# *Cosmic Cauldrons and Exotic Nuclei: New reaction theory developments for determining unknown cross sections*

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**Where do the chemical elements come from?**

**Nuclear reactions are key to this question!**

**Collaborators:**
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Lawrence Livermore National Laboratory

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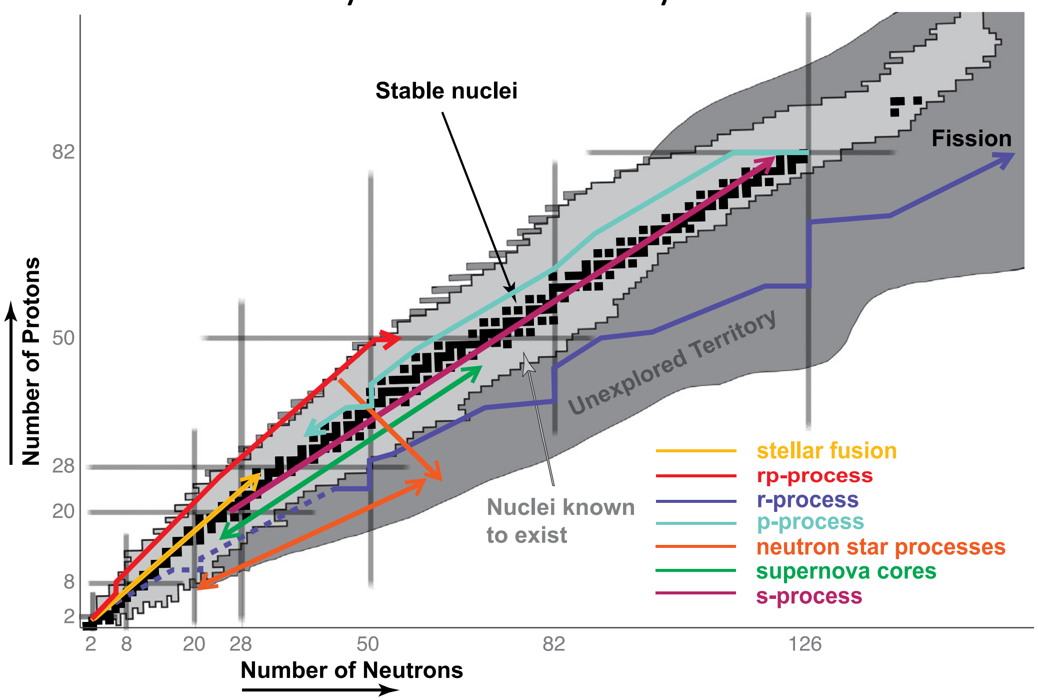
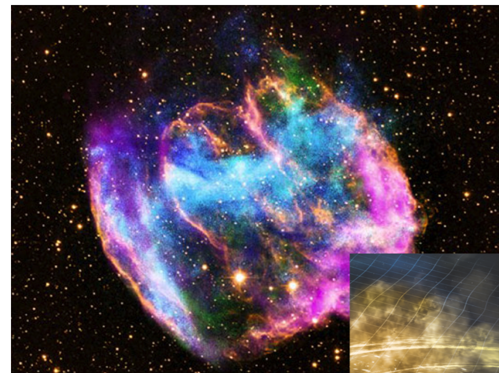
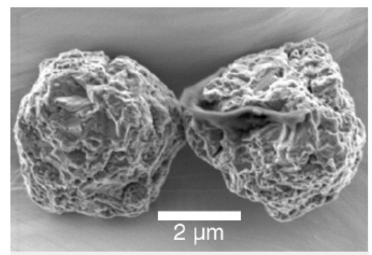
**ASRC International Workshop**
**Nuclear Fission and Structure of Exotic Nuclei (Sakura 2019)**
**Tokai, Japan**
**March 24-27, 2019**

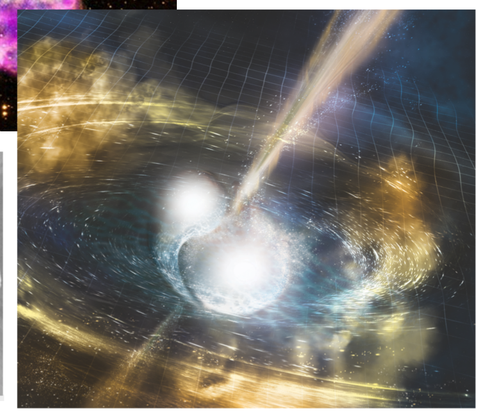
# Nuclear reactions play a key role in the production of the elements

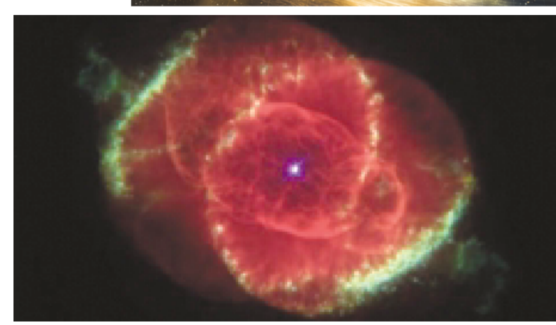
**Scientific challenge: Origin of the heavy elements?**
Capture reactions are required to shed light on stellar evolution and heavy-element nucleosynthesis







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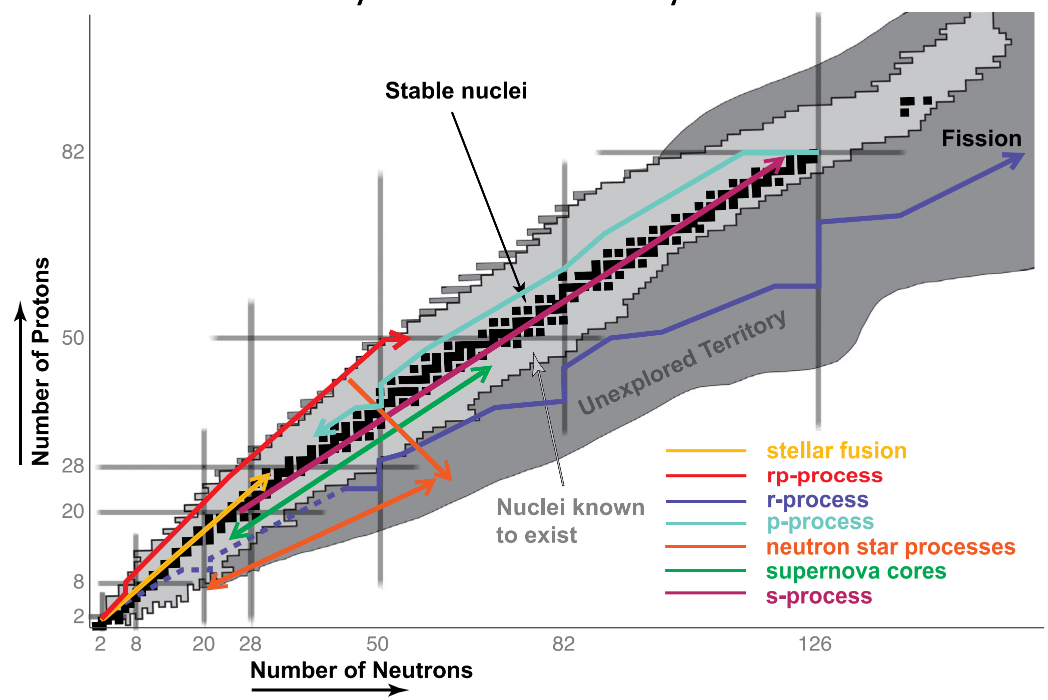
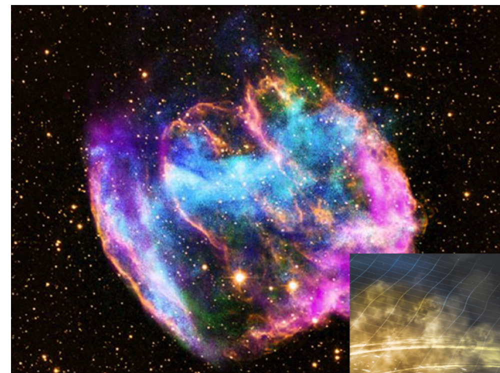
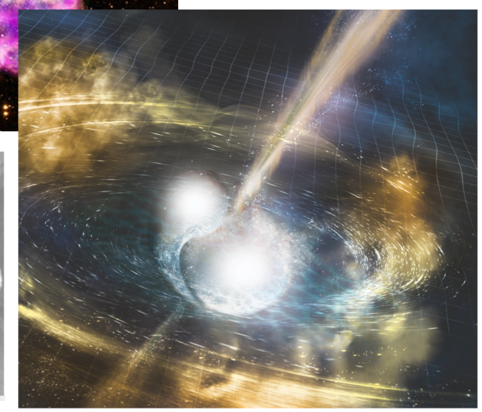
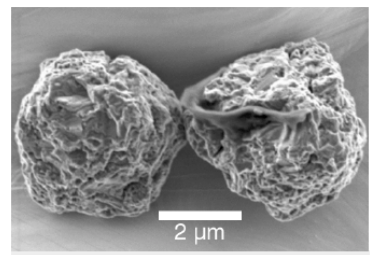
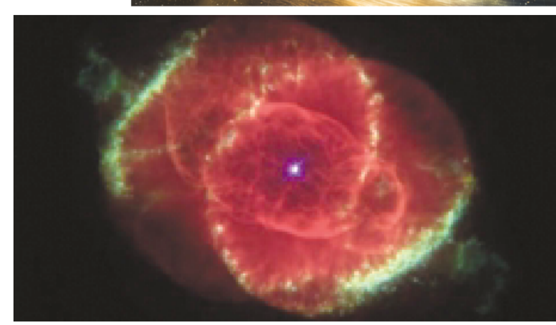
Capture reactions are required to shed light on stellar evolution and heavy-element nucleosynthesis





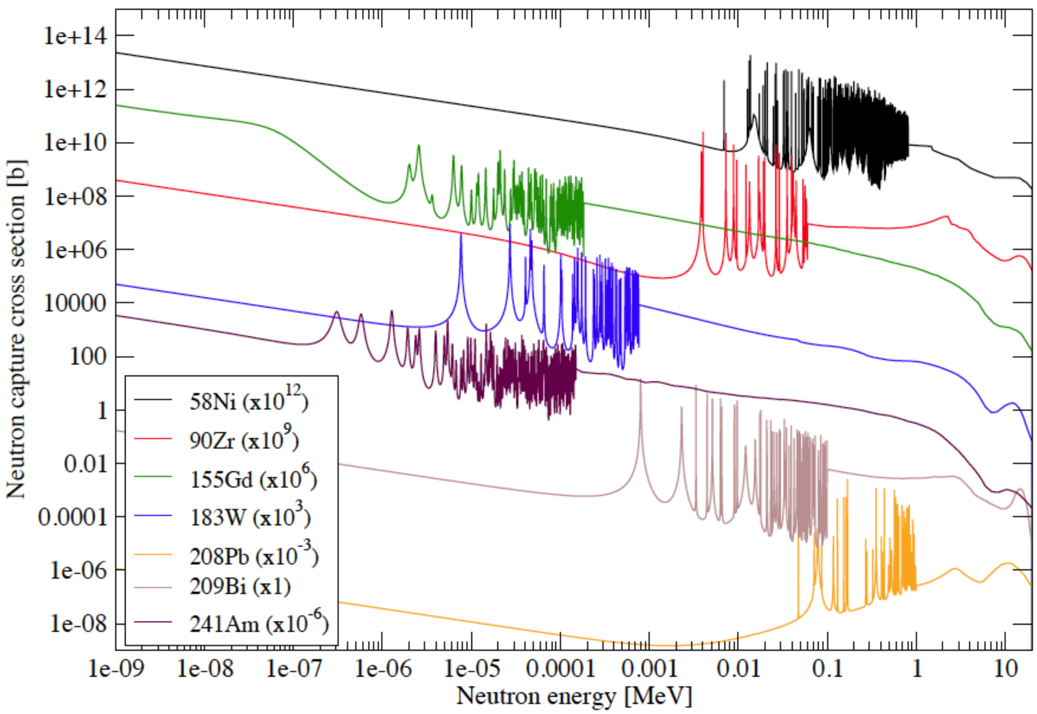


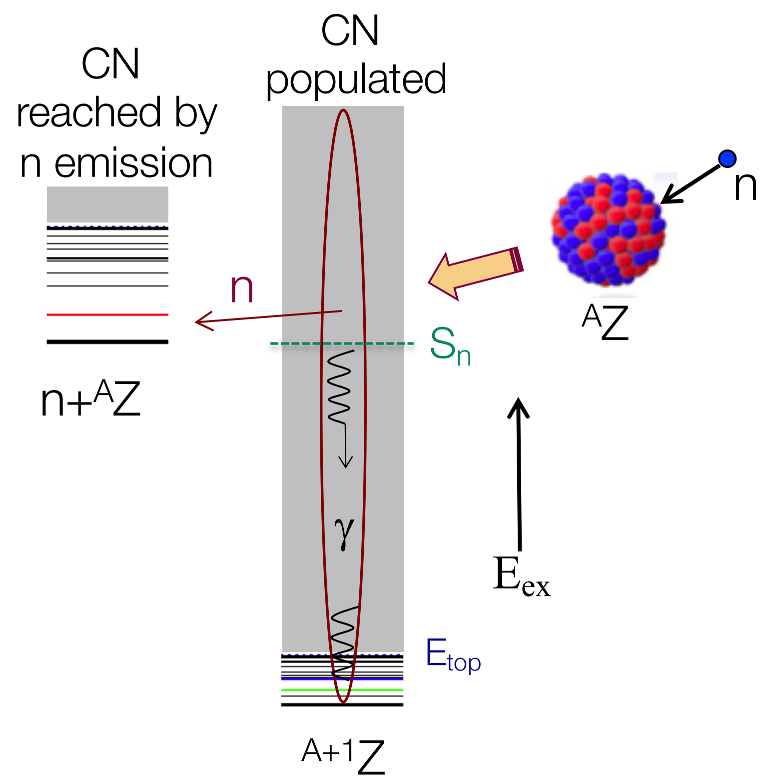



Need: Cross sections
s-process: (n,$\gamma$) on branch point nuclei
r-process: (n,$\gamma$) on very n-rich nuclei
p-process: (p,$\gamma$) on n-poor nuclei

# Neutron capture reactions

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



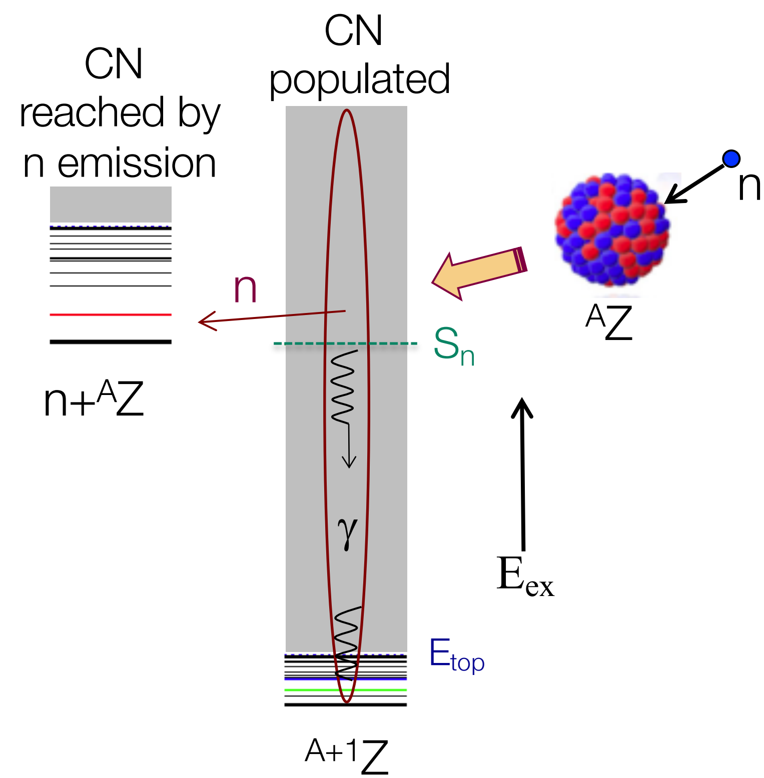

**Hauser-Feshbach formalism:**

$$\frac{d\sigma^{HF}_{\alpha\chi}(E_a)}{dE_\chi} = \pi\lambda\!\!\!^{-}{}^2_\alpha \sum_{J\pi} \omega^J_\alpha \sum_{\ell s \ell' s' I'} \frac{T^J_{\alpha\ell s} T^J_{\chi\ell' s'} \rho_{I'}(U') W_{\alpha\chi}(J)}{\sum'_{\chi''\ell''s''} T^J_{\chi''\ell''s''} + \sum_{\chi''\ell''s''I''} \int T^J_{\chi''\ell''s''}(E_{\chi''}) \rho_{I''}(U'') dE_{\chi''}}$$

# Neutron capture reactions

(n,γ) cross sections
for unstable isotopes

**???**

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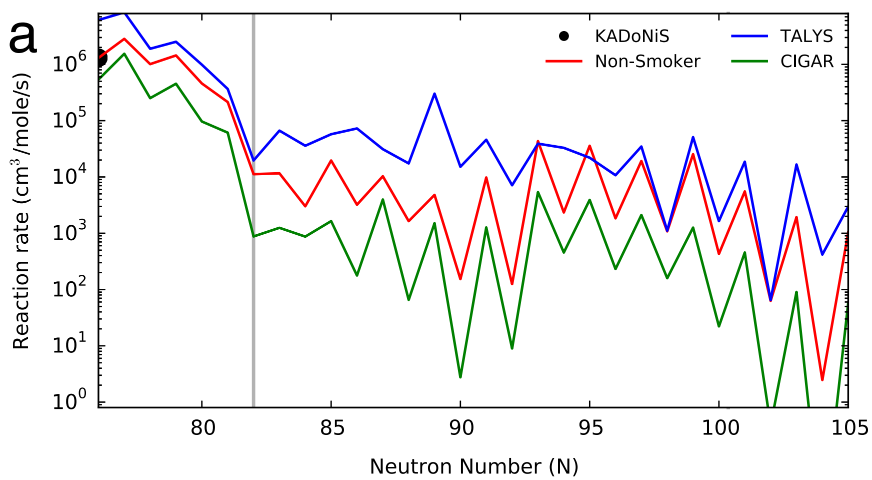
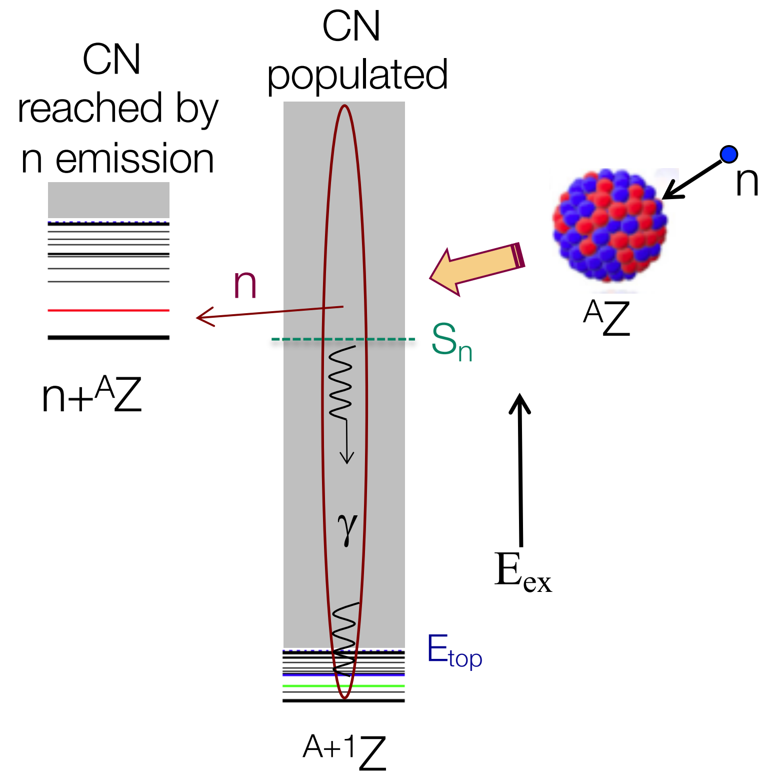
# Capture cross sections for unstable isotopes

Challenge: uncertainties increase dramatically with distance from stability

**Calculated (n,γ) cross sections for Sn isotopes**




Mumpower et al. Prog. Part. Nucl. Phys (2016)

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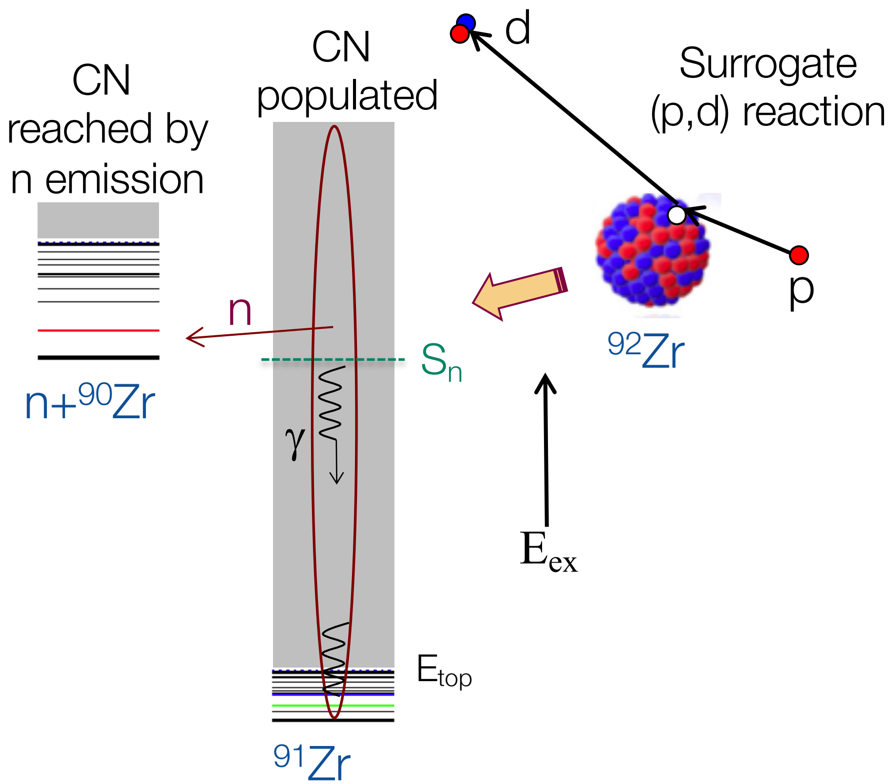
# Capture cross sections from surrogate (p,d) reaction

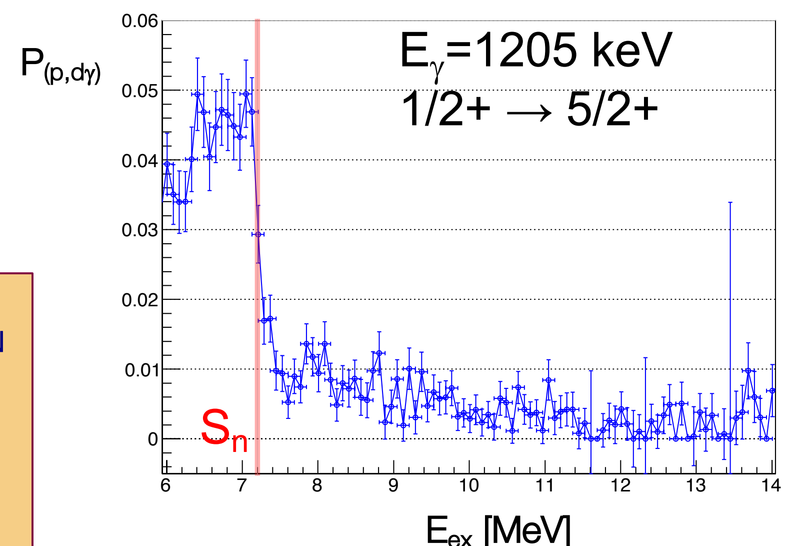



Hauser-Feshbach description of "desired" CN reaction

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

A Surrogate experiment gives

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



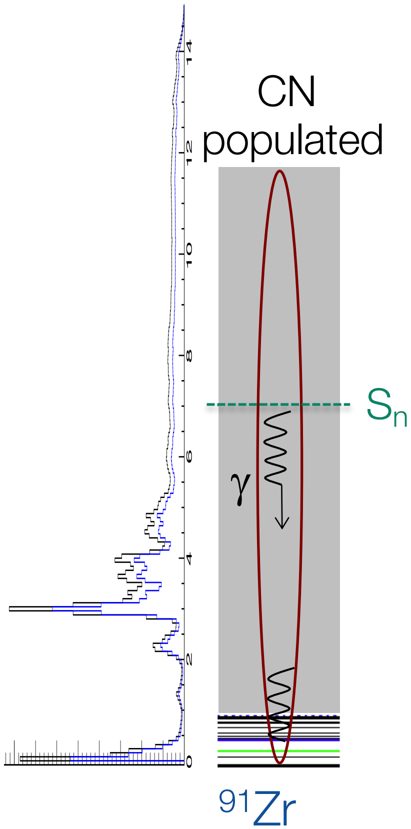

**Turning measurement into cross section**

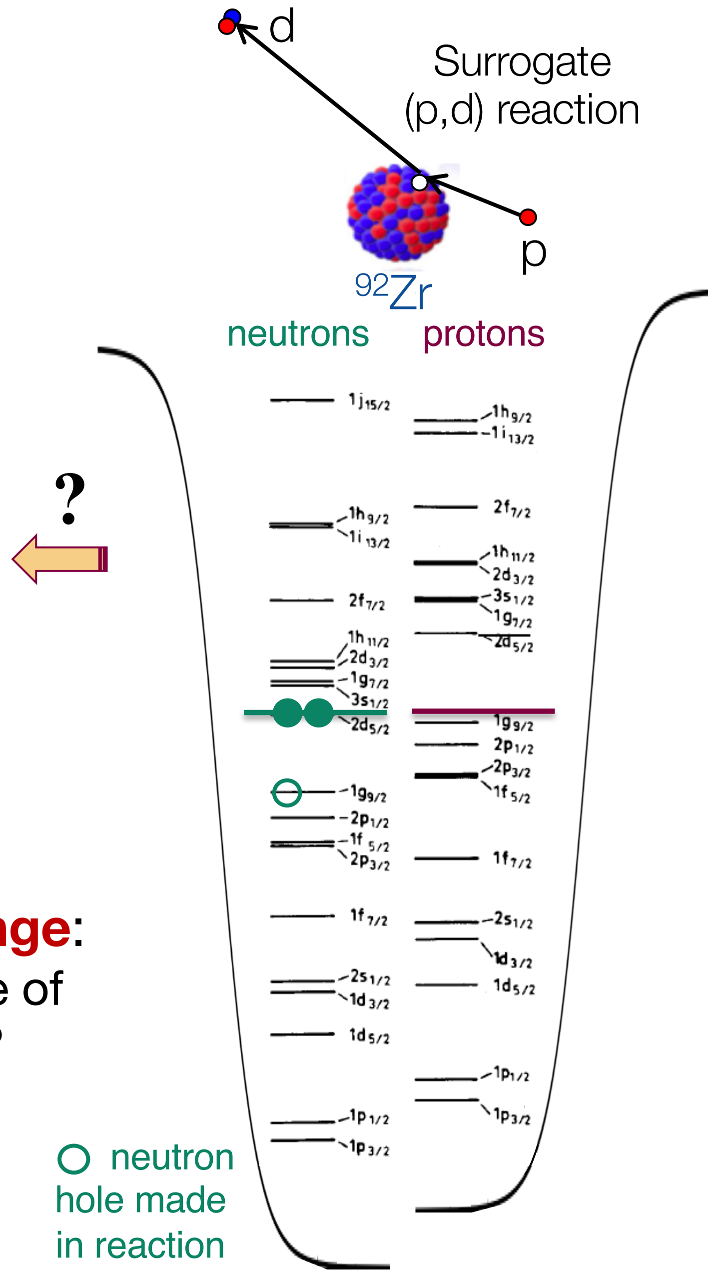
1. Use theory to describe Surrogate reaction, predict $F_{(p,d)}{}^{CN}$
2. Develop rough decay model $G^{CN}{}_{\gamma}$
3. Fit uncertain parameters in $G^{CN}{}_{\gamma}$ to reproduce $P_{(p,d\gamma)}$
4. Use best-fit parameters to calculate desired $\sigma_{(n,\gamma)}$

**Result**: Experimentally constrained cross section calculation.

Escher et al, RMP 84 (2012) 353

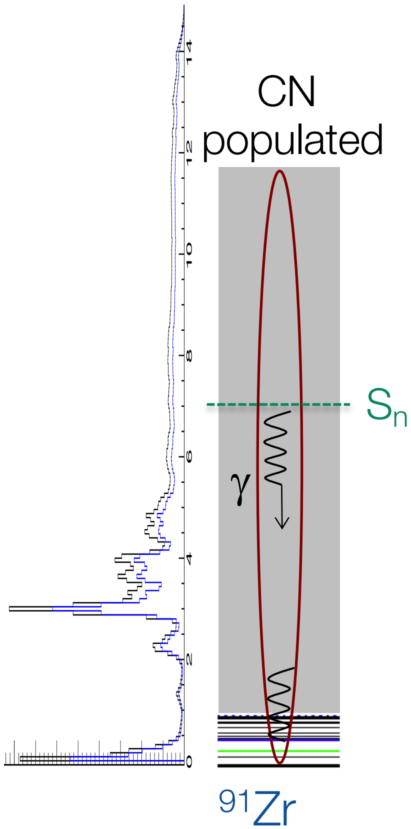
# Neutron hole structure relevant to (p,d) reaction?



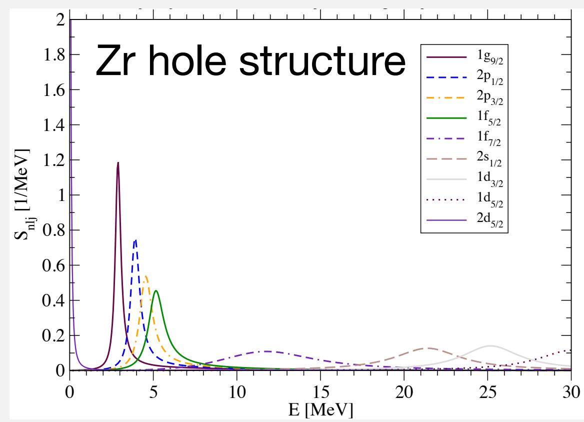

**Structure Challenge**:
What is the structure of deep neutron holes?
Location?
Fragmentation?

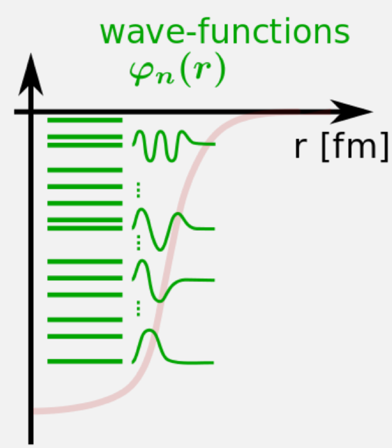
# Structure of deep neutron holes




**Structure Challenge**:
What is the structure of deep neutron holes?
Location?
Fragmentation?

Spectral functions $S_{nlj}$




## Dispersive Optical Model

- Connects OMP for scattering to nuclear mean field:

  Empirical scattering information yields OMP at positive energies

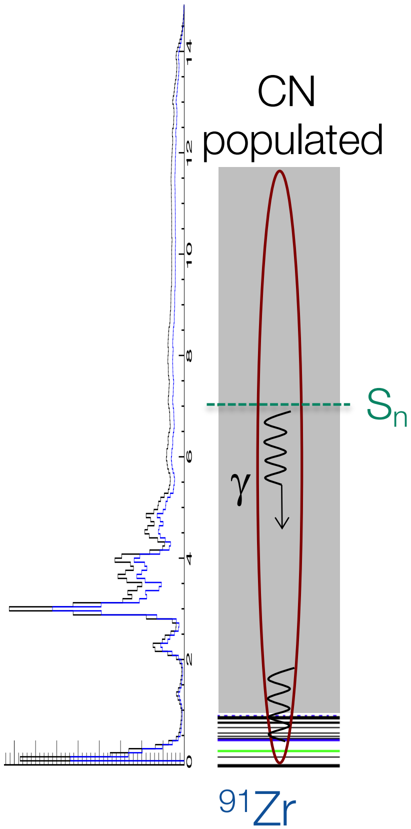
  Mean field gives energy-averaged nuclear properties: single-particle $E_{nlj}$, spectral functions $S_{nlj}$, etc.

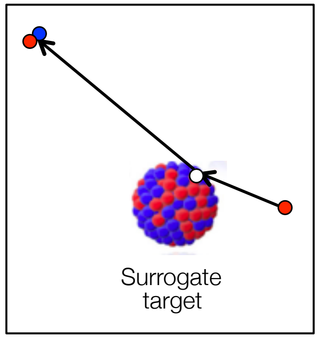
- DOMP of renewed interest for obtaining reliable potentials for scattering calculations

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

**Gives energy-averaged nuclear properties**

# Reaction mechanism includes higher-order processes



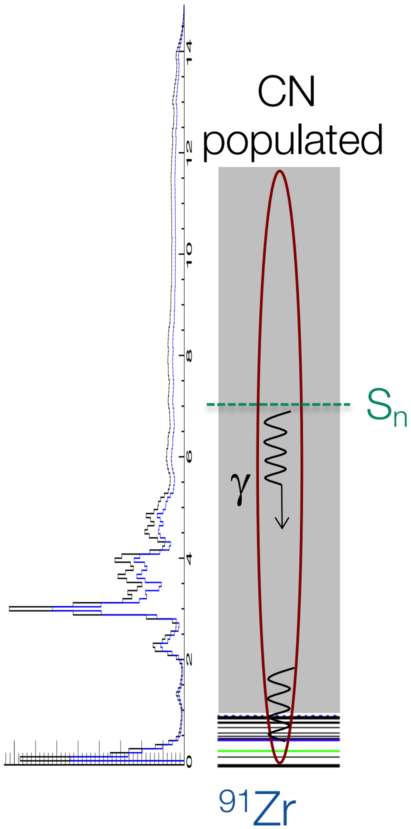

**First-order processes:**

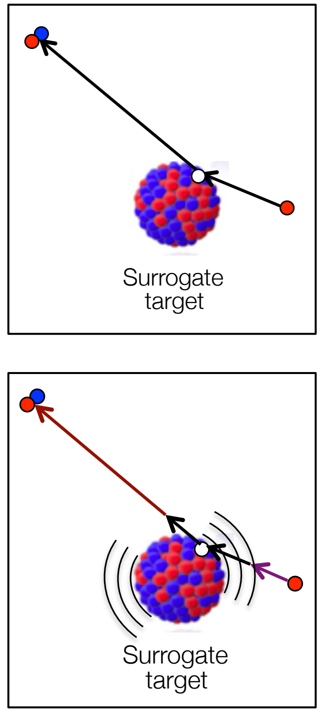
- neutron pickup makes deep hole
- Reaction calculation uses DWBA with $S_{nlj}$ from DOMP

DWBA: Distorted-Wave Born Approximation

**Reaction Challenge**:
Standard DWBA (p,d) calculations insufficient
Two-step mechanisms important

# Reaction mechanism includes higher-order processes



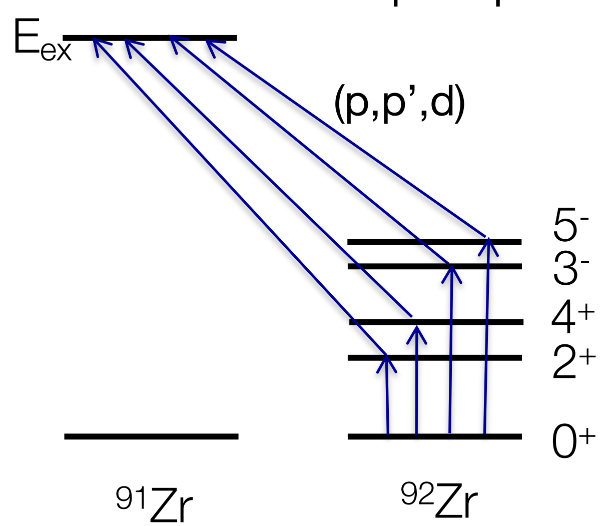

**First-order processes:**

- 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



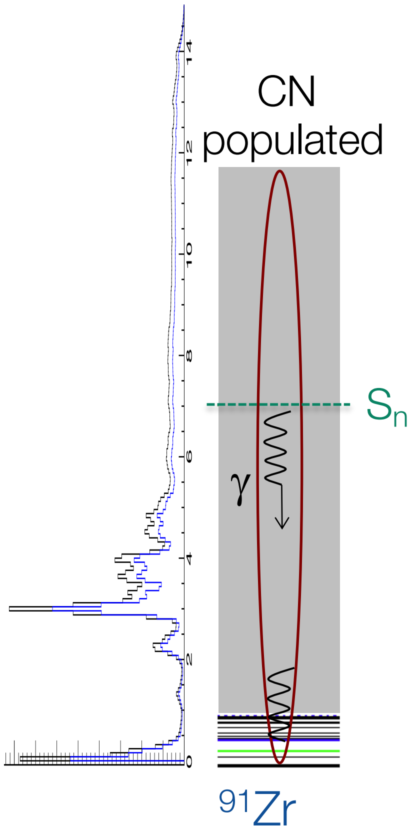

(p,d',d) analogously

**Reaction Challenge**:

Standard DWBA (p,d) calculations insufficient

Two-step mechanisms important

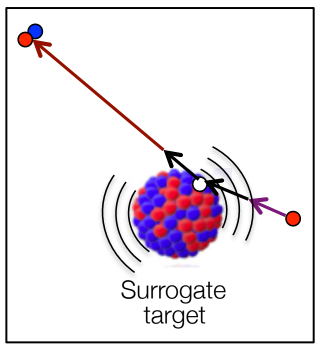
# CN formation involves 2-step processes




- Include (p,p')(p',d) and (p,d')(d',d)
- Philosophy of pre-equilibrium theories: forward coupling, spectator approximation, no interference
- Structure information on inelastic states from experimental literature
- Couple all angular momenta explicitly

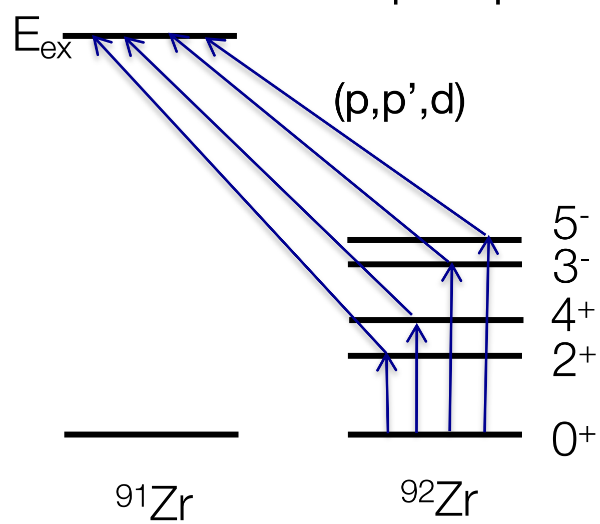
**Wide range of angular momenta possible:**

**0.5 to 11.5**




**Second-order processes:**

- Inelastic scattering preceeds or follows neutron pickup



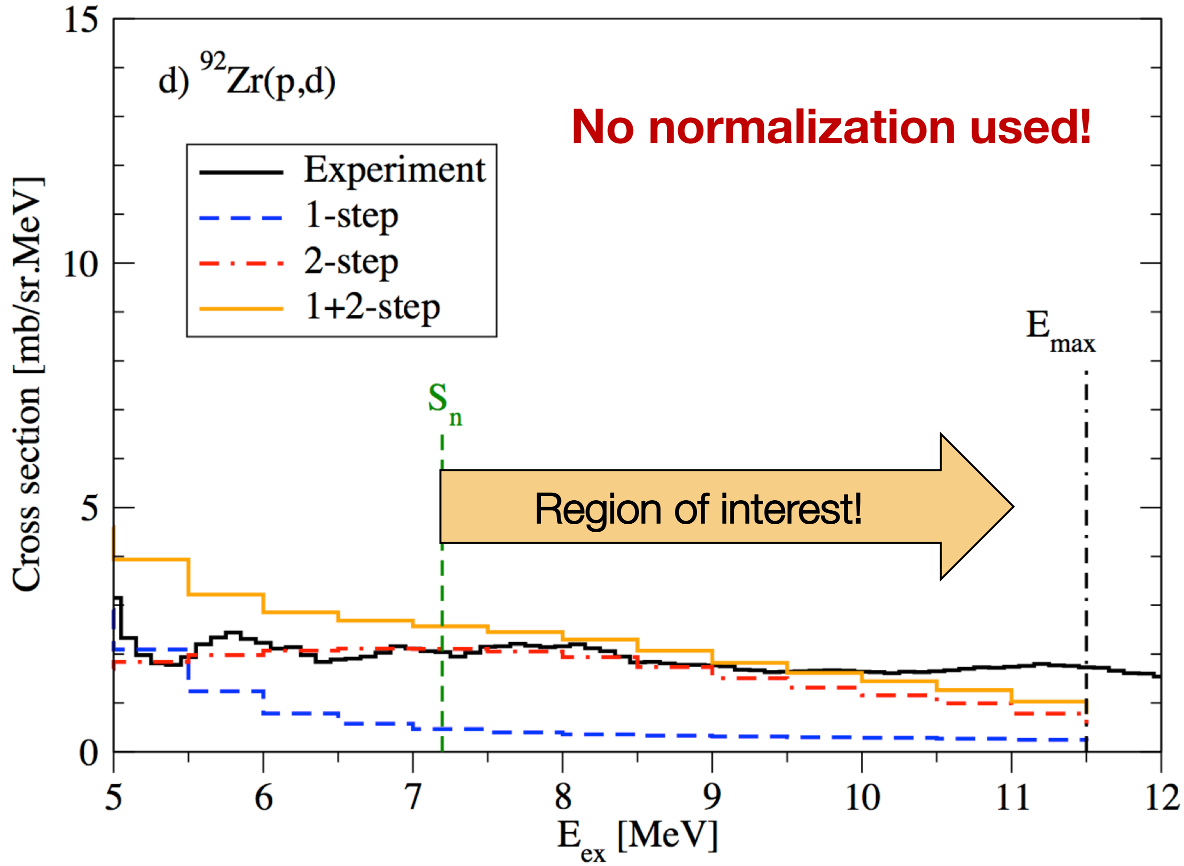

(p,d',d) analogously

**Reaction Challenge**:

Standard DWBA (p,d) calculations insufficient

Two-step mechanisms important

# Result: Compound-Nucleus Formation via (p,d)




2-step processes dominate the region of interest!

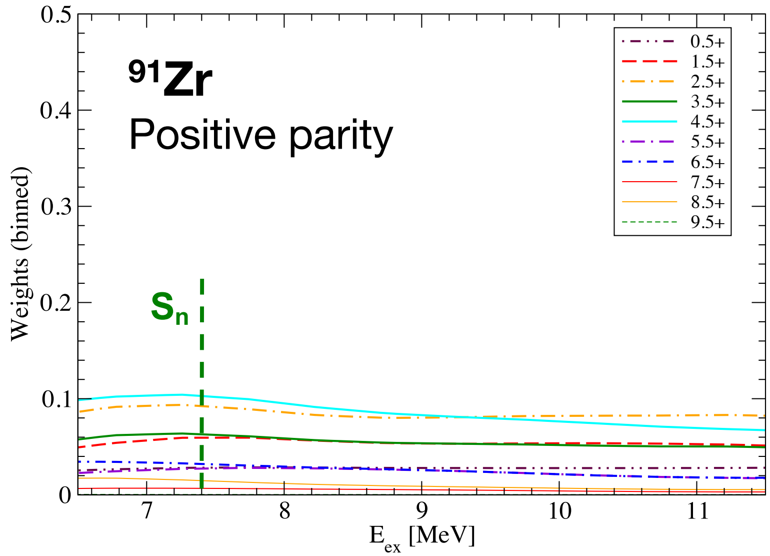
High energies (region of interest):

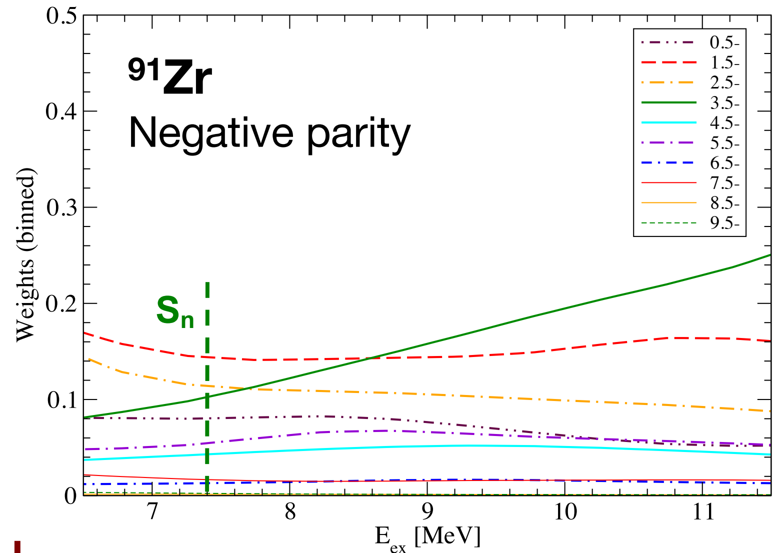
- absolute cross section approximately reproduced, **no normalization!**
- 2-step processes dominate
- measurement and calculation agree, model assumptions valid

# Result: Compound-Nucleus $J^{\pi}$ Distribution

**Spin-parity distribution**:

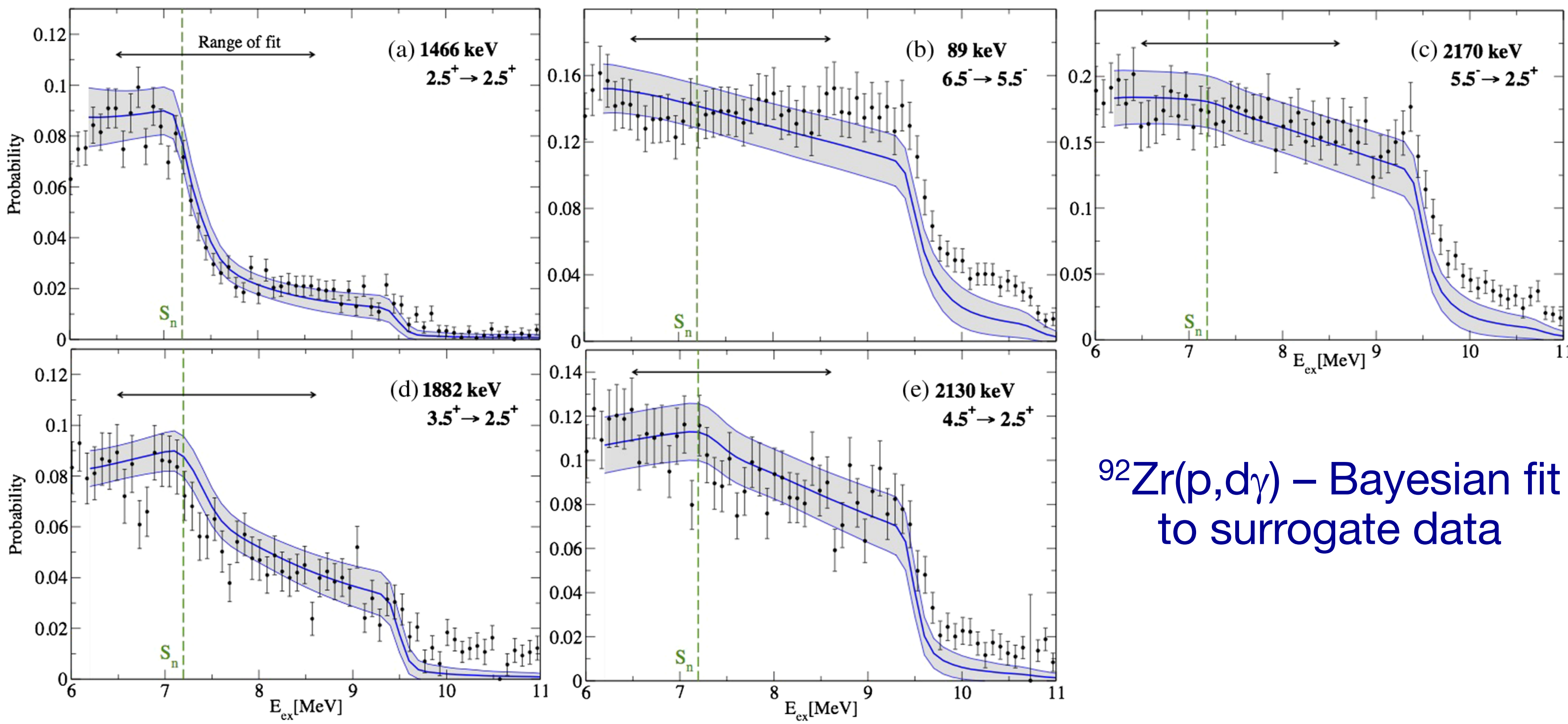
- As function of excitation energy of $^{91}$Zr
- Calculated from relative contributions of final $J^{\pi}$ to total (p,d) cross section
- Contributions from spins up to ~J=10




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

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




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

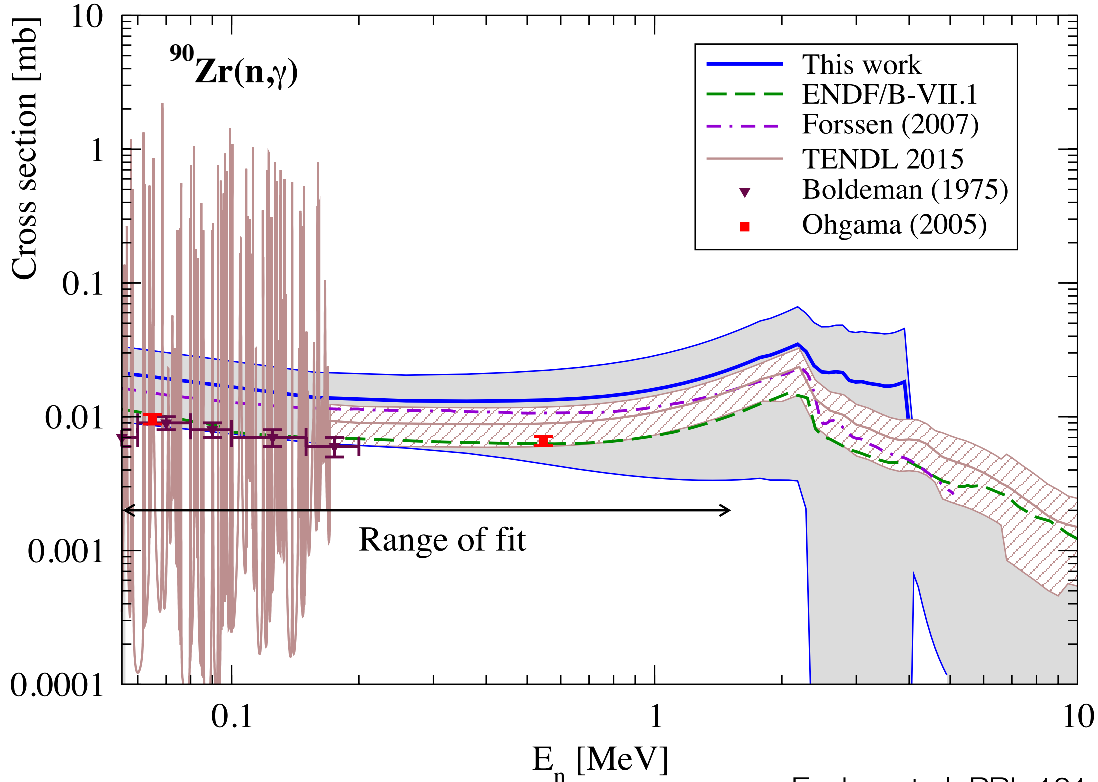
- Select relevant $^{91}$Zr γ transitions
- Fit to data from 0.5 MeV below $S_n$ to 1.5 MeV above $S_n$

Fit yields best set of parameters & uncertainty estimate.

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

# $^{90}$Zr(n,$\gamma$) cross section from surrogate (p,d) data

- Surrogate data constrains cross section up to $E_n$=1.5 MeV
- Result in agreement with direct measurements & evaluations
- Result includes experimental & theoretical uncertainties



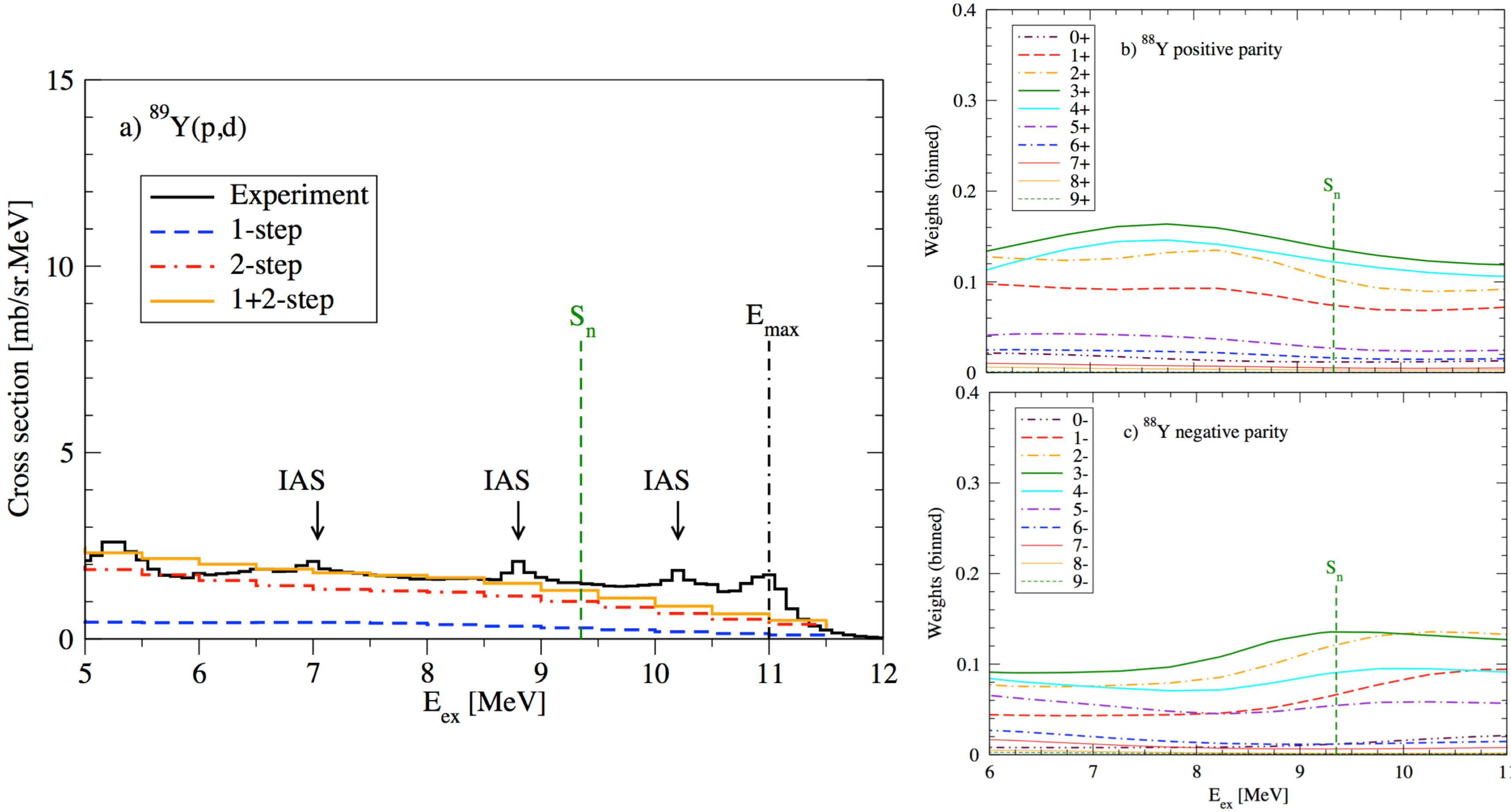

**Surrogate method does not use $D_0$ or $\langle\Gamma_\gamma\rangle$**

Escher et al, PRL 121, 025501 (2018)

Using best set of parameters to calculate $^{90}$Zr(n,$\gamma$)

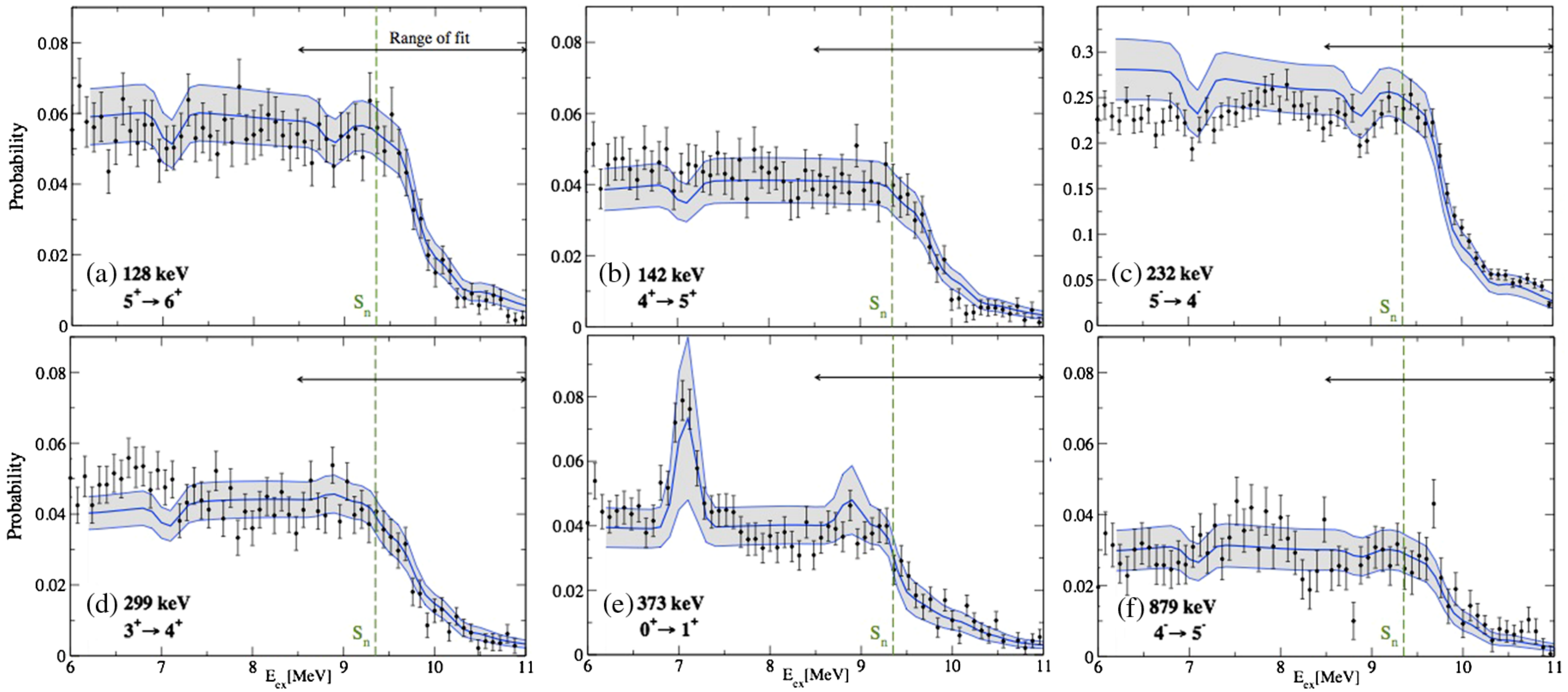
$$\sigma_{(n,\gamma)} = \sum_{J,\pi} \sigma_{n+target}{}^{CN}(E,J,\pi) \cdot G^{CN}{}_{\gamma}(E,J,\pi)$$

# $^{89}$Y(p,d) singles results




- Procedure is analogous to the Zr case
- Special feature: Isobaric Analog States (IAS)

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




# $^{89}$Y(p,dγ) – Bayesian fit to surrogate data

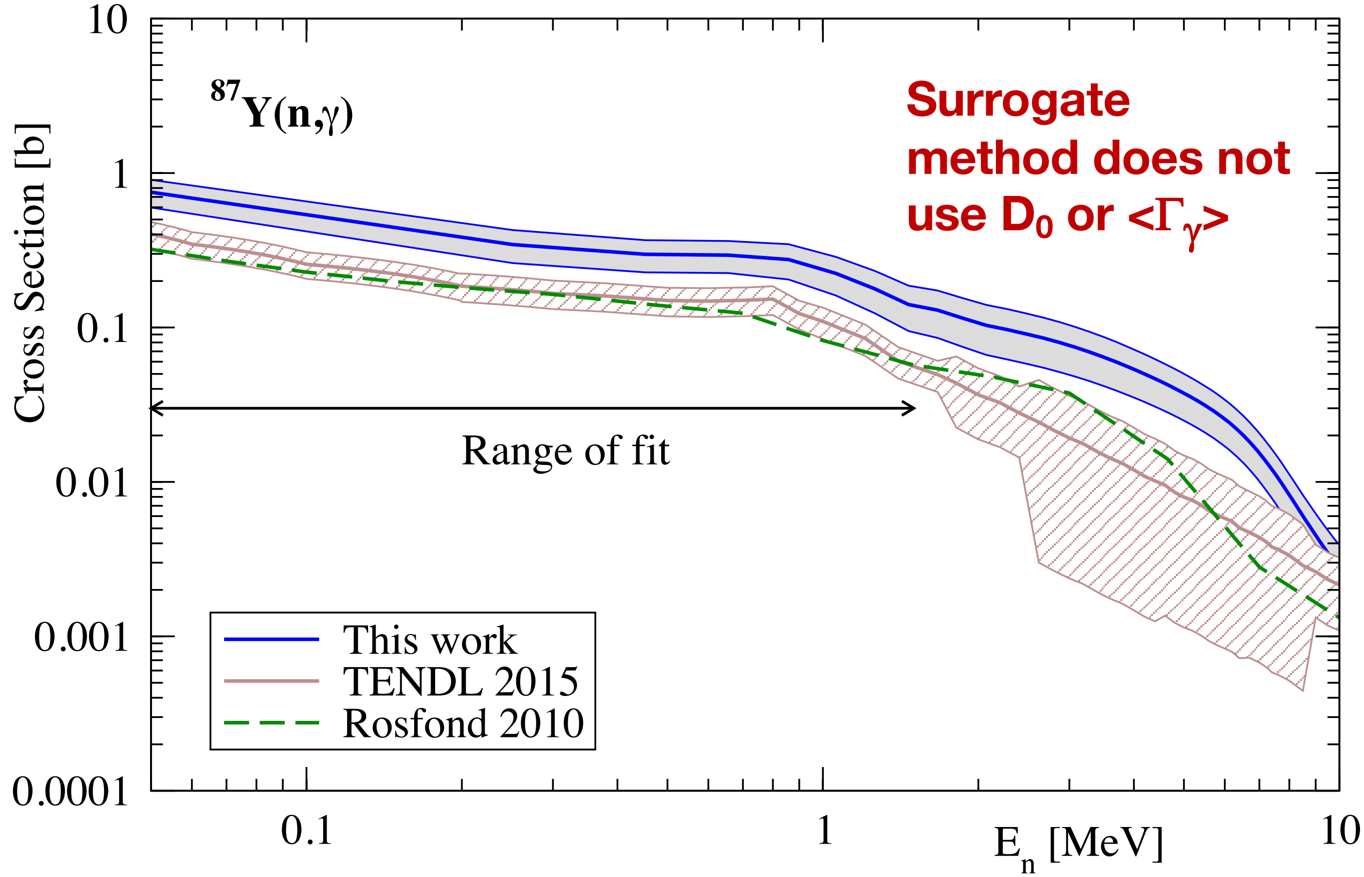
- Procedure is analogous to the Zr case
- Special feature: Isobaric Analog States (IAS)

Fit yields best set of parameters & uncertainty estimate.

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

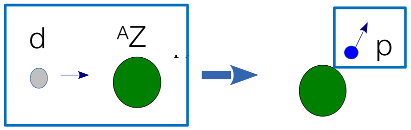
# $^{87}$Y(n,γ) cross section from surrogate (p,d) data

Surrogate data constrains cross section up to $E_n$=1.5 MeV
Result differs from evaluations (based on regional systematics)
Result includes experimental & theoretical uncertainties




Escher et al, PRL 121, 025501 (2018)

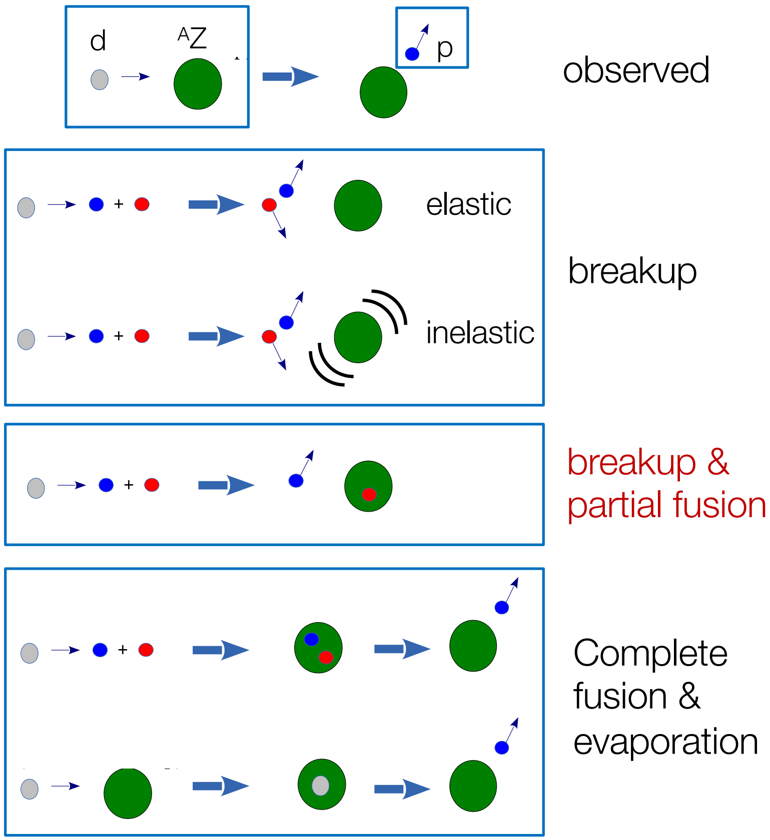
# Towards inverse-kinematics applications with RIBs…
# …the (d,p) reaction




observed

**(d,p) reaction: ideal substitute for n+A?**

# Towards inverse-kinematics applications with RIBs…
# …the (d,p) reaction



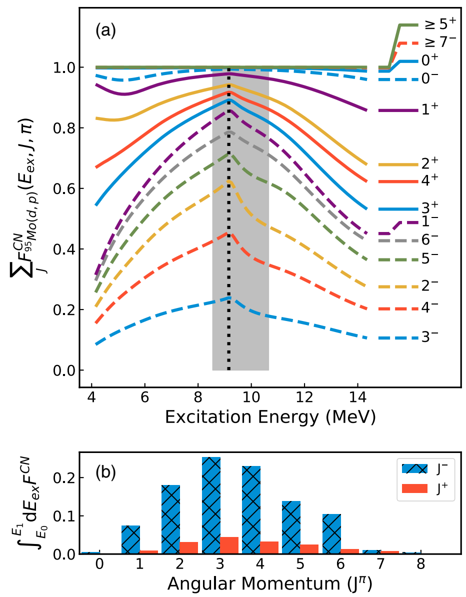

**Inclusive (d,p) reactions recently revisited: formalism**

- Based on earlier work by Udagawa & Tamura and Ichimura, Austern & Vincent
- Goal: describe breakup-fusion, which contains CN formation
- 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

**Applications:**

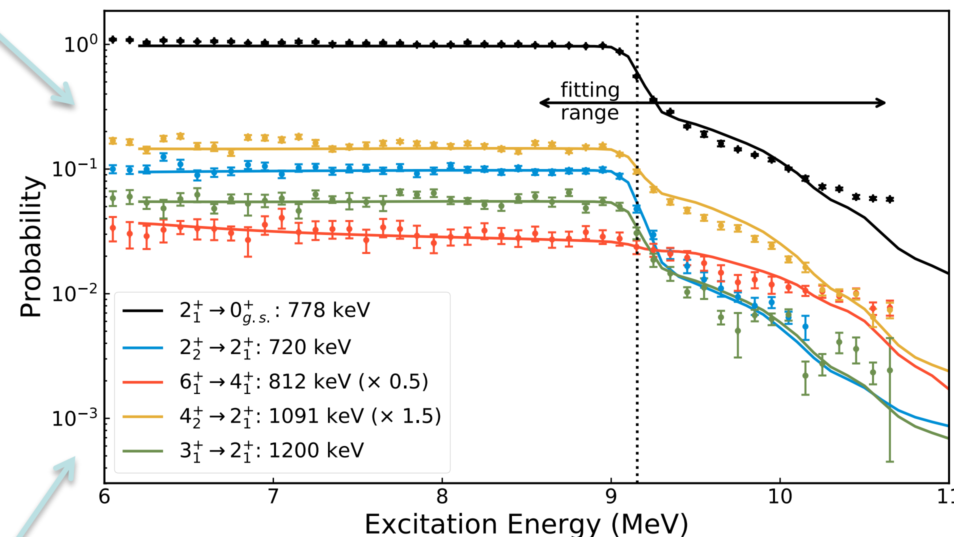
- Comparison to $^{93}$Nb(d,p) inclusive cross sections - Potel et al., PRC 92, 034611 (2015)
- Predictions for $^{40,48,60}$Ca(d,p $\gamma$) – Potel et al., EPJ 53, 178 (2017)
- Application: **Surrogate for $^{95}$Mo(n,$\gamma$)** with Cizewski, Ratkiewicz et al.: Measurements in regular and inverse kinematics, at Texas A&M and ANL, respectively

PHYSICAL REVIEW LETTERS **122,** 052502 (2019)

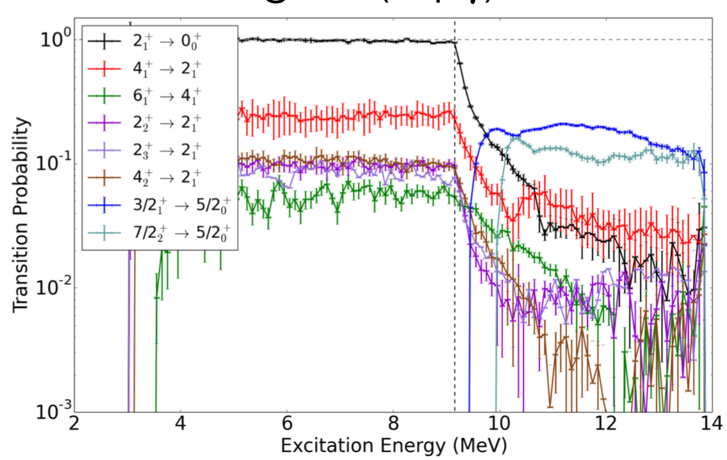



## $^{96}$Mo spin distribution

# The $^{95}$Mo(d,pγ) benchmark

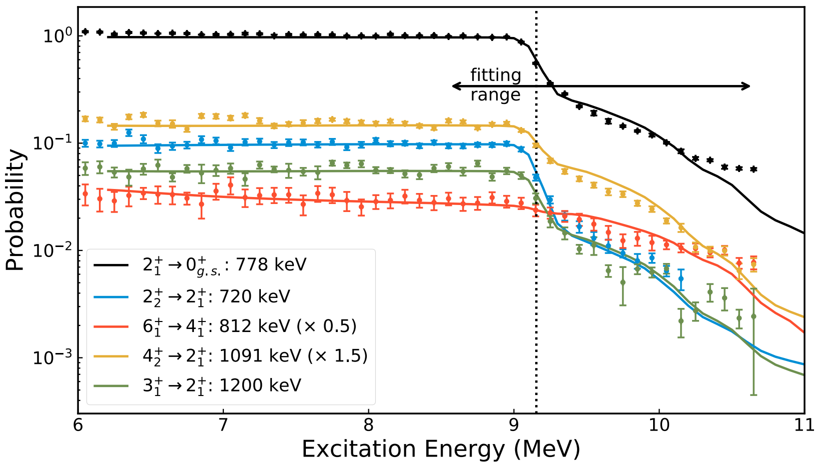


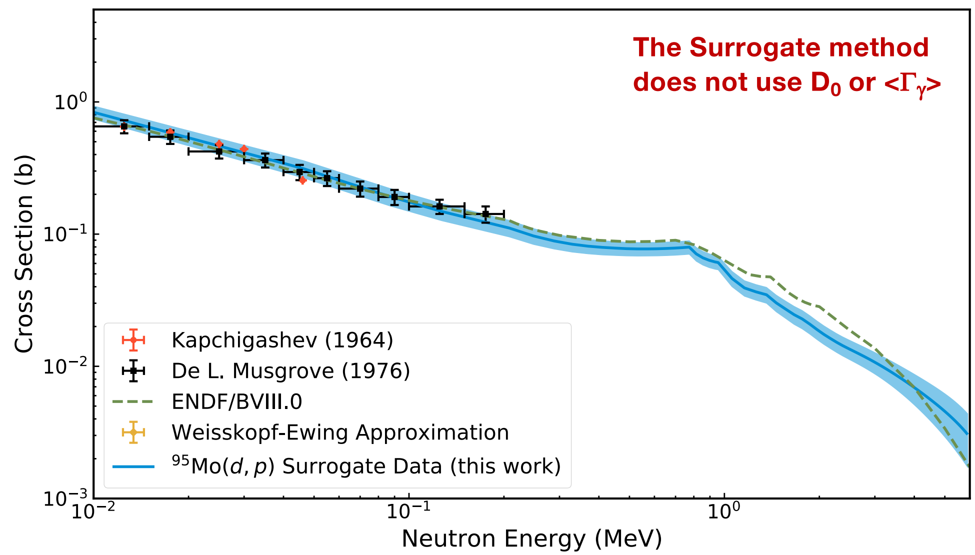

## Surrogate (d,pγ) data




Data by A. Ratkiewicz, J. Cizewski, et al.
Spin distribution calculated by G. Potel

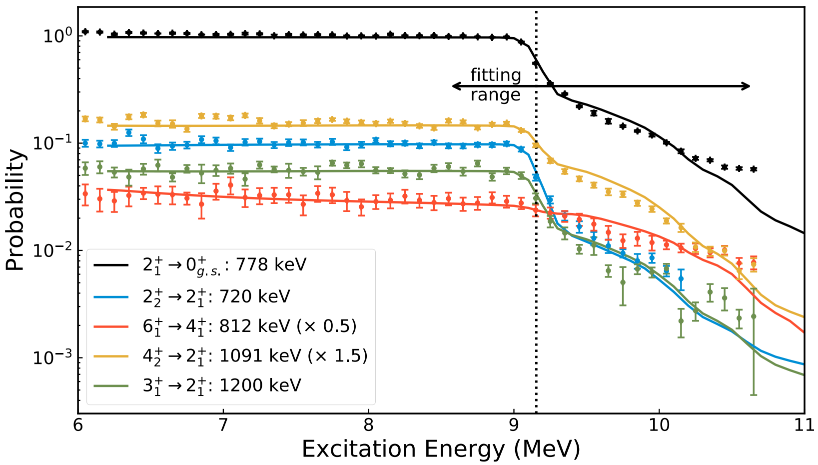
# $^{95}$Mo(n,γ) cross section
# from surrogate (d,pγ) data, reaction theory, and decay modeling

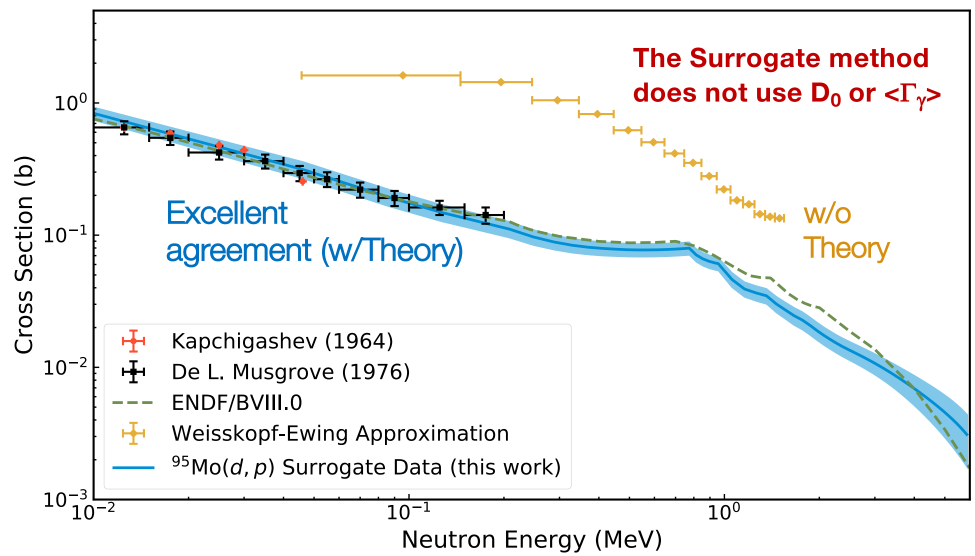



Excellent agreement of cross section with benchmark.
This is encouraging for inverse-kinematics (d,p) measurements.

# $^{95}$Mo(n,γ) cross section
# from surrogate (d,pγ) data, reaction theory, and decay modeling



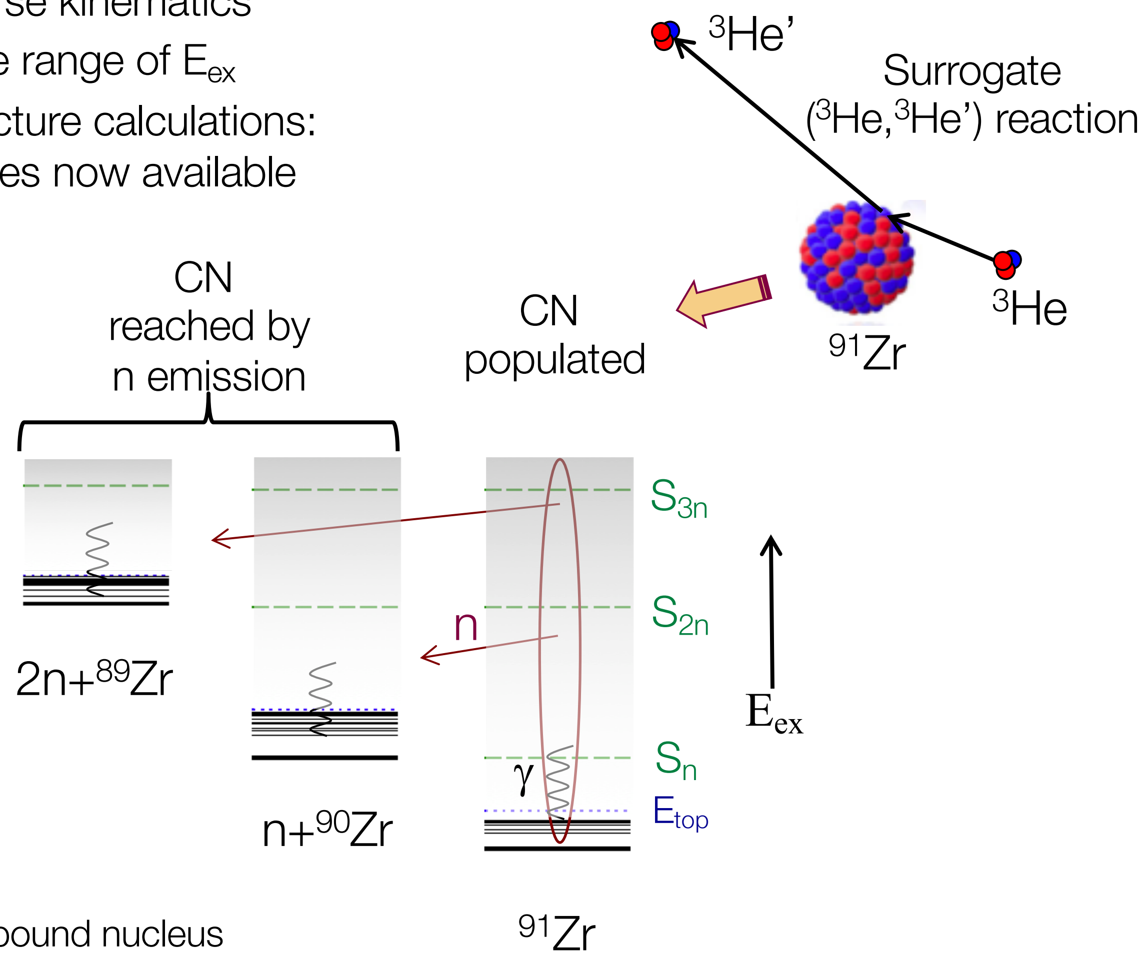




Excellent agreement of cross section with benchmark.
This is encouraging for inverse-kinematics (d,p) measurements.
The theoretical description of (d,p) is critical to obtaining (n,γ).

# Inelastic scattering as a surrogate reaction?
# The $^{90}Zr(n,2n)$ cross section as a first goal

## Inelastic scattering:

- Potentially useful in inverse kinematics
- Reaction populates wide range of $E_{ex}$
- Progress in nuclear structure calculations: (Q)RPA transition densities now available



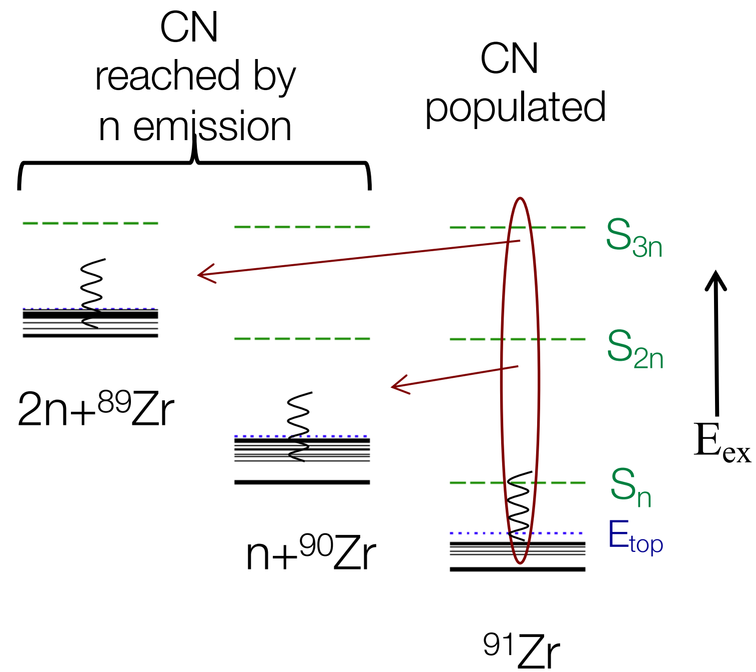

Benchmark case:
Experiment populates compound nucleus in energy range $E_{ex}$ = 0 – 30 MeV

# Using inelastic scattering to determine (n,γ), (n,n'), (n,2n)

Preliminary - Work in progress

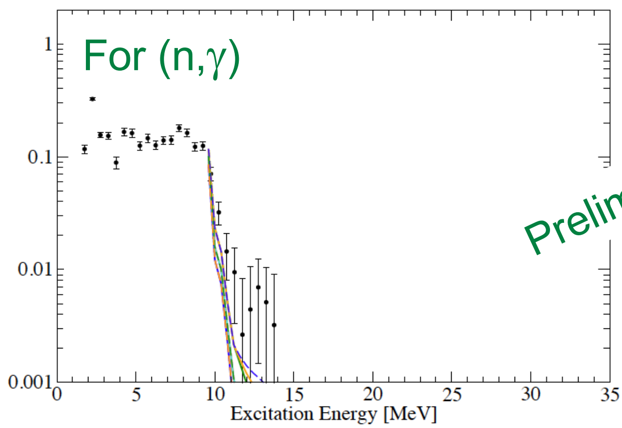
**Experiment at LBNL:**

- $^{90,91,92}$Zr($^3$He,$^3$He') and $^{89}$Y($^3$He,$^3$He')
- Measured by N.D. Scielzo et al
- Goal: determine (n,2n) cross section
- Observed γ-rays in 3 isotopes, corresponding to (n,γ), (n,n'), (n,2n)
- Inelastic scattering calculations using (Q)RPA transition densities
- Decay calculations simultaneously reproduce observed γ



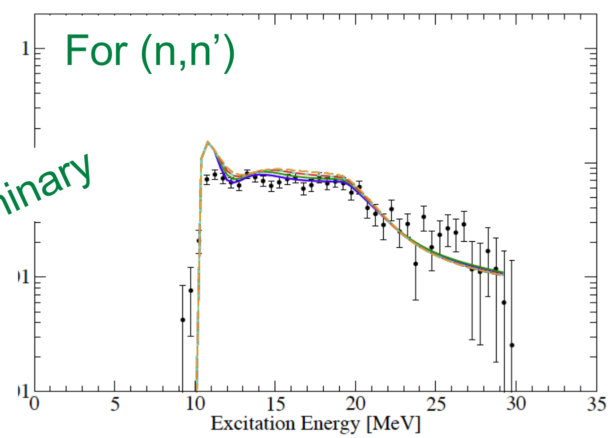

Data from N.D. Scielzo

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

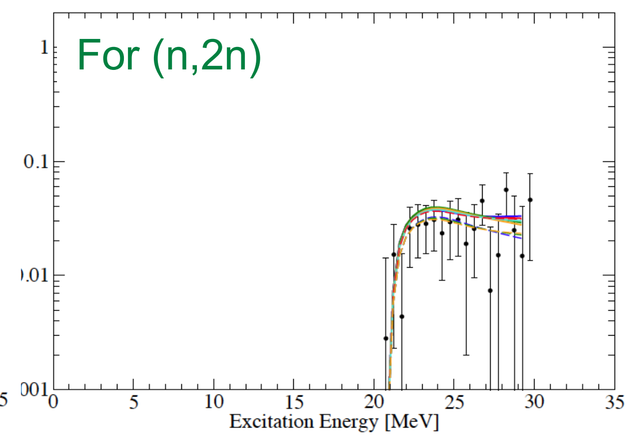



Preliminary

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

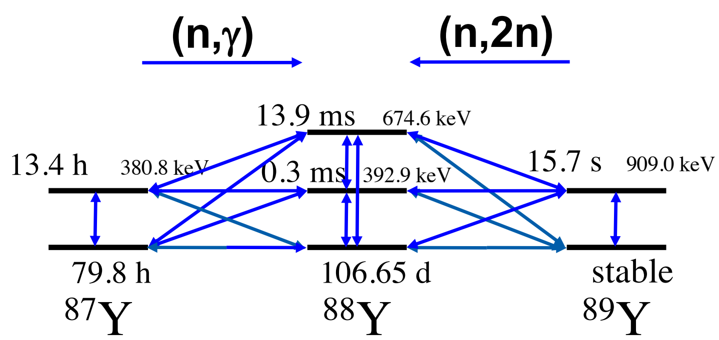



$P_\gamma$(E) for 1512 keV in $^{89}$Zr
Predictions vs. data



# What else can we do with the surrogate reactions approach?

**Another network of reactions:**

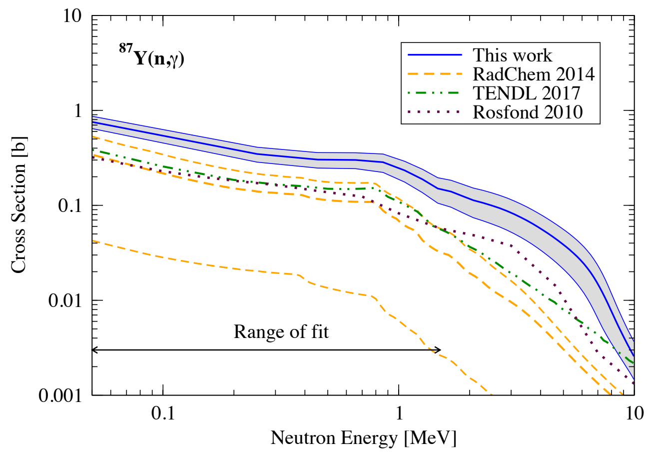


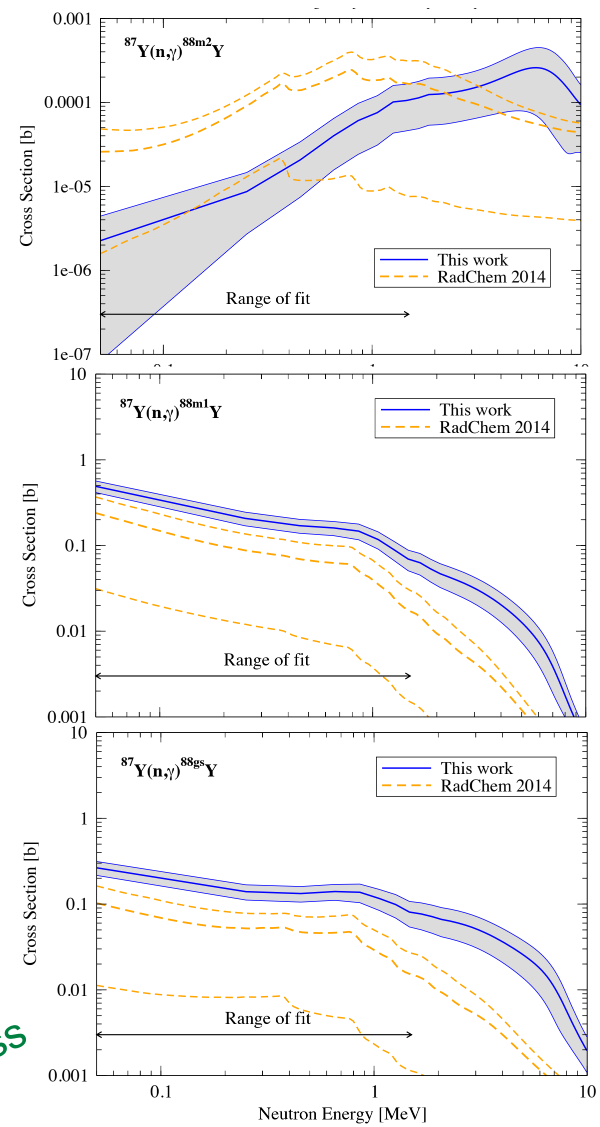

To fully understand the network one needs to have cross sections for reaction of isomers.

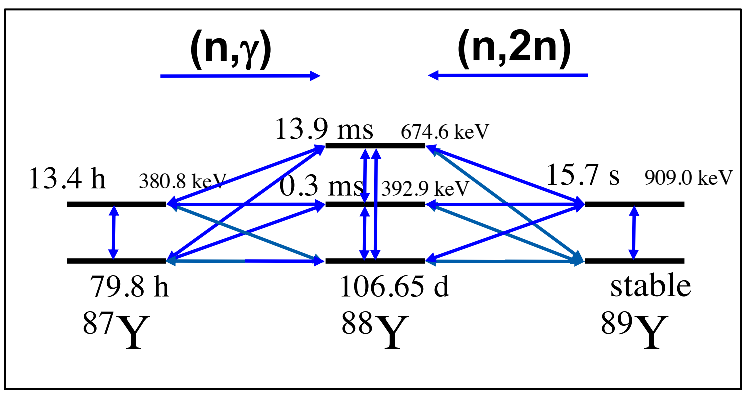
- Can we determine reactions involving isomers?
- Can we determine proton-induced reactions?
- Can we determine fission cross sections?

# We can we determine reactions involving isomers!

$^{87}Y(n,\gamma)$ from $^{89}Y(p,d\gamma)$



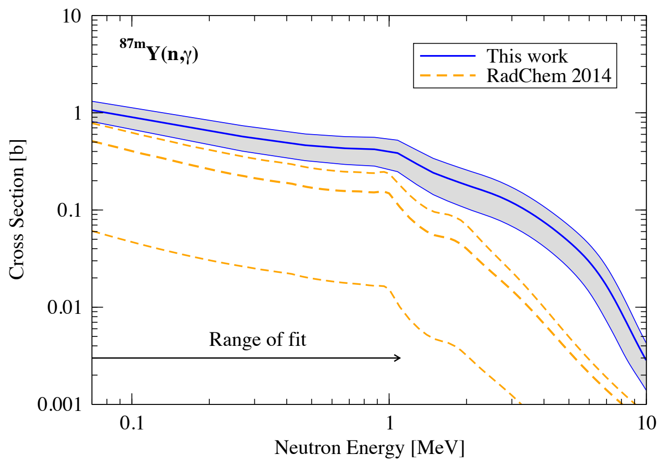



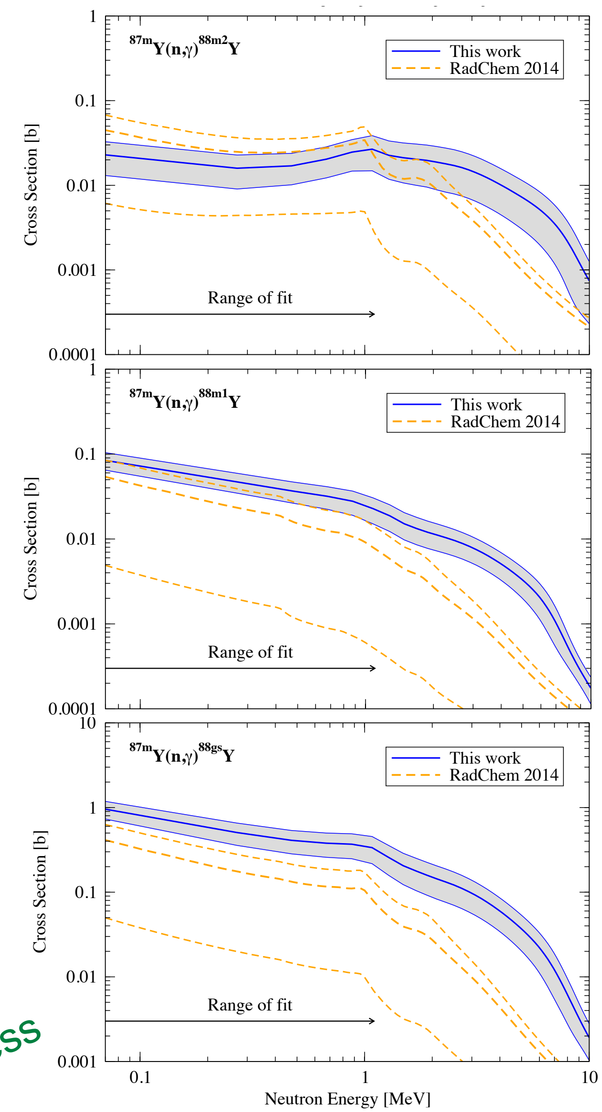

Preliminary -
Work in progress

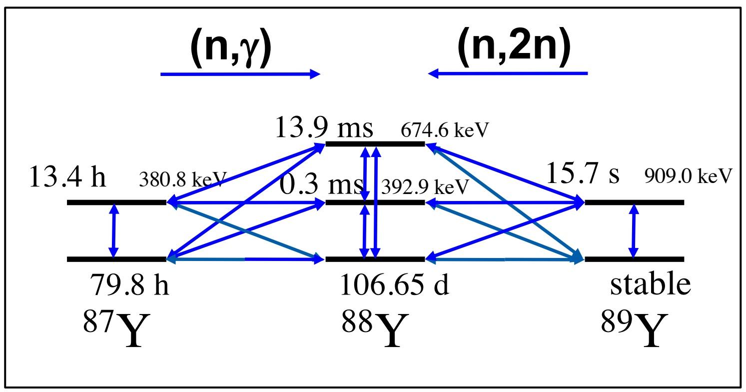
RadChem results from R.D. Hoffman

# We can we determine reactions involving isomers!

$^{87m}Y(n,\gamma)$ from $^{89}Y(p,d\gamma)$



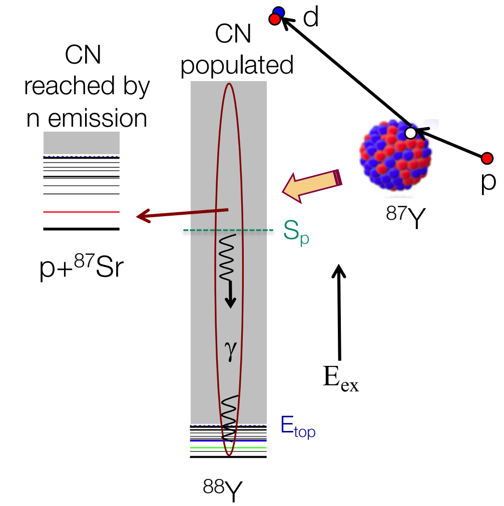




Preliminary - Work in progress

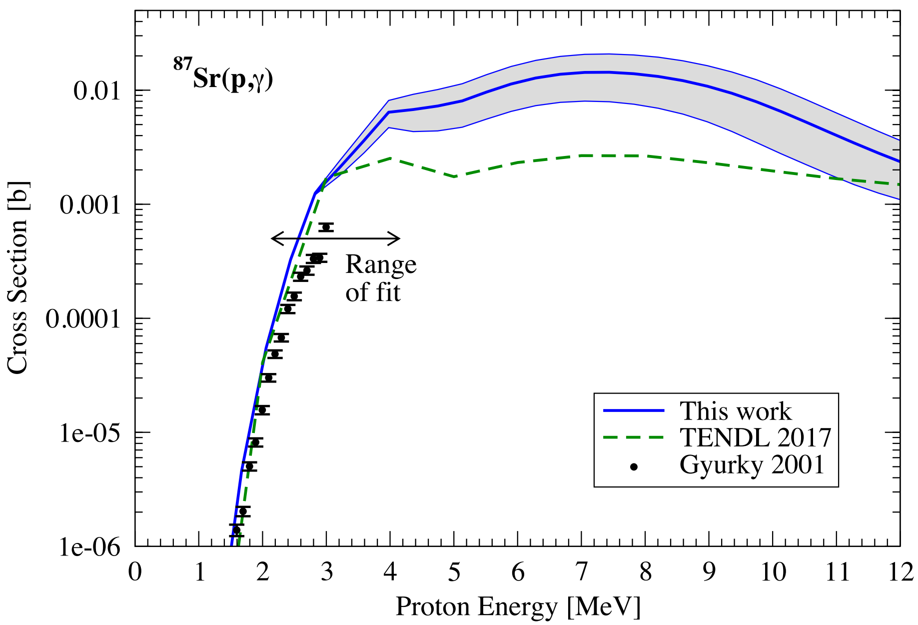
RadChem results from R.D. Hoffman

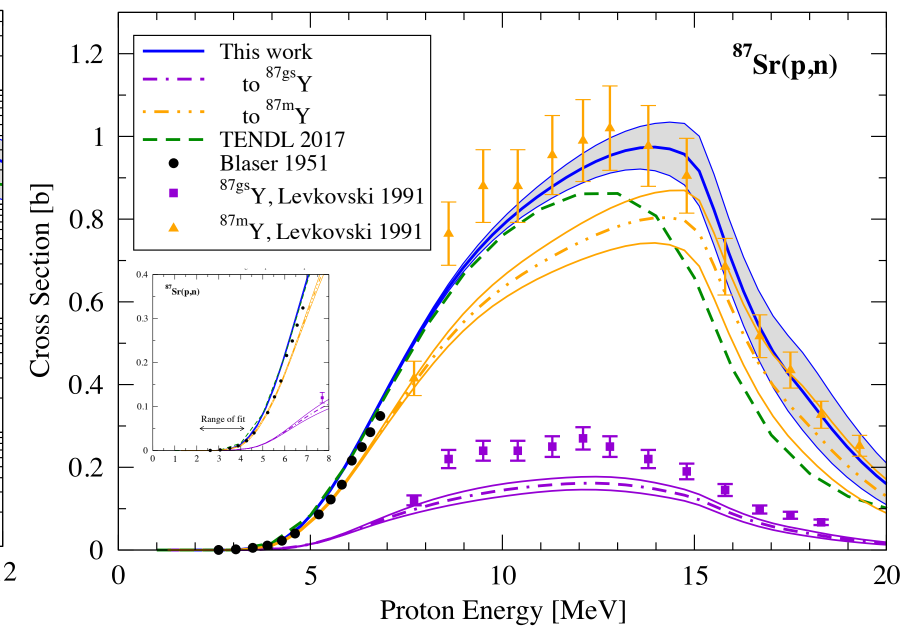
# We can determine cross sections for proton-induced reaction!




Preliminary -
Work in progress

## $^{87}Sr(p,\gamma)$ and $^{87}Sr(p,n)$ from $^{89}Y(p,d\gamma)$



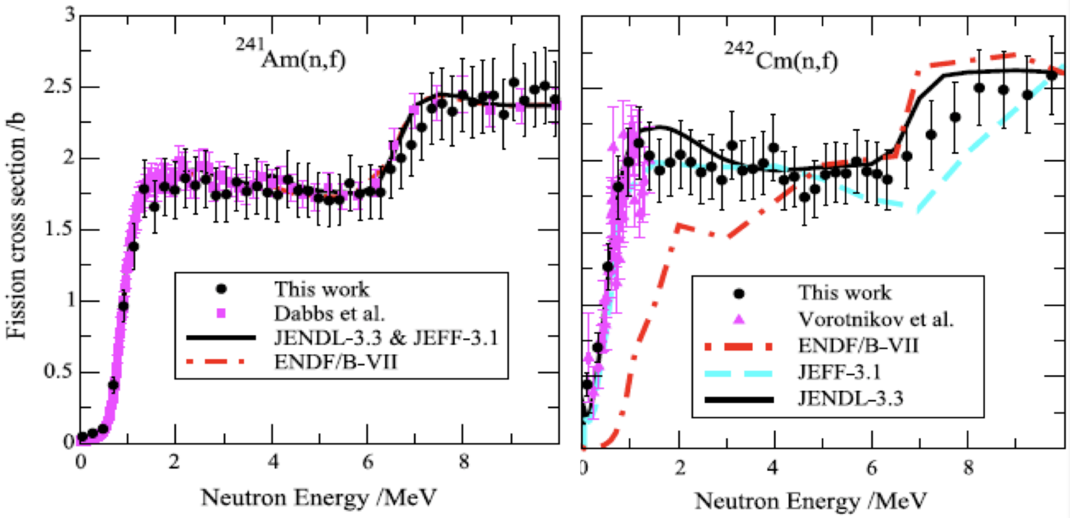

Astrophysically relevant: $E_p$=1.5-3.0 MeV

$S_p(^{88}Y)$=6.71 MeV   $S_n(^{88}Y)$=9.35 MeV

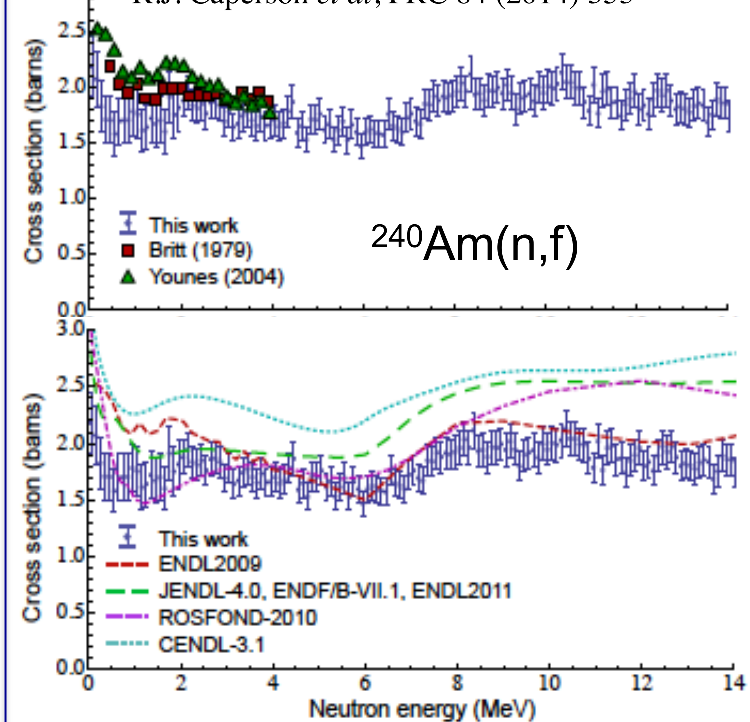
# (n,f) cross sections from surrogate measurements

- Typically agree within 10-15% with benchmarks
- Use Weisskopf-Ewing approximation: ignore spin distribution

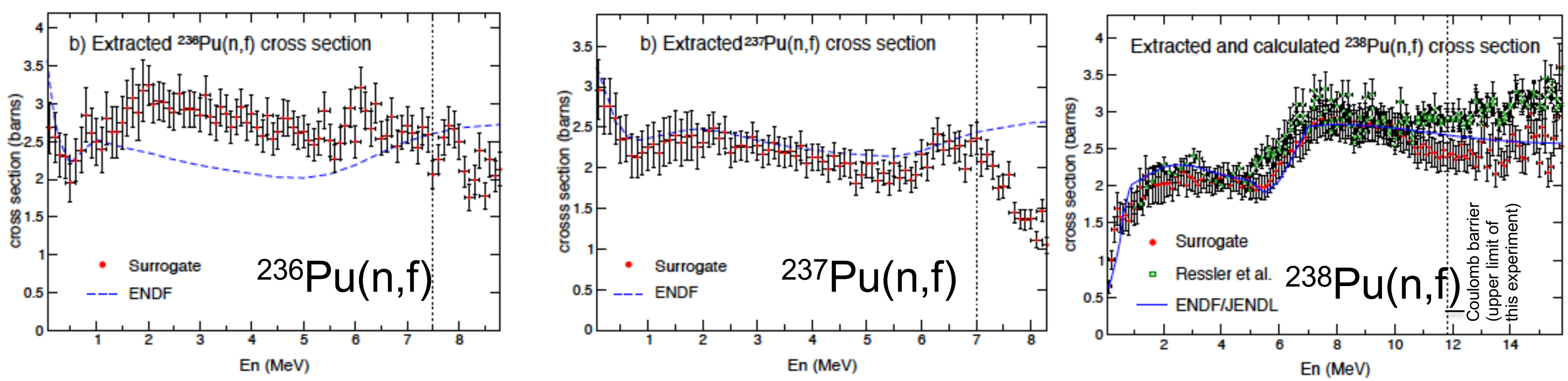
Kessedjian *et al*. (CENBG), PLB 692 (2010) 297




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




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



# Concluding remarks

**General:**

- Cross sections for reactions on unstable isotopes are important & difficult to determine
- Indirect methods are critical & need further development
- Complementary methods are needed to reach large number of isotopes and to cross-check

**Light-ion surrogate reactions:**

- Different target-projectile combinations possible, method can be used at RIB facilities in inverse kinematics
- Method does not use $D_0$ or $<\Gamma_\gamma>$
- Understanding CN formation is important to account for spin-parity mismatch (inelastic scattering, pickup, stripping)
- Concept also applicable to other reactions: (p,$\gamma$), (n,2n), (n,f), reactions involving isomers, etc.

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S. Ota (Texas A&M), J. Cizewski (Rutgers), G. Potel (MSU/FRIB)