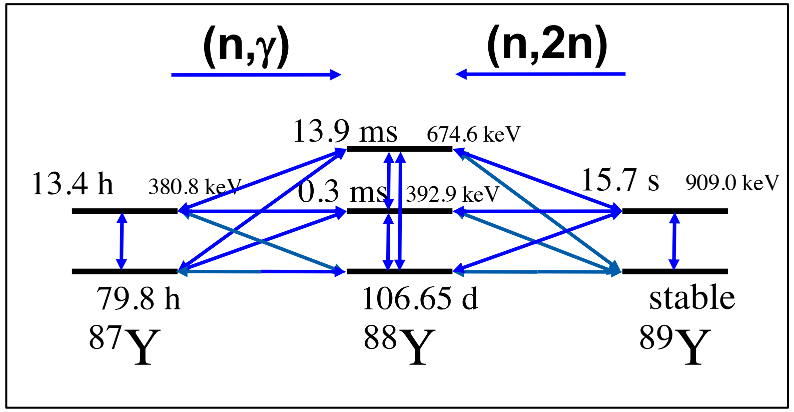


Surrogate (p,dγ) reaction

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

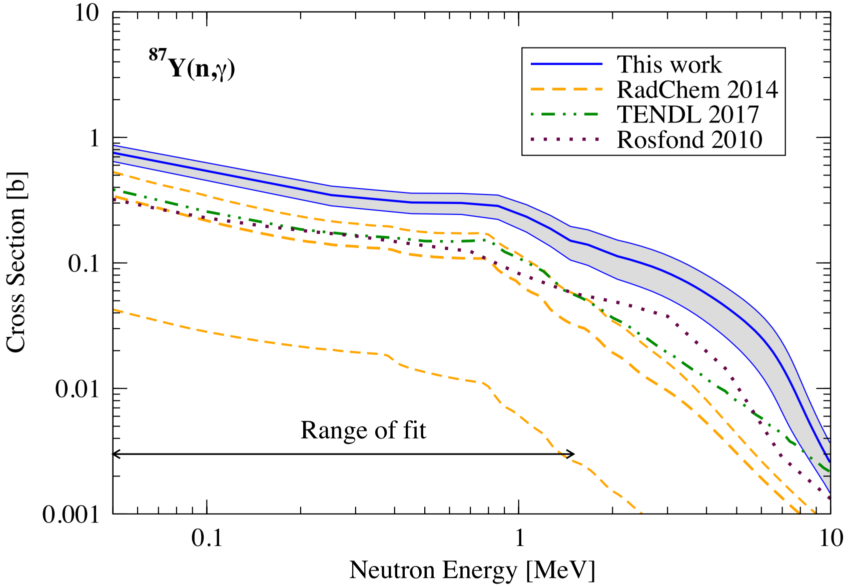
Procedure analogous to Zr(p,d) case

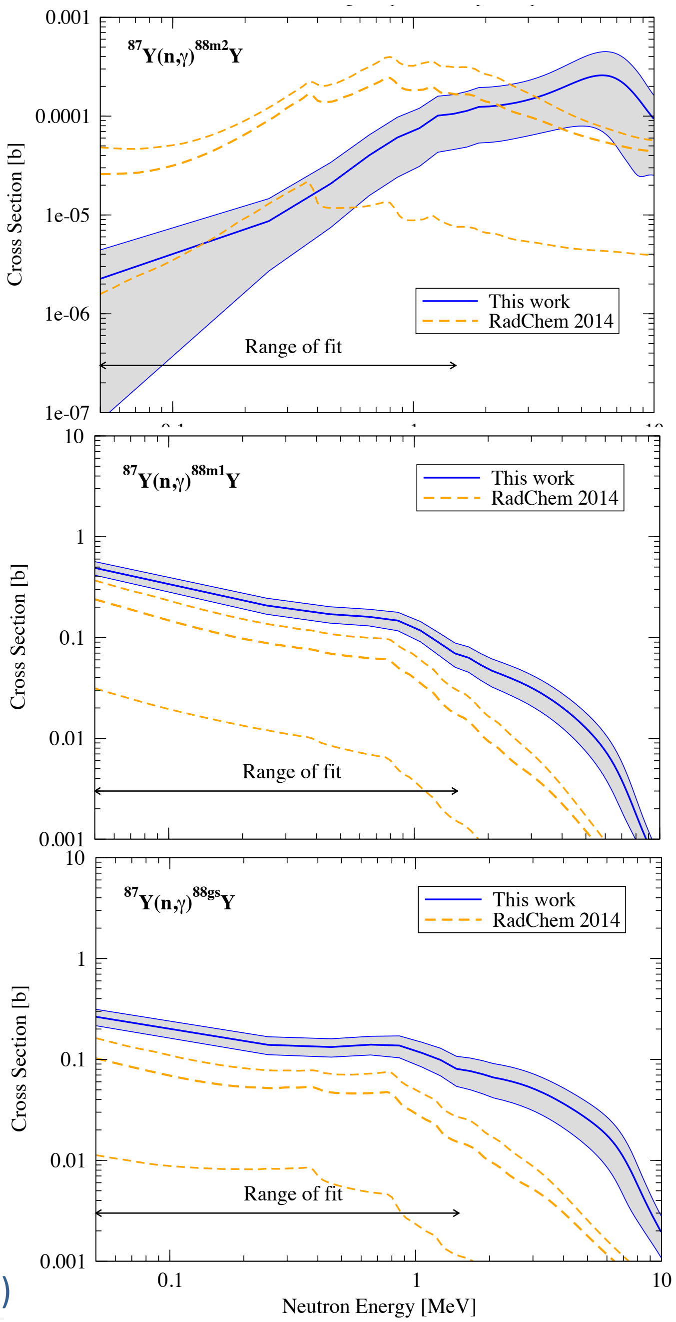
Results I: ^{87}Y(n,γ) cross sections from ^{89}Y(p,dγ) data



n + ^{87}Y

Capture on 1/2$^-$ g.s.



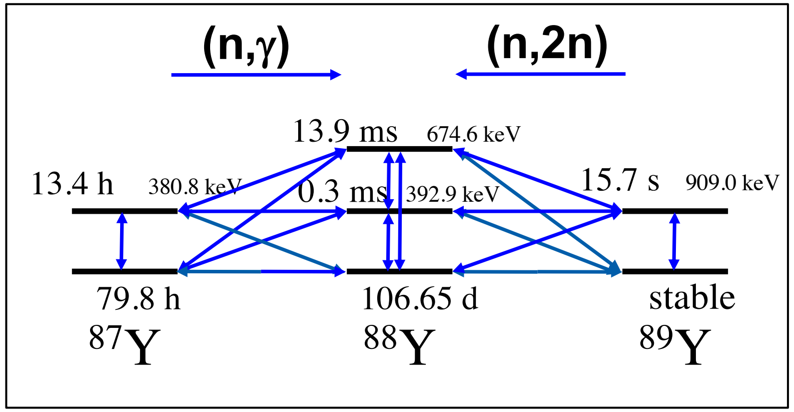


Earlier calculations relied on regional systematics.

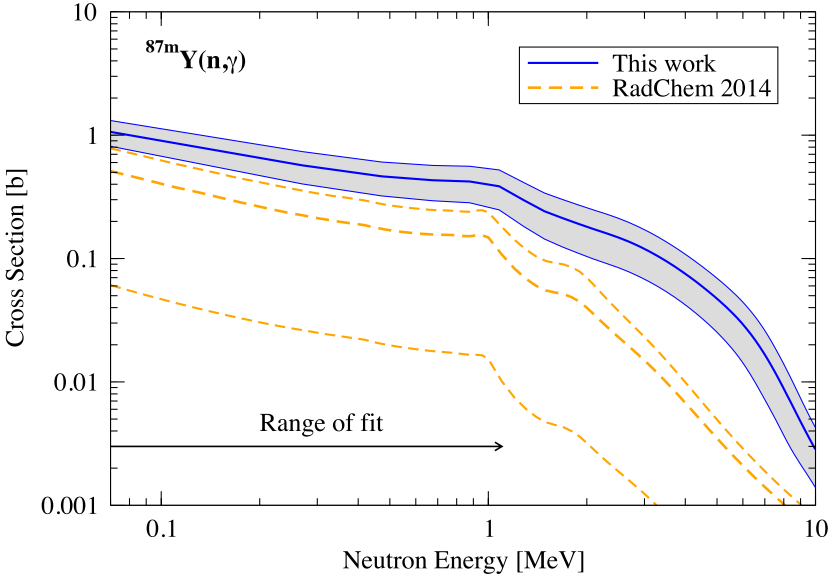
No D_0 or $\langle\Gamma_\gamma\rangle$ available.

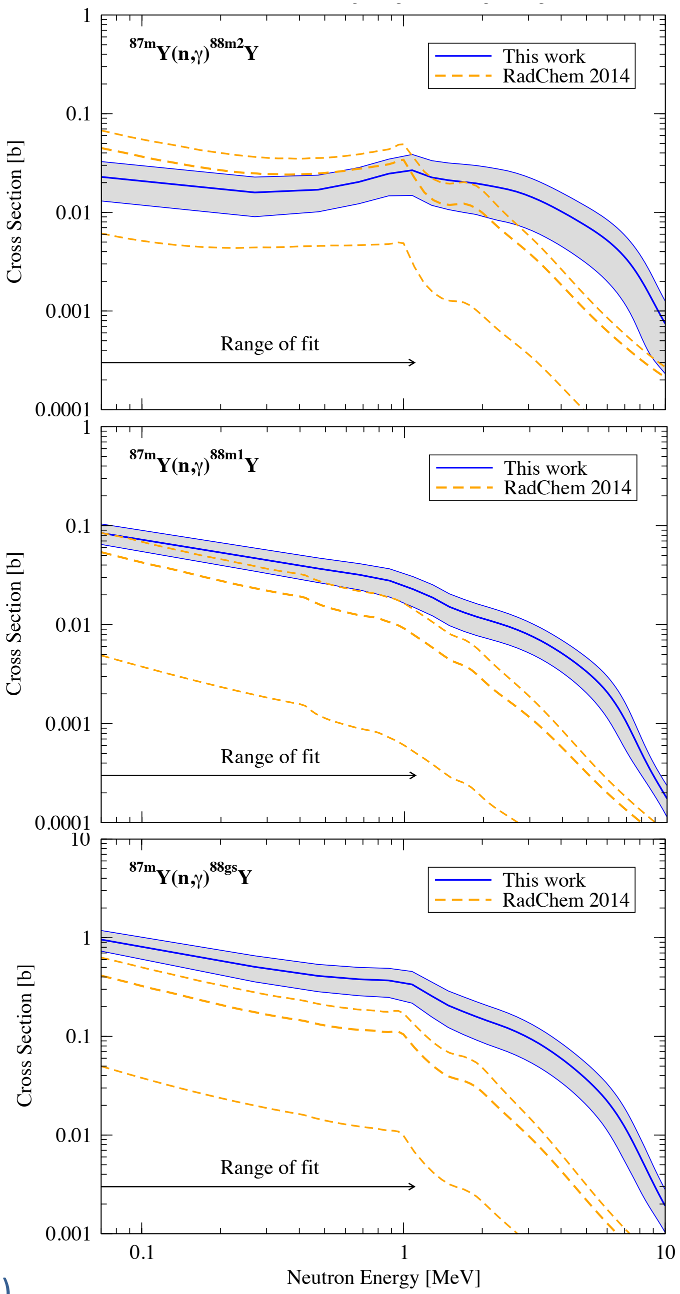
Escher et al, LLNL Tech. Rep. (2019)

Results II: ^{87m}Y(n,γ) cross sections from ^{89}Y(p,dγ) data



n + ^{87m}Y
Capture on $9/2^+$
isomer at 381 keV





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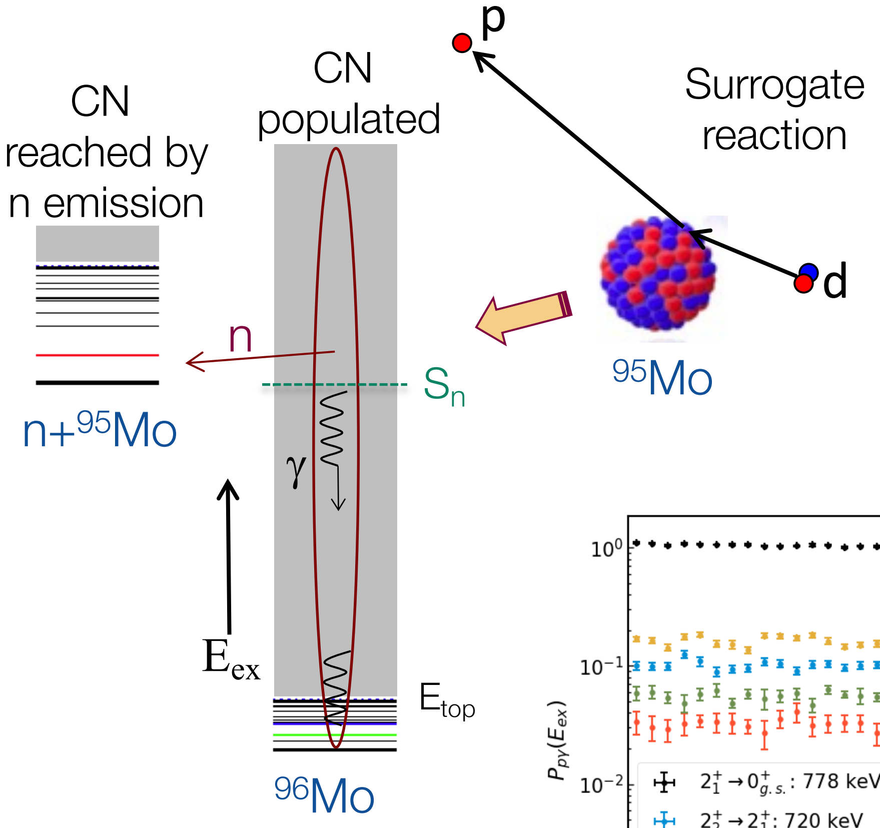
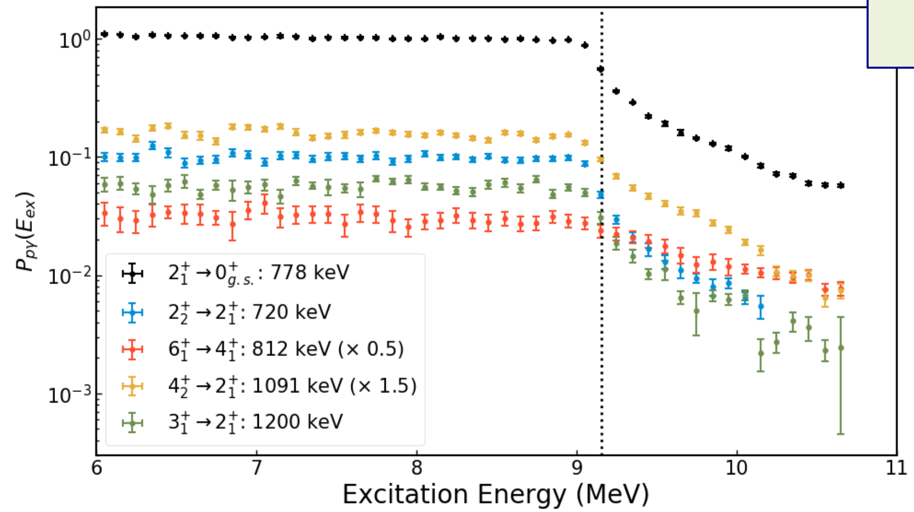
- **(d,p) as a surrogate reaction mechanism**
- Inelastic scattering as a surrogate reaction mechanism

Surrogate reactions method for neutron capture - using γ transitions



From experiment



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

^{95}Mo (n,γ) cross section*:

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The new cross section we want

Well modelled from nuclear theory

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Surrogate (d,p) transfer reactions enable determination of (n,γ) cross sections - benchmark ^{95}Mo(n,γ)

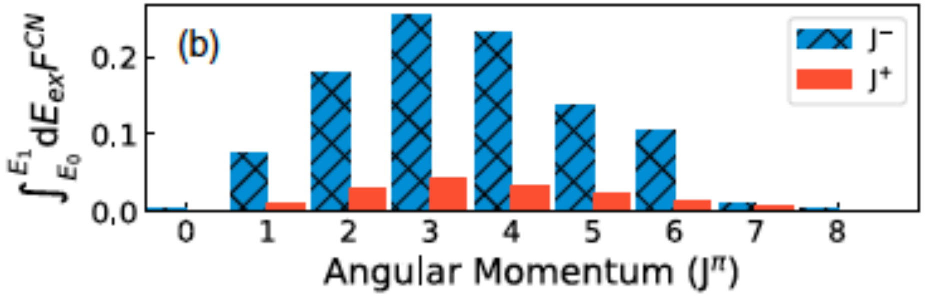
Ratkiewicz, Cizewski, JE, Potel, et al, PRL 122, 052502 (2019)

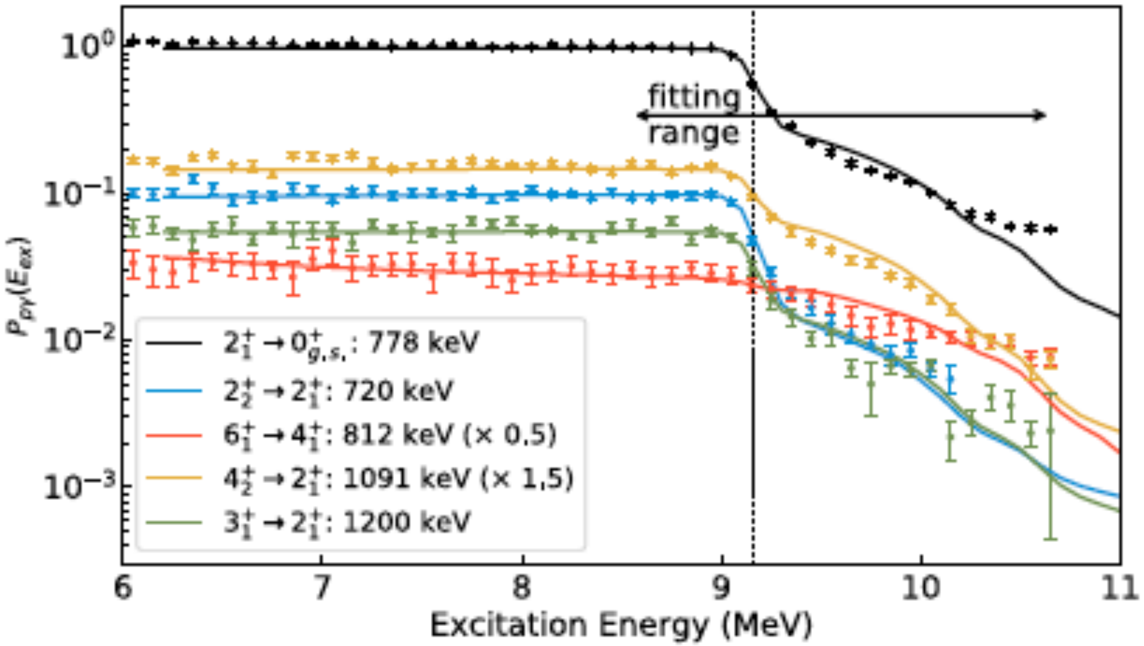
Coincidence probabilities from surrogate experiment

Surrogate coincidence probabilities

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

Spin-parity population from direct-reaction theory





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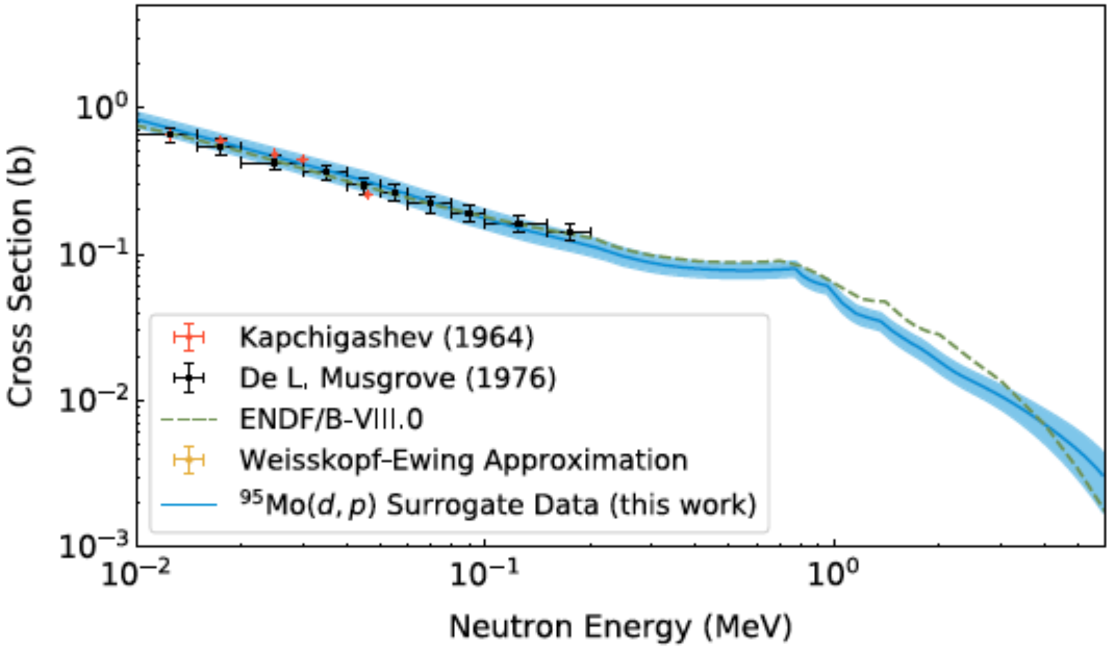

Procedure

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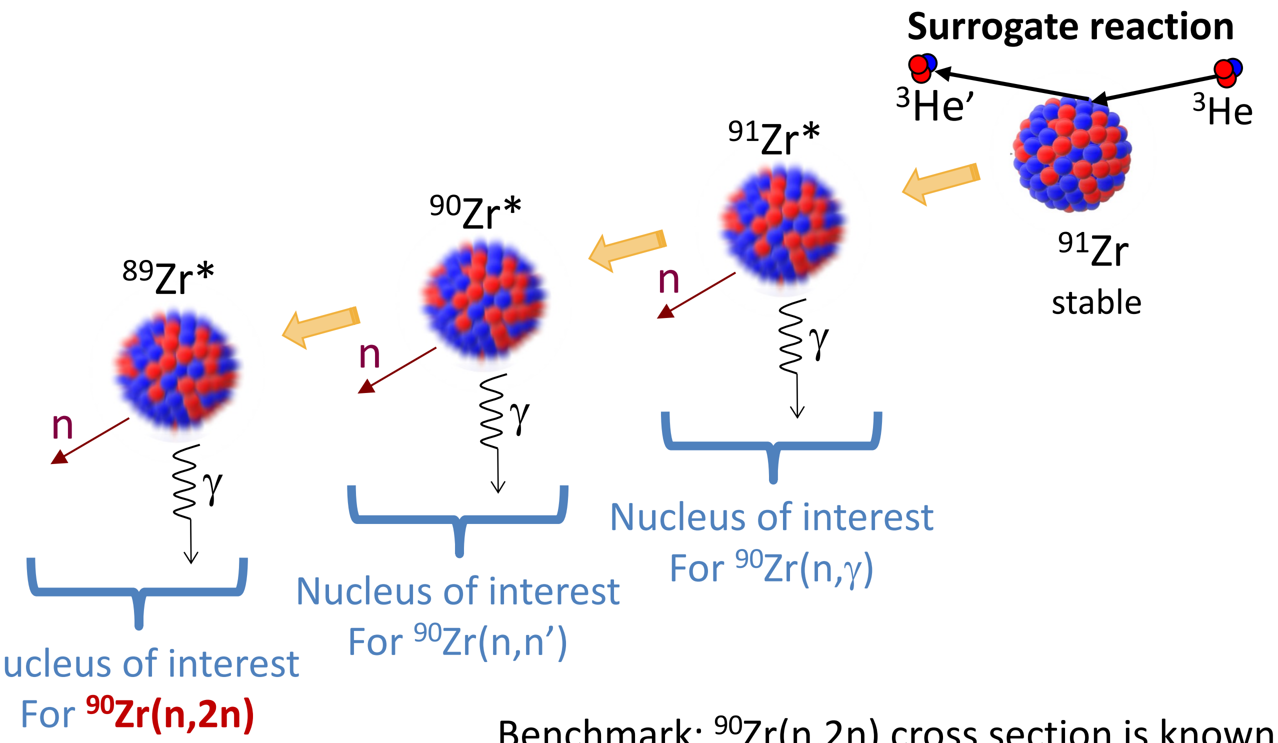
- ➢ Model CN decay and perform Bayesian parameter fit to surrogate coincidence probabilities
- ➢ Sample posterior HF parameter distributions to obtain neutron-capture cross section

- Concept
- (p,d) as a surrogate reaction mechanism
- (d,p) as a surrogate reaction mechanism
- **Inelastic scattering as a surrogate reaction mechanism**

Using inelastic scattering as a surrogate mechanism provides new opportunities: Determining (n,n’) and (n,2n) reaction cross sections

- Opportunities:
  - Unknown (n,n’) and (n,2n) reactions become accessible. Examples: ^{88}Y(n,2n), ^{168}Tm(n,2n)
  - Obtain multiple desired reaction cross sections simultaneously
  - Inverse-kinematics experiments at radioactive beam facilities
- Challenges:
  - Compound nucleus highly excited
  - Multiple intermediate nuclei involved
  - Non-statistical effects expected

^{90}Zr(n,2n) cross section from inelastic scattering



Surrogate reaction

^{3}He’

^{3}He

^{91}Zr

stable

^{91}Zr*

^{90}Zr*

^{89}Zr*

n

n

n

γ

γ

γ

Nucleus of interest
For ^{90}Zr(n,γ)

Nucleus of interest
For ^{90}Zr(n,n’)

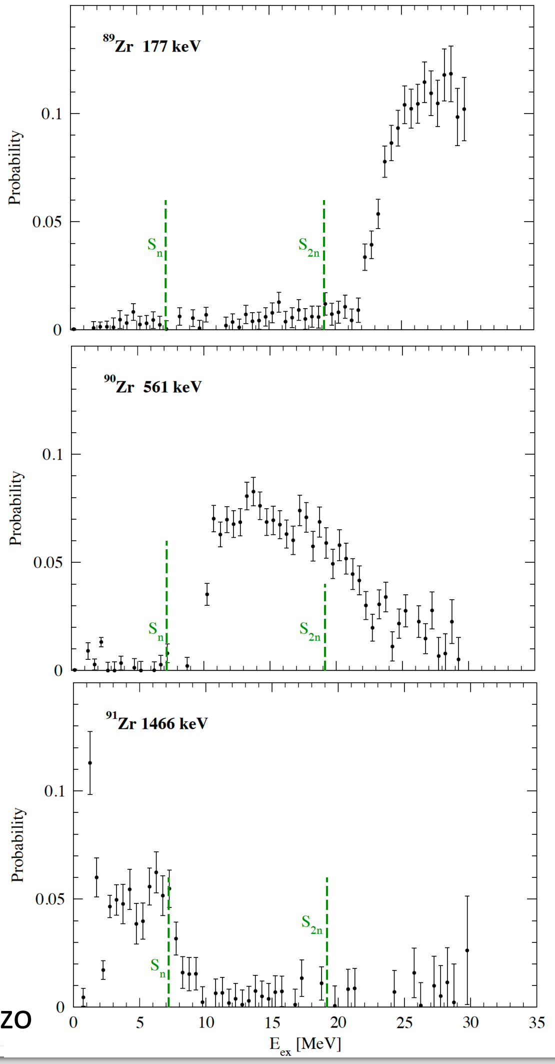
Nucleus of interest
For **^{90}Zr(n,2n)**

Benchmark: ^{90}Zr(n,2n) cross section is known

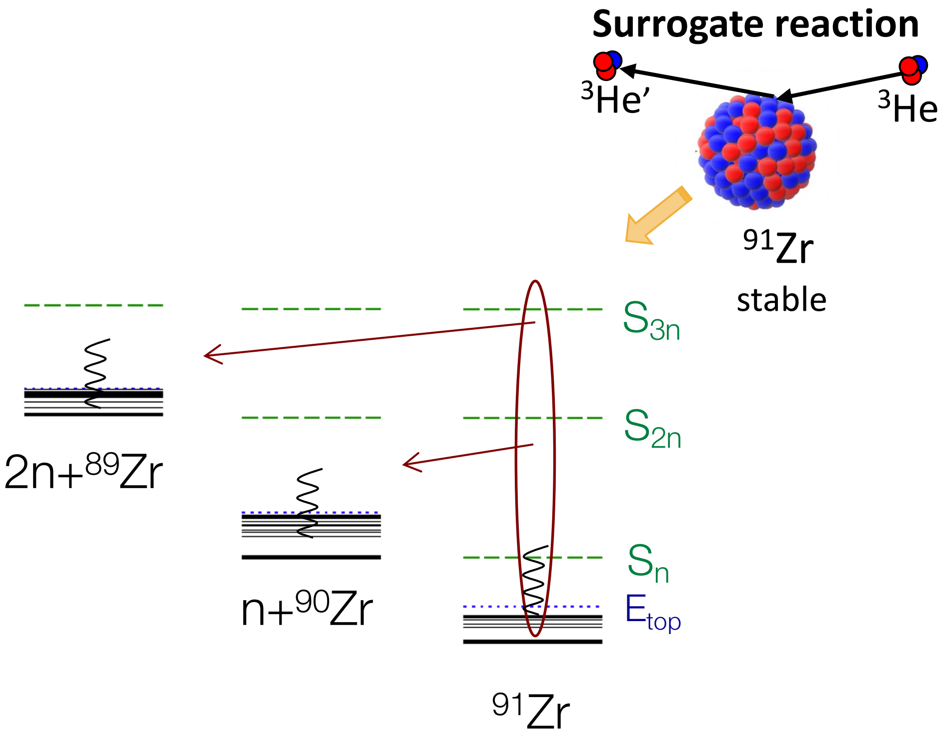
Surrogate reactions method for (n,n’) and (n,2n)

The Zr case provides a benchmark for the method

- Experiment provides:
  - — ^{91}Zr(^{3}He,^{3}He’) ‘singles’ cross section as function of E_{ex} and ejectile angle
  - — Coincidence probabilities $P_{(3He,3He')\gamma}(E_{ex})$ for γ-transitions in 3 different nuclei
- Theory must:
  - — Calculate ^{91}Zr(^{3}He, ^{3}He’) ‘singles’ cross section and determine spin-parity population
  - — Model ^{91}Zr decay into 3 final nuclei and fit decay parameters
  - — Sample posterior HF parameter distribution and calculate desired cross sections



Surrogate data from N. Scielzo



Inelastic scattering enables determination of ^{90}Zr(n,γ), ^{90}Zr(n,n'), ^{90}Zr(n,2n) Benchmark cross sections

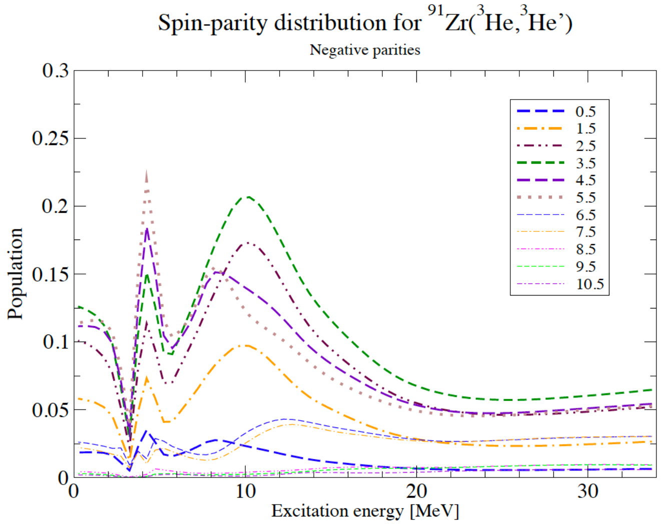
Escher et al., WIP (2024)

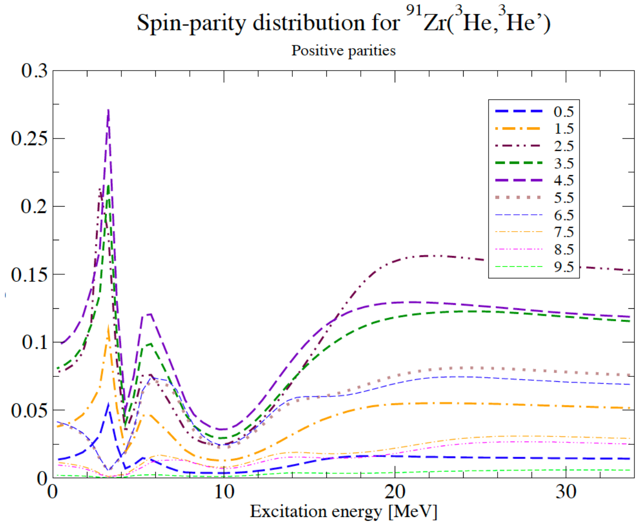
Coincidence probabilities from surrogate experiment

Surrogate coincidence probabilities

$$P_{(3He,3He'\gamma)}(E) = \sum_{J,\pi} F_{(3He,3He')}^{CN}(E,J,\pi)\cdot G^{CN}_{\gamma}(E,J,\pi)$$

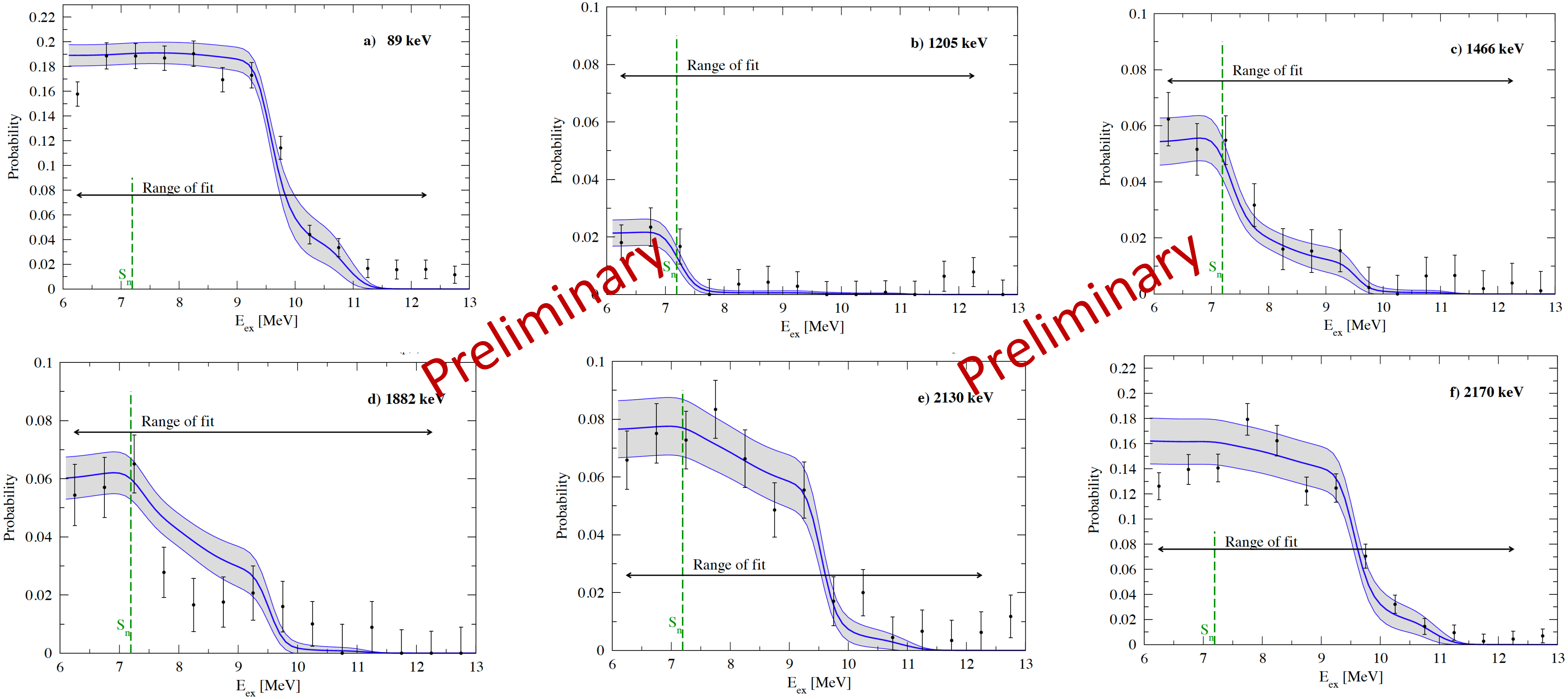
Spin-parity population from direct-reaction theory





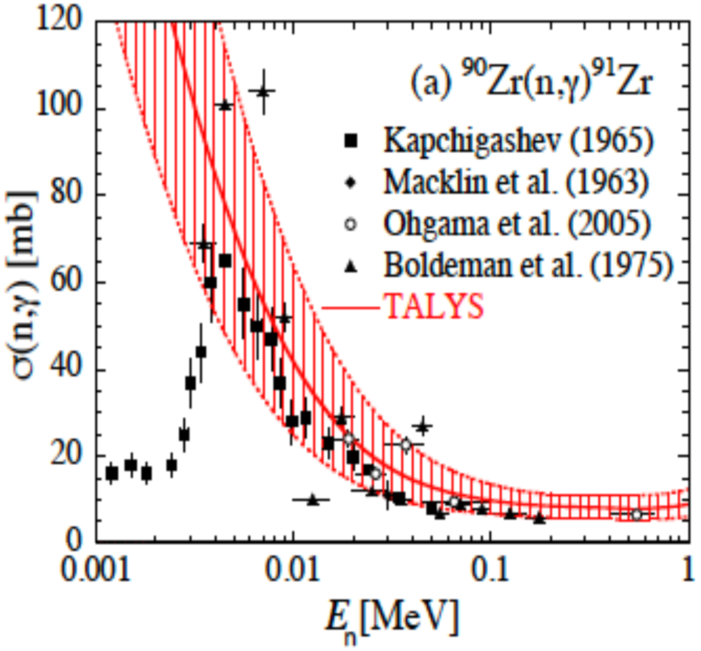
Fits to gamma transitions in ^{91}Zr → constrain LDs and γSF in ^{91}Zr

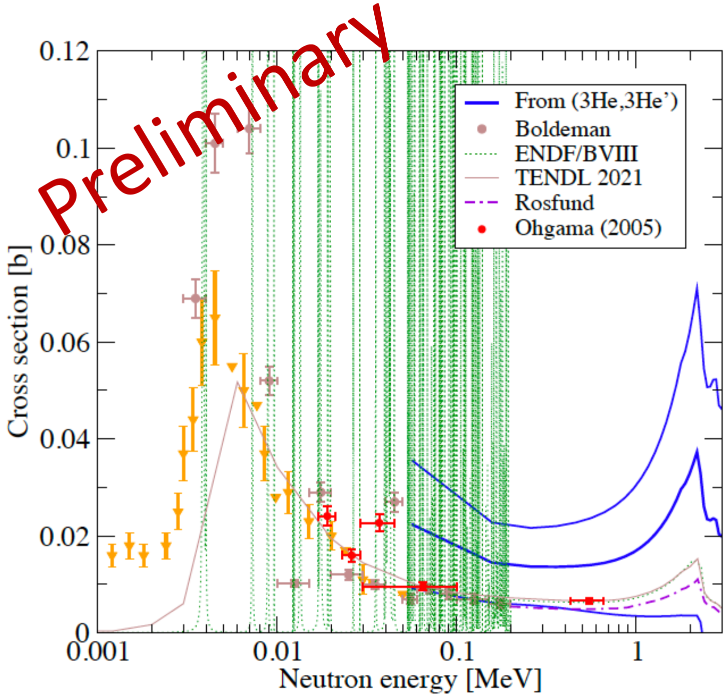
Escher et al., WIP (2024)



Neutron capture cross section from ^{91}Zr(^{3}He,^{3}He’) surrogate data compared to results from other indirect measurements

Escher et al., WIP (2024)





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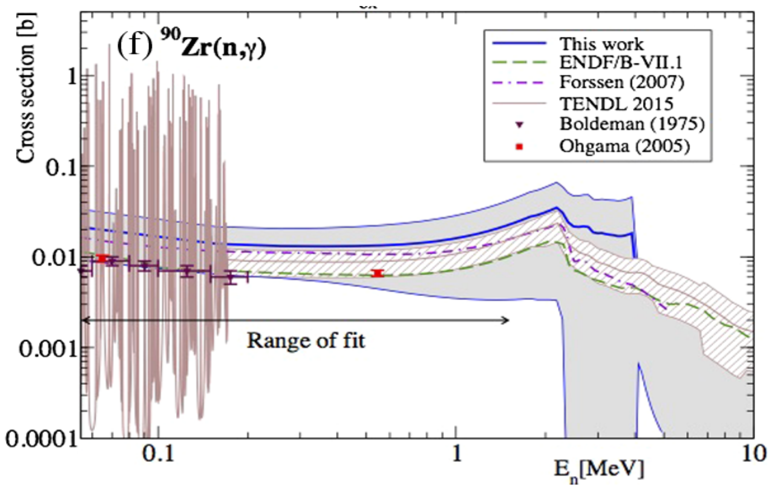


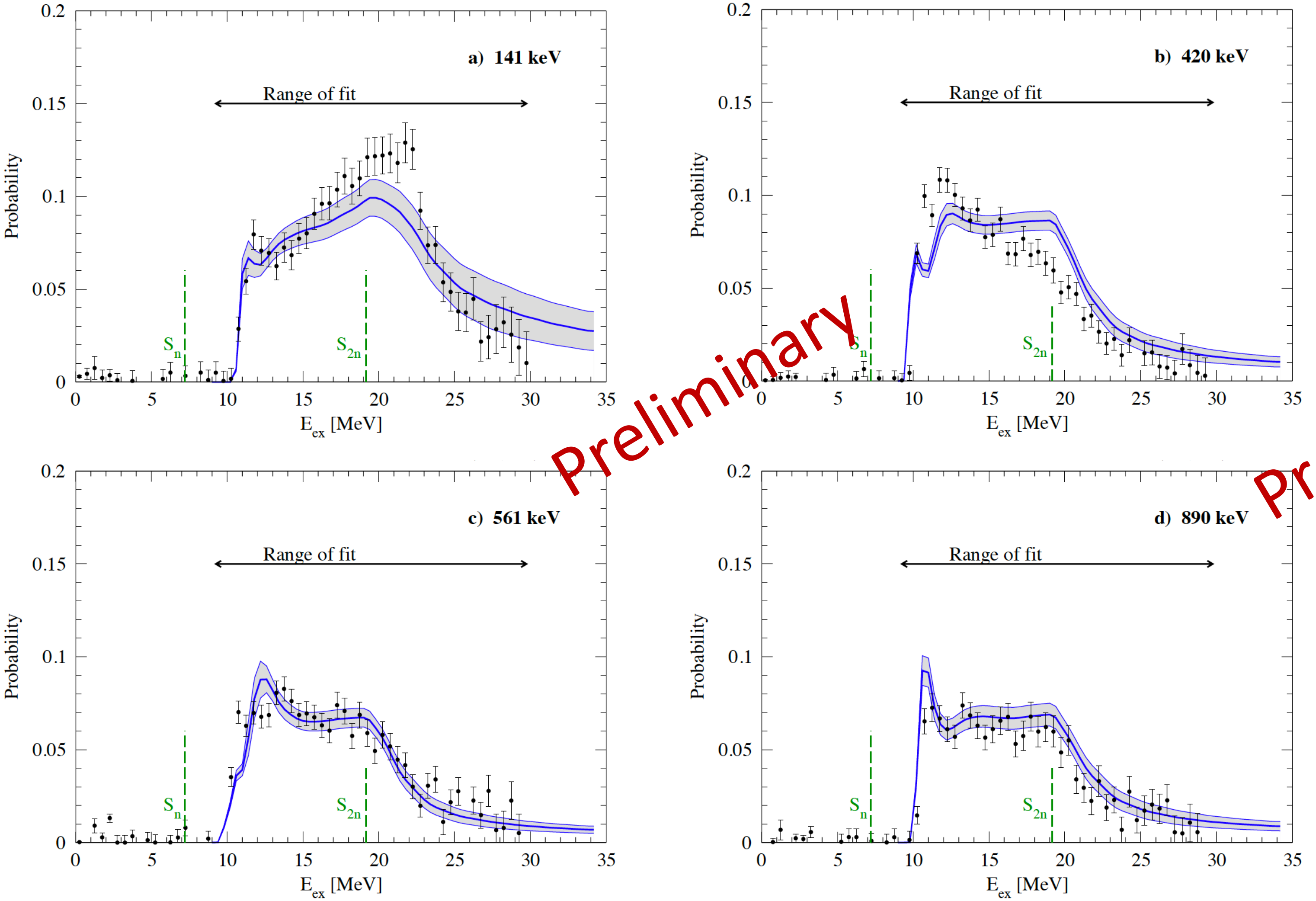
Guttormsen et al, PRC 2019
Oslo method, ^{92}Zr(p,d)

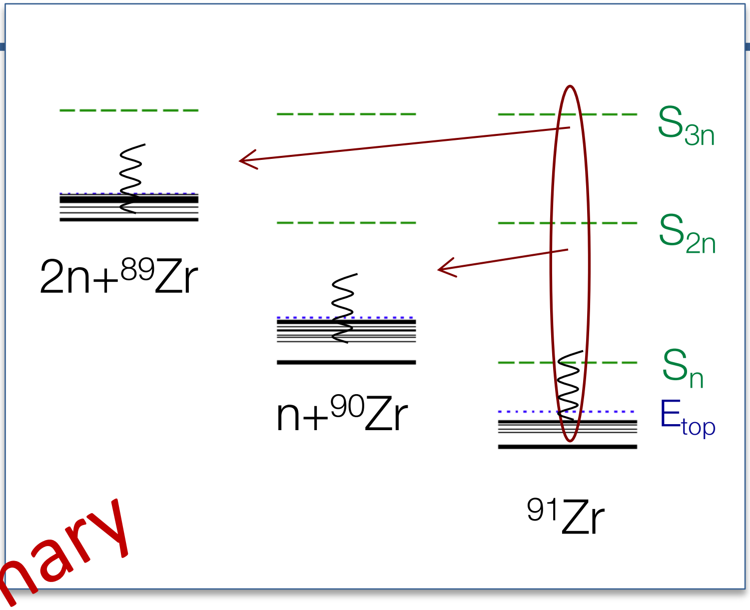
This work
(preliminary)

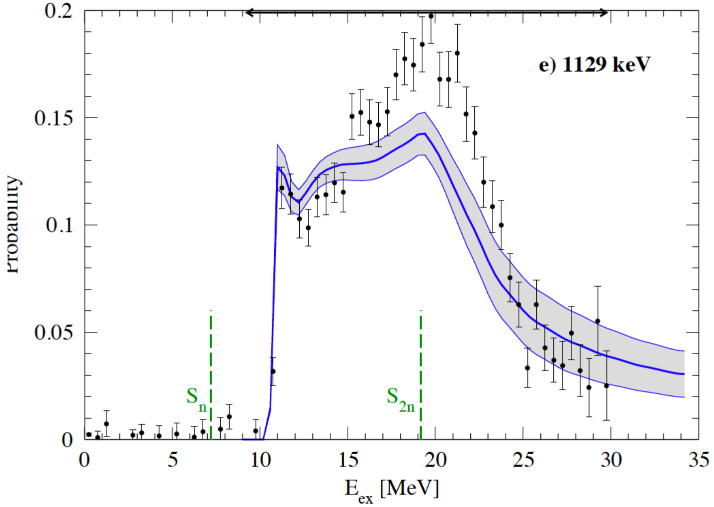
Escher et al, PRL 2019
Surrogate method, ^{92}Zr(p,d)

Simultaneous fit to gammas in ^{90}Zr and ^{89}Zr

Escher et al., WIP (2024)







Simultaneous fit to gammas in ^{90}Zr and ^{89}Zr

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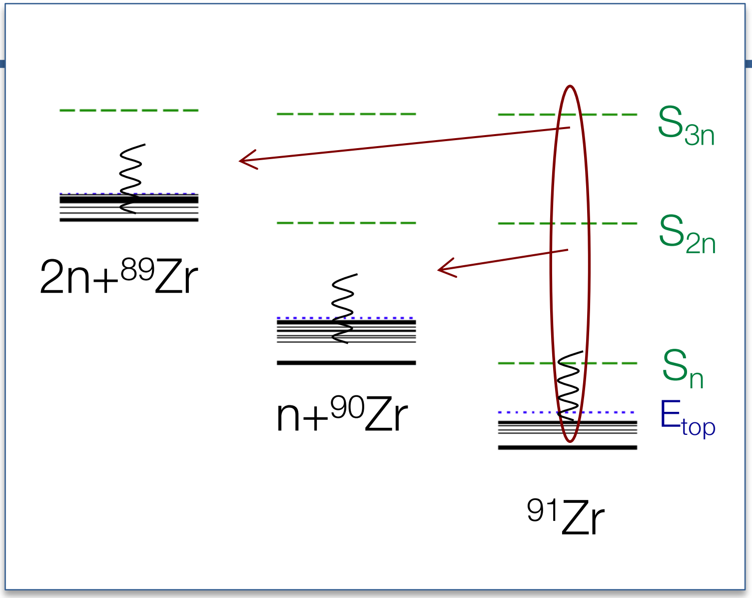
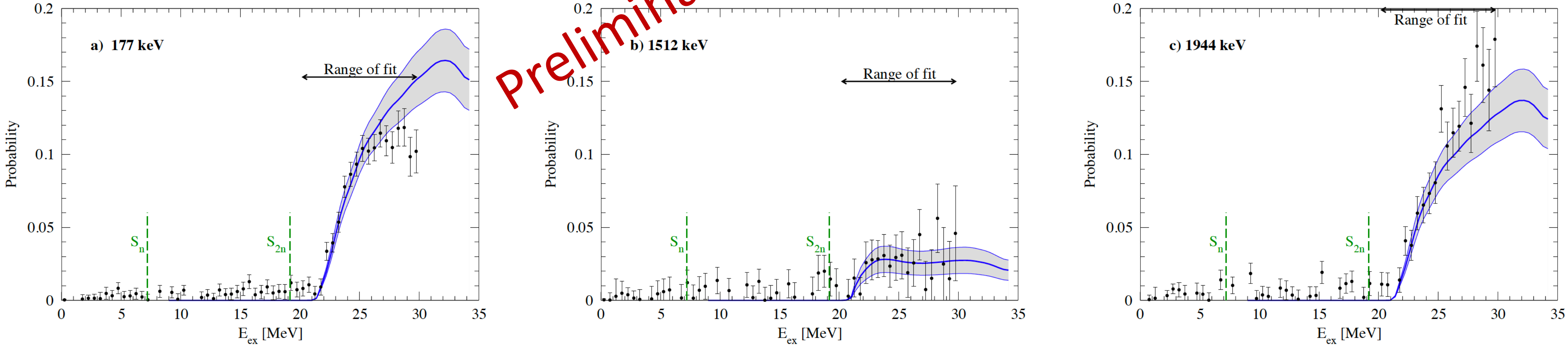
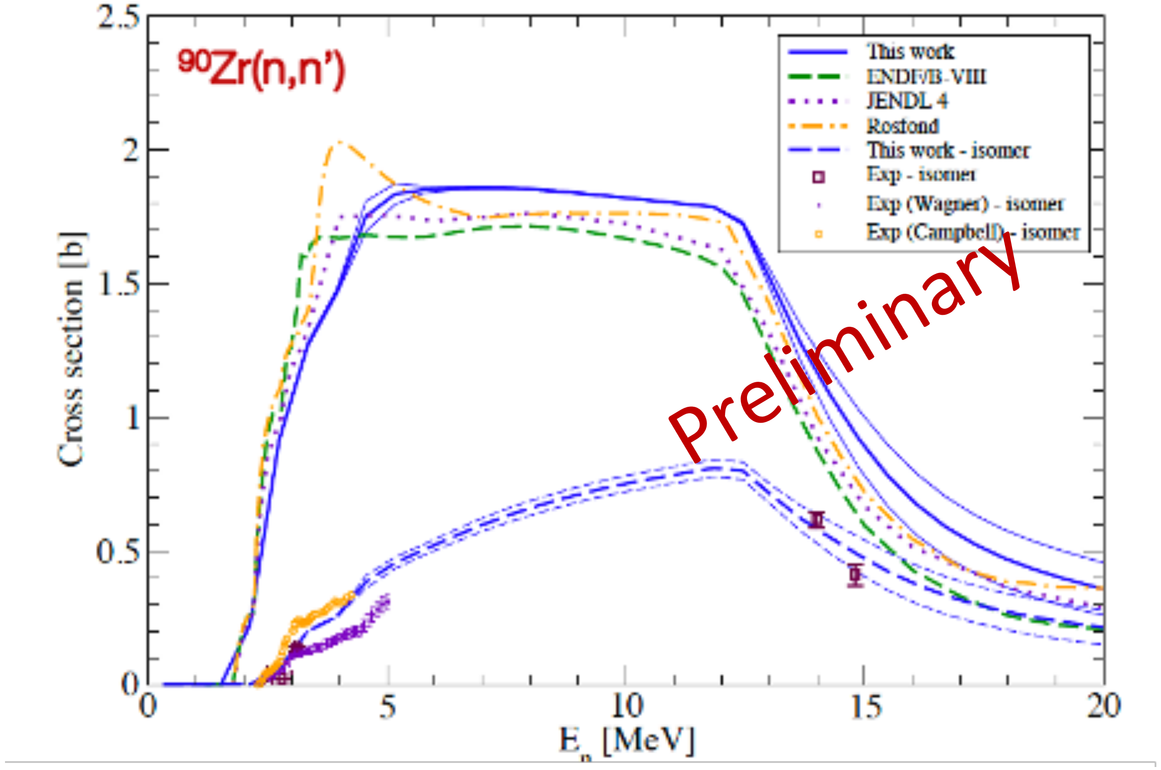


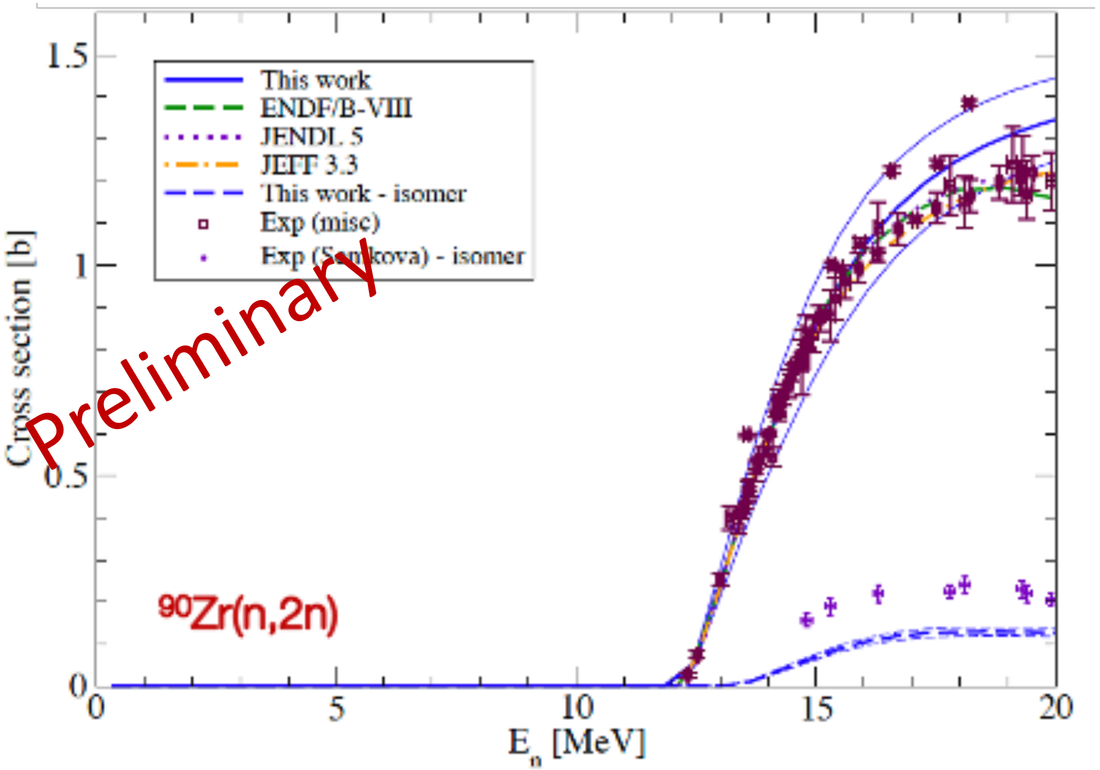
Preliminary



^{90}Zr(n,n') and (n,2n) cross sections from ^{91}Zr(^{3}He,^{3}He’) data and theory

Escher et al., WIP (2024)



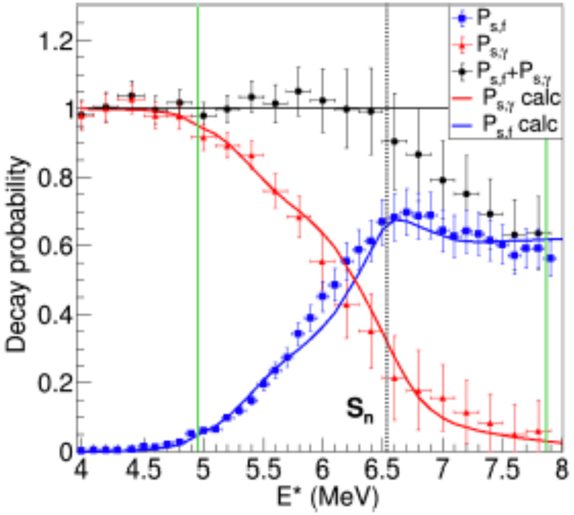


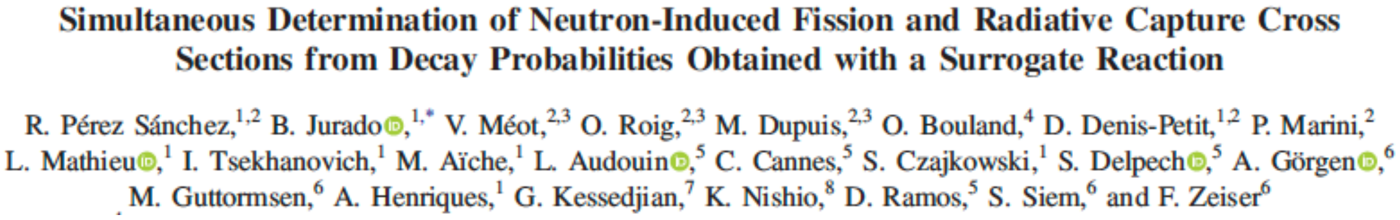
(preliminary)

Actinides:
Inelastic alpha scattering

Pérez Sánchez et al, PRL 125, 122502 (2020)

- Decay probabilities for fission and γ emission measured in ^{240}Pu(α,α’) experiment
- Calculated Jp population using QRPA structure information in reaction description
- Adjusted HF decay parameters to minimize χ^2
- Obtained both ^{239}Pu(n,γ) and ^{239}Pu(n,f)

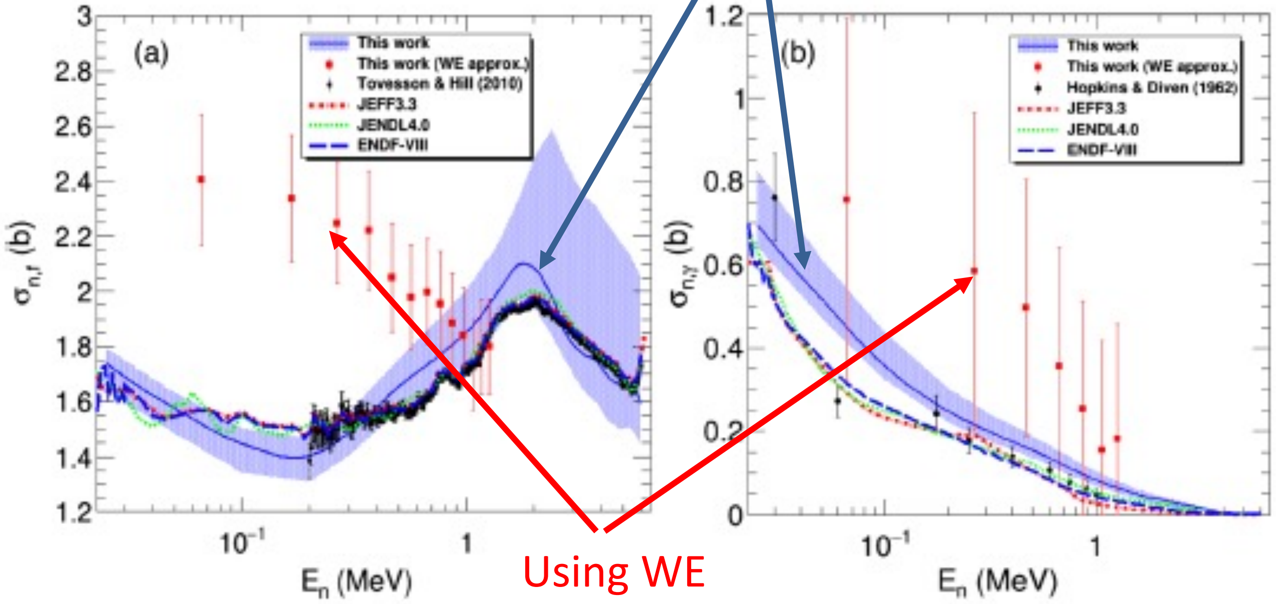




Simultaneous Determination of Neutron-Induced Fission and Radiative Capture Cross Sections from Decay Probabilities Obtained with a Surrogate Reaction

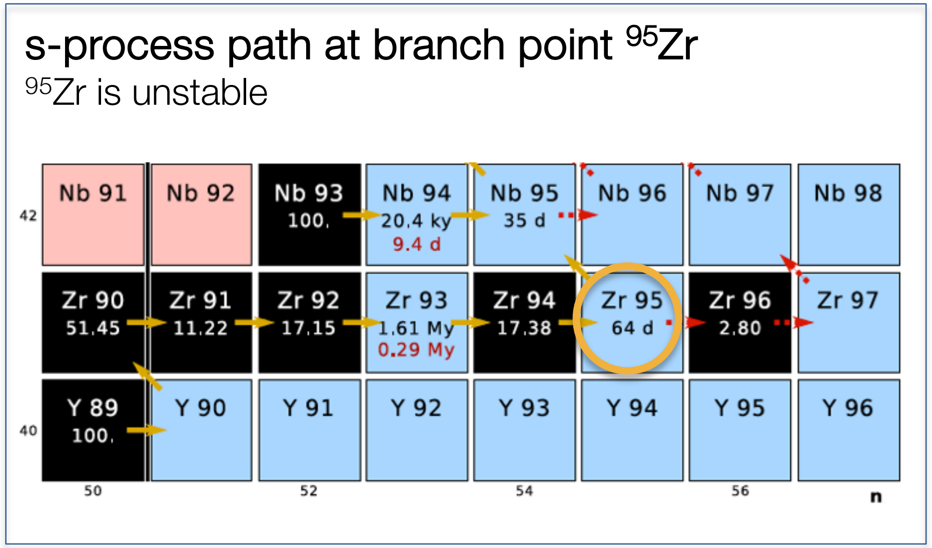
R. Pérez Sánchez,[1,2] B. Jurado,[1,*] V. Méot,[2,3] O. Roig,[2,3] M. Dupuis,[2,3] O. Bouland,[4] D. Denis-Petit,[1,2] P. Marini,[2] L. Mathieu,[1] I. Tsekhanovich,[1] M. Aïche,[1] L. Audouin,[5] C. Cannes,[5] S. Czajkowski,[1] S. Delpech,[5] A. Görgen,[6] M. Guttormsen,[6] A. Henriques,[1] G. Kessedjian,[7] K. Nishio,[8] D. Ramos,[5] S. Siem,[6] and F. Zeiser[6]

From fit using calculated J$^\pi$



Using WE approximation

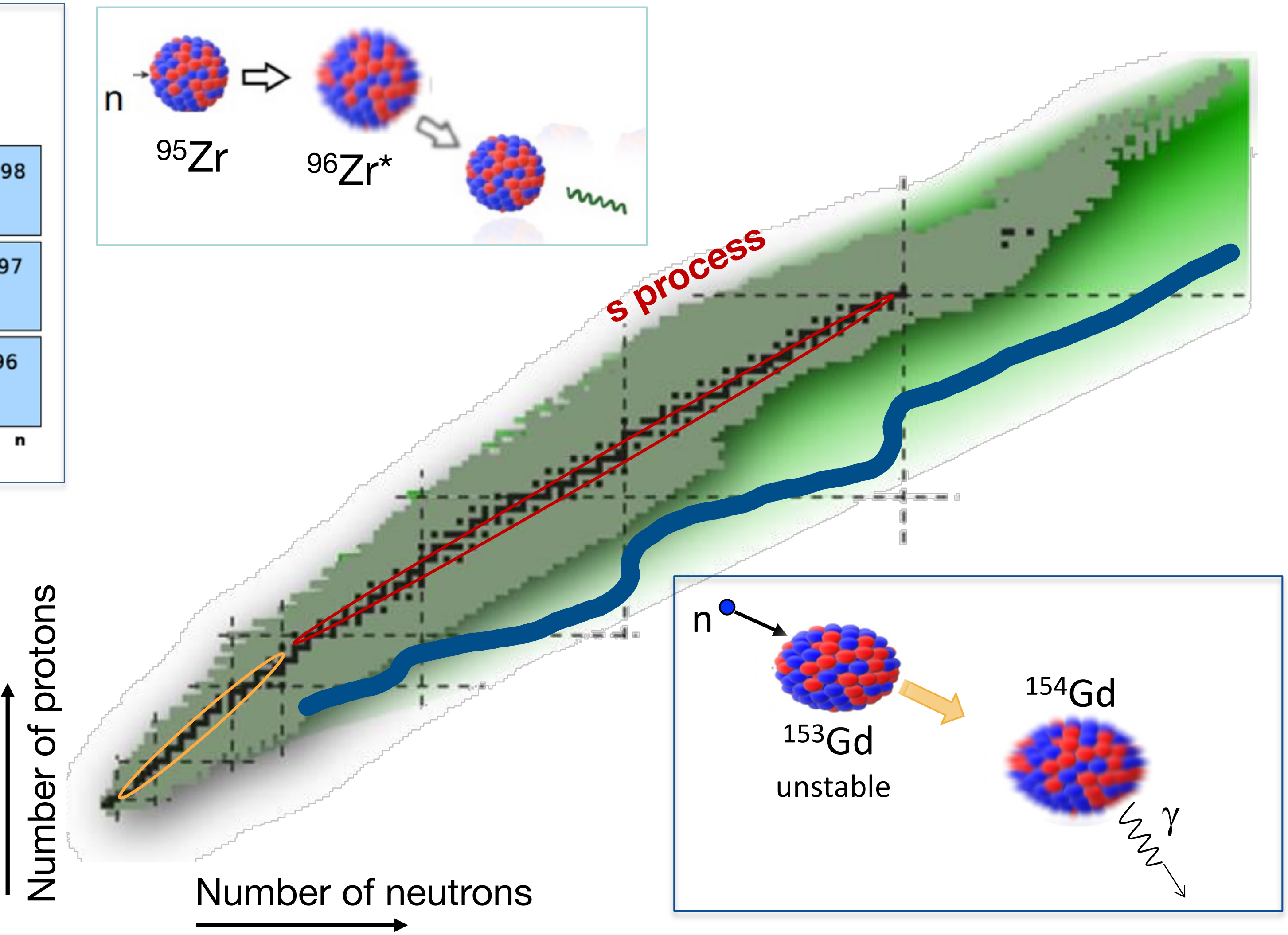
Using inelastic scattering as a surrogate mechanism provides new opportunities: Neutron capture on s-process branch points



s-process path at branch point ^{95}Zr

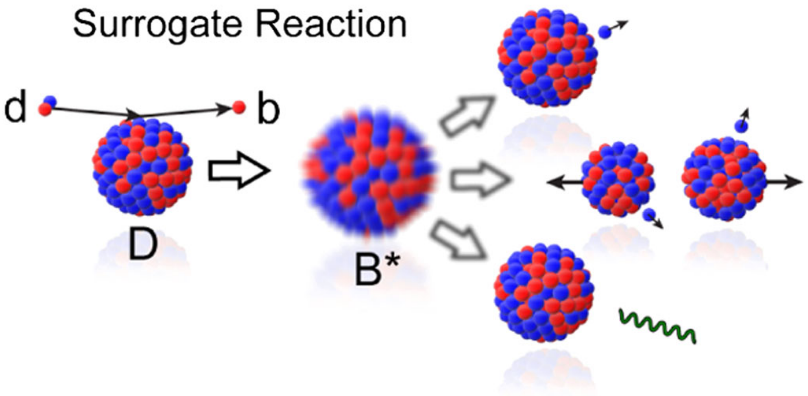
^{95}Zr is unstable

	50		52		54		56	n
42	Nb 91	Nb 92	Nb 93 100.	Nb 94 20.4 ky 9.4 d	Nb 95 35 d	Nb 96	Nb 97	Nb 98
	Zr 90 51.45	Zr 91 11.22	Zr 92 17.15	Zr 93 1.61 My 0.29 My	Zr 94 17.38	Zr 95 64 d	Zr 96 2.80	Zr 97
40	Y 89 100.	Y 90	Y 91	Y 92	Y 93	Y 94	Y 95	Y 96



- Experiments (Alan, Scielzo, et al):
  - ^{94,96}Zr(p,p’) at Texas A&M, E_p = 21 MeV
  - ^{154,156,158}Gd(p,p’) at LBNL, E_p = 22 MeV
- Theory (Thapa, Escher, et al)
  - 1-step contributions
  - 2-step contributions
  - deformation

Spin-parity populations: Why they matter and how we calculate them

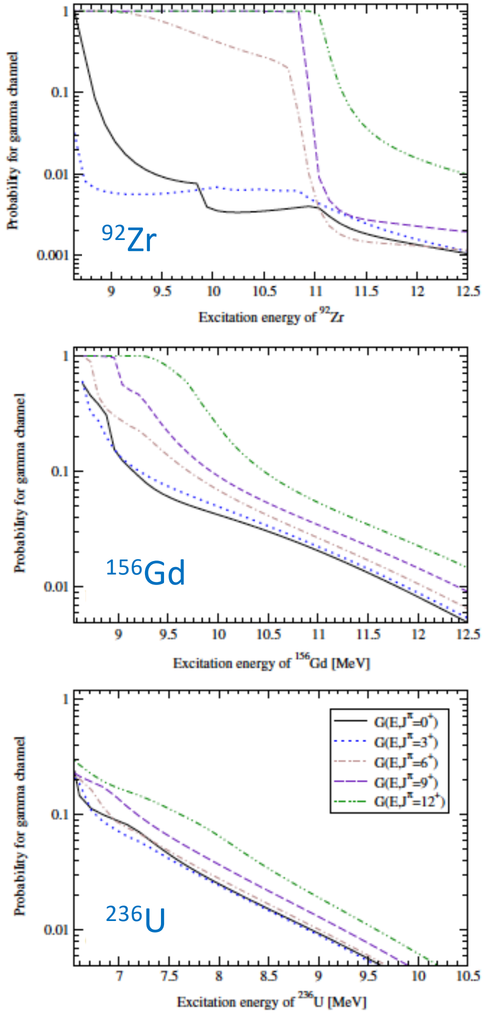


Why it is important to describe the CN formation well: Spin-parity dependence of the decay probabilities

- The CN formed in neutron fusion has different J^{π} than when formed in inelastic scattering or transfer reactions >> The 'spin-parity mismatch' !!

- Sensitivity studies show
  - Decay into γ-channel depends very strongly on CN J^{π}
  - Decay by fission is less sensitive
  - Decay by p, n, or 2n emission is `in-between' but J^{π} cannot be ignored

γ-channel probabilities



The Surrogate experiment gives:

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

HF theory of the "desired" reaction:

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

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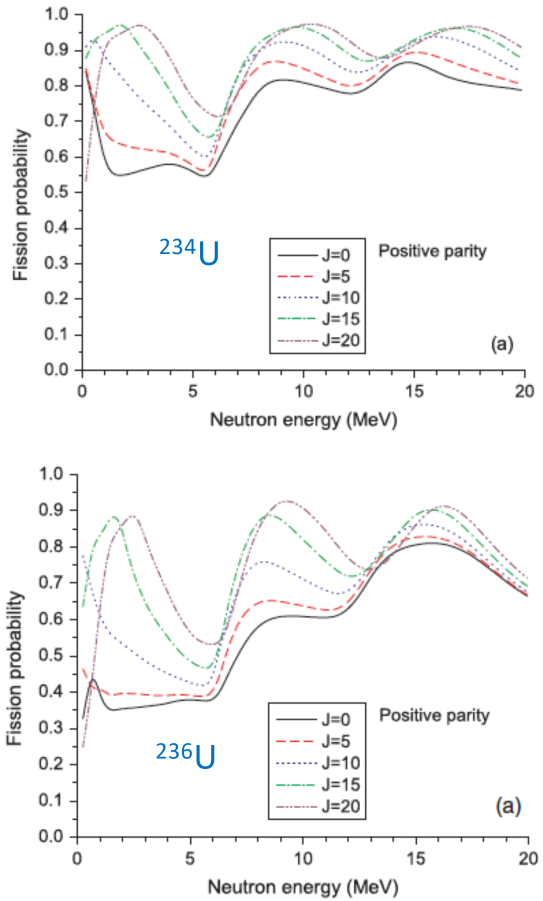
fission probabilities



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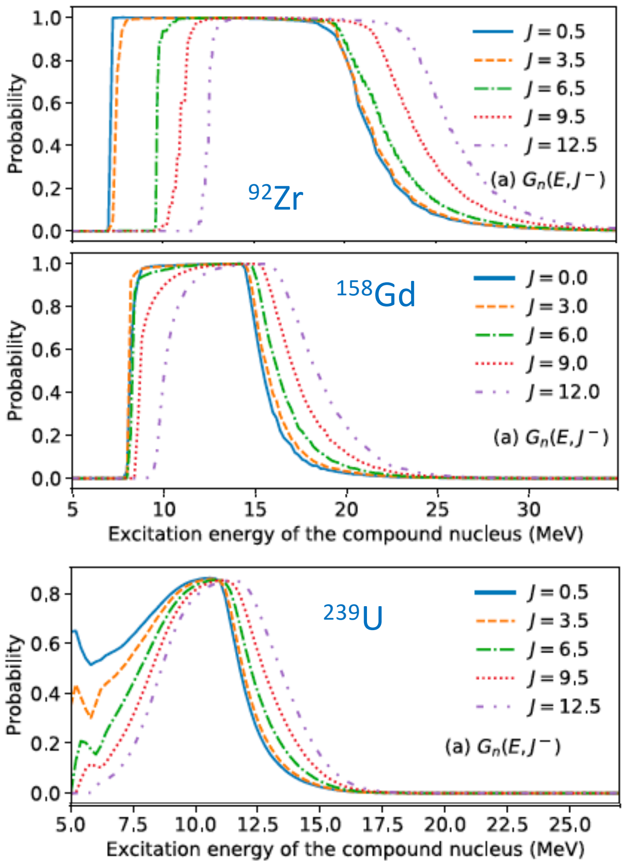
n-channel probabilities



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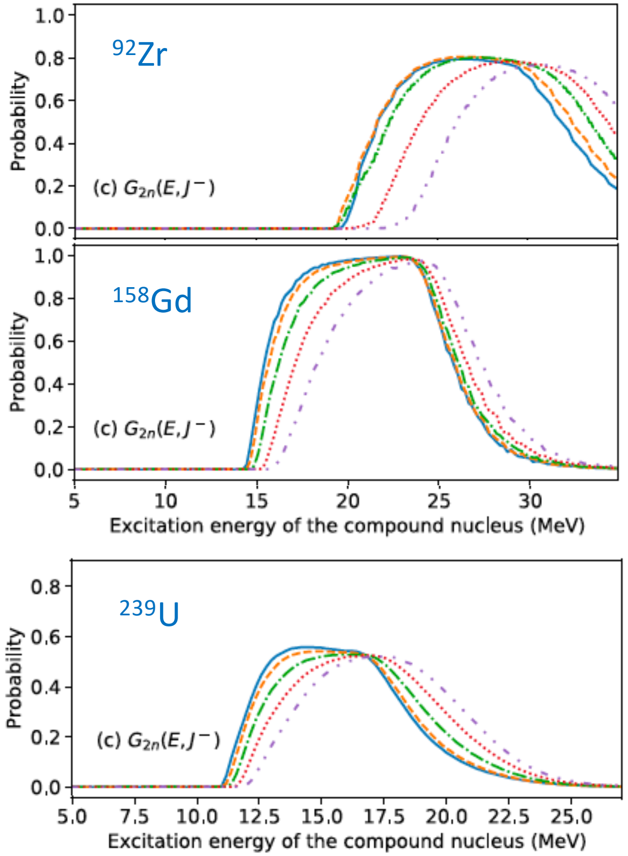
2n-channel probabilities



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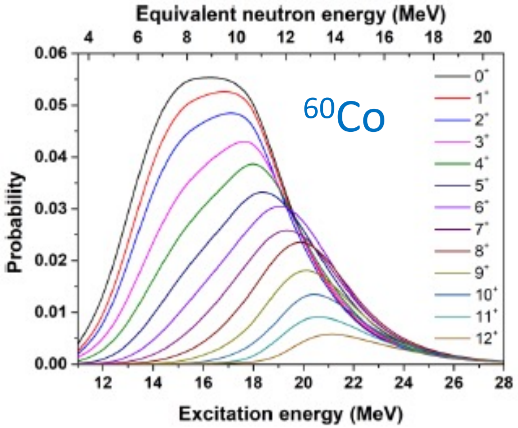
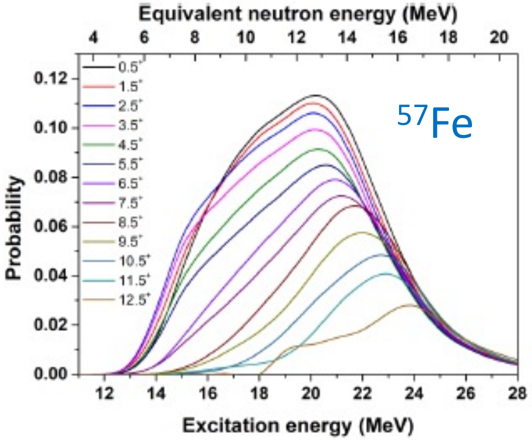
p-channel probabilities





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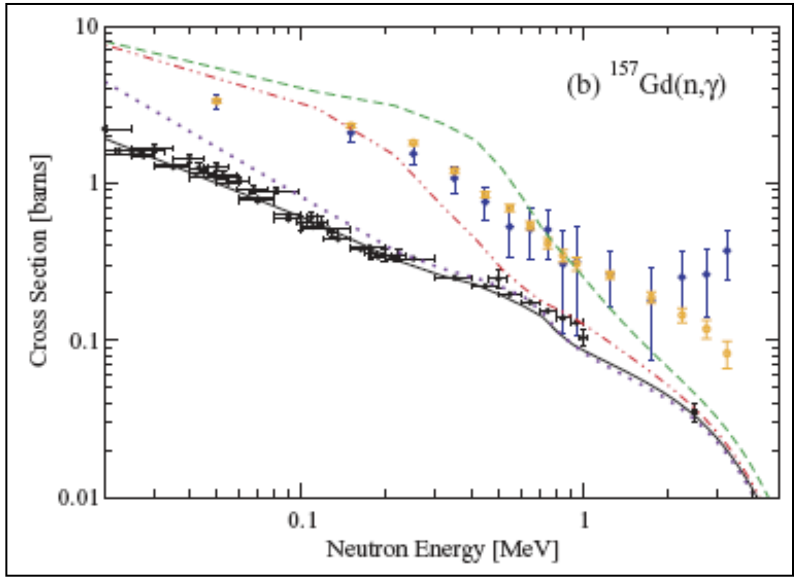
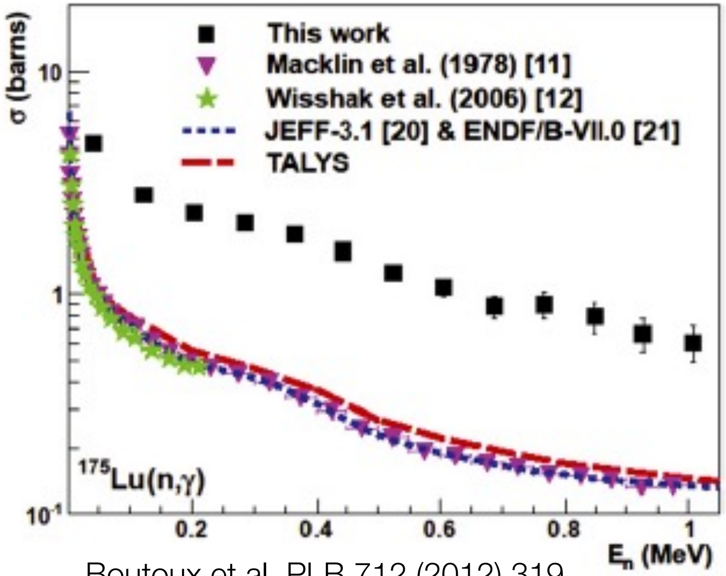
Ignoring the spin-parity mismatch is not valid for (n,γ): Impact on capture cross sections extracted using the Weisskopf-Ewing approximation

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



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

^{175}Lu(n,γ) extracted from ^{178}Yb(^{3}He,p) data using the WE approximation



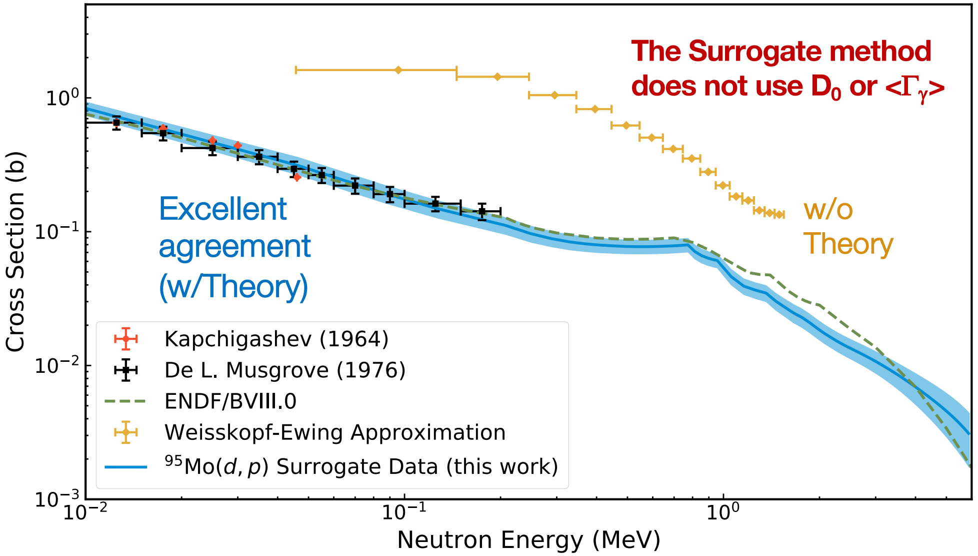
Boutoux et al, PLB 712 (2012) 319

Using the WE approximation is NOT valid for capture!

^{95}Mo(n,γ) cross section from surrogate data
Full theory analysis vs Weisskopf-Ewing approximation

Ratkiewicz, Cizewski, JE, Potel, et al, PRL 122, 052502 (2019)

- ^{95}Mo(n,γ) from surrogate data
  - Using calculated J$^{\pi}$ and fitting procedure (blue band)
- ^{95}Mo(n,γ) from surrogate data
  - Using WE approximation (yellow data points): $\sigma_{(n,\gamma)}(E_n) = \sigma^{CN}_{(n+T)}(E_n) \cdot P_\gamma(E_{ex})$



The Surrogate method does not use D_0 or $<\Gamma_\gamma>$

Excellent agreement (w/Theory)

w/o Theory

Using the WE approximation is NOT valid for capture!

Accounting for the spin-parity population in surrogate reaction applications is important for obtaining correct results

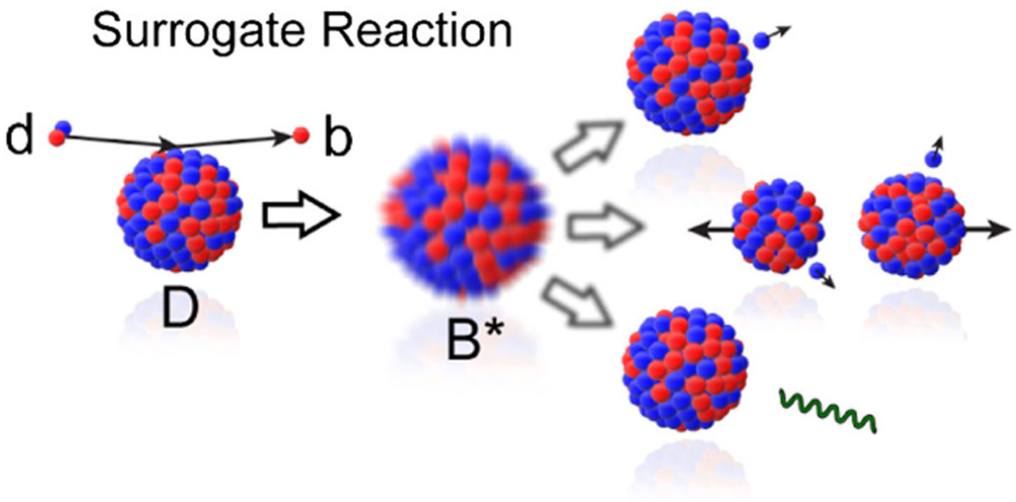
Common misconceptions:
How to NOT obtain the spin-parity population

- Spin-parity population is equal to that of the neutron-induced reaction
  - Strong claims require strong proofs!
- Spin-parity population is equal to the spin-parity distribution of the level density
  - Reactions populate only a subset of states!
- ‘Just use DWBA’
  - 2-step mechanisms contribute at high E_{ex}
- ‘Just use Talys’
  - Hmm….???

How should we then calculate the J^{π} population? The role of doorway states

Forming the CN in a surrogate reaction:

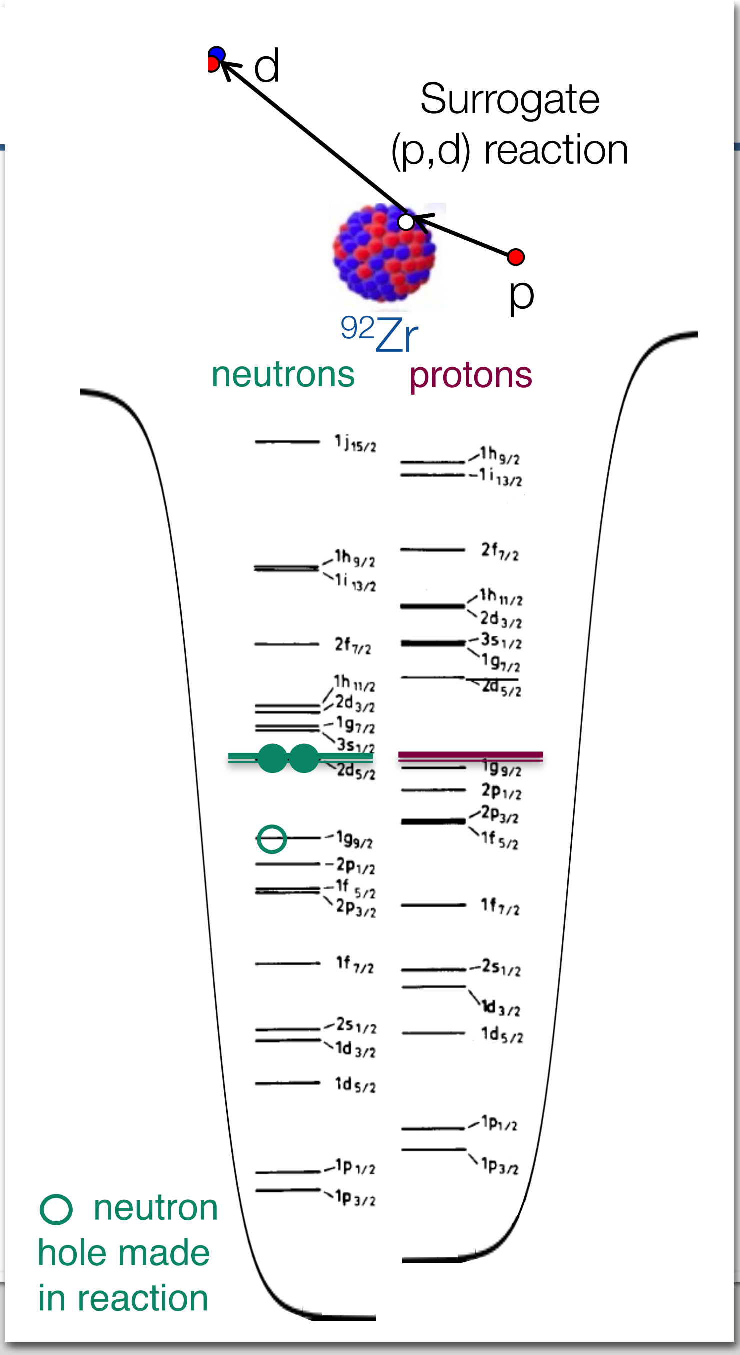
- Starts with a 'direct' reaction that produces a 'doorway state' at E_{ex} > several MeV
- Doorway evolves into a CN
- Spin population of doorway state = spin population of the CN

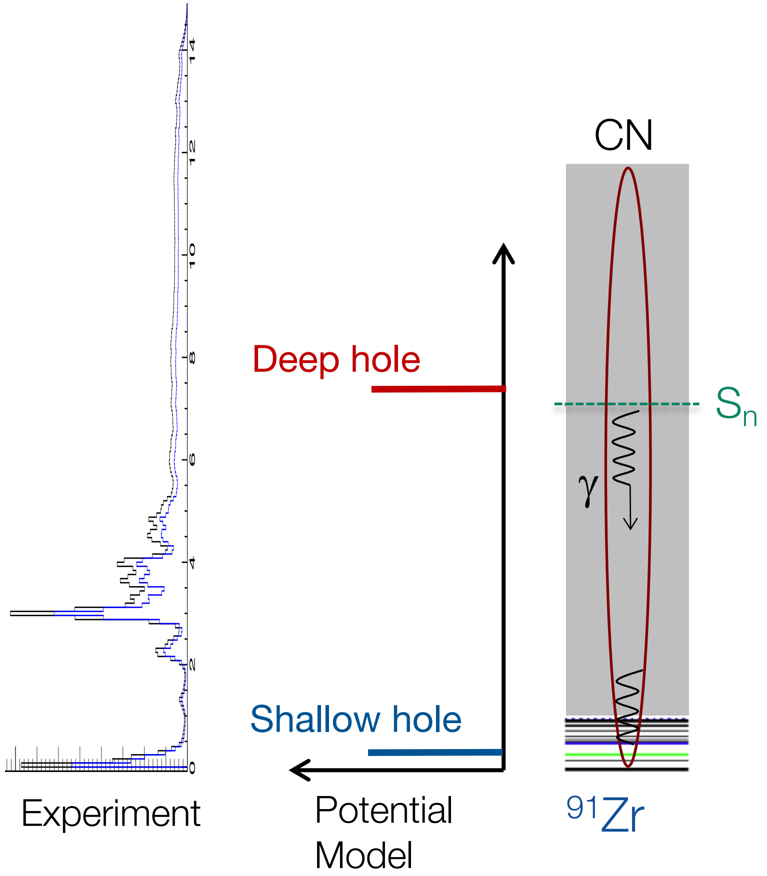


Theory for (p,d) surrogate reactions: Deep neutron holes

Challenge: Naïve potential-model picture not useful for deep holes

- Hole location
- Fragmentation

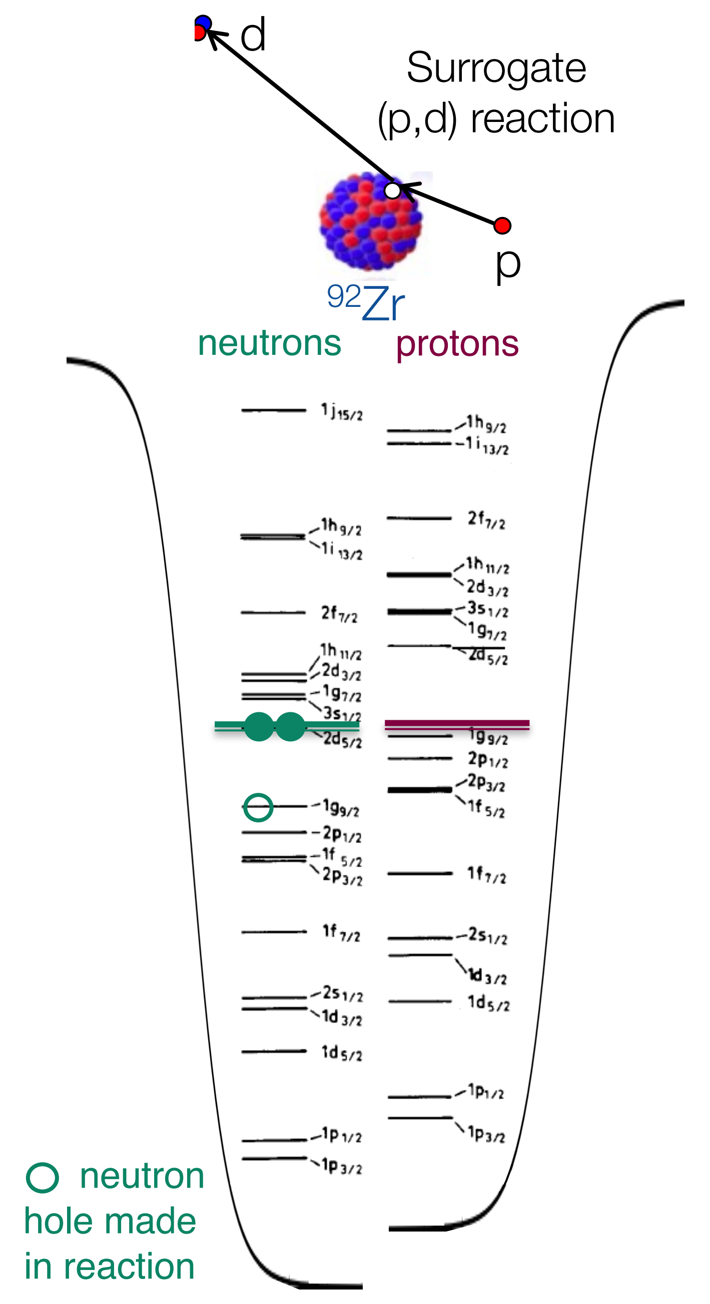




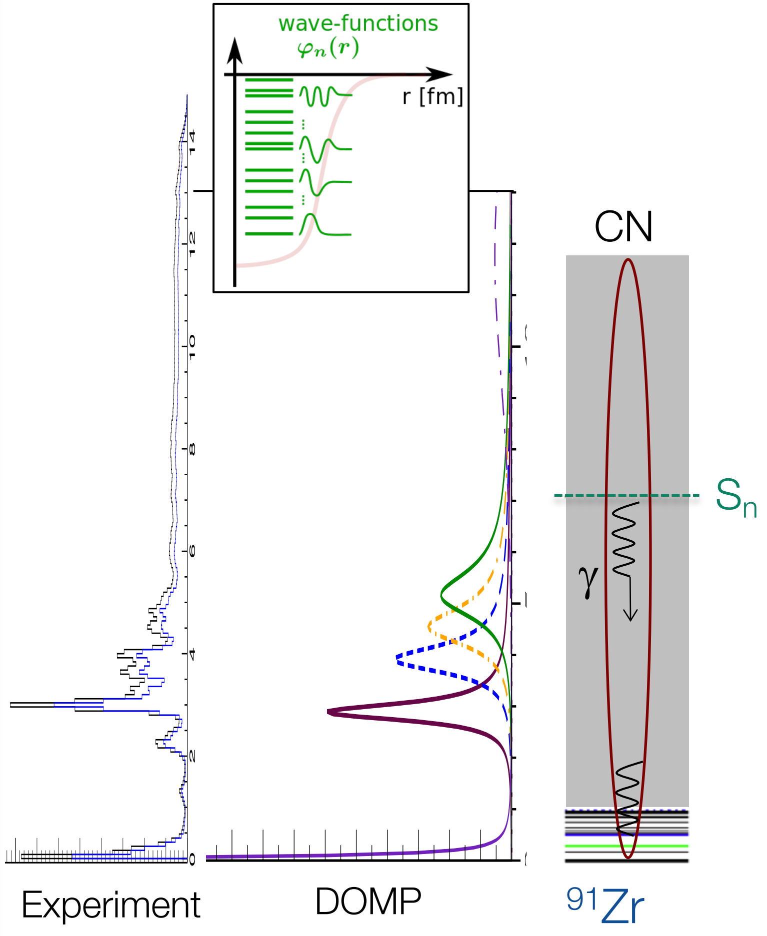
Theory for (p,d) surrogate reactions: Deep neutron holes

Challenge: Naïve potential-model picture not useful for deep holes
- Hole location
- Fragmentation

Solution: Dispersive optical potential connects OMP for scatter to mean field
- Scatter info gives DOMP at positive energies
- Mean field gives energy-averaged nuclear properties: single-particle E_{nlj}, spectral functions S_{nlj}, etc.



○ neutron hole made in reaction

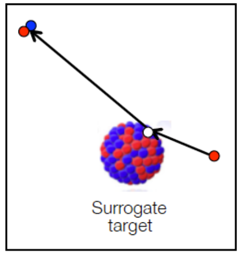


Mahaux & Sartor, Adv. Nucl. Phys. 1991
Delaroche et al, PRC 39, 391 (1989)

Theory for (p,d) surrogate reactions:
Deep neutron holes + two-step reaction mechanisms

- Challenge: Nucleon removal accompanied by inelastic excitations:
  - In entrance channel: $^{92}Zr(p,p')^{92}Zr^{**}(p',d)^{91}Zr^{*}$
  - In exit channel: $^{92}Zr(p,d')^{91}Zr^{**}(d',d)^{91}Zr^{*}$
- Solution: 2nd-order DWBA with collective model for inelastic scattering

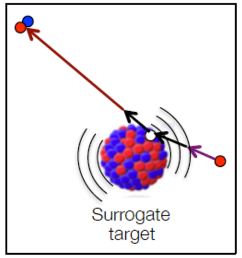
Surrogate (p,d) reaction



First-order processes:

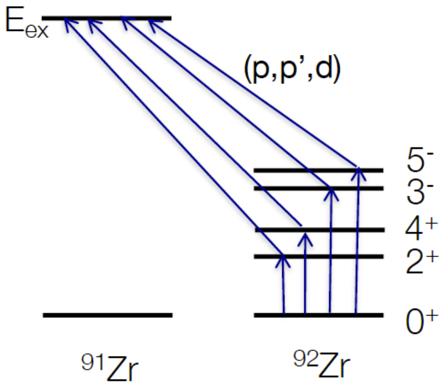
- neutron pickup makes deep hole
- Reaction calculation uses DWBA with S_{nlj} from DOMP

DWBA: Distorted-Wave Born Approximation

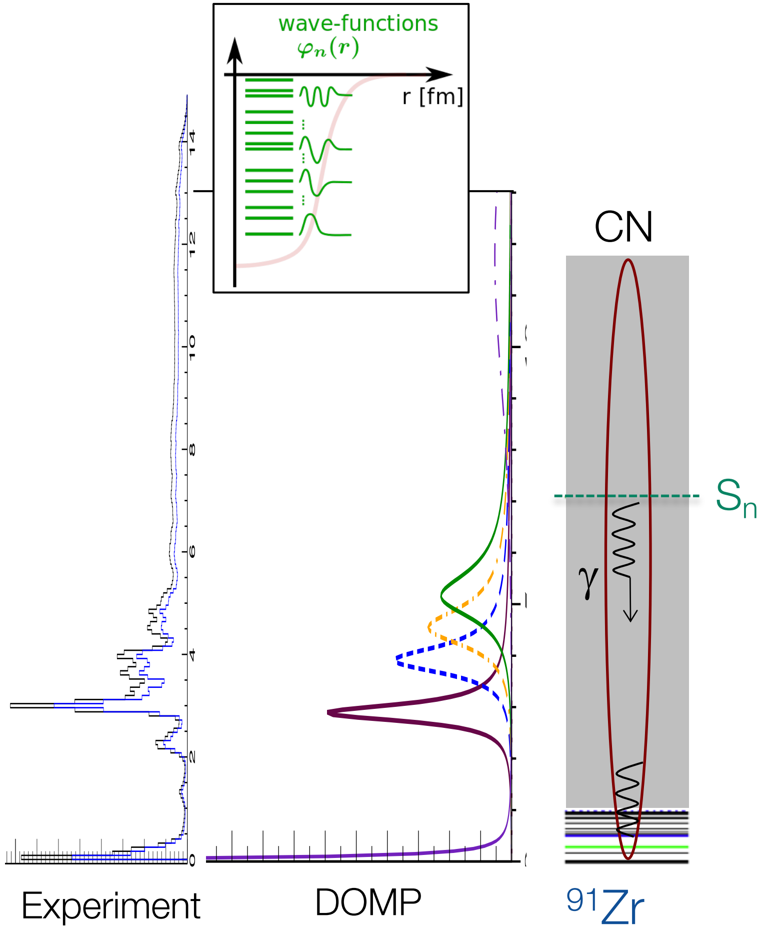


Second-order processes:

- Inelastic scattering preceeds or follows neutron pickup



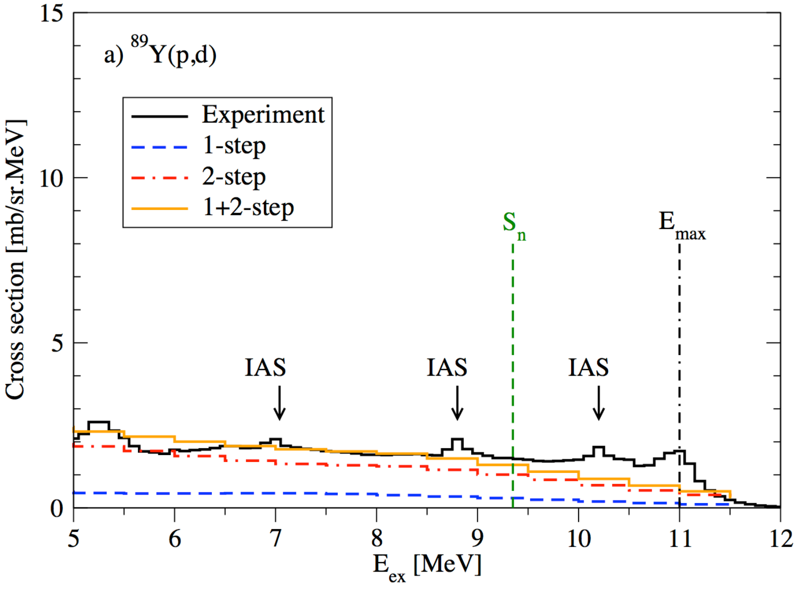
(p,d',d) analogously

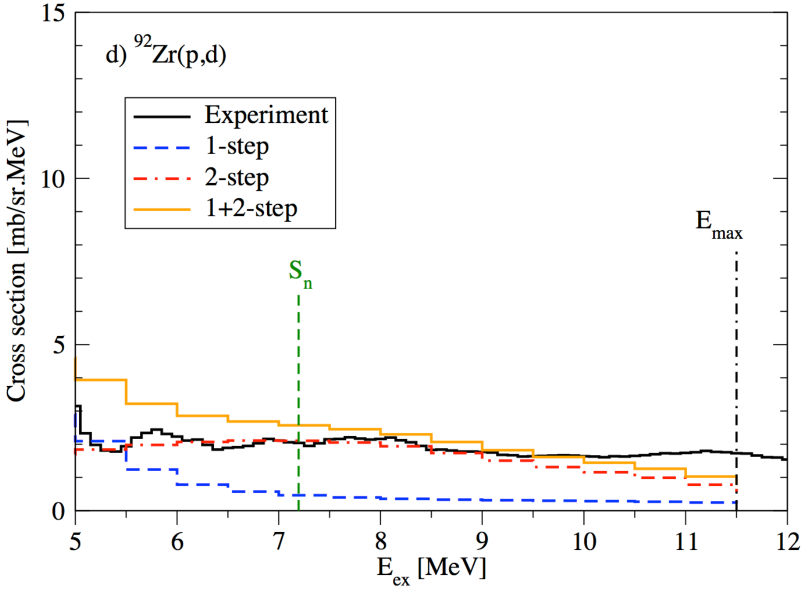


Future: use global DOMP for hole states + QRPA structure theory to describe inelastic scattering component

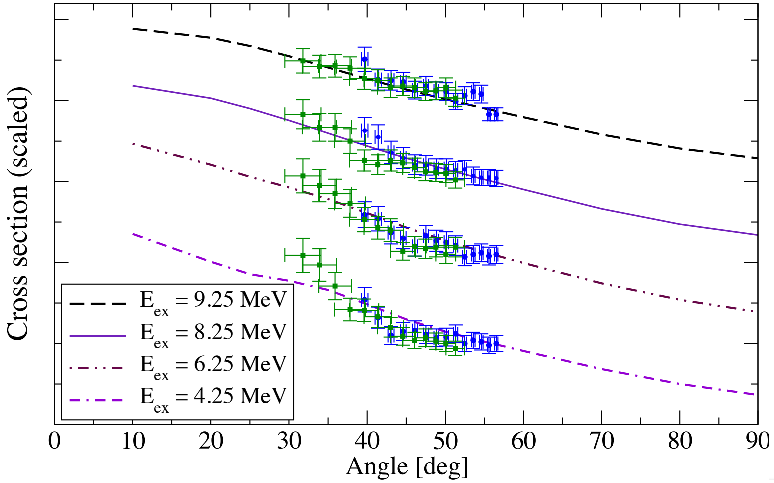
Gaining confidence in the calculated spin-parity population: Cross checks

Escher et al, PRL 121, 052501 (2018)
Escher et al, EPJ Conf. 178, 03002 (2018)





Does the calculated ‘singles’ cross section agree with the surrogate measurement? ✓



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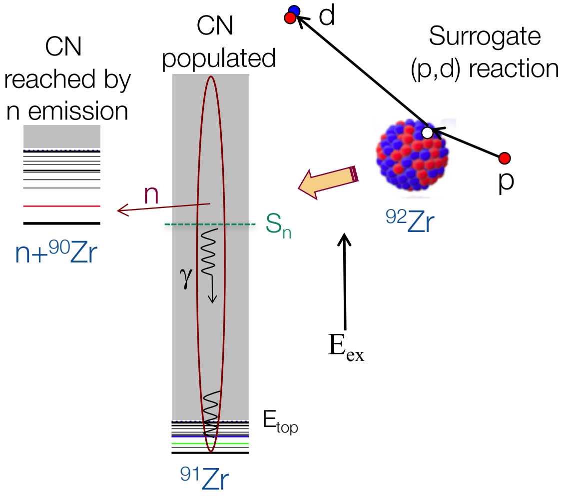
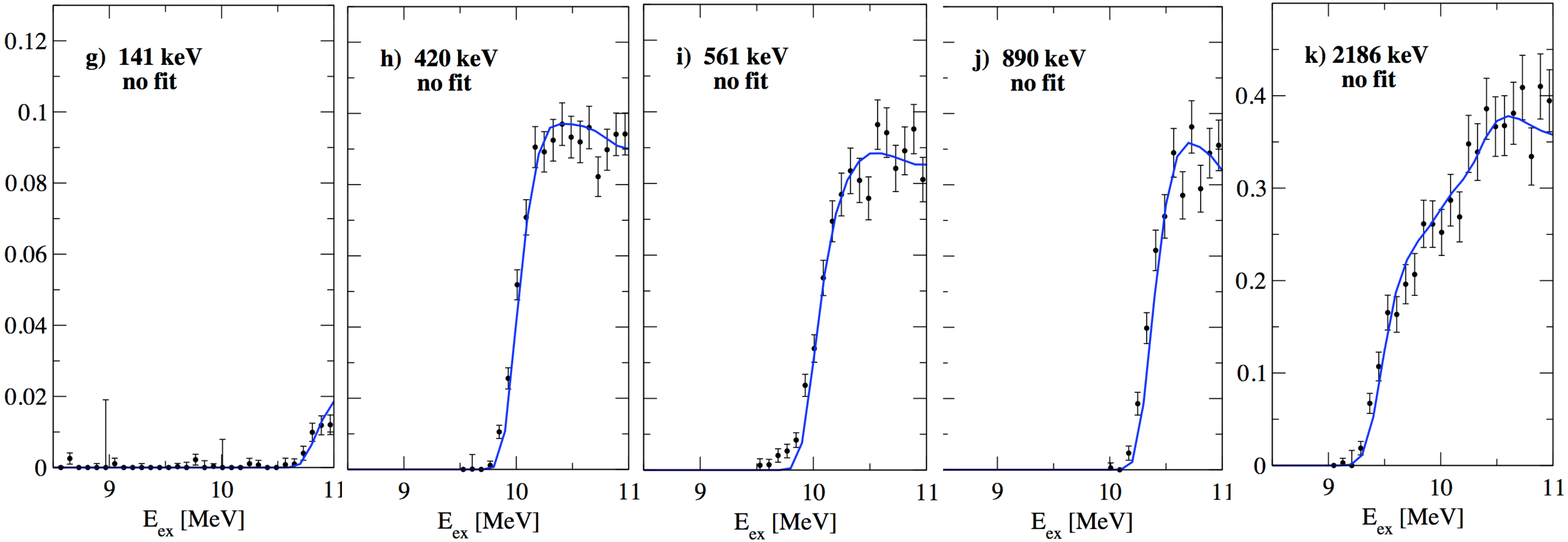
Escher et al, CNR*18 Conf. Proc. (2019)



Can we use the resulting HF parameters to predict other observables, not used for the fit?

Here, the γ-transitions* following n emission are reproduced ✓



*scaled

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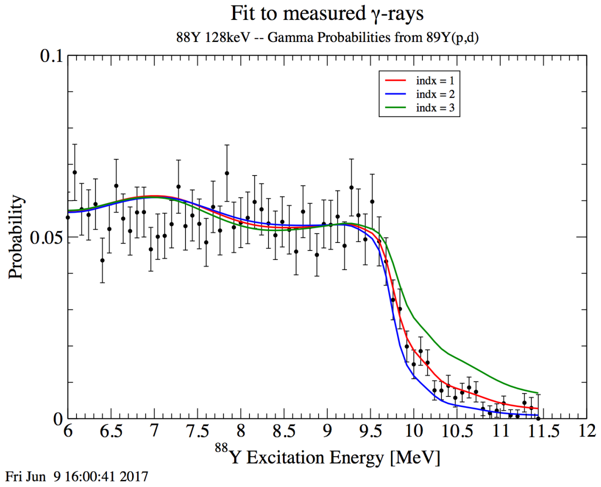
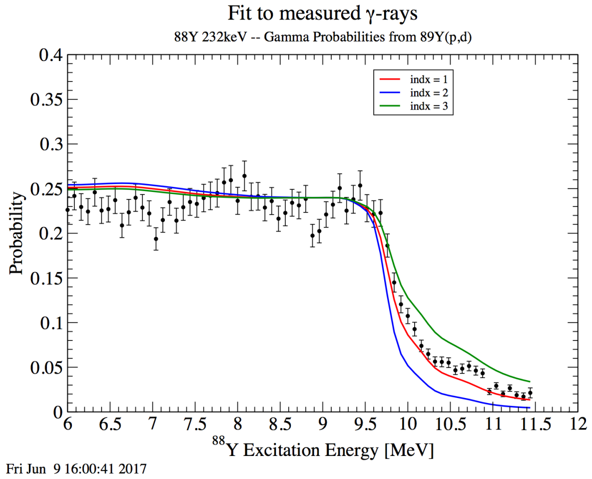
Escher, unpublished (2018)


Fit to measured γ-rays

88Y 128keV -- Gamma Probabilities from 89Y(p,d)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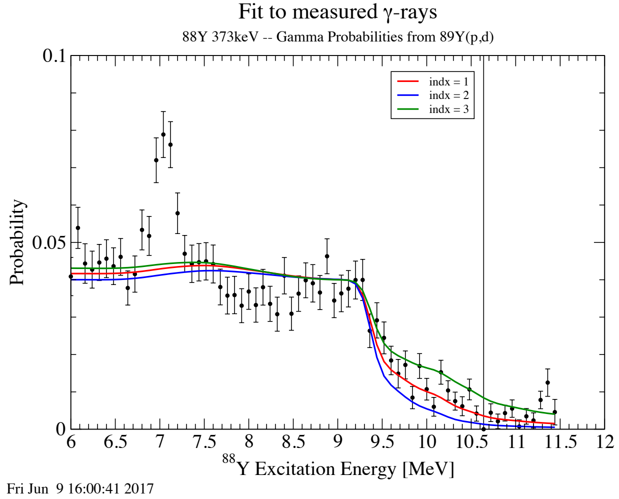
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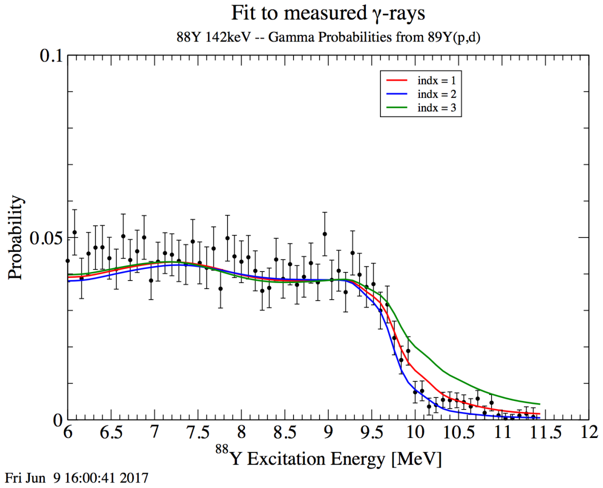
IAS have known J^{π} and ‘perturb’ the spin-parity population in a very specific manner.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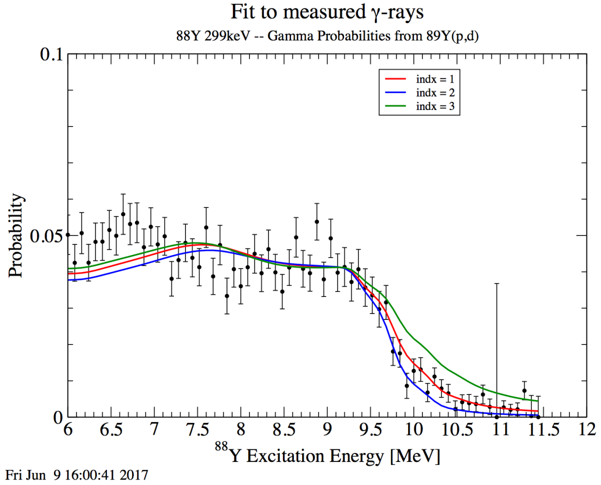
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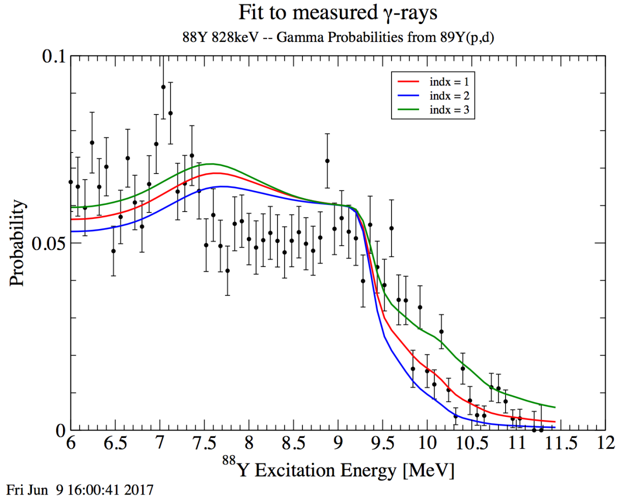
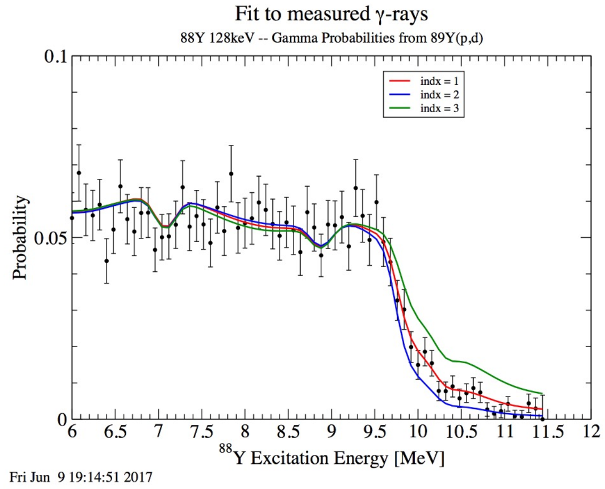

Fit to measured γ-rays

88Y 828keV -- Gamma Probabilities from 89Y(p,d)

And this is reflected in the γ-transitions of the decaying CN

Gaining confidence in the calculated spin-parity population: Cross checks

Escher, unpublished (2018)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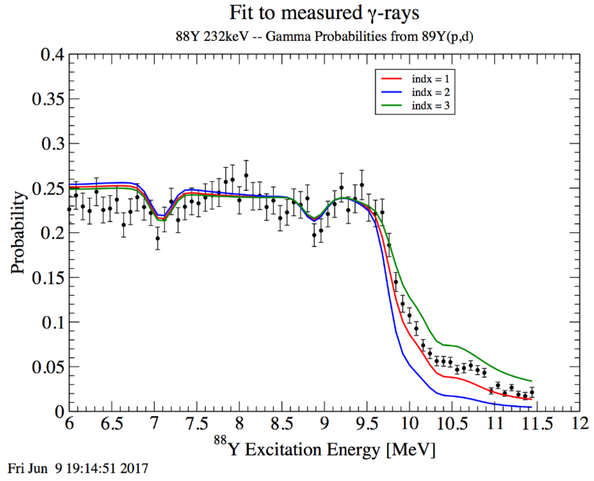
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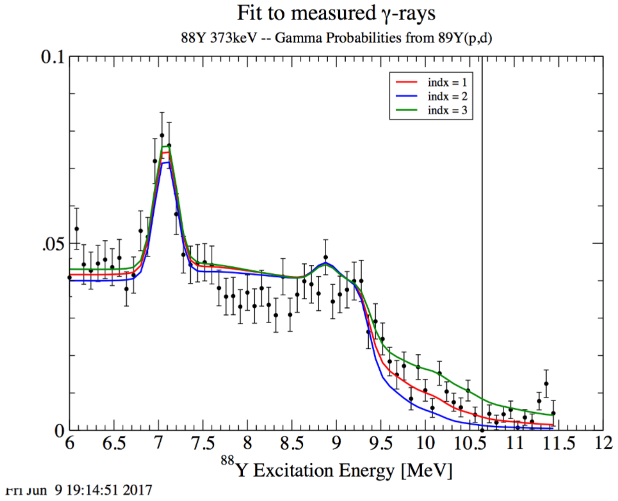
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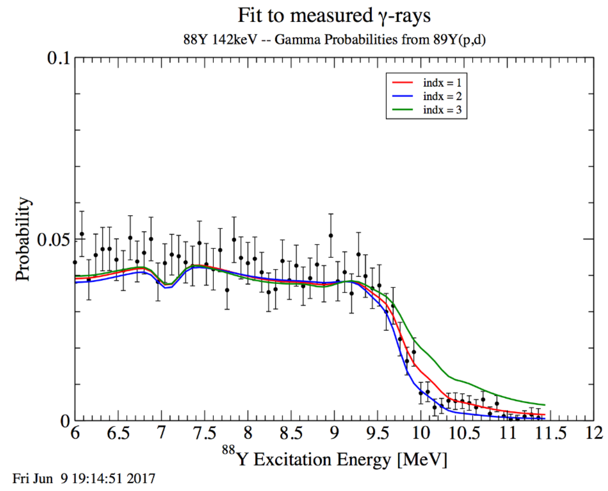
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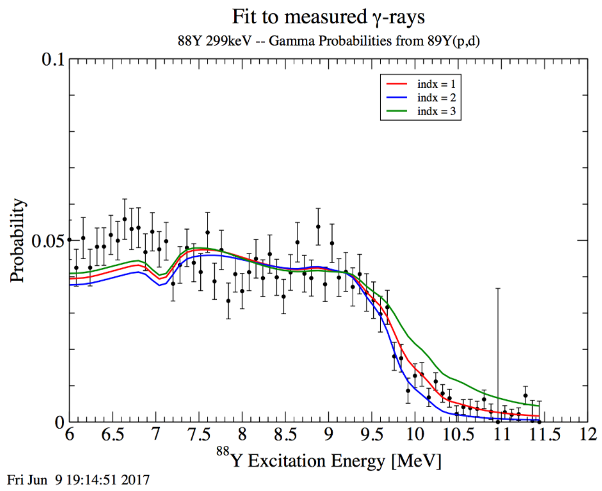
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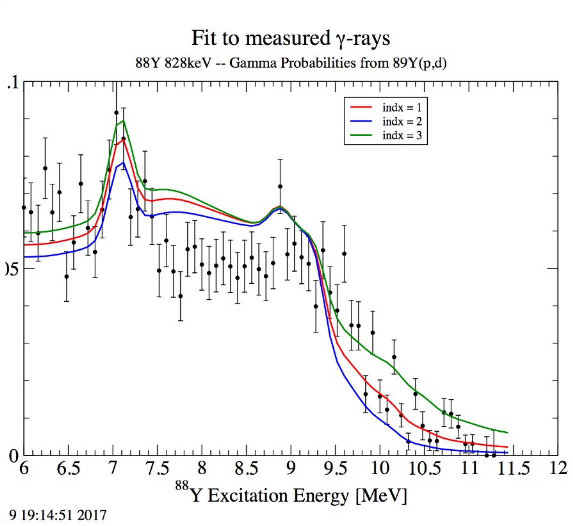
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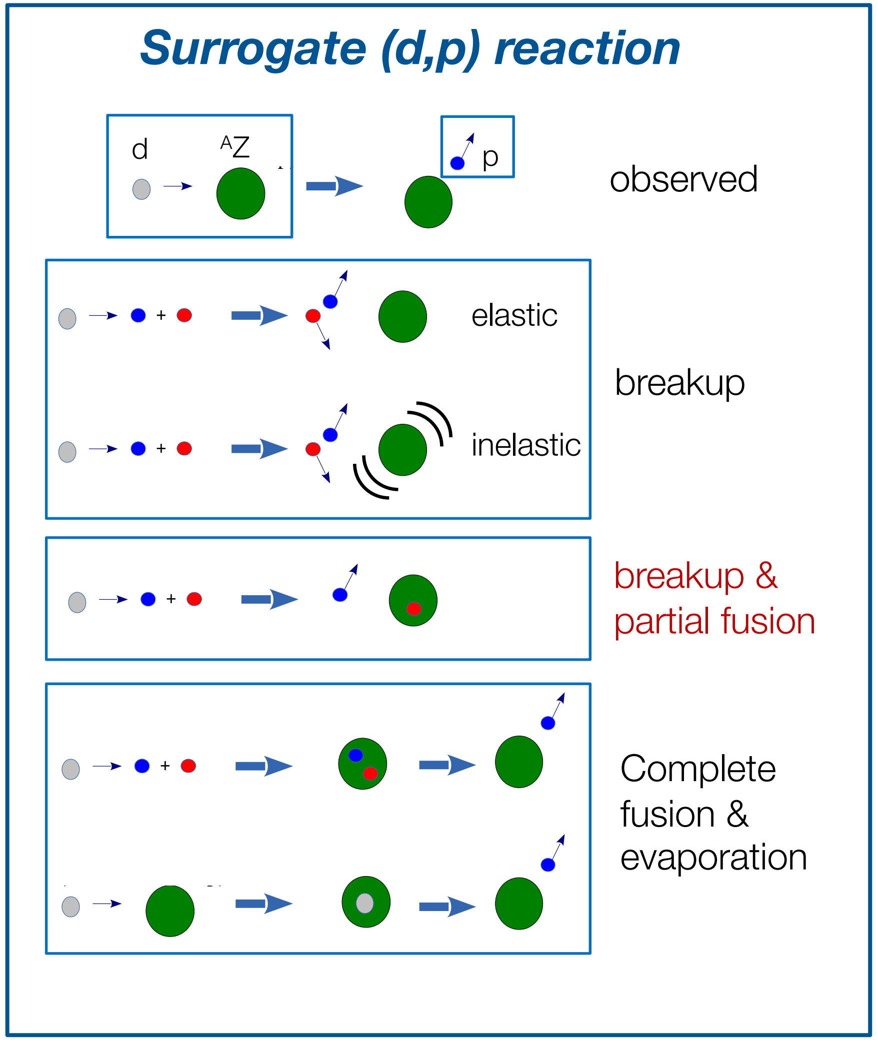
88Y 828keV -- Gamma Probabilities from 89Y(p,d)

IAS have known J^{π} and 'perturb' the spin-parity population in a very specific manner.

And this is reflected in the γ-transitions of the decaying CN ✓

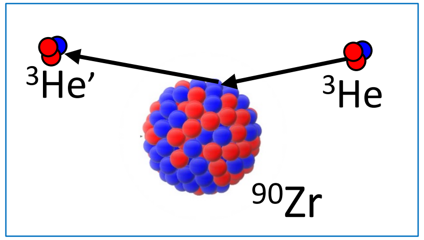
Calculating spin-parity populations for (d,p) surrogate reactions: deuteron breakup followed by partial fusion

- Challenges:
  - Multiple reaction processes lead to observation of proton, while only breakup-fusion is relevant
- Theory developments:
  - Describe deuteron breakup and propagation in nuclear field
  - Describe neutron absorption with optical model potential
  - Formalism to be extended to deformed systems
- Relevant (d,p) formalism has been developed, vetted, applied
  - Three theory groups describe breakup-fusion, which contains CN formation, based on earlier work by Udagawa & Tamura and Ichimura, Austern & Vincent:
    - Potel et al, PRC 92, 034611 (2015)
    - Lei & Moro, PRC 92, 044616 (2015)
    - Carlson et al, Few-Body Syst 57, 307 (2016), arxiv:1508.01466
  - Workshop compared formalisms and codes
    - Potel et al, EPJA 53, 178 (2017)



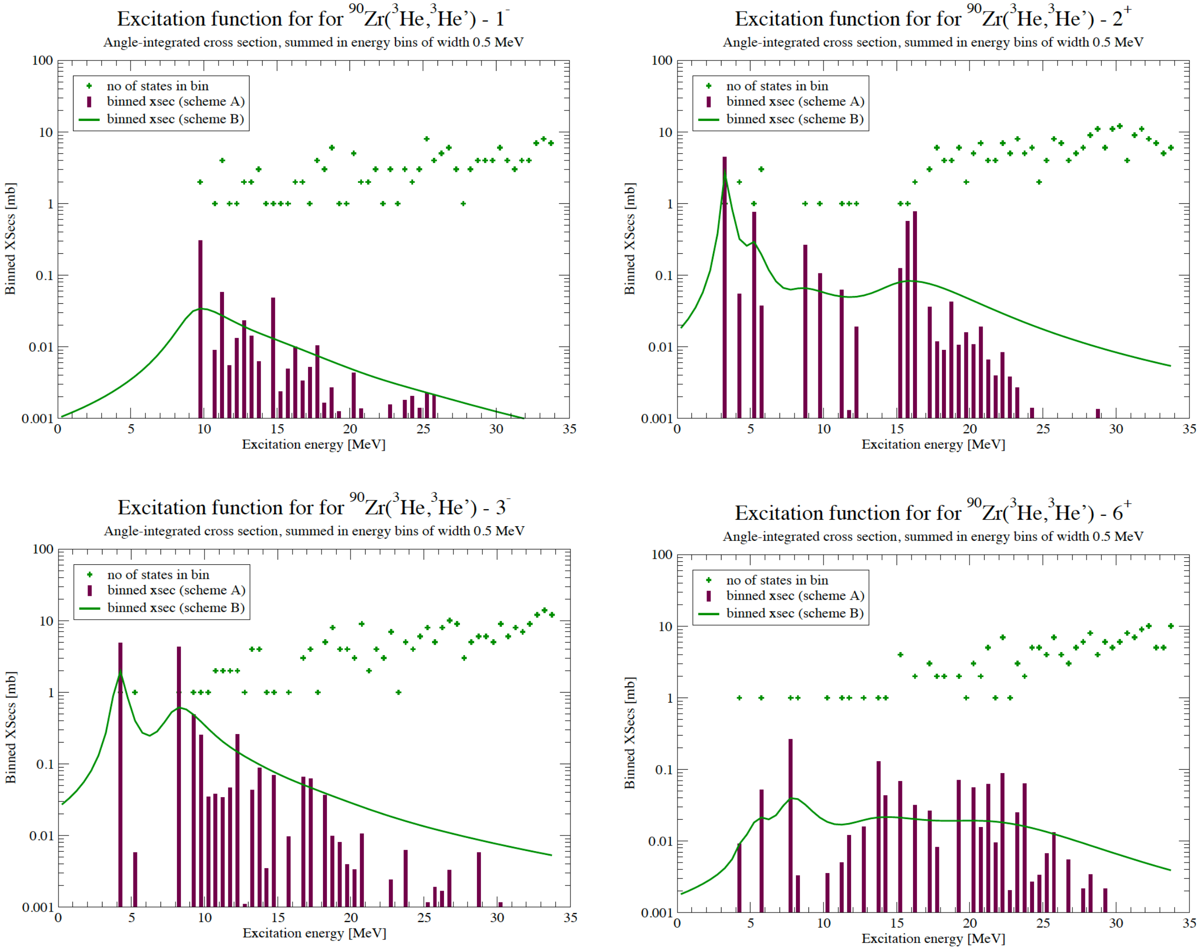
Calculating spin-parity populations for inelastic scattering surrogate reactions: Inelastic states and two-step contributions

Escher, wip (2024)



- Challenges:
  - Zr(^{3}He,^{3}He’) populates states up to E_{ex}=34 MeV
  - Inelastic scattering is accompanied by (^{3}He,α)(α,^{3}He’) and (^{3}He,d)(d, ^{3}He’)
- Theory:
  - Describe states excited in scattering microscopically using QRPA
  - Calculate inelastic cross sections using DWBA (use transition potentials)
  - Calculate 2-step contributions in 2nd-order DWBA

Some inelastic contributions to ^{90}Zr(^{3}He,^{3}He’)^{90}Zr*

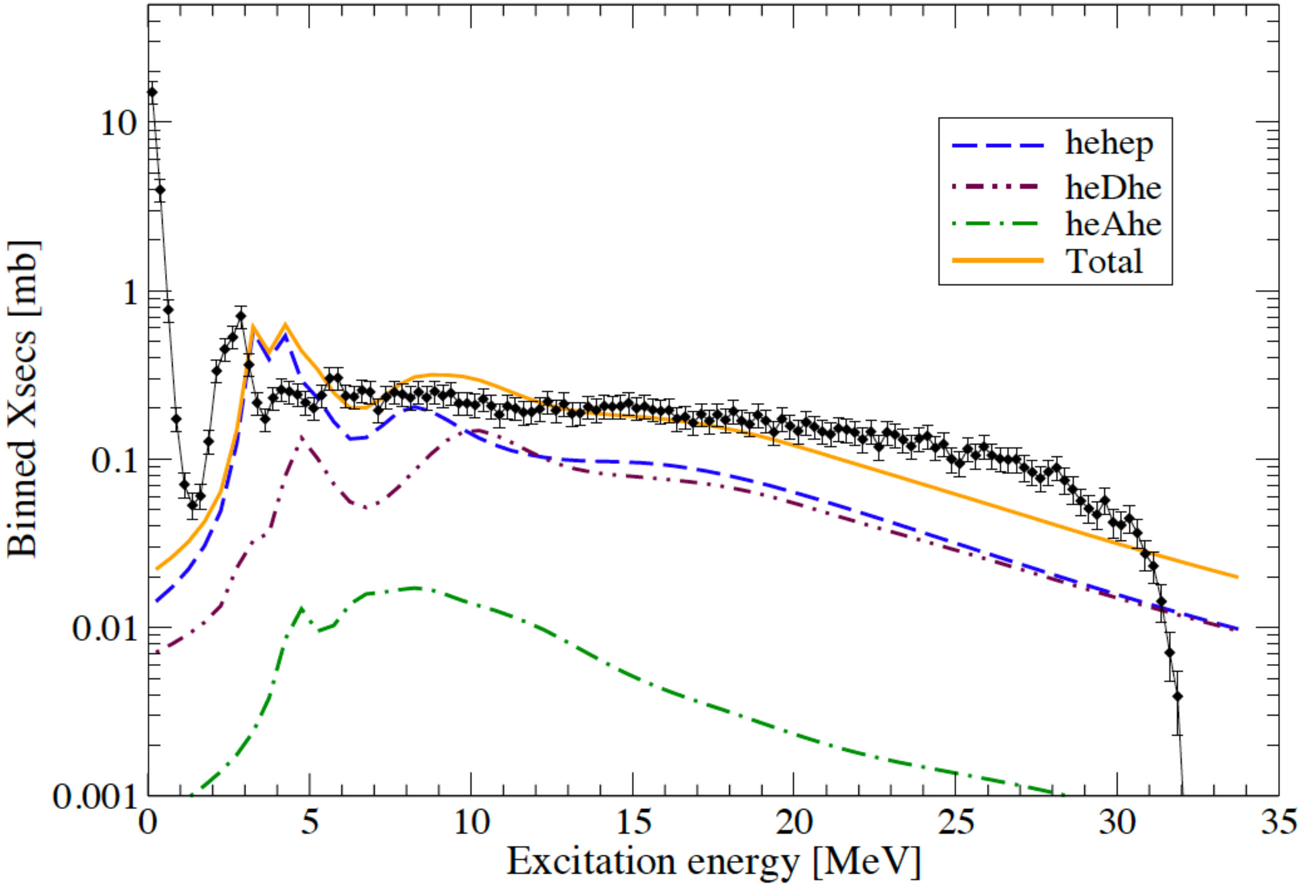


Calculating spin-parity populations for inelastic scattering surrogate reactions: 1-step inelastic and 2-step transfers contribute

Escher, wip (2024)

Adding all contributions reproduces the measured singles cross section ✓

Adding by J^π give the spin-parity population



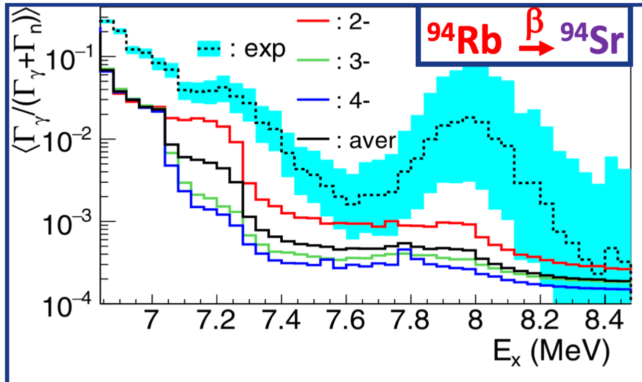
Inverse-kinematics experiments

Inverse-kinematics (d,p) surrogate reactions at TRIUMF: Neutron capture on ^{93}Sr

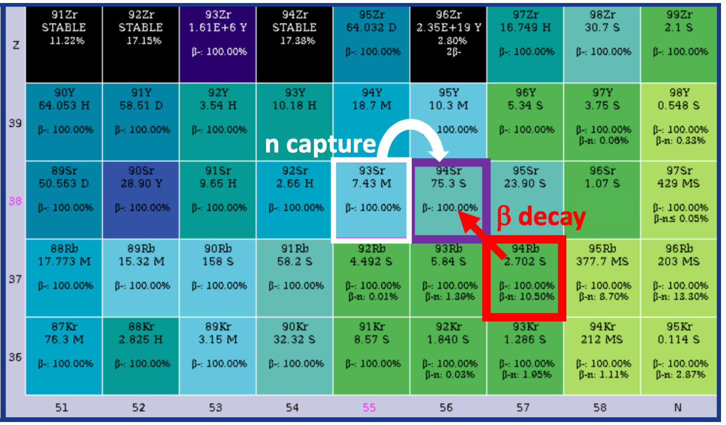
Richard, Hughes, JEE, Potel, *et al* (WIP)

- Motivation
  - β-delayed γ-emission found surplus of gammas, with potential implications for a strong ^{93}Sr(n,γ) rate
  - Provide an alternate way to place constraints on the γSF

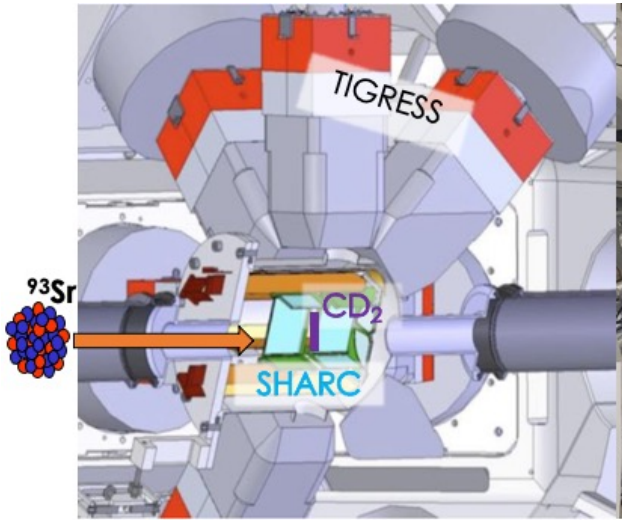
- Experiment at TRIUMF (2021)
  - ^{93}Sr RIB (8MeV/u) on CD_2 target
  - SHARC (segmented Si array) to detect p
  - TIGRESS (12 HPGe clovers, 2π) to detect gammas
  - Analysis underway

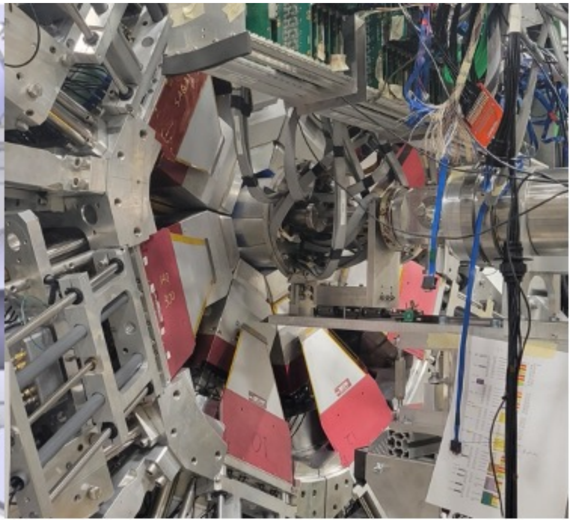


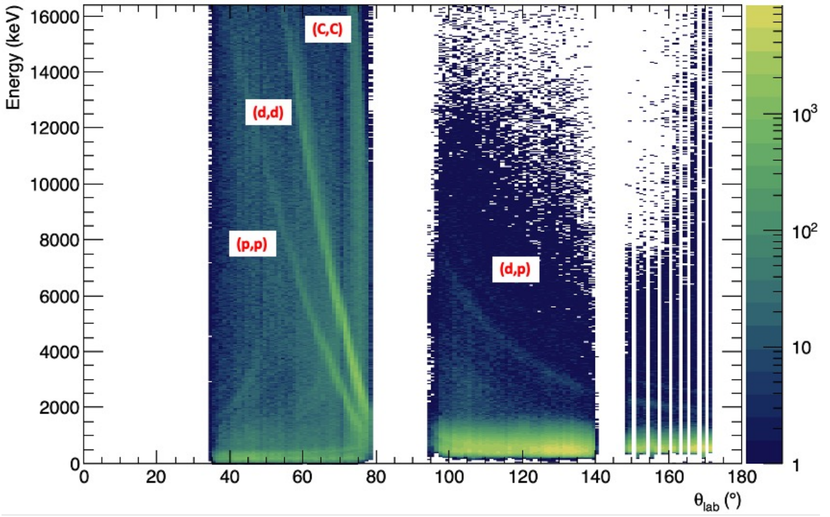
J.L. Tain et al., Phys. Rev. Lett. 115, 062502 (2015)



Z	91Zr STABLE 11.22%	92Zr STABLE 17.15%	93Zr 1.61E+6 Y β-: 100.00%	94Zr STABLE 17.38%	95Zr 64.032 D β-: 100.00%	96Zr 2.35E+19 Y 2.80% 2β-	97Zr 16.749 H β-: 100.00%	98Zr 30.7 S β-: 100.00%	99Zr 2.1 S β-: 100.00%
39	90Y 64.053 H β-: 100.00%	91Y 58.51 D β-: 100.00%	92Y 3.54 H β-: 100.00%	93Y 10.18 H	94Y 18.7 M	95Y 10.3 M 100.00%	96Y 5.34 S β-: 100.00%	97Y 3.75 S β-: 100.00% β-n: 0.06%	98Y 0.548 S β-: 100.00% β-n: 0.33%
38	89Sr 50.563 D β-: 100.00%	90Sr 28.90 Y β-: 100.00%	91Sr 9.65 H β-: 100.00%	92Sr 2.66 H β-: 100.00%	93Sr 7.43 M β-: 100.00%	94Sr 75.3 S β-: 100.00%	95Sr 23.90 S	96Sr 1.07 S	97Sr 429 MS β-: 100.00% β-n≤ 0.05%
37	88Rb 17.773 M β-: 100.00%	89Rb 15.32 M β-: 100.00%	90Rb 158 S β-: 100.00%	91Rb 58.2 S β-: 100.00%	92Rb 4.492 S β-: 100.00% β-n: 0.01%	93Rb 5.84 S β-: 100.00% β-n: 1.39%	94Rb 2.702 S β-: 100.00% β-n: 10.50%	95Rb 377.7 MS β-: 100.00% β-n: 8.70%	96Rb 203 MS β-: 100.00% β-n: 13.30%
36	87Kr 76.3 M β-: 100.00%	88Kr 2.825 H β-: 100.00%	89Kr 3.15 M β-: 100.00%	90Kr 32.32 S β-: 100.00%	91Kr 8.57 S β-: 100.00%	92Kr 1.840 S β-: 100.00% β-n: 0.03%	93Kr 1.286 S β-: 100.00% β-n: 1.05%	94Kr 212 MS β-: 100.00% β-n: 1.11%	95Kr 0.114 S β-: 100.00% β-n: 2.87%
	51	52	53	54	55	56	57	58	N







Inverse-kinematics (d,p) surrogate reactions at MSU/NSCL (now FRIB): Detecting recoils instead of gammas

Exp: Sims, Cizewski, Ratkiewicz, Pain,…
Theory: Escher, Potel, Gorton

- Motivation
  - Develop techniques to move far away from stability
  - Can we use recoils instead of gammas to detect channel of interest?
- Experiment at NSCL (2017)
  - ^{84}Se RIB on CD_2 target
  - ORRUBA/S800 spectrometer to detect p and beam-like particles
  - Preliminary ^{84}Se(n,γ) results available

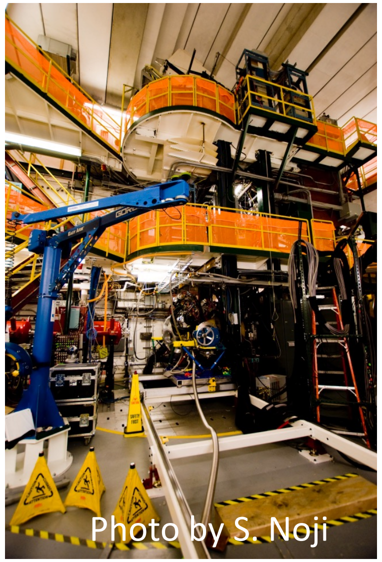
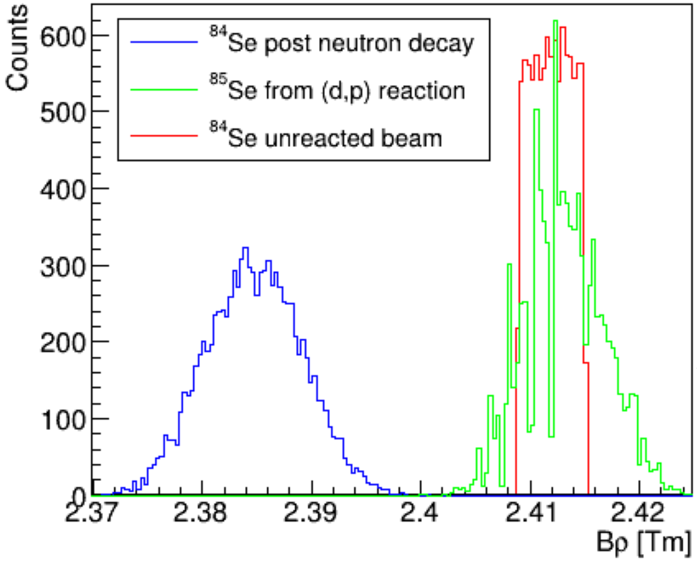
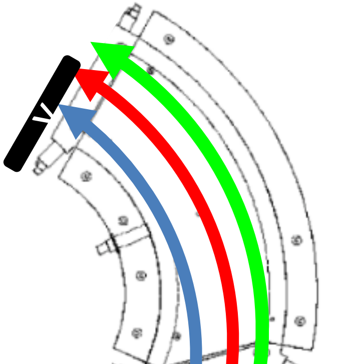


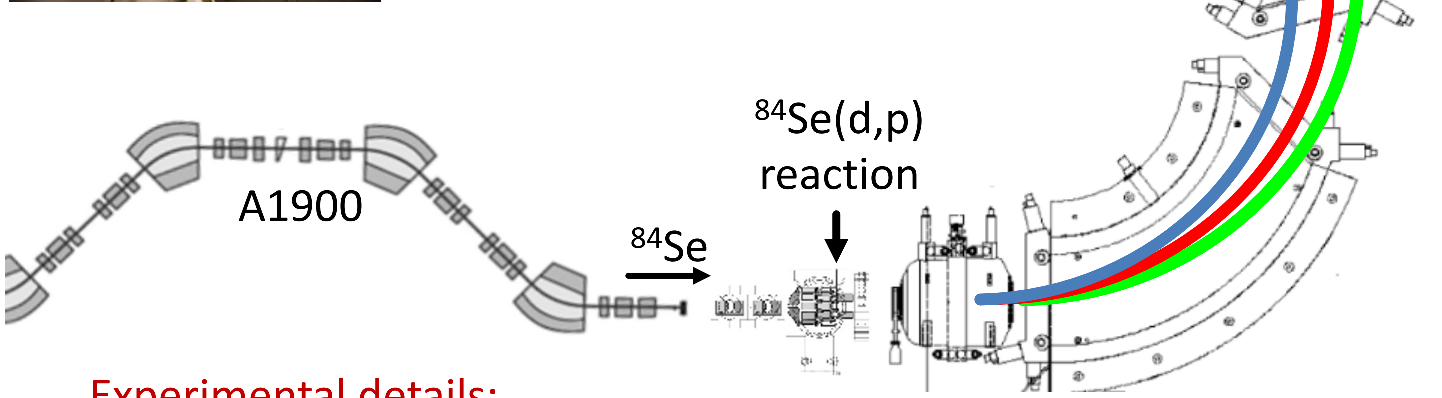
Photo by S. Noji



Three scenarios:

1. ^{84}Se does not react with CD_2 target — **Bρ = 2.4136 Tm**
2. ^{84}Se undergoes (d,p) reaction at CD_2 target to form ^{85}Se then gamma-decays to ground state. — **Bρ = 2.4119 Tm**
3. Same as point 2, except nucleus emits neutron => ^{84}Se — **Bρ = 2.3849 Tm**



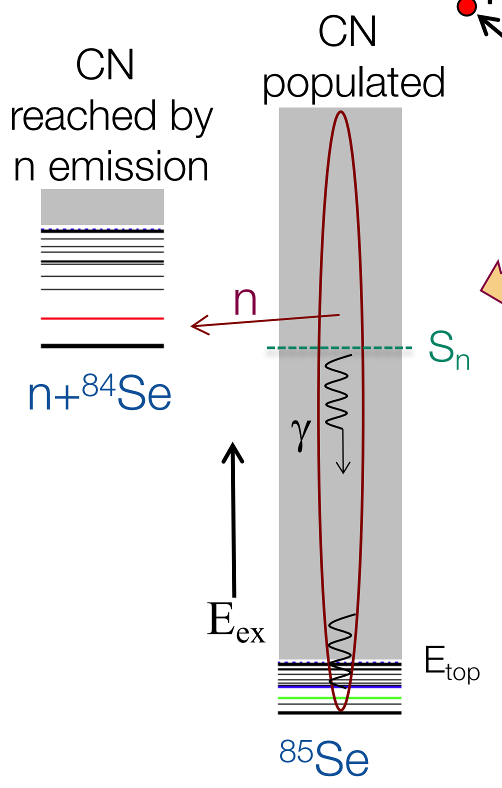


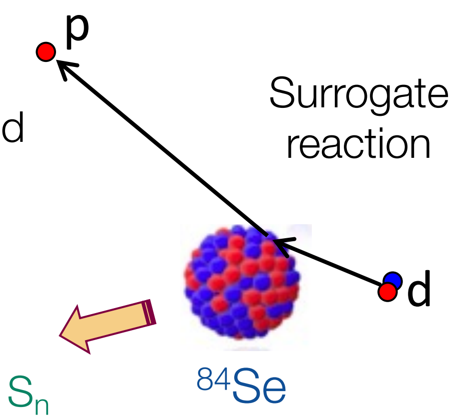
Experimental details: see talk by J. Cizewski

Adapted from slide by H. Sims

Here recoils are utilized instead of gammas

Surrogate reactions method for neutron capture - using recoiling nucleus





From theory

To be determined

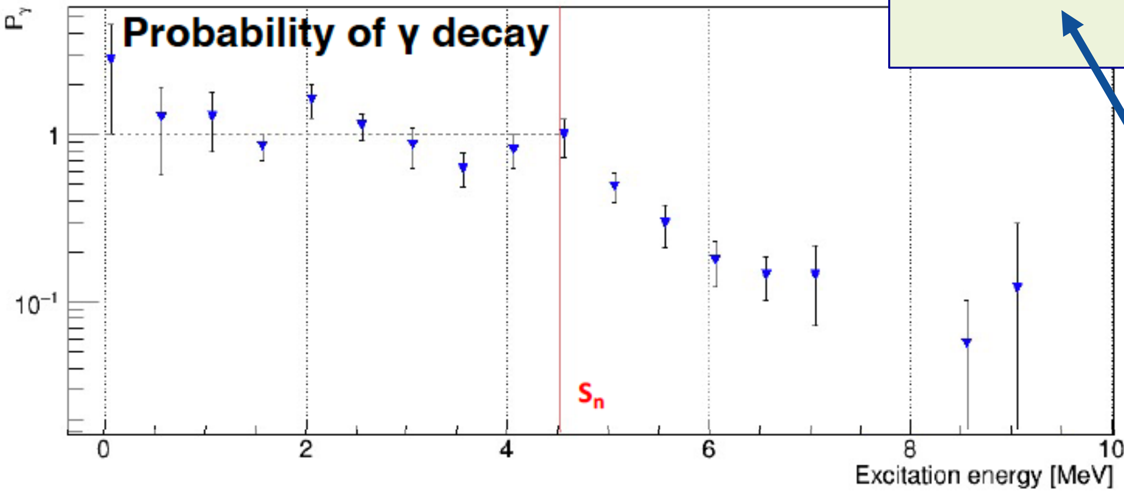
A Surrogate experiment gives

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

$^{84}Se(n,\gamma)$ cross section*:

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

From experiment



Well modelled from nuclear theory

The new cross section we want

---

*Width fluctuation corrections are omitted here, but accounted for in applications.

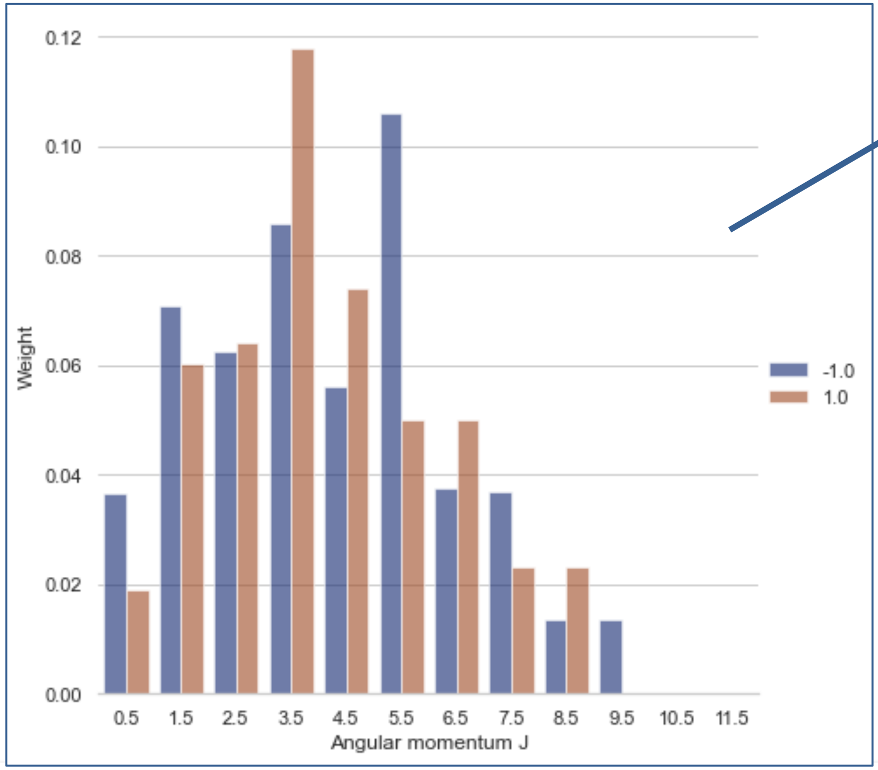
Theory for surrogate reactions: Parameter constraints from Markov-Chain Monte-Carlo fit to recoil observables

Escher et al, prelim (2024)

Coincidence probabilities from surrogate experiment

Surrogate coincidence probabilities

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

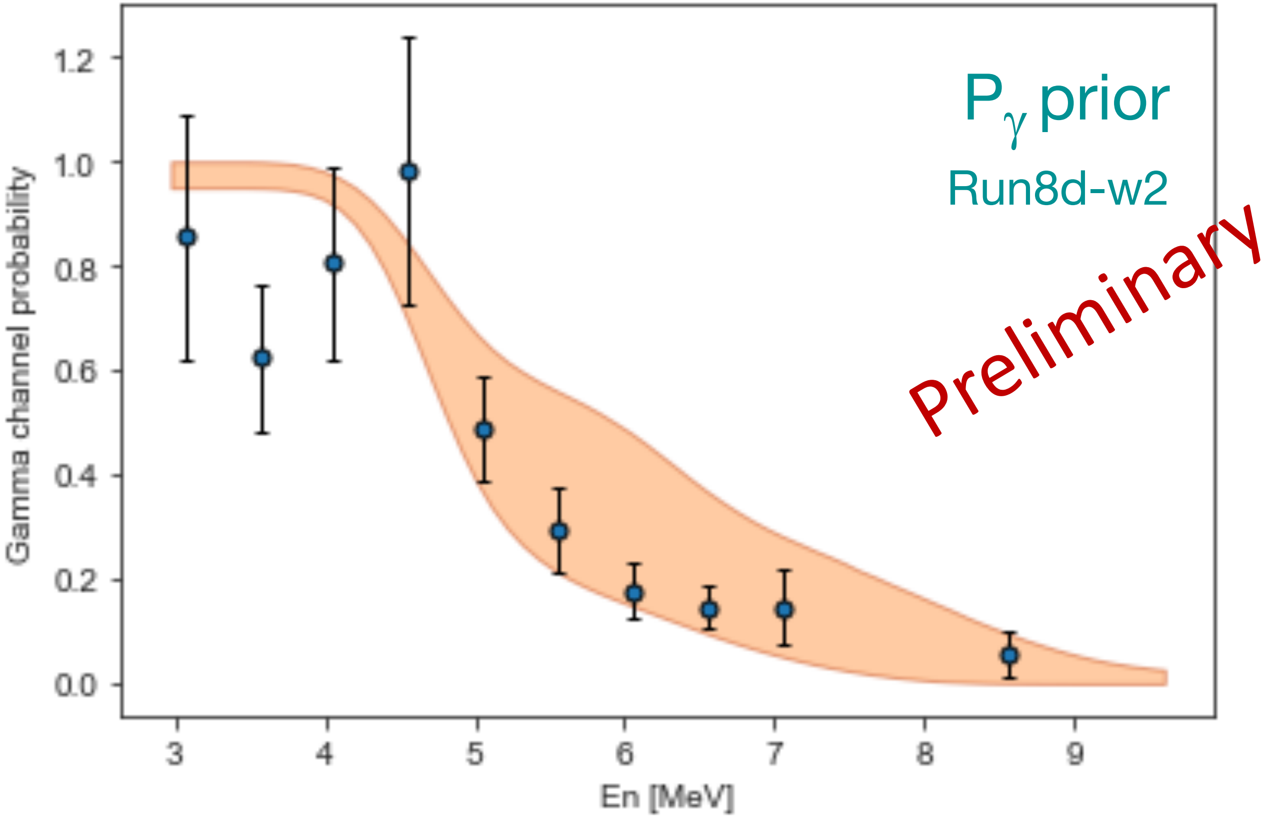


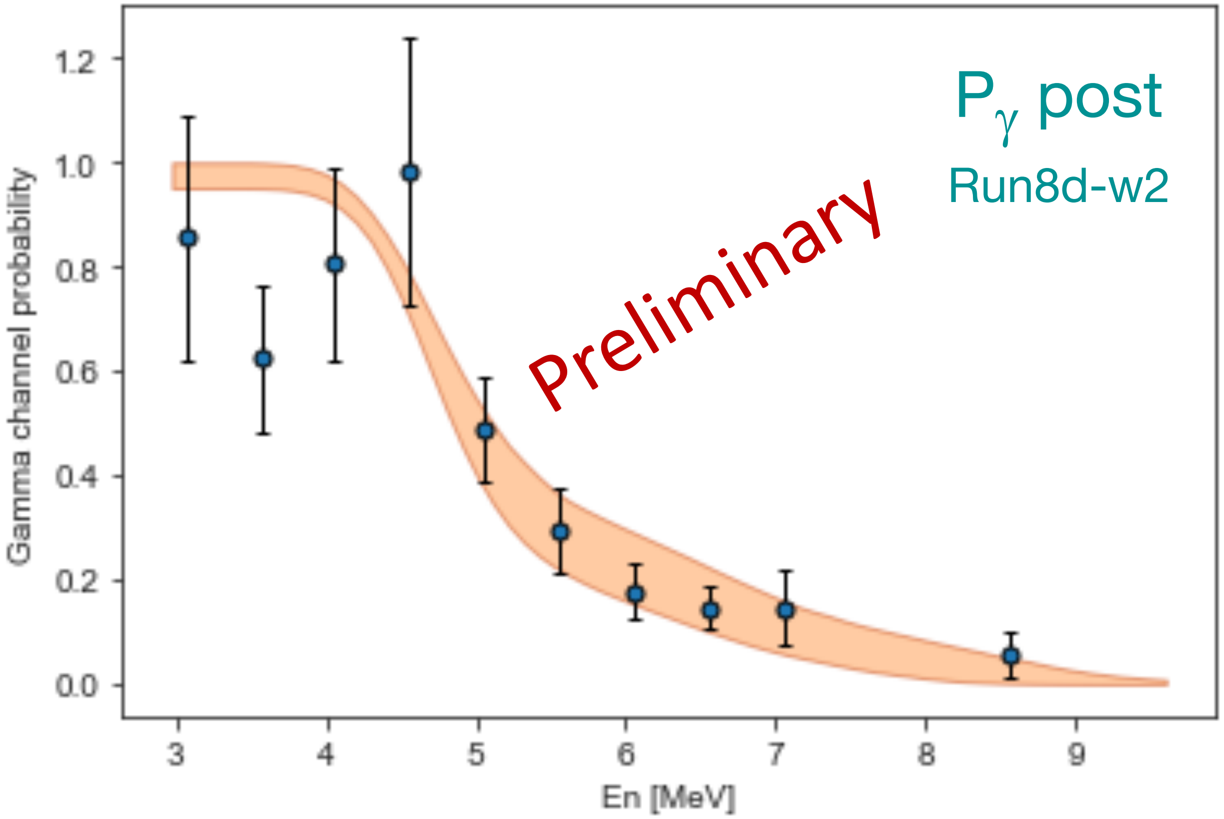
Spin-parity population near S_n from direct-reaction theory for ^{84}Se(d,p) at 45 MeV/U

(Calculation: G. Potel)

MCMC fit to surrogate decay probabilities: Prior and posterior P_γ

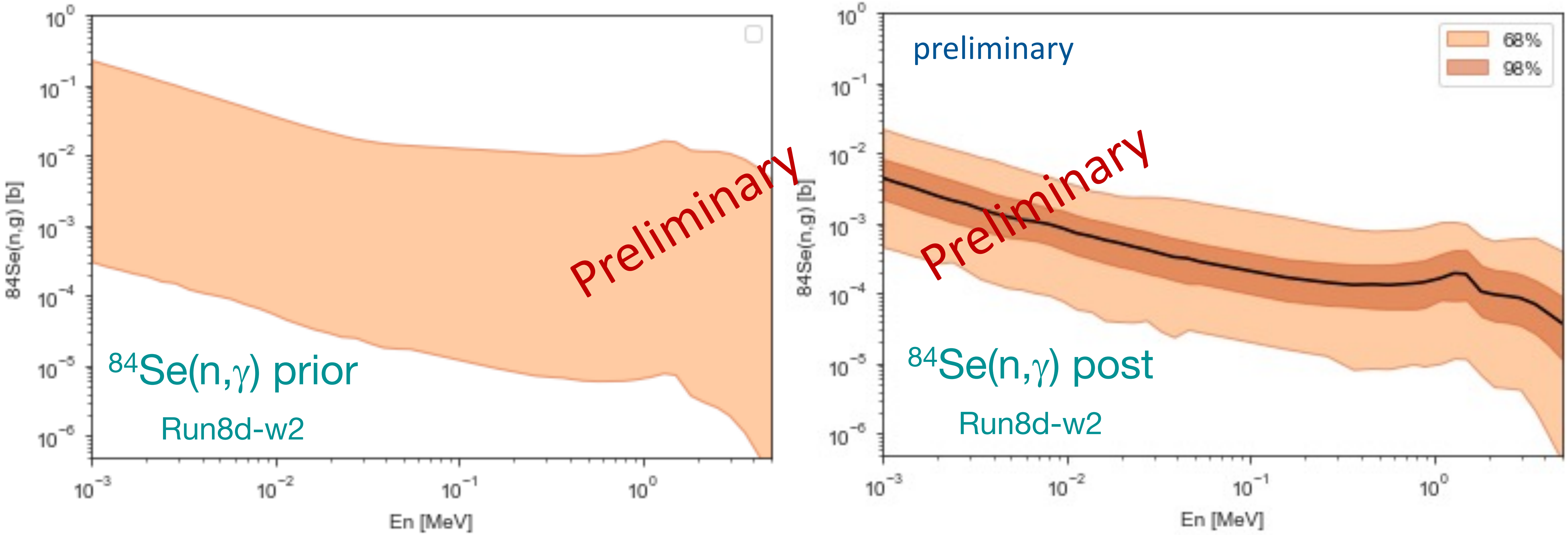
Escher et al, prelim (2024)





Sample parameter distributions and calculate capture cross section: Prior to posterior results

Escher et al, prelim (2024)

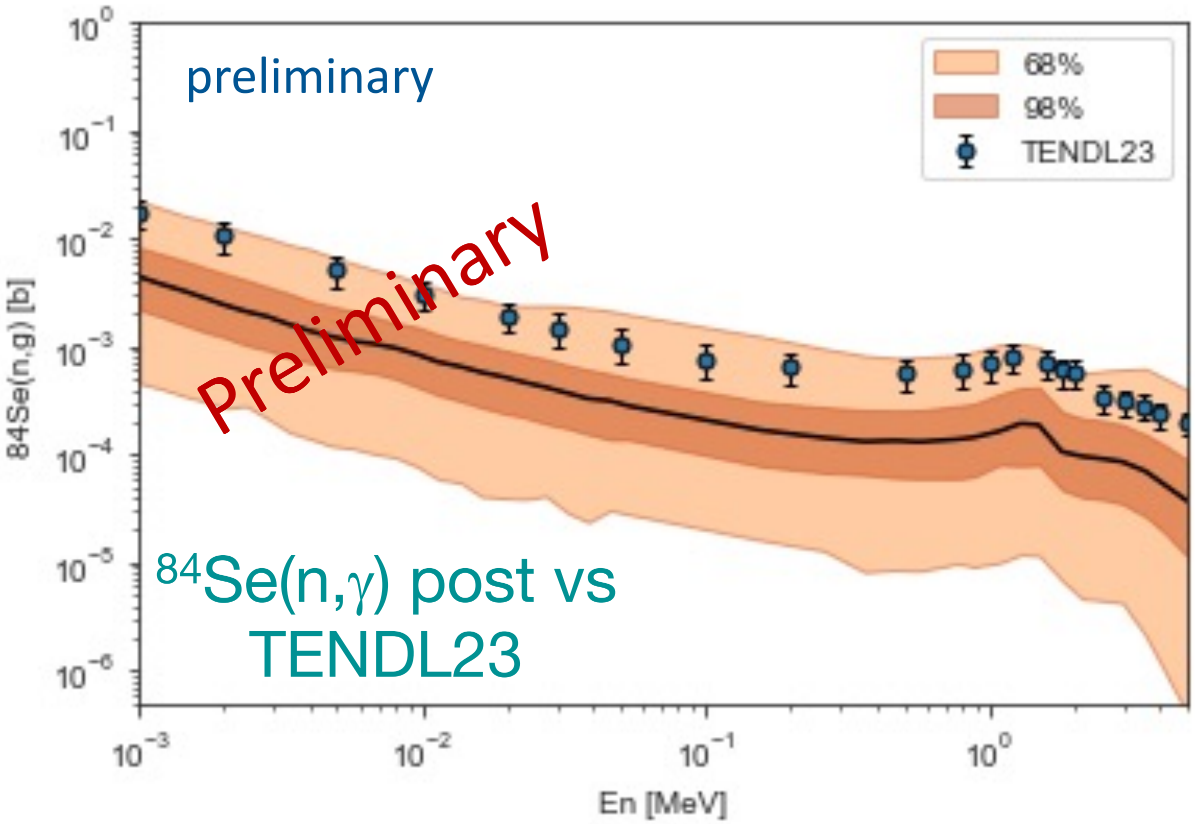


Cross section calculation constrained by surrogate decay data ONLY

No-gamma surrogate reaction data constrains the ^{84}Se(n,γ) cross section
Preliminary results slightly lower than systematics suggest

Escher et al, prelim (2024)

- ^{84}Se(n,γ) cross section constrained by surrogate data, no need for auxiliary quantities (D_0 or $\langle\Gamma_\gamma\rangle$)
- Fits not sensitive to details of the γSF, e.g. M1 LEE or E1 pygmy resonance.
- Using different warmstart parameter vectors give similar cross section results



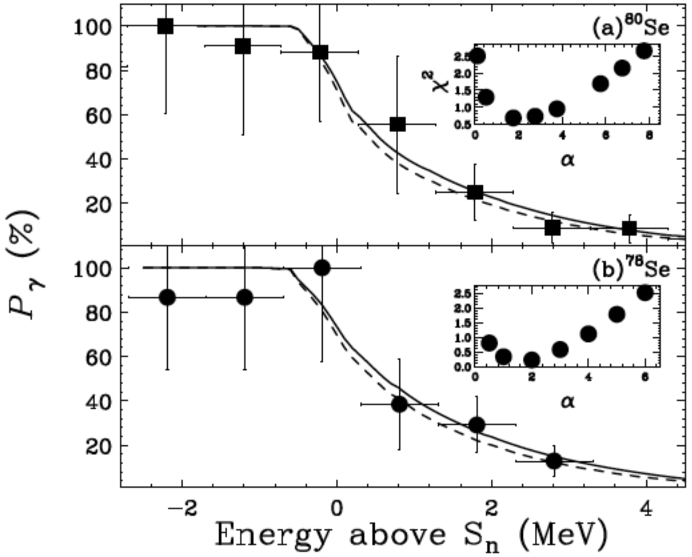
^{84}Se(n,γ) post vs TENDL23

Future: Improving energy resolution and detecting additional exit channels. Field experiments at FRIB.

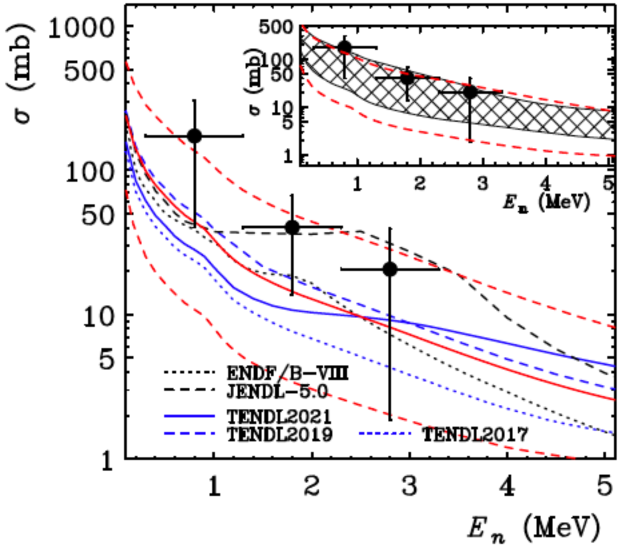
Inverse-kinematics (d,p) at RIKEN/RIBF: Detecting residual nuclei ^{78,80}Se to determine ^{79}Se(n,γ)

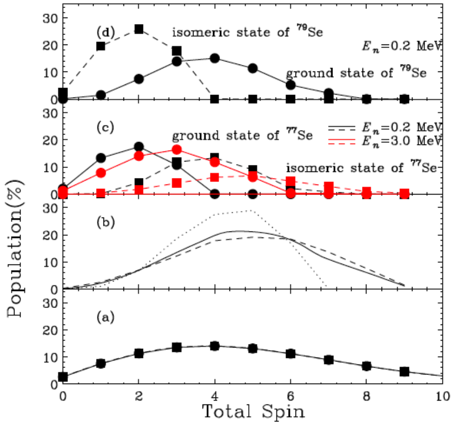
Imai et al, PLB 850, 138470 (2024)

Absolute SRM



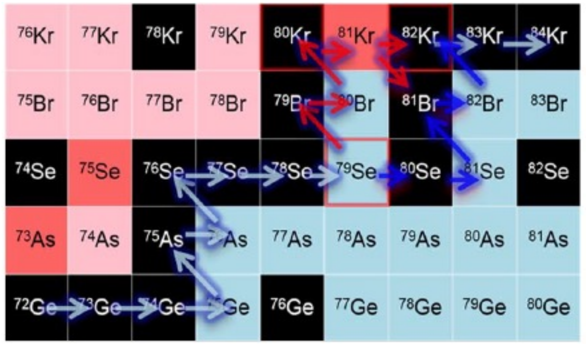
Ratio SRM





$$\sigma^{(n,\gamma)}_{^{79}\mathrm{Se}}(E) = \sigma^{(n,\gamma)}_{^{77}\mathrm{Se}}(E) \times \frac{\sigma^{CN}(^{80}\mathrm{Se})}{\sigma^{CN}(^{78}\mathrm{Se})} \times \frac{P_\gamma^{^{80}\mathrm{Se}}(E)}{P_\gamma^{^{78}\mathrm{Se}}(E)}.$$

	^{77}Se		^{79}Se	
E_x (keV)	0.0	161.9	0.0	95.8
J^π	$1/2^-$	$7/2^+$	$7/2^+$	$1/2^-$
half-life	stable	17.4 s	3.26×10^5 y	3.92 m



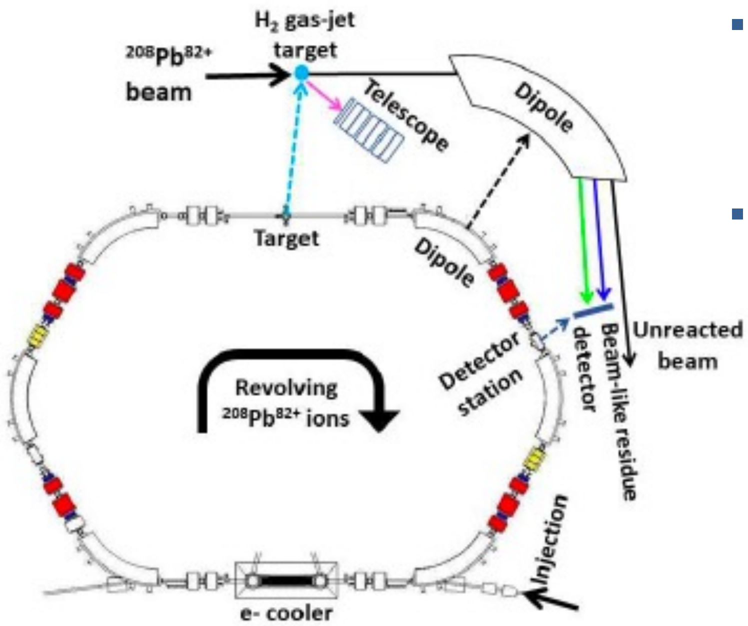
Domingo-Pardo, LoI to Isolde nTOF (2014)

- Motivation
  - Study options for transmutation of nuclear waste (long-lived fission products) via neutron-induced reactions
  - Neutron capture rates for s-process nucleosynthesis

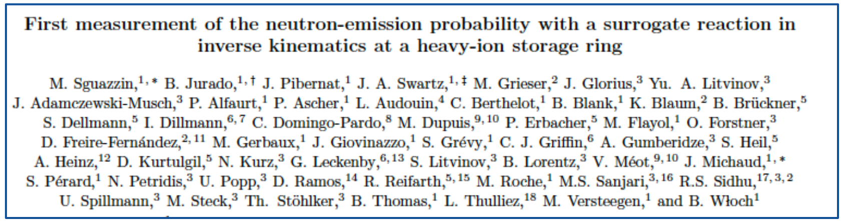
- Experiment at RIBF:
  - BigRIPS separator produced Se beams (from 238U+Be), which were degraded, here to 20MeV/u, impinging on CD_2 target
  - Outgoing protons detected upstream in lampshade-arranged Si strip detector (9^o-34^o com)
  - Energy resolution E_{com}=0.8 (1.3) MeV at E_{ex}=10 (13) MeV
  - Residual nuclei detected in SHARAQ spectrometer, identified by A/Q, magnetic rigidity, ionization chamber

Inverse-kinematics surrogate measurements at a heavy-ion storage ring at GSI/FAIR: Detecting recoils from ^{208}Pb(p,p’) to determine ^{207}Pb(n,γ)

Sguazzin et al, arXiv:2312.13742 (2023)

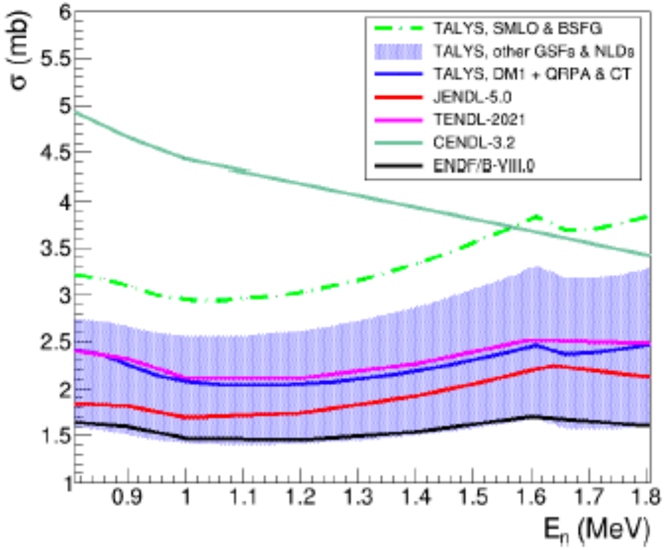


- Motivation
  - Cross section for design of lead-cooled fast reactors
  - Neutron capture rates for s-process nucleosynthesis
- Experiment at GSI/FAIR:
  - Experimental storage ring (ESR)
  - E_{Pb}=30.77MeV/u, scatter from gas-jet hydrogen target
  - Outgoing protons in Si ΔE-E detector (54.8°-64.6°)
  - Energy resolution E_{com}=250 keV (RMS)
  - Residual nuclei detected in DSSD

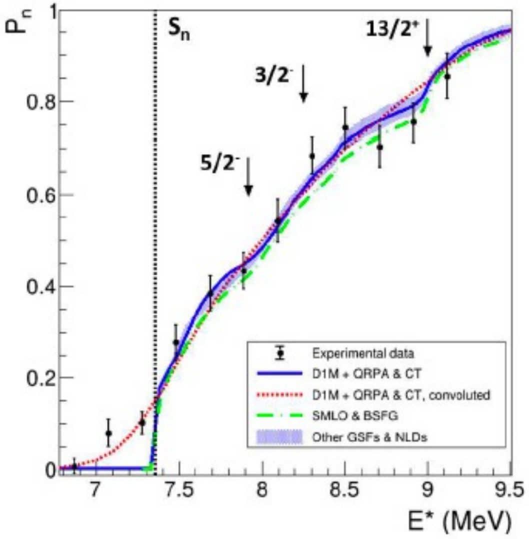

First measurement of the neutron-emission probability with a surrogate reaction in inverse kinematics at a heavy-ion storage ring

M. Sguazzin,[1,*] B. Jurado,[1,†] J. Pibernat,[1] J. A. Swartz,[1,‡] M. Grieser,[2] J. Glorius,[3] Yu. A. Litvinov,[3]
J. Adamczewski-Musch,[3] P. Alfaurt,[1] P. Ascher,[1] L. Audouin,[4] C. Berthelot,[1] B. Blank,[1] K. Blaum,[2] B. Brückner,[5]
S. Dellmann,[5] I. Dillmann,[6,7] C. Domingo-Pardo,[8] M. Dupuis,[9,10] P. Erbacher,[5] M. Flayol,[1] O. Forstner,[3]
D. Freire-Fernández,[2,11] M. Gerbaux,[1] J. Giovinazzo,[1] S. Grévy,[1] C. J. Griffin,[6] A. Gumberidze,[3] S. Heil,[5]
A. Heinz,[12] D. Kurtulgil,[5] N. Kurz,[3] G. Leckenby,[6,13] S. Litvinov,[3] B. Lorentz,[3] V. Méot,[9,10] J. Michaud,[1,*]
S. Pérard,[1] N. Petridis,[3] U. Popp,[3] D. Ramos,[14] R. Reifarth,[5,15] M. Roche,[1] M.S. Sanjari,[3,16] R.S. Sidhu,[17,3,2]
U. Spillmann,[3] M. Steck,[3] Th. Stöhlker,[3] B. Thomas,[1] L. Thulliez,[18] M. Versteegen,[1] and B. Włoch[1]

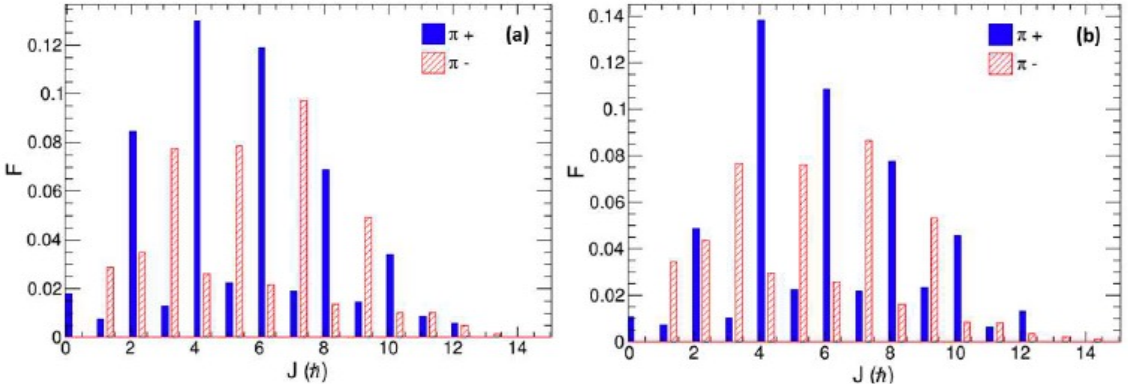
Resulting ^{207}Pb(n,g) vs Evals



Determine best HF decay



J^π from QRPA+DWBA

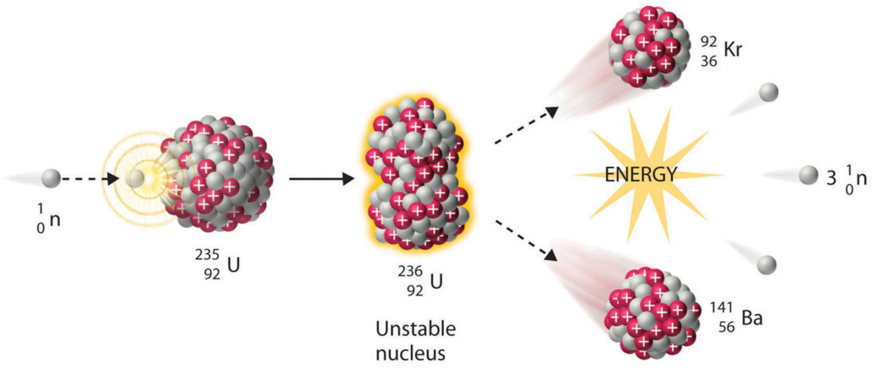


Fission

Surrogate reactions approach to obtain (n,f) cross sections and insights into the fission process

Describing fission challenges theory (and experiment)

- Descriptions range from phenomenological to microscopic
- Lots of data needed to provide constraints



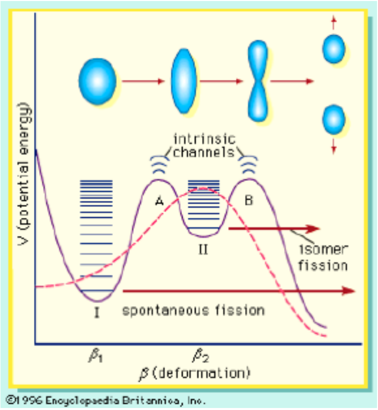
Opportunity: Surrogate fission measurements

- Observe fission properties in coincidence with surrogate ejectile
- Control over energy of fissioning nucleus, including sub-threshold

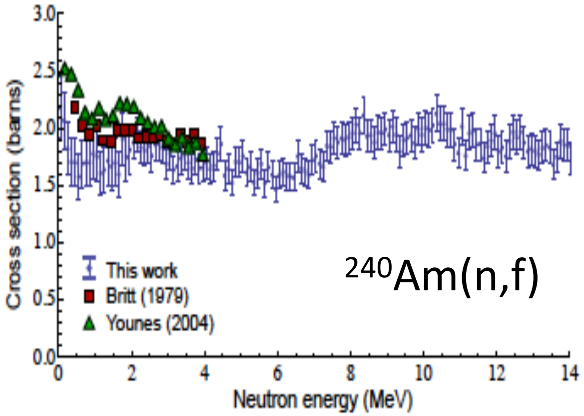
Opportunity: Extending theoretical treatments

- Role of pre-equilibrium, width fluctuation corrections, damping effects

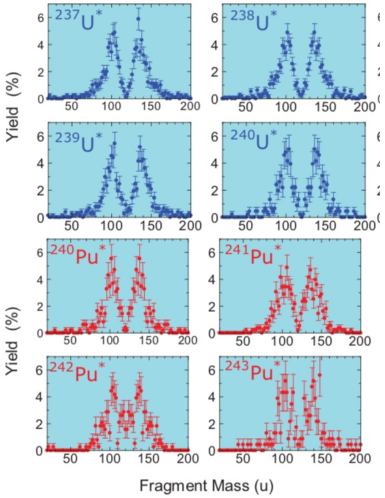
Schematic view of fission



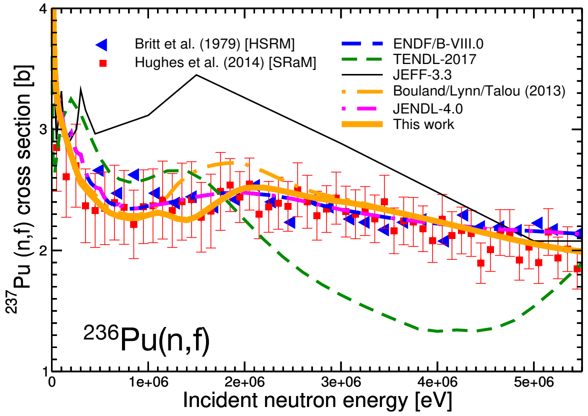
R.J. Caperson *et al*, PRC 84 (2014) 353



Fragment mass distributions
Chiba et al, NDS 119, 229 (2014)



Bouland & Marini, NDS 193, 195 (2024)

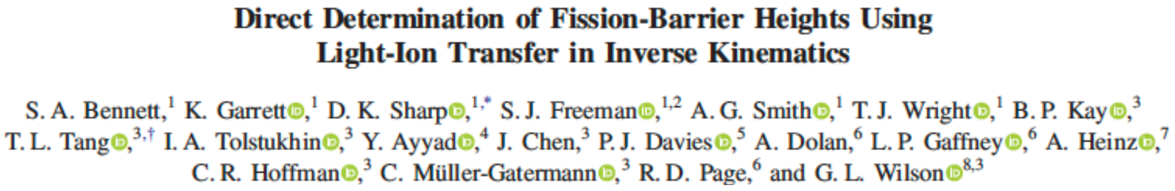


Inverse-kinematics (d,p) with HELIOS at ANL: Determining fission barriers in ^{239}U from ^{238}U(d,pf)

Bennett et al, PRL 130, 202501 (2023)

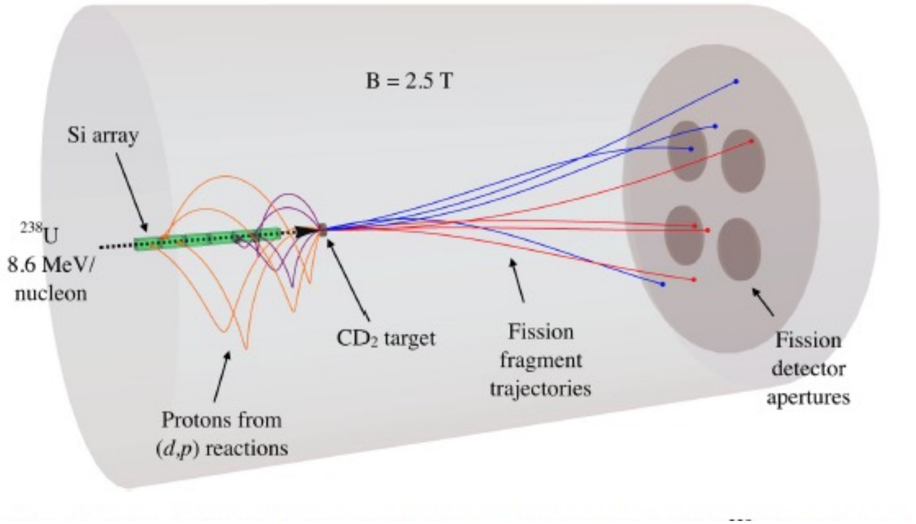
- Motivation
  - Collect fission data (barriers, mass and charge yields) for nuclear astrophysics (‘fission recycling’), future power systems, safeguard applications
  - Benchmarks for fission models

- Experiment at ANL:
  - Use of solenoidal spectrometer HELIOS
  - ^{238}U beam (E^b=8.6 MeV/u) on CD$_2$ target
  - Outgoing protons deflected in magnetic field and detected upstream on 4-sided position-sensitive Si array
  - Fission fragments detected in gas-filled heavy-ion detectors



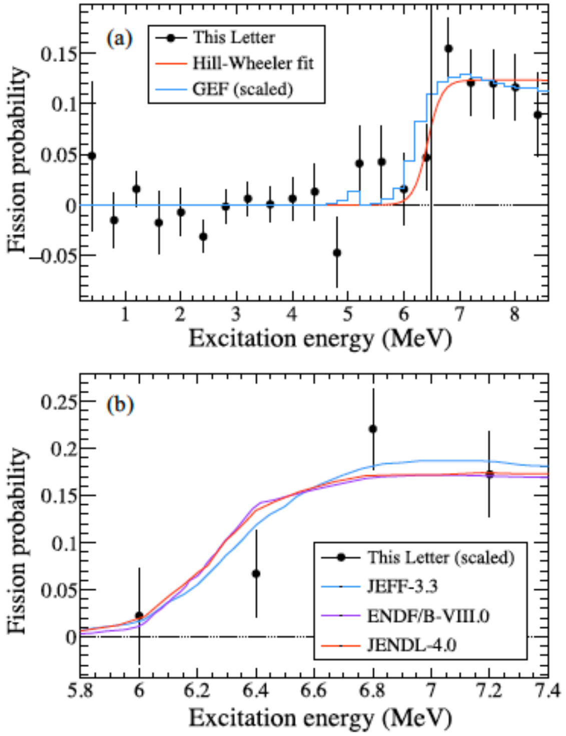
Direct Determination of Fission-Barrier Heights Using Light-Ion Transfer in Inverse Kinematics

S. A. Bennett,[1] K. Garrett,[1] D. K. Sharp,[1,*] S. J. Freeman,[1,2] A. G. Smith,[1] T. J. Wright,[1] B. P. Kay,[3] T. L. Tang,[3,†] I. A. Tolstukhin,[3] Y. Ayyad,[4] J. Chen,[3] P. J. Davies,[5] A. Dolan,[6] L. P. Gaffney,[6] A. Heinz,[7] C. R. Hoffman,[3] C. Müller-Gatermann,[3] R. D. Page,[6] and G. L. Wilson[8,3]



$$\sigma_f^A = \sigma_{\mathrm{CN}}^{A+1} \times P_f^{A+1}$$

$$P_f(E_x) = \frac{N_{d,pf}(E_x)}{N_{d,p}(E_x)\cdot \epsilon_f}$$



Experimental fission probability compared to GEF (top) and (scaled) compared to results deduced from evaluations (bottom).

Future: measurements with SOLARIS at FRIB and ISOLDE Solenoidal Spectrometer (ISS) at CERN

Limitations

Limitations of the SRM (in its present form)

- Forming a CN in the resonance region
  - Cannot use present approach which relies on HF decay calculations
  - Investigate the role of width fluctuations

- Failure to form a compound nucleus
  - 'just a little fail' *aka* preequilibrium: has to be accounted for > see Zr(n,2n) applications
  - Need to understand how doorway states damp into CN
  - No CN at all > need other approach

- Trying to measure direct capture cross section
  - Need a different method (ANC, Trojan Horse, Coulomb dissociation, ….)

- There are thousands of unstable nuclei for which we would like cross sections
  - Need to develop predictive theory
  - SRM can provided targeted cross section results to validate theory and address specific needs

Concluding remarks

1. Surrogate reaction method combines theory and experiment to constrain cross section calculations for compound reactions that cannot be measured directly.

2. Method uses inelastic scattering or transfer reactions in regular or inverse kinematics.

3. Uses experimental observable indicating decay into channel of interest. Does not use auxiliary quantities (D0, <Gg>) which are unavailable for unstable isotopes. When use Bayesian parameter inference, UQ and correlations are built in.

4. The last decade has seen significant progress on both the theory and experimental side. New experimental facilities are providing opportunities to further expand.

4. There is very interesting physics associated with surrogate reaction mechanism:
    - We need broadly-applicable theoretical descriptions of inelastic scattering and transfer reactions
    - Doorway states play an important role in producing the CN. We need to better understand how they damp.
    - Width fluctuations in surrogate reactions are understudied.

5. We will not be able to measure all reactions of interest. Predictive theory is needed. Surrogate measurements can be used to validate and complement theory

A thank you to my collaborators:

LLNL: O. Gorton, E. In, G. Potel, C. Pruitt, A. Thapa, I.J. Thompson, W. Younes,
B. Alan, R. Casperson, J. Harke, R. Hughes, A. Ratkiewicz, N. Scielzo
ORNL: S.Pain
Rutgers U.: J. Cizewski, H. Sims
Ohio U: A. Richard
CEA/France: M. Dupuis, S. Peru

Thank you!

CNR*24 invited keynote talk (40+10 min):
Surrogate nuclear reactions method

Abstract:

Cross sections for compound-nuclear (CN) reactions are important for nuclear astrophysics and other applications. Direct measurements are not always possible for the reactions of interest and calculations without experimental constraints can be quite uncertain. Thus indirect approaches, such as the surrogate reaction method (SRM), are being developed to fill the gaps. The SRM, which uses a (direct) inelastic scattering or transfer reaction to obtain information on the decay of a specific compound nucleus, has a long history of providing probabilities for fission, gamma and particle emission. While earlier implementations of the method used minimal theory to provide approximate cross sections for (n,f) reactions, better theoretical descriptions of the underlying reaction mechanisms have made it possible to also obtain (n,g), (n,n'), and (n,2n) cross sections that agree well with benchmarks. I will discuss multiple applications of the modern implementation of the SRM, highlight theory advances that enable them, and comment on opportunities offered at new experimental facilities.

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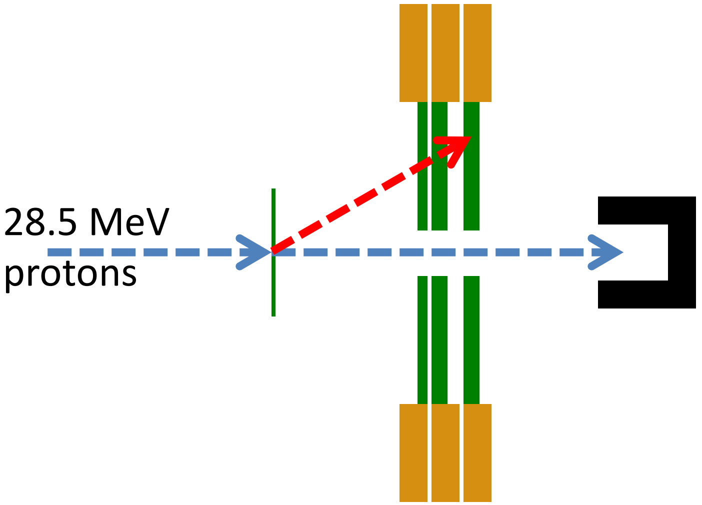
StarLiTeR at Texas A&M



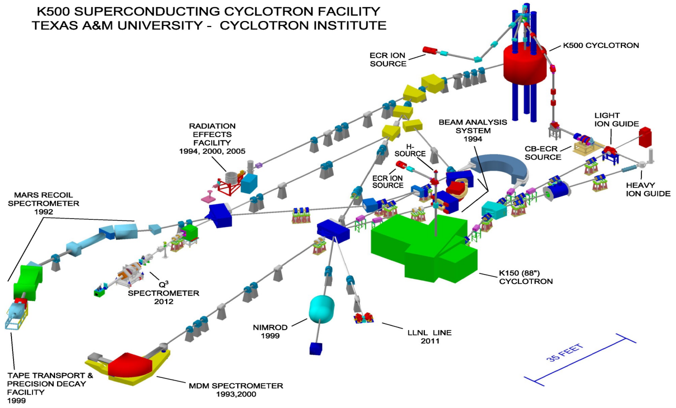
Si = 140, 1000, 1000 µm
ΔE E1 E2 detectors

28.5 MeV
protons

Faraday
Cup

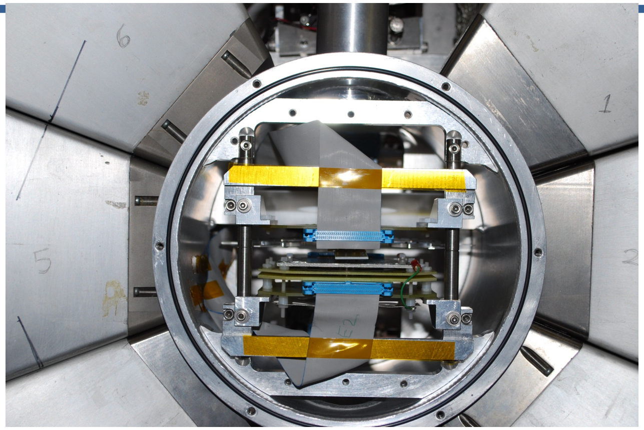
We record the total energy, angle and determine the particle type

Some experimental details:
- 13-day run (LLNL experimental team & collaborators
- Si energy resolution 75 keV one sigma
- Gamma energy resolution 1.7 keV one sigma
- Angle range 30 to 60 degrees
- Y89 mono-isotopic 760 micrograms/cm^2

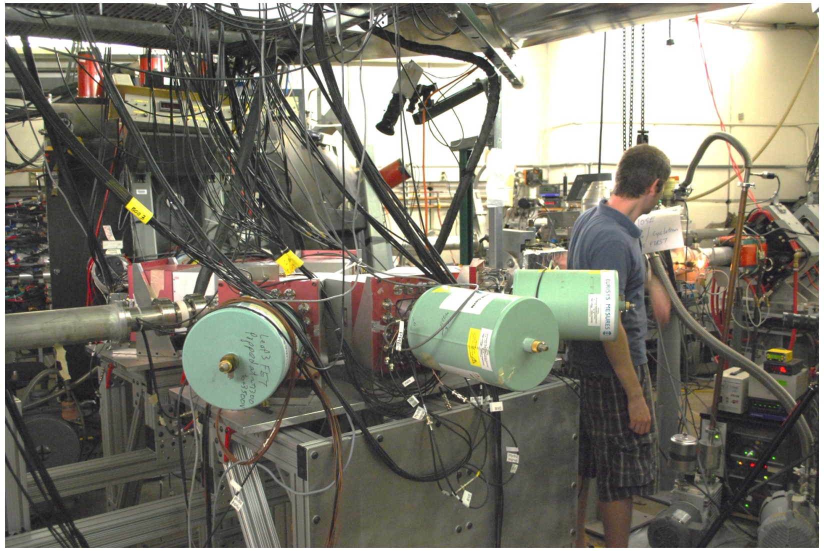


Experiment at Texas A&M Cyclotron Institute

Top view of the STARLiTeR array.
HPGe surrounds chamber Si telescope.



STARLiTeR array closed up around the chamber.
Cyclotron beam comes from right and exits on left.



J.T. Burke, priv. commun.

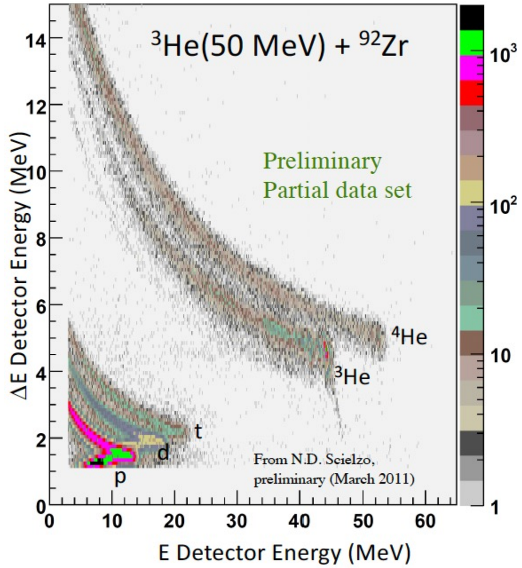
Surrogate reactions method for (n,n') and (n,2n)

STARS/LiBerACE experiments at LBNL

^{90,91,92}Zr(^{3}He,^{3}He') and ^{90,91,92}Zr(^{3}He,α)

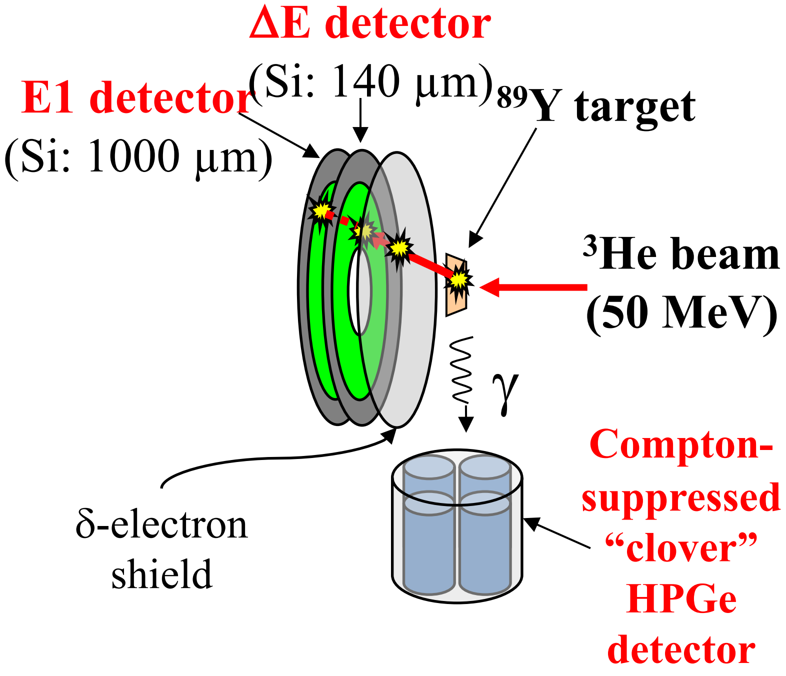
^{89}Y(^{3}He,^{3}He') and ^{89}Y(^{3}He,α)

Scielzo et al.



Preliminary
Partial data set

From N.D. Scielzo, preliminary (March 2011)



ΔE detector
(Si: 140 μm)

E1 detector
(Si: 1000 μm)

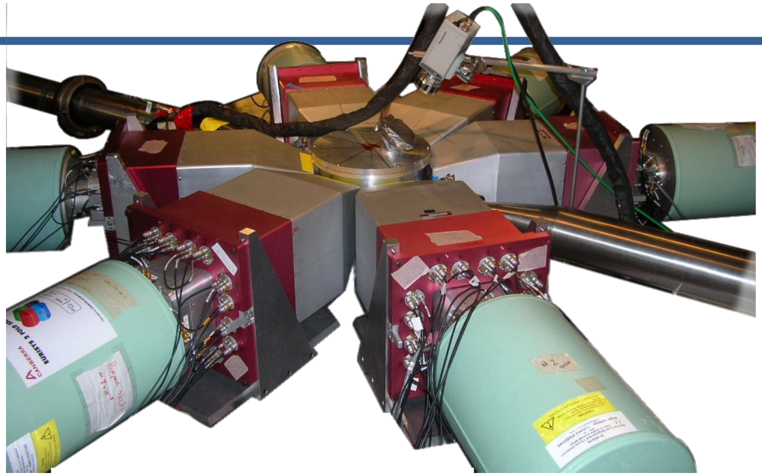
^{89}Y target

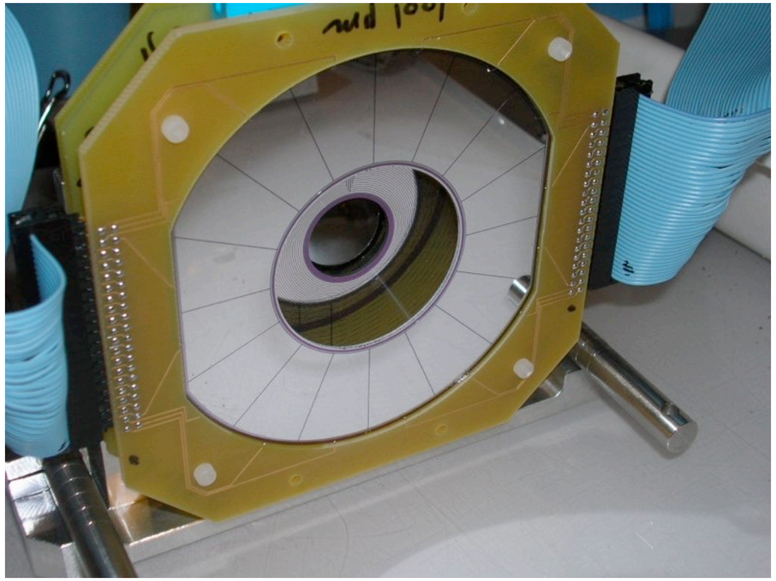
^{3}He beam
(50 MeV)

γ

δ-electron
shield

Compton-
suppressed
"clover"
HPGe
detector

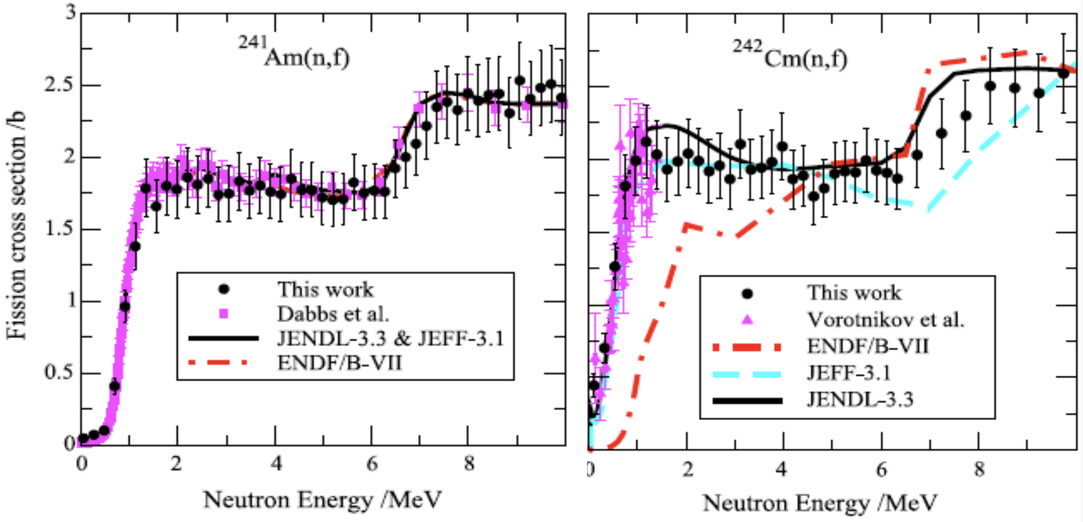




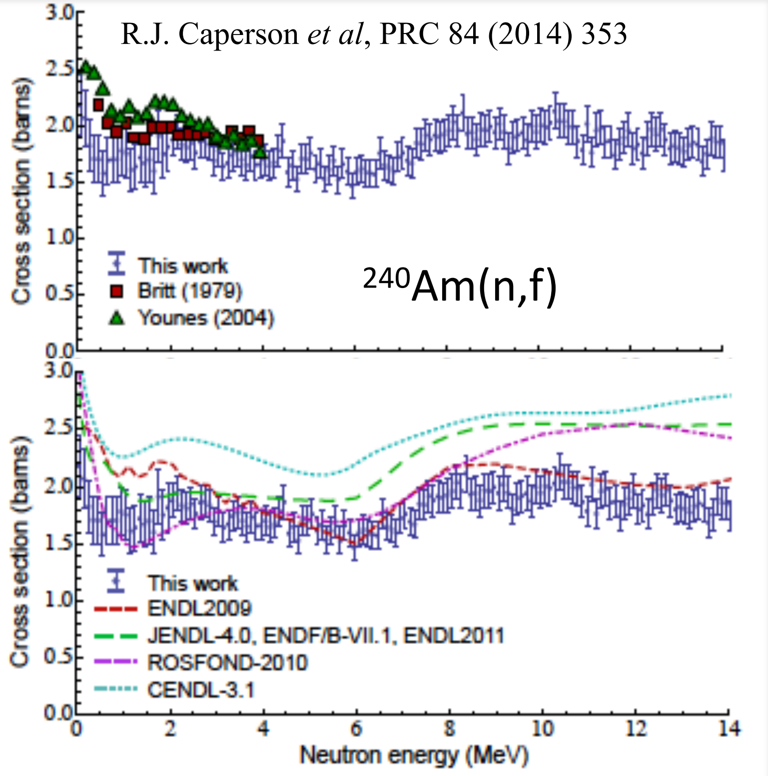
SRM for (n,f) cross sections

- Results used the Weisskopf-Ewing approximation: ignore spin-parity mismatch
- Typically agree within 10-15% with benchmarks
- Low energies and fission barriers tend to be more sensity to J$^{\pi}$ mismatch
- Role of preequilibrium needs to be explored further

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