Nuclear reaction theory for astrophysics and other applications

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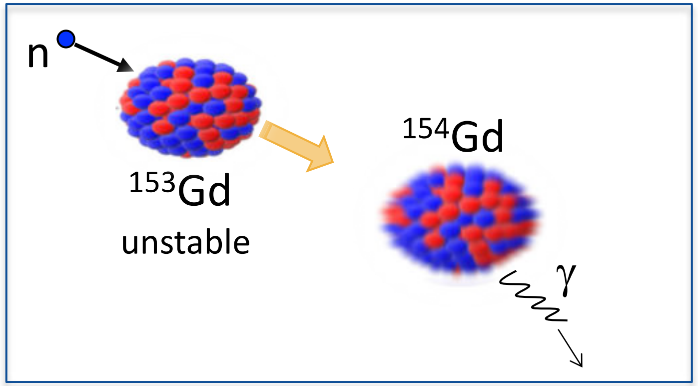
Abstract:

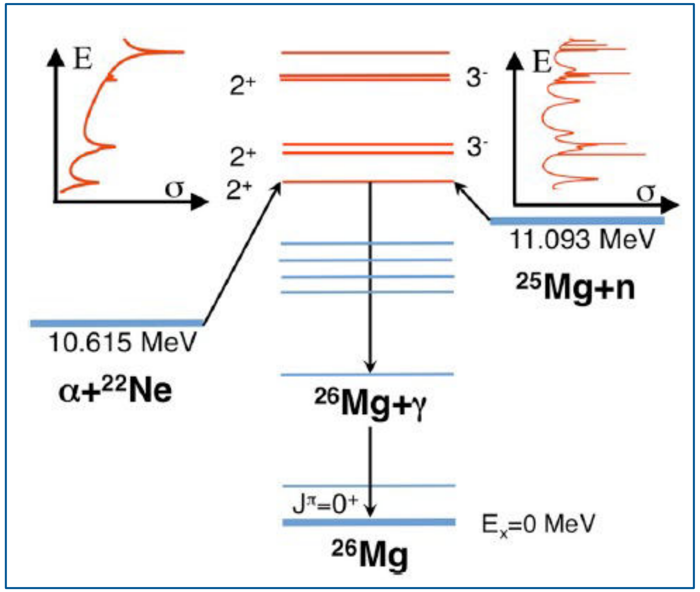
The last decade has seen much progress in the development of theory tools that allow us to achieve more accurate calculations for both direct and compound (statistical) nuclear reactions. Integrated nuclear structure and reaction descriptions provide the basis for making cross-section predictions and enable indirect determination of cross sections that are difficult to measure directly. This is particularly important for applications involving reactions with unstable nuclei, such as astrophysics simulations.

I will discuss recent advances at the intersection of direct and compound-nuclear reactions. I will give examples where progress in theory has enabled indirect (surrogate) measurements of compound-nuclear reactions, including both low-energy neutron capture and other desired reactions. I will also comment on efforts underway to measure reactions in inverse-kinematics experiments at radioactive-beam facilities.

*This work is performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Support from the LDRD Program, Projects 19-ERD-017, 20-ERD-030, 21-LW-032, 22-LW-029, 23-SI-004, and 24-ERD-023 is acknowledged.

Nuclear astrophysics requires information on multiple types of reactions

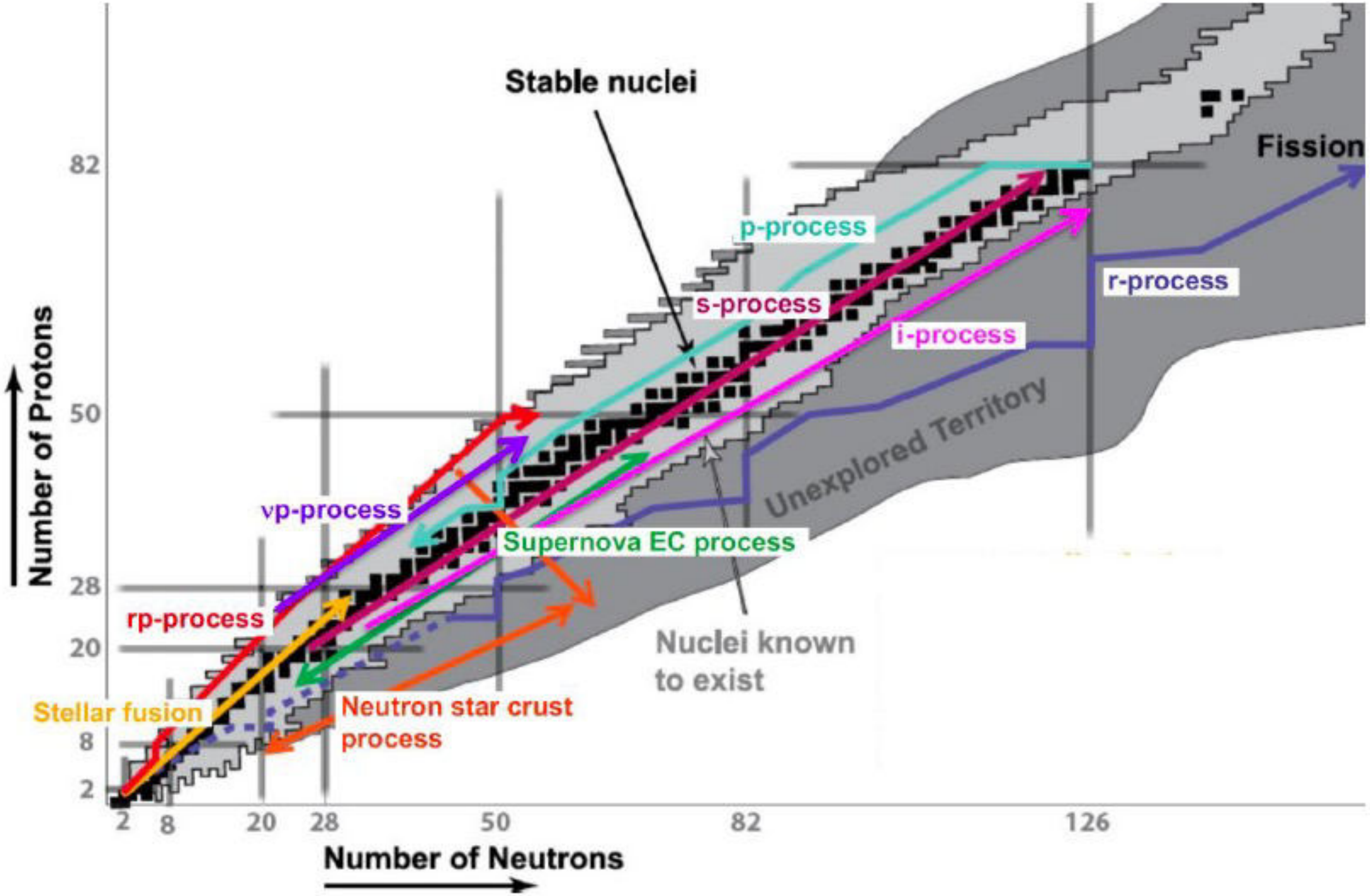




Massimi et al, PLB (2017)

- Many low-energy reactions of interest are compound reactions
  - Cross sections can exhibit resolved resonances
  - Cross sections may be dominated by smooth averages over dense, overlapping resonances
- Direct reactions typically play a smaller role

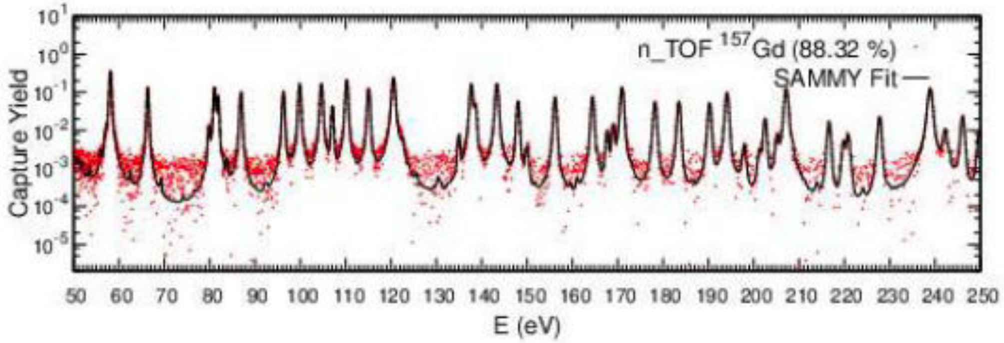
Nuclear astrophysics requires information on multiple types of reactions for a wide range of isotopes



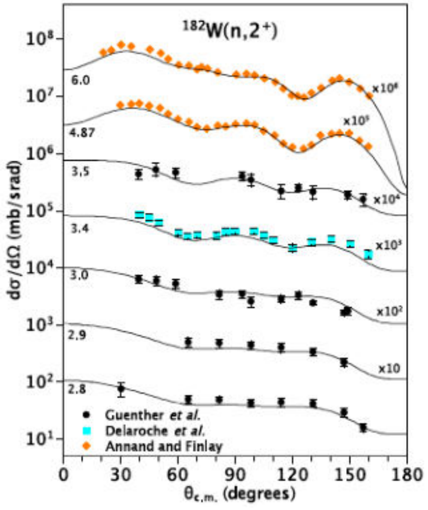
White Paper on Nuclear Structure, Reactions, and Astrophysics

We have robust reaction theories and flexible data evaluation tools to describe a wide variety of reactions

- Multiple reaction mechanism & types
  - Direct, resonance, compound (overlapping resonances)
  - n-induced, charged-particle
  - γ emission, particle emission, fission
- Evaluations
  - Tools: coupled-channels, R-matrix, Hauser-Feshbach codes
  - RIPL-3 parameters
  - Covariances
- Reaction theories
  - Contain simple nuclear structure description
  - Adjust parameters to experimental data

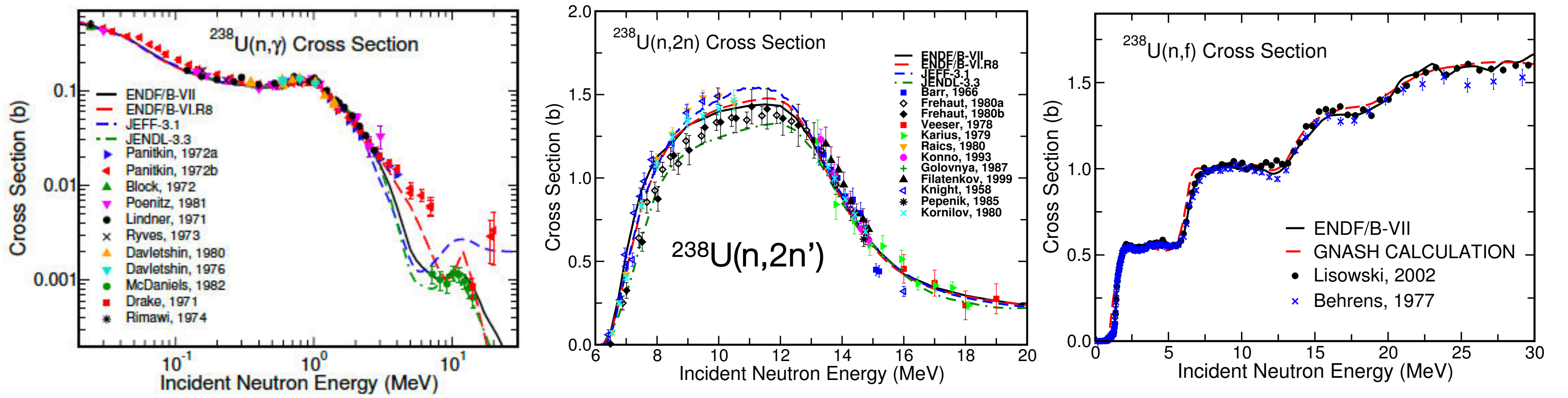


Leal, EPJ Conf 239, 11004 (2020)



Nobre, PRC 91, 024618 (2015)

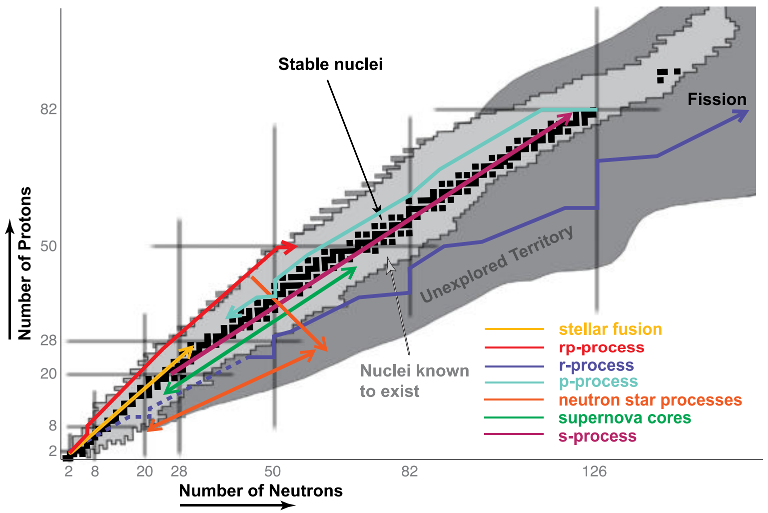
Young et al, NDS 108 (2007) 2589



‘Simple’ descriptions require data to adjust parameters in phenomenological models

‘Simple’ descriptions of reactions have limited predictive power

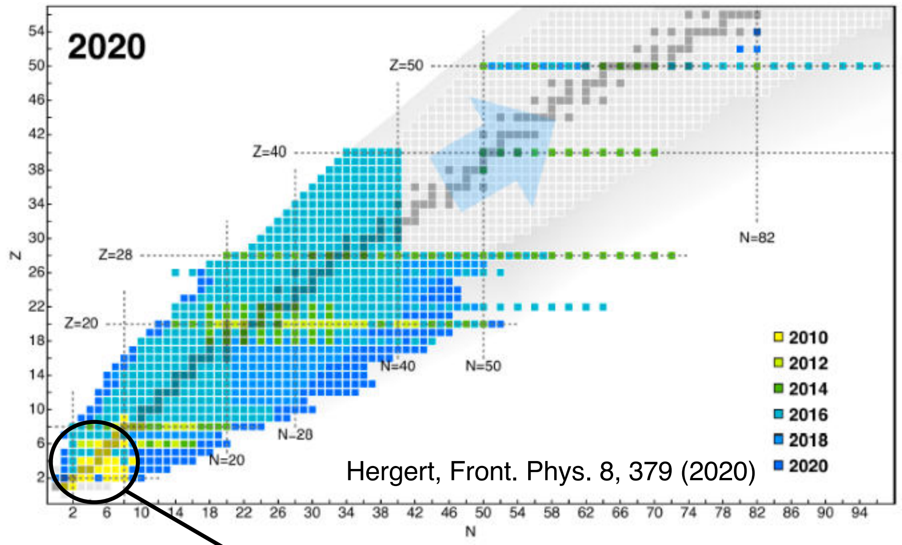
- Challenges:
  - Ambiguous model combinations, large parameter uncertainties, and multiple reaction channels produce large uncertainties in reaction calculations
  - Away from stability, where few/no constraints are known, minor processes may become significant
- Needed – a multipronged approach:
 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



Substantial progress in integrating nuclear structure & reaction theory for light nuclei

Successful ab initio reaction descriptions

- Treat structure and reactions simultaneously (NCSM/RGM approach)
- State-of-the-art NN+3N nuclear interactions
- Computationally challenging
- Restricted to selected area(s) of nuclear chart



Hergert, Front. Phys. 8, 379 (2020)

Resonating Group Method (RGM):

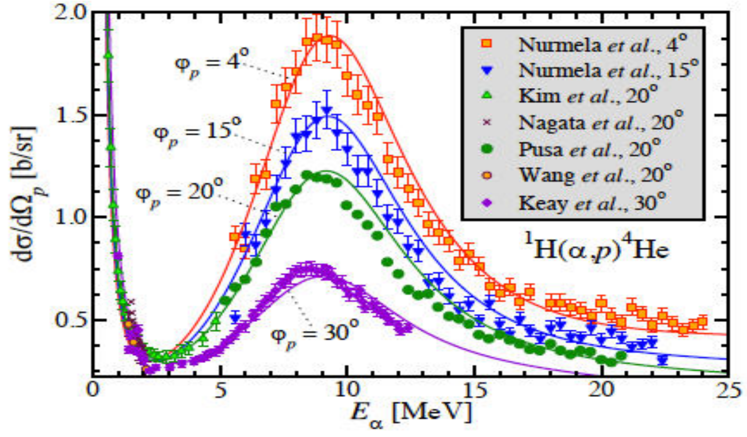
- *Ansatz:*

$$|\Psi\rangle = \sum_{\nu} \int_{r} dr\, r^2 \frac{g_\nu(r)}{r} \hat{A} |\Phi_{\nu r}\rangle$$

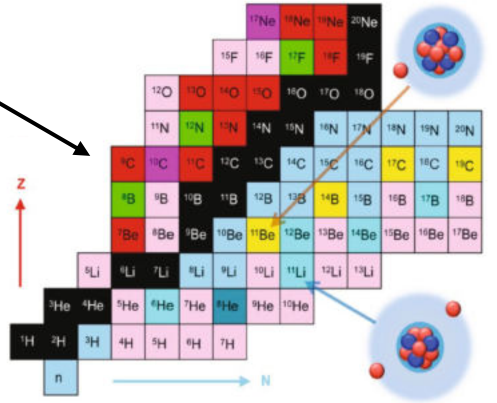
- *Solve Hill-Wheeler eqn to obtain amplitude $g_\nu(r)$:*

$$\sum_{\nu} \int dr\, r^2 \left[H_{\nu'\nu}(r', r) - E N_{\nu'\nu}(r', r) \right] \frac{g_\nu(r)}{r} = 0$$

Johnson et al, J. Phys.G 47, 123001 (2020)



Quaglioni & Navratil, Nucl. Phys. News 30, 12 (2020)


Quaglioni, EPJ 133, 103738 (2018)

Using symmetry-adapted bases to push approach toward medium-mass nuclei

Mercenne, Launey, Dytrych, Escher, et al, CPC 280, 108476 (2022)
Launey, Dytrych, Mercenne, Ann. Rev. Nucl. Part. Sci. 71, 253 (2021)
Dreyfuss, Launey, Escher, Sargsyan, et al., PRC 102, 044608 (2020)

Resonating Group Method (RGM):

- *Ansatz:*

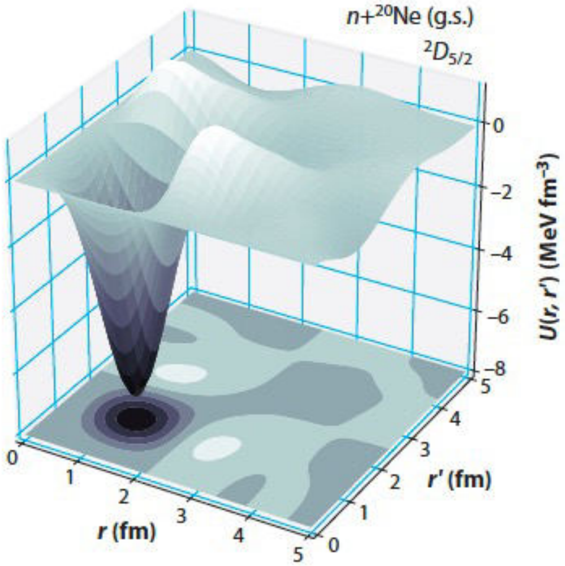
$$|\Psi^{J^\pi M}\rangle = \sum_c \int_r drr^2 \frac{g_c^{J^\pi M}(r)}{r} \mathcal{A}_c |\Phi_{cr}^{J^\pi M}\rangle$$

- *Solve Hill-Wheeler eqn to obtain amplitude $g_\nu(r)$:*

$$\sum_c \int drr^2 \left[H_{c'c}(r',r) - EN_{c'c}(r',r)\right] \frac{g_c^{J^\pi M}(r)}{r} = 0.$$

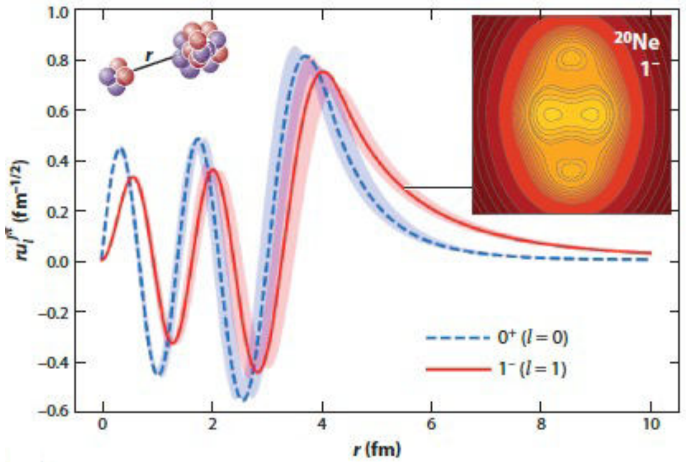
- Norm and potential kernels expressed in terms of SU(3) re-coupling coefficients and one-body (and two-body) density matrix elements
- Advantages:
  - Triple-reduced matrix elements
  - Block-diagonal norm kernel
  - Proton-neutron formalism

Initial steps for calculating phase shifts and N+A scattering



Non-local potential kernel

Overlaps for α-induced reactions



α+^{16}O l=0 and 1 relative wave functions (ab initio SA-NCSM)

Initial results are promising. More development needed to predict reactions like $^{22}Ne(\alpha,n)^{25}Mg$

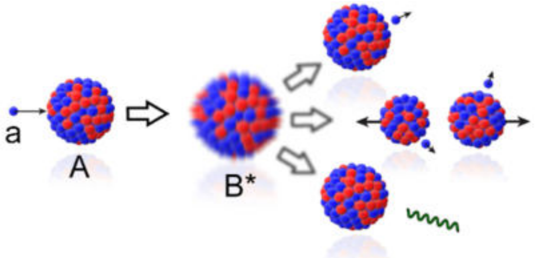
What about reaction theory for medium-mass and heavy nuclei?

Direct reactions

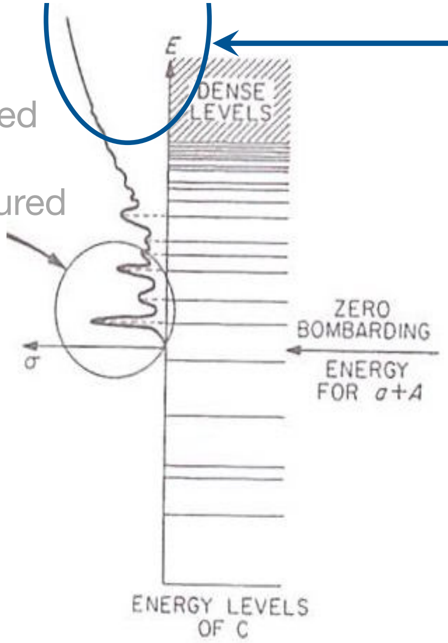
- Reduction to few-body problems with effective interactions
- Mechanisms: transfer, inelastic scattering, breakup
- Higher-order processes: multi-step, coupled-channels, breakup-fusion,...
- Efforts underway to integrate nuclear-structure descriptions

Compound-nuclear (CN) reactions

- R-matrix theory describes CN reactions through isolated resonances
- Hauser-Feshbach (HF) theory describes CN reactions that can be statistically averaged
- Both are essential for nuclear data evaluations and calculating astrophysical reaction rates



R-matrix regime
- Assumes isolated resonances
- Requires measured data or fully microscopic calculation



Hauser-Feshbach regime
- Assumes strongly overlapping resonances
- Requires structure models and parameters

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

*WFC omitted here to simplify notation.

Hauser-Feshbach calculations

- Inputs needed:
  - Optical-model potentials
  - Level densities (LDs)
  - γ-ray strength functions (γSF)
  - Constraints: D_0, $<\Gamma_\gamma>$, cross section data
- Challenges:
  - Ambiguous model combinations, large parameter uncertainties, and multiple reaction channels
  - Uncertainty quantification
  - Away from stability there are few/no known constraints

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

Formation of CN

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

Width fluctuation corrections

Probability for decay of CN

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

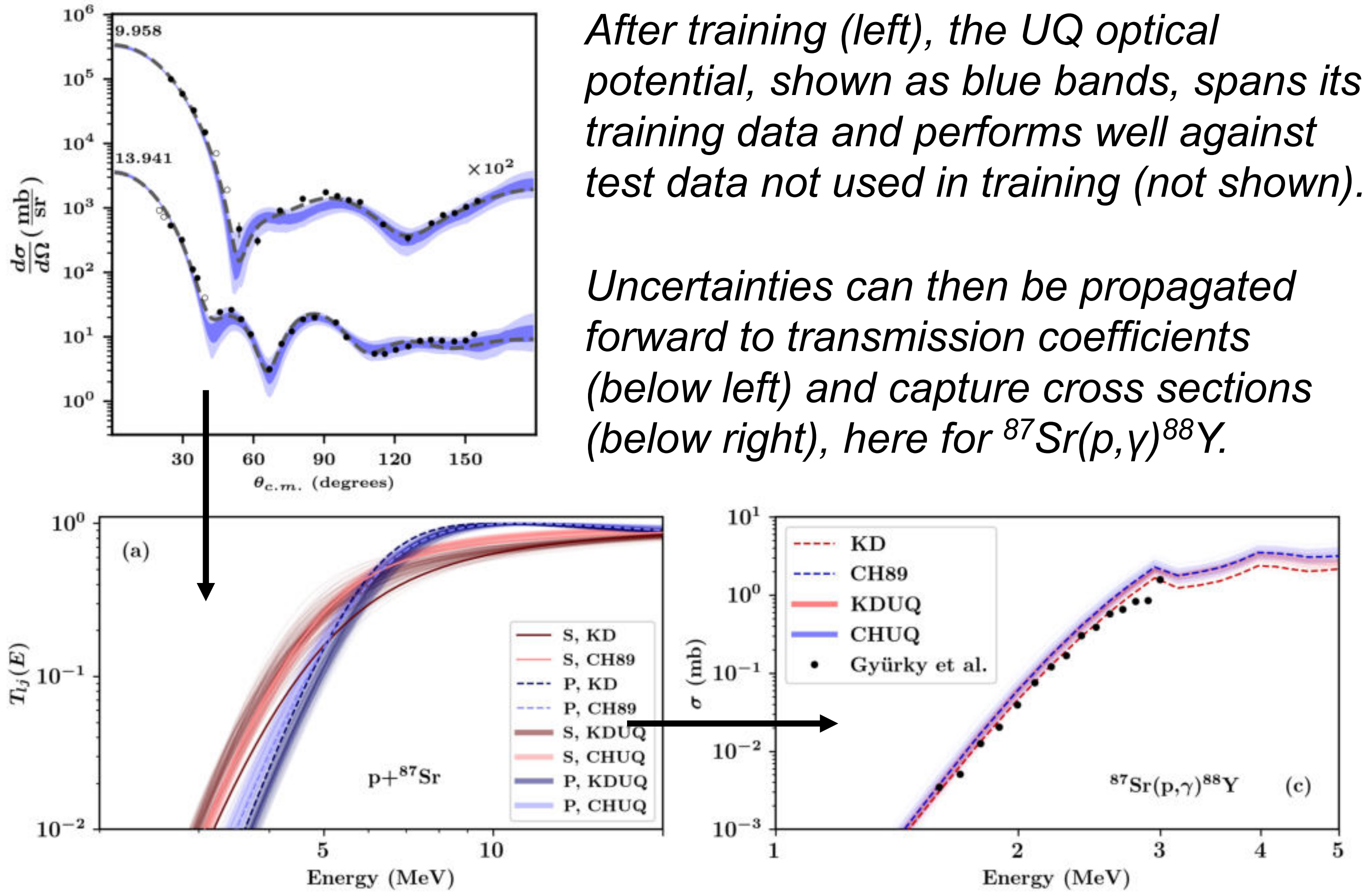
Uncertainty-Quantified (UQ) Optical Potentials for isotopes near stability: KDUQ and CHUQ

Pruitt, Escher, Rahman, PRC 107, 014602 (2023)

- We developed *well-calibrated uncertainties* for two widely used optical potentials
- Advances include *outlier identification*, assessment of *unaccounted-for uncertainty*
- We can now pinpoint how optical-potential uncertainties impact compound (low-energy) and direct (higher energy) reactions within a self-consistent framework
- Parameters provided with uncertainty ranges and as posterior collection - see PRC supplement.

After training (left), the UQ optical potential, shown as blue bands, spans its training data and performs well against test data not used in training (not shown).

Uncertainties can then be propagated forward to transmission coefficients (below left) and capture cross sections (below right), here for $^{87}Sr(p,\gamma)^{88}Y$.



A global phenomenological dispersive OMP is under development.
Dispersive OMPs connect to bound-state properties - which helps address the lack of data for exotic nuclei.

Optical-Model Potentials

- Expected influx of data for reactions on unstable isotopes from FRIB requires developing new OMPs for neutron-rich isotopes, including fission fragments.
- The status of OMPs was reviewed at a Topical Program at FRIB and findings were published in a review paper:
  C. Hebborn *et al*, "Optical potentials for the rare-isotope beam area," J. Phys. G. 50, 060501 (2023).
  https://arxiv.org/abs/2210.07293
- The publication discusses state-of-the-art potentials, identifies shortcomings, and charts a path for future theoretical and experimental work.

	Mass	Energy	D.	Mic.	UQ
KD	$24 \leq A \leq 209$	$1\ \mathrm{keV} \leq E \leq 200\ \mathrm{MeV}$	✗	✗	✗
KDUQ	$24 \leq A \leq 209$	$1\ \mathrm{keV} \leq E \leq 200\ \mathrm{MeV}$	✗	✗	✓
DOM (STL)	C, O, Ca, Ni, Sn, Pb isotopes	$-\infty < E < 200\ \mathrm{MeV}$	✓	✗	✓
MR	$12 < Z < 83$	$E < 200\ \mathrm{MeV}$	✓	✗	✗
MBR	$12 < Z < 83$	$E < 200\ \mathrm{MeV}$	✓	✗	✗
NSM	^{40}Ca, ^{48}Ca, ^{208}Pb	$E < 40\ \mathrm{MeV}$	✓	✓	✗
SCGF	O, Ca, Ni isotopes	$E < 100\ \mathrm{MeV}$	✓	✓	✗
MST-B	$A \leq 20$	$E \gtrsim 70\ \mathrm{MeV}$	✗	✓	✗
MST-V	$4 \leq A \leq 16$	$E \gtrsim 60\ \mathrm{MeV}$	✗	✓	✗
WLH	$12 \leq A \leq 242$	$0 \leq E \leq 150\ \mathrm{MeV}$	✗	✓	✓
JLMB	$A > 30$	$1\ \mathrm{keV} < E < 340\ \mathrm{MeV}$	✗	✓	✗

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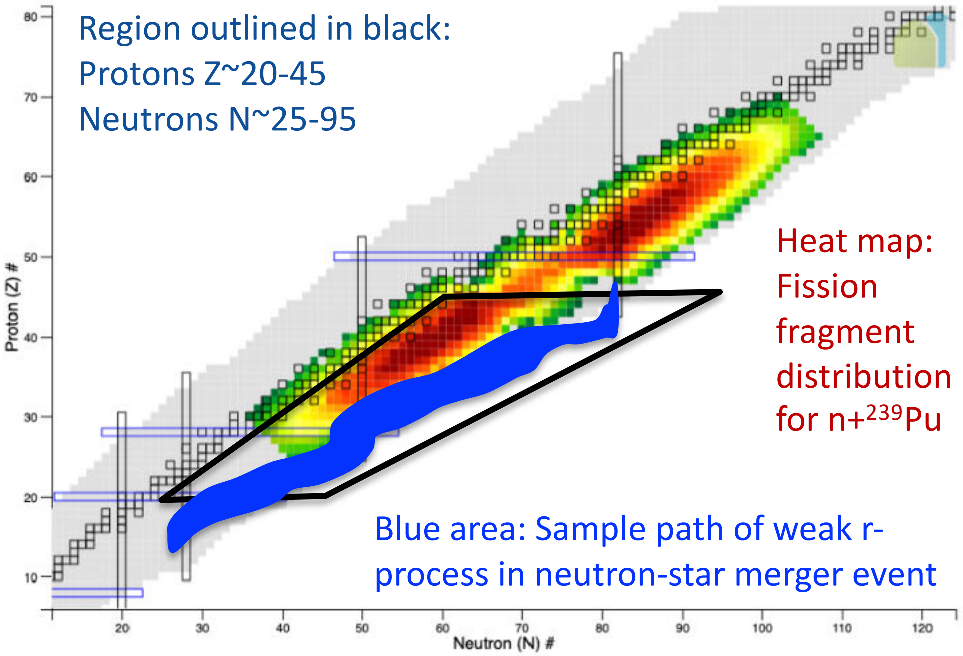
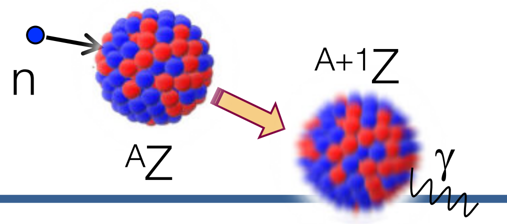
Escher, Kravvaris, Potel, Pruitt, Berryman, Gorton (wip)

- Opportunity: Advances in nuclear theory place region of the weak r-process (light fission fragments) within striking distance

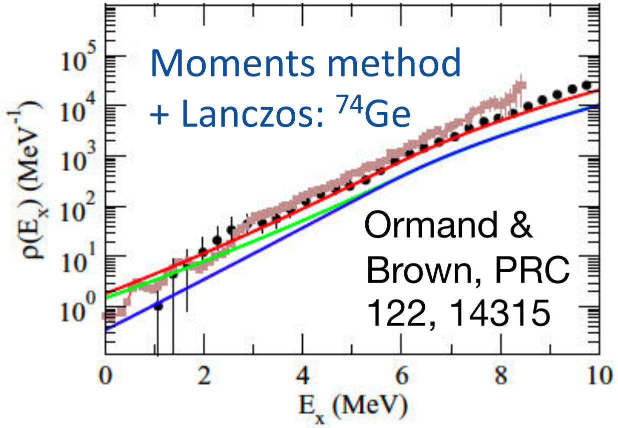
- Goal: Develop capability to predict neutron capture reactions for weak r-process isotopes
  - Systematically replace 3 key ingredients by newly-developed quantities: LDs, gSFs, optical model
  - Develop optical model (*aka* effective nucleon-nucleus interaction) for weak r-process region
  - Perform statistical reaction calculations with YAHFC and provide capture rates with UQ
  - Benchmark calculations and assess uncertainties (UQ)



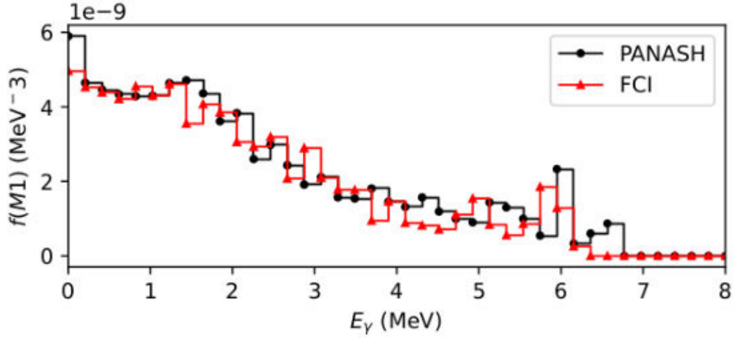
Extending nuclear shell model to predict static properties of relevant nuclei



- The shell model provides a microscopic predictions for LDs and γSFs
- Smart truncations and modern computers increase reach of shell model
- Innovative combination of moments method with Lanczos algorithm enable new LD calculations
- Shell-model advantages:
  - Includes important correlations
  - Yields total and partial level densities
  - Gives low-energy γSF
  - Provides insights into structure
- Challenges:
  - Model space sizes for very heavy nuclei
  - Interactions needed



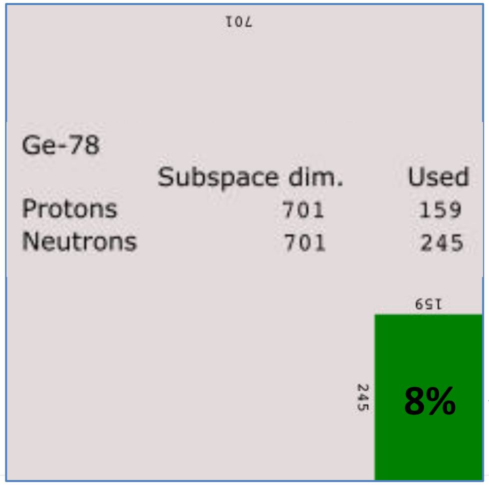
Gamma strength function (γSF, M1) well-reproduced in truncated basis: ^{78}Ge

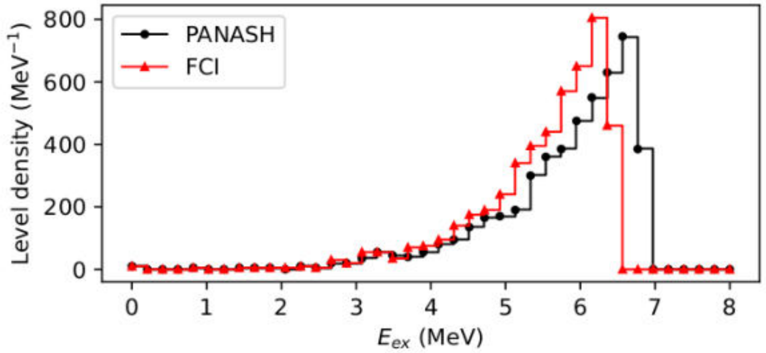


Panash truncation scheme is promising

Level density (LD) is approximated in same truncated basis : ^{78}Ge

Gorton, Johnson, Escher, EPJ Web. Conf. 284, 03013 (2023)





Smart truncation
to small fraction of FCI model space

Hauser-Feshbach calculations

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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:

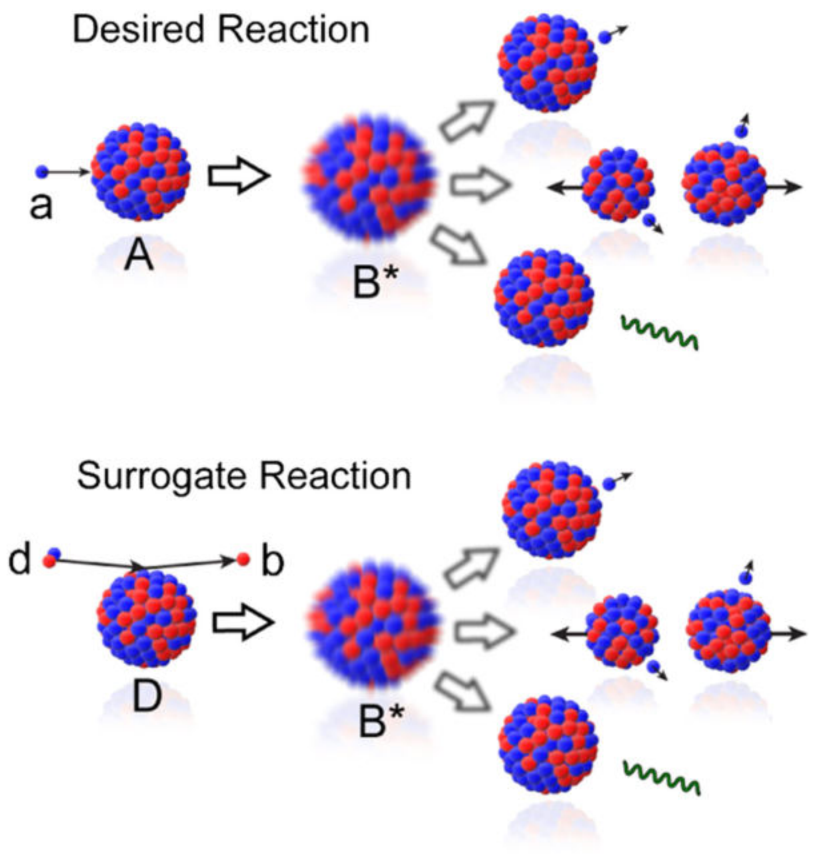
- Starts with a ‘direct’ reaction to produce a ‘doorway state’ at E_{ex} > several MeV
- Doorway evolves into a CN
- Spin distribution of doorway state = spin distribution of the CN

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:

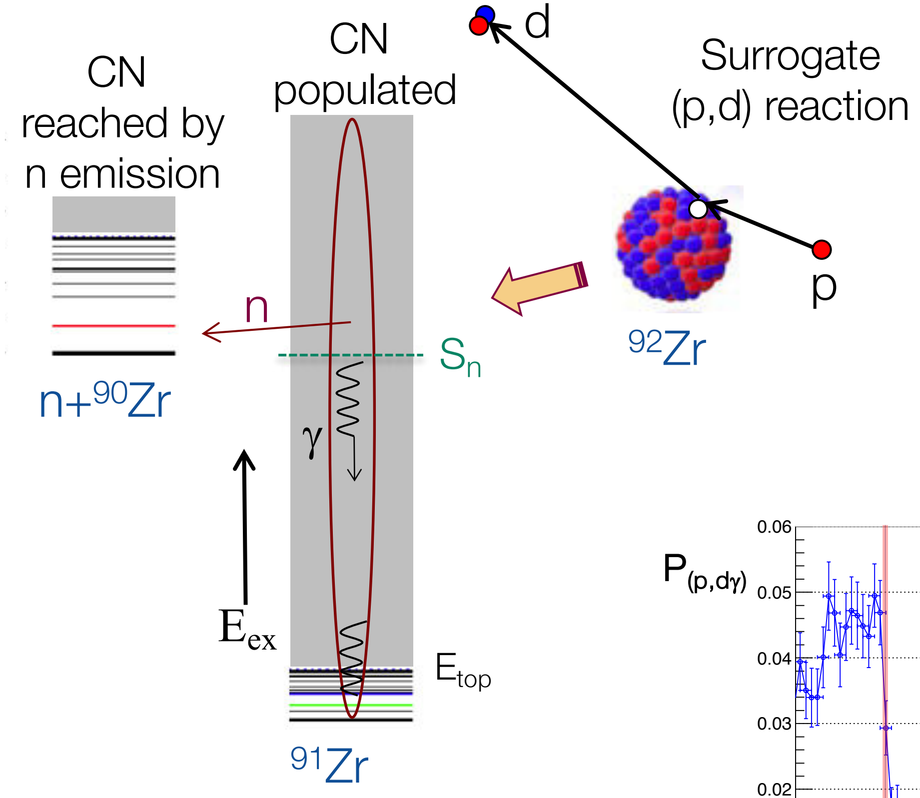
- Calculate desired reaction cross section using inferred parameters

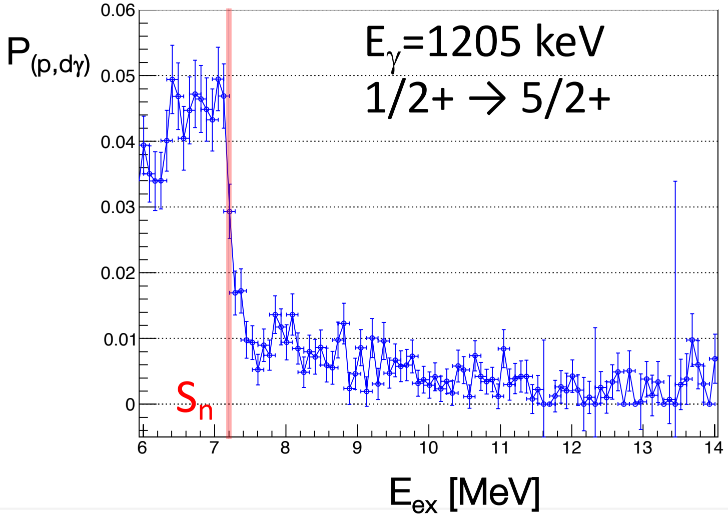


- Concept
- **(p,d) as a surrogate reaction mechanism**
- (d,p) as a surrogate reaction mechanism
- Inelastic scattering as a surrogate reaction mechanism

Surrogate reactions method for neutron capture

Escher et al, PRL 121, 052501 (2018)





From theory

To be determined

A Surrogate experiment gives

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

$^{90}Zr(n,\gamma)$ cross section:

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

From experiment

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

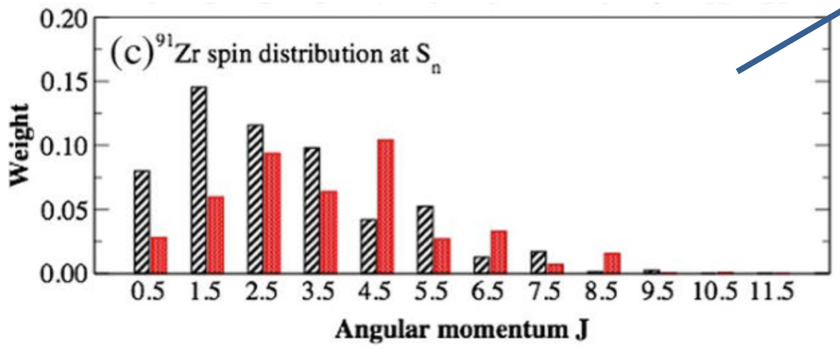
Escher et al, PRL 121, 052501 (2018)

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 distribution from direct-reaction theory



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Escher et al, PRL 121, 052501 (2018)

Coincidence probabilities from surrogate experiment

Surrogate coincidence probabilities

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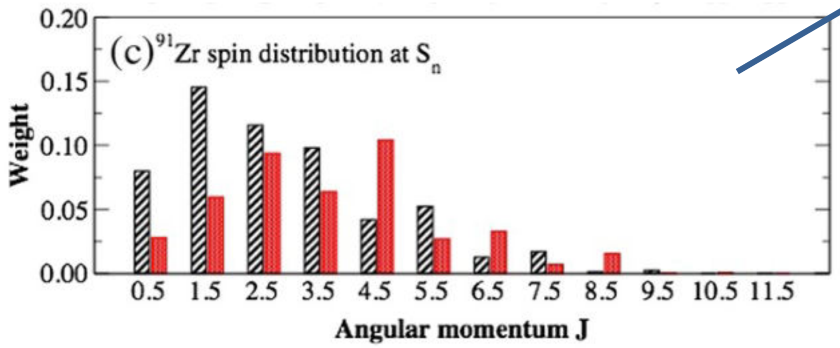
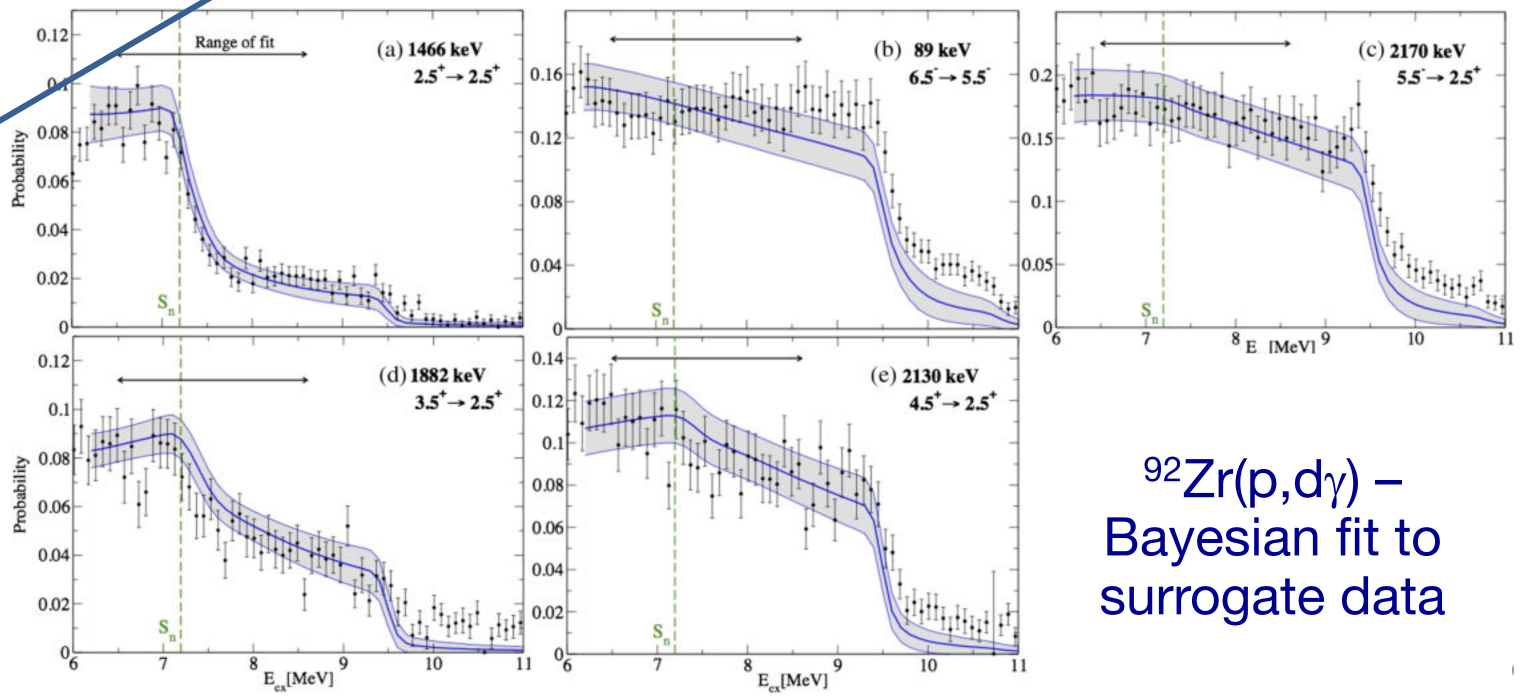
Spin-parity distribution from direct-reaction theory



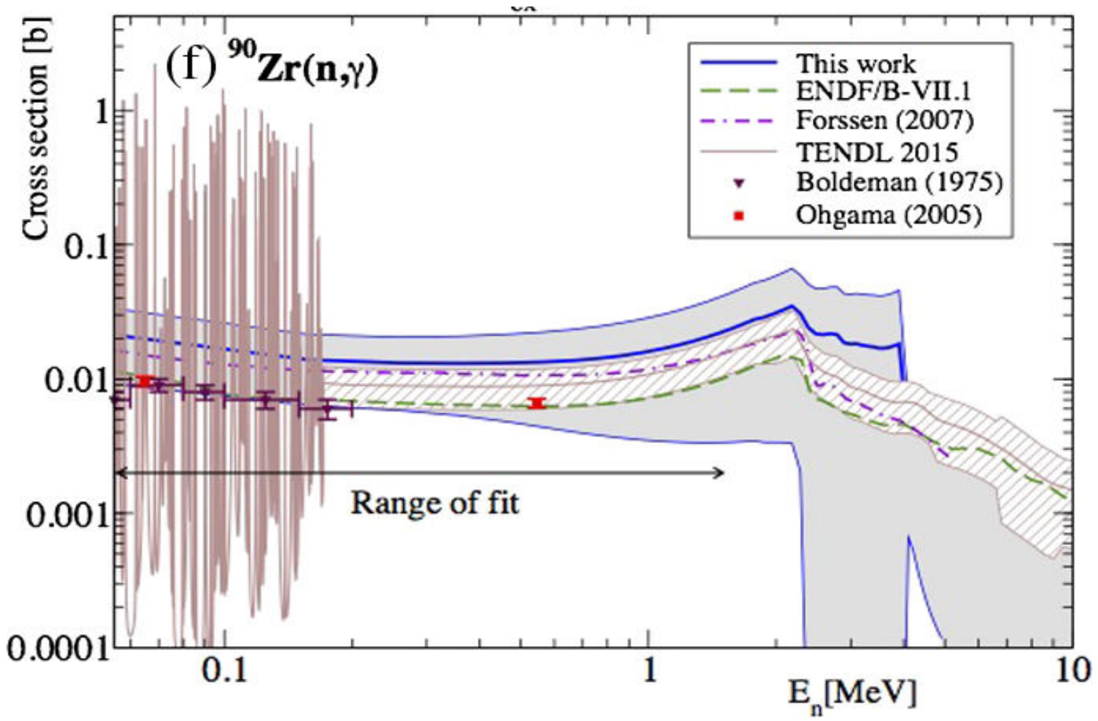
PHYSICAL REVIEW LETTERS **121,** 052501 (2018)



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

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

Escher et al, PRL 121, 052501 (2018)



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

Procedure

- ➢ Measure the surrogate reaction coincidence probability
- ➢ Calculate the spin-parity distribution 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

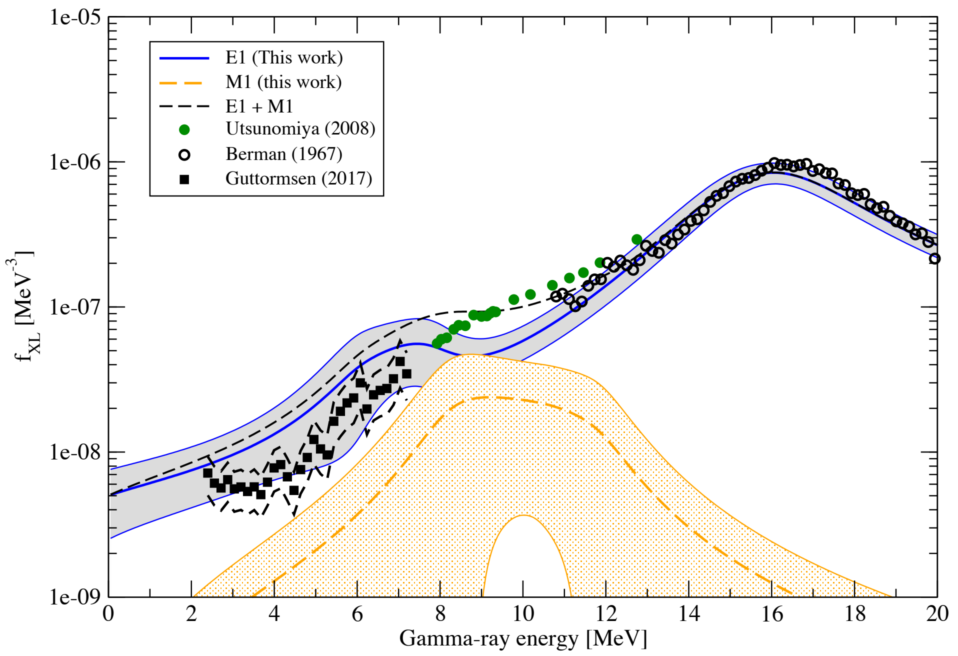
The surrogate reactions method also yields experimentally-constrained level densities and γ-ray strength functions

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

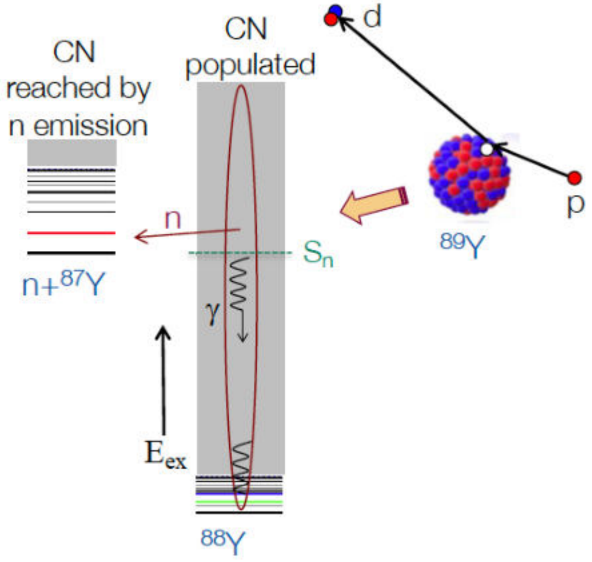


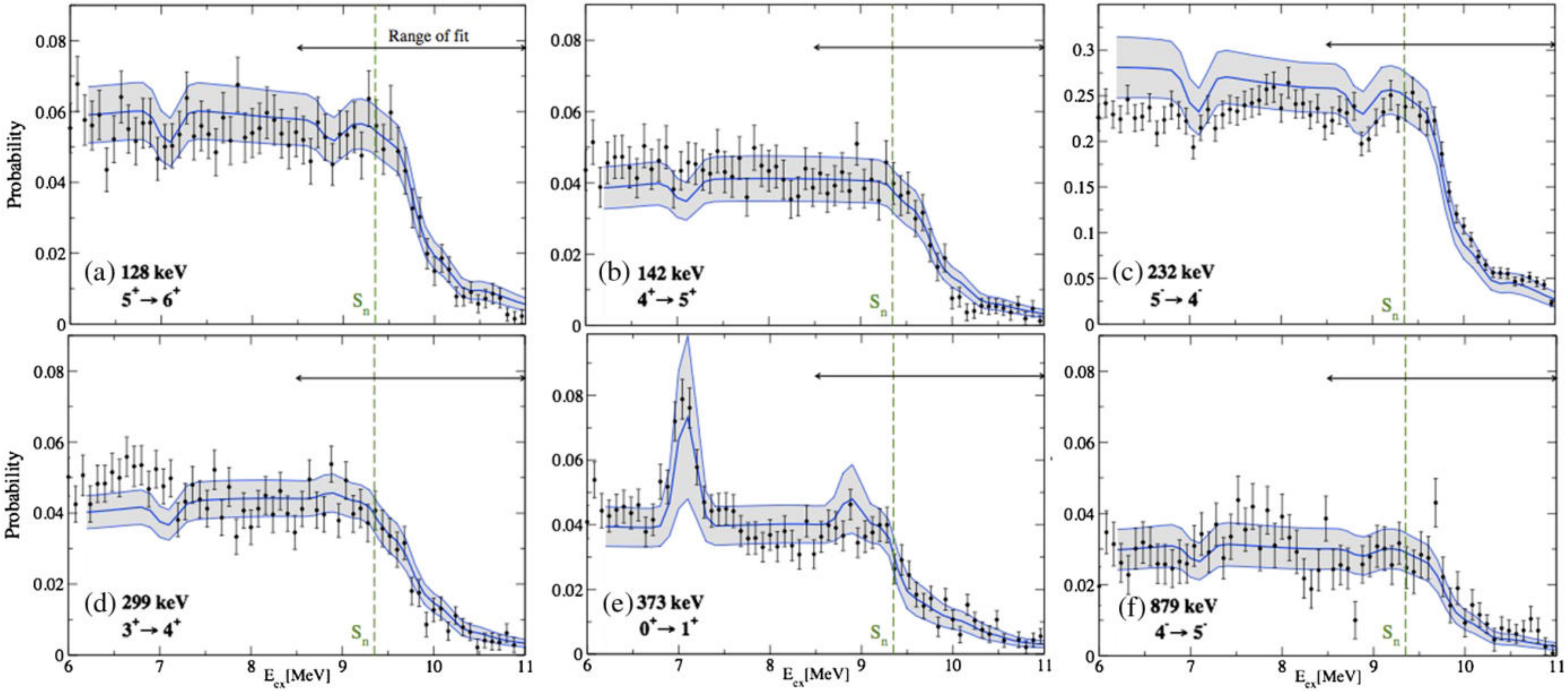
Oslo data from:
Guttormsen et al, PRC 96, 024313 (2017)

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

Application to neutron capture on unstable target: ^{87}Y(n,γ) cross sections from ^{89}Y(p,dγ) surrogate reaction data

Escher et al, PRL 121, 052501 (2018)



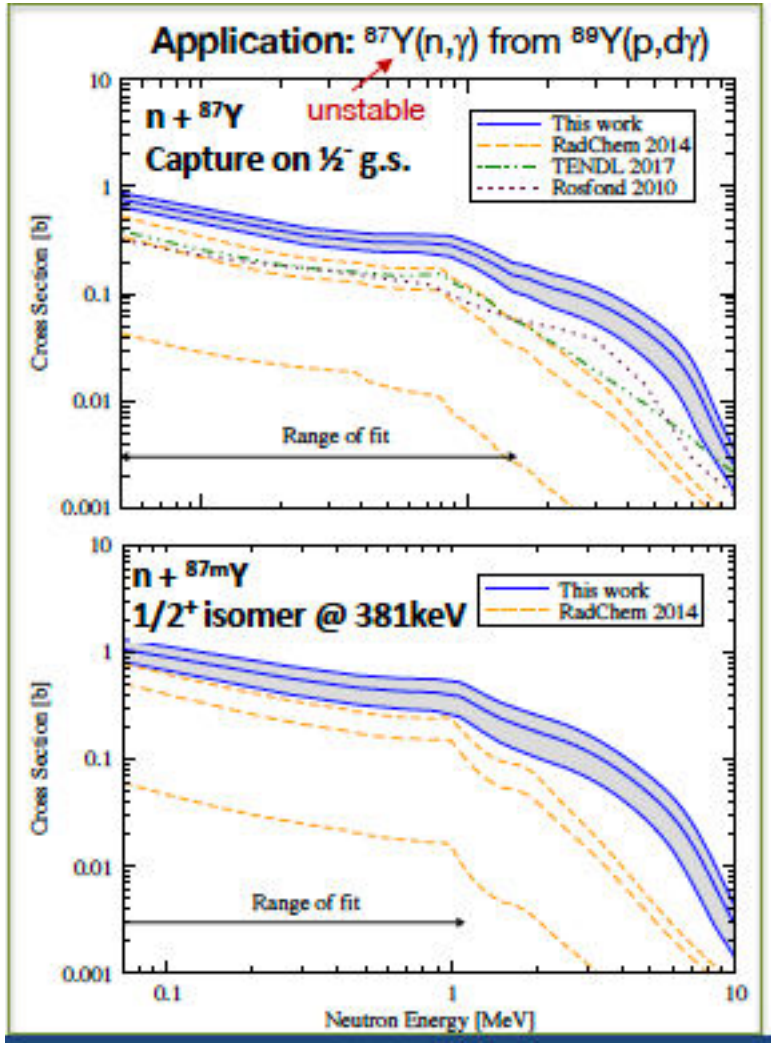


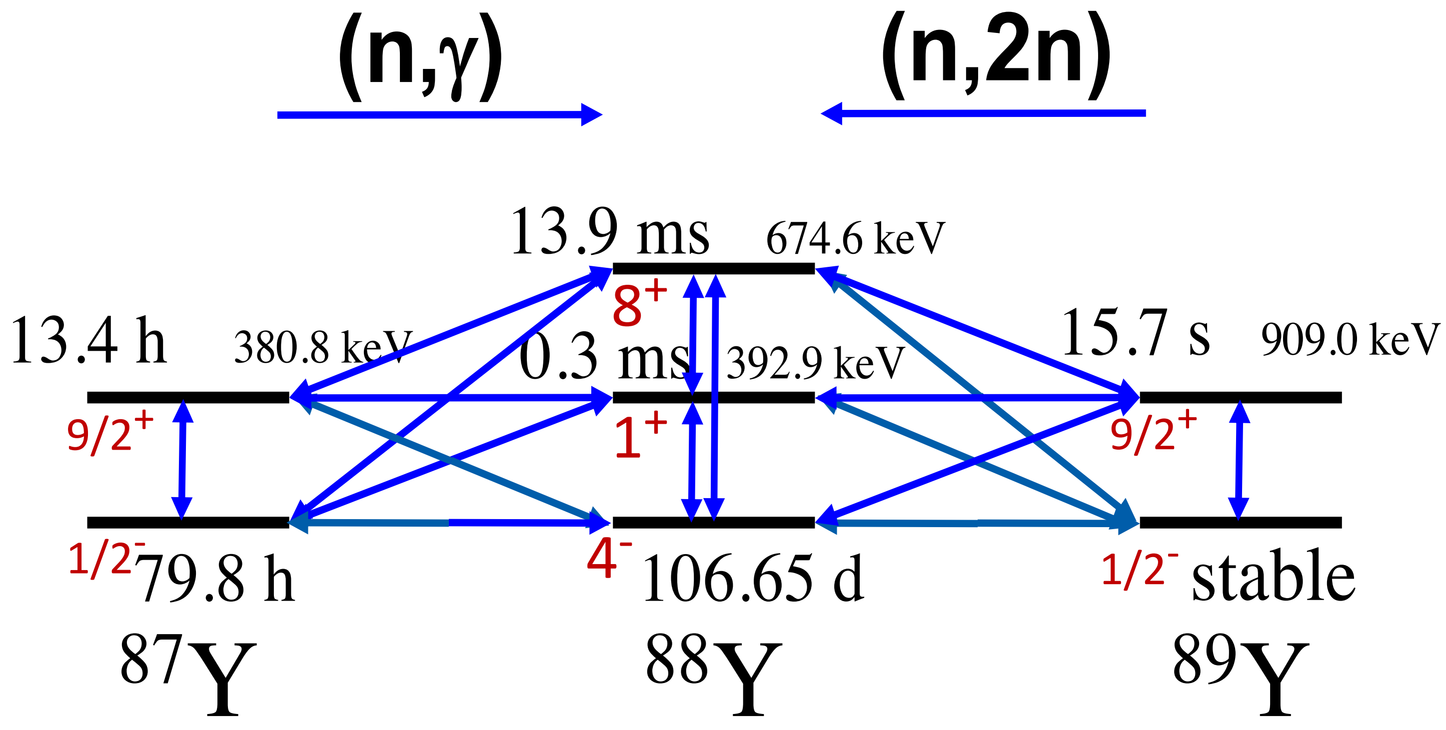
Surrogate (p,dγ) reaction

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

Procedure analogous to Zr(p,d) case

Application to neutron capture on unstable target:
We also obtained cross sections for reactions involving isomers





Multiple isomers occur in the unstable Y isotopes

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

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

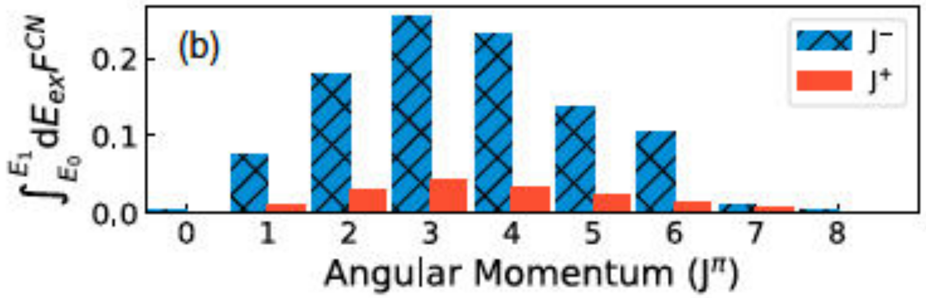
Ratkiewicz, Cizewski, JE, Potel, et al, PRL 122, 052502 (2019)

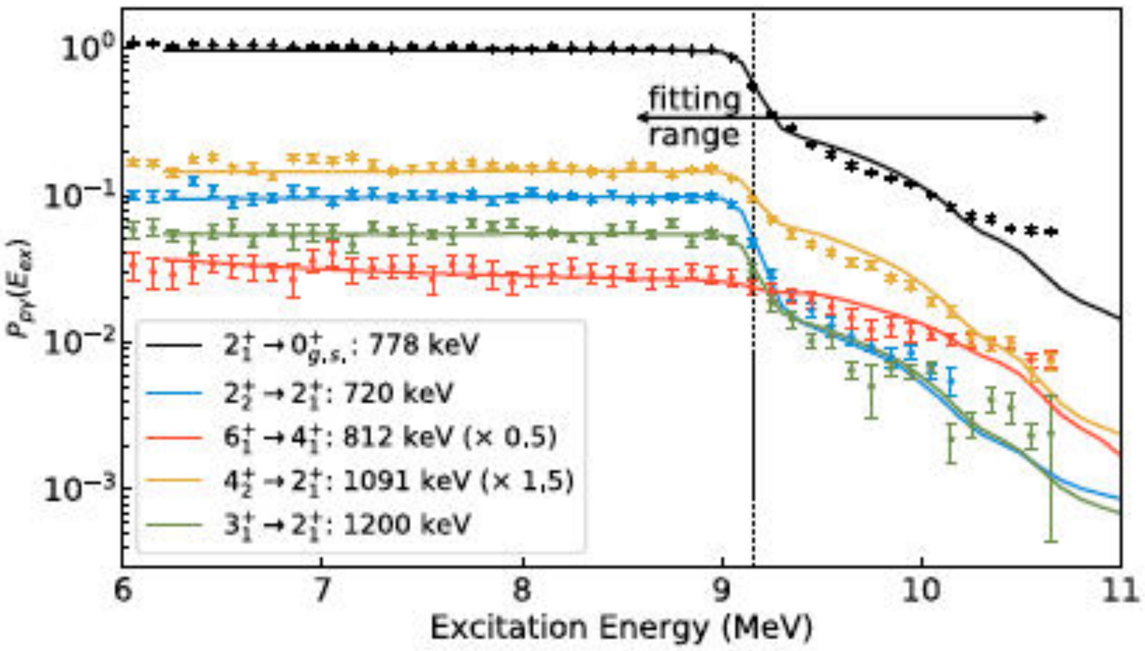
Coincidence probabilities from surrogate experiment

Surrogate coincidence probabilities

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

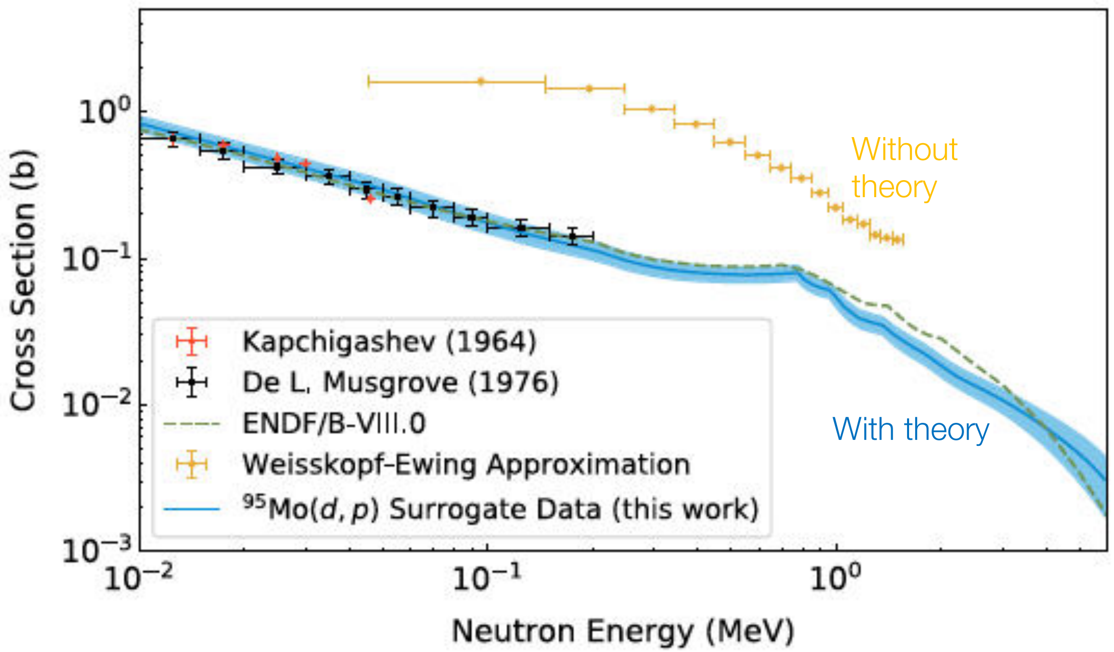
Spin-parity distribution from direct-reaction theory





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)



Procedure

- Measure the surrogate reaction coincidence probability
- Calculate the spin-parity distribution 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

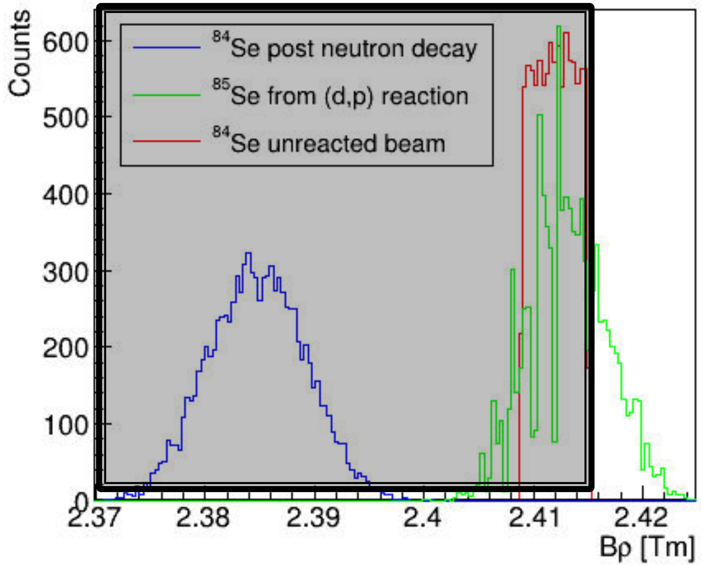
We are developing the surrogate reactions method in inverse kinematics
Experiments performed at ANL, TRIUMF, and FRIB

GODDESS 2021

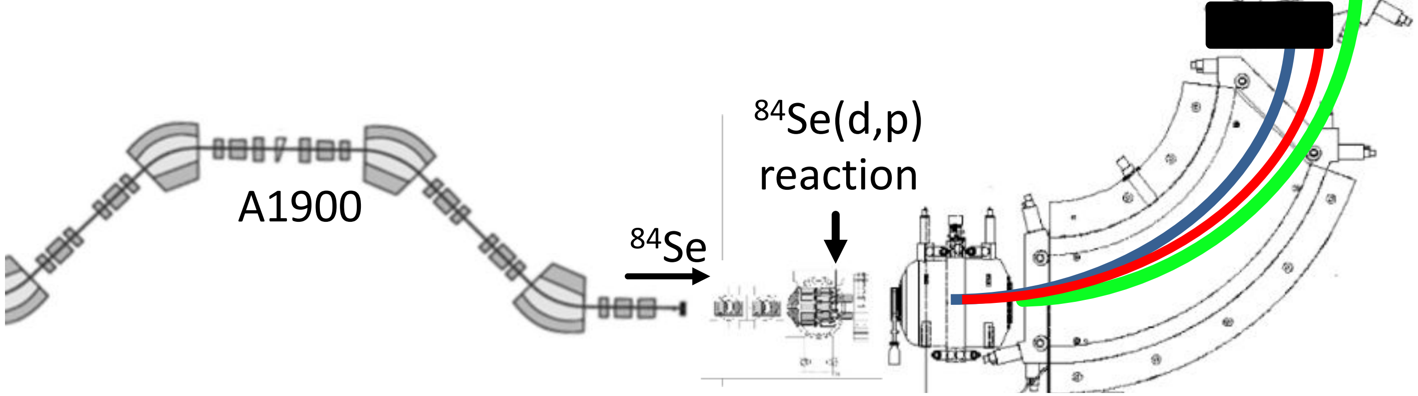
Three scenarios:

1. ^{84}Se does not react with CD_2 target, continues with same momentum distribution as determined by slits in A1900. — **Bρ = 2.4136 Tm**

2. ^{84}Se undergoes (d,p) reaction at CD_2 target to form ^{85}Se above the neutron separation. Nucleus gamma-decays to ground state. — **Bρ = 2.4119 Tm**



- S800 FP is rate-limited to ~6 kHz, so we use the "soap-on-a-rope" to block the beam.
    - **Use the recoils to determine whether CN decay channel (^{84}Se/^{85}Se) – by tagging on ^{85}Se**



Slide from A. Ratkiewicz

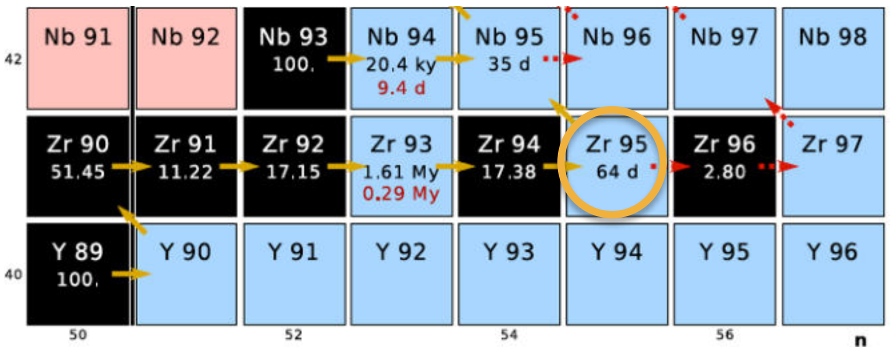
Here recoils are utilized instead of gammas

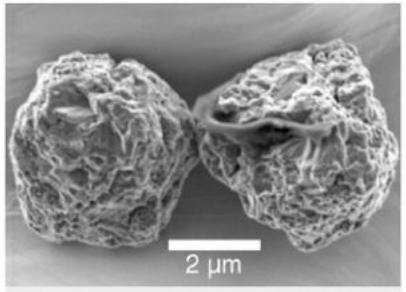
- Concept
- (p,d) as a surrogate reaction mechanism
- (d,p) as a surrogate reaction mechanism
- **Inelastic scattering as a surrogate reaction mechanism**

Using inelastic scattering as a surrogate mechanism provides new opportunities: Applications to s process

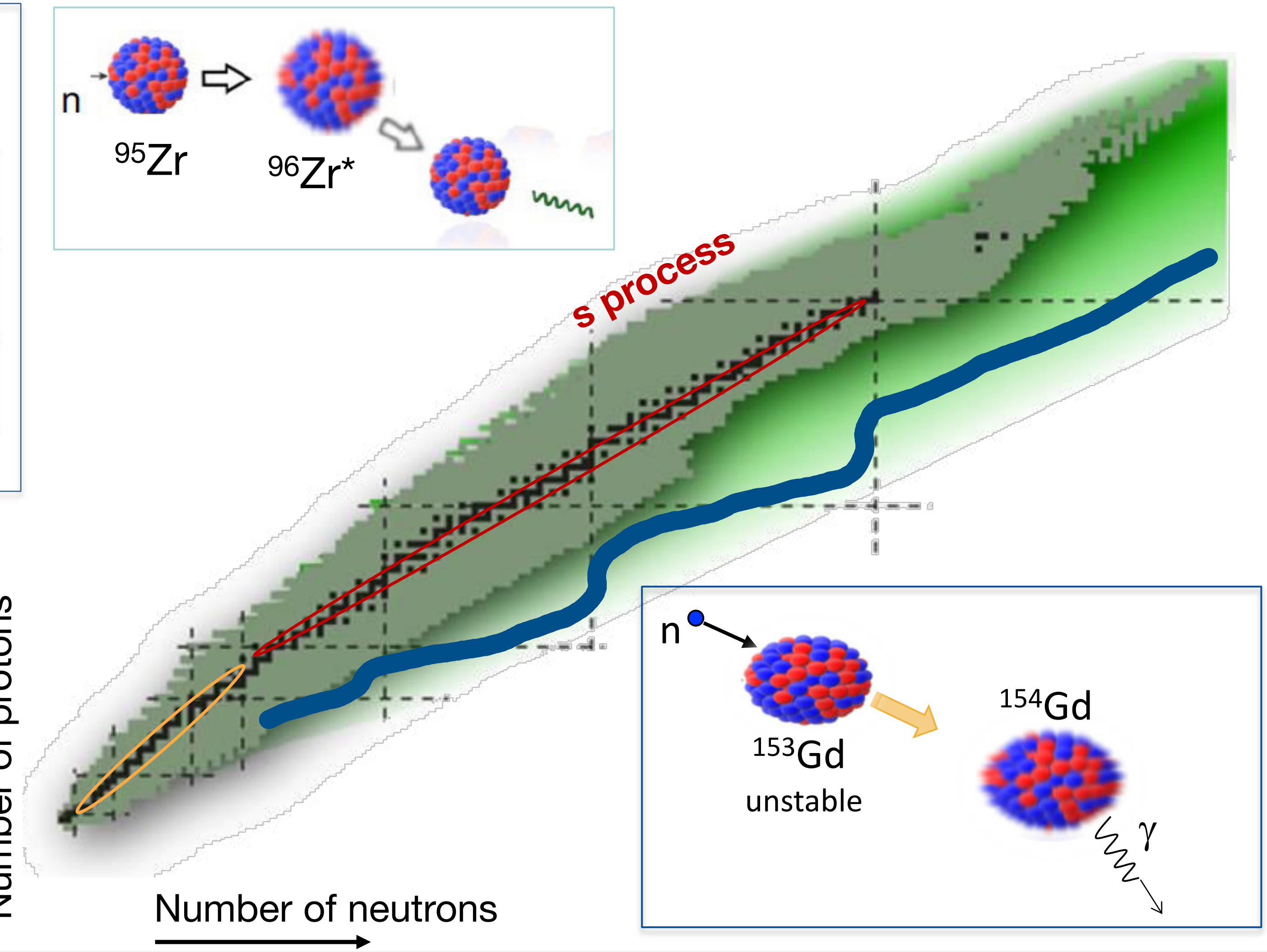
s-process path at branch point ^{95}Zr

^{95}Zr is unstable





Stardust
Presolar grains carry isotopic ratio information

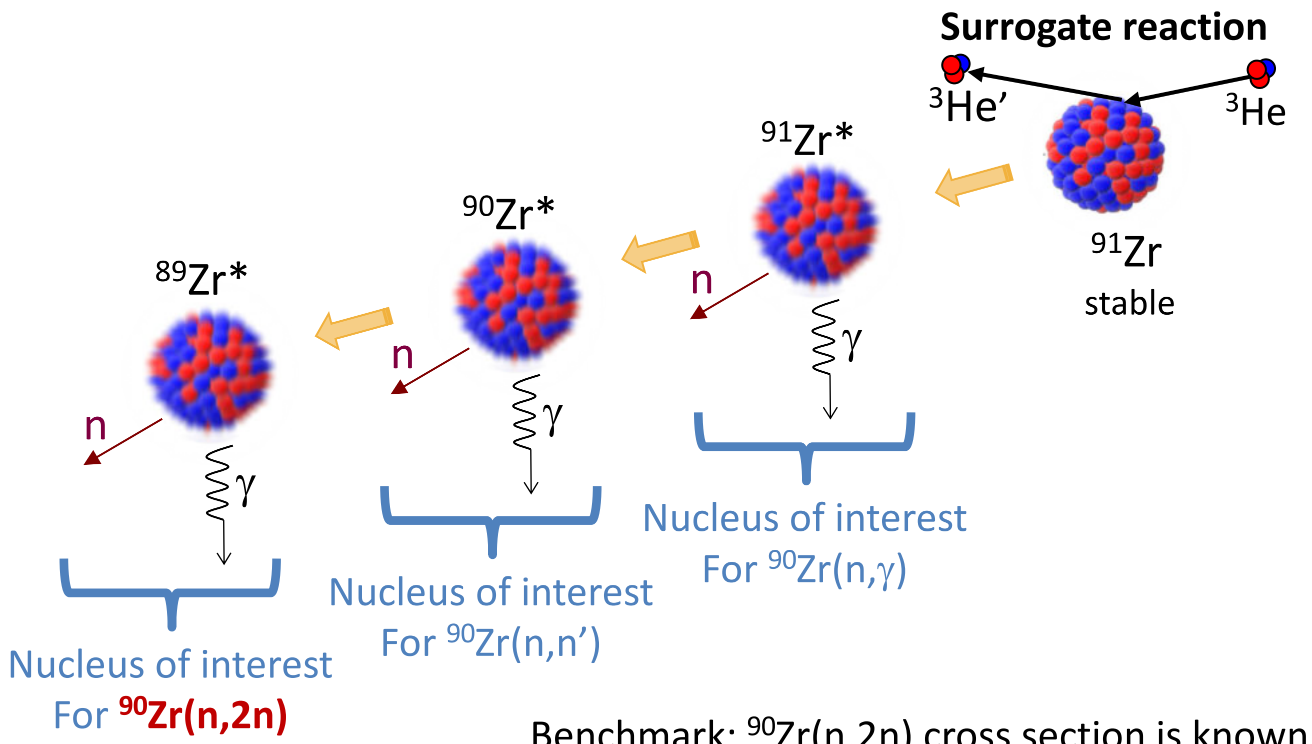


Using inelastic scattering as a surrogate mechanism provides new opportunities: Determining (n,n') and (n,2n) reaction cross sections

- 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



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

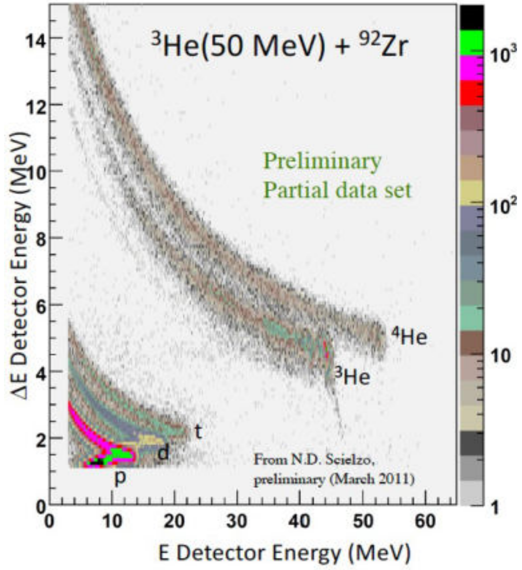
Surrogate reactions method for (n,n') and (n,2n)

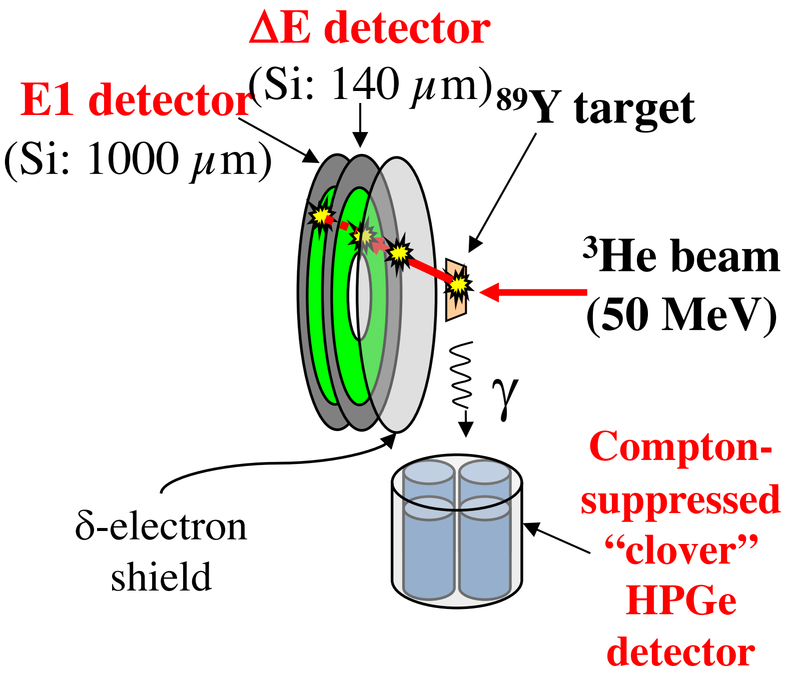
STARS/LiBerACE experiments at LBNL

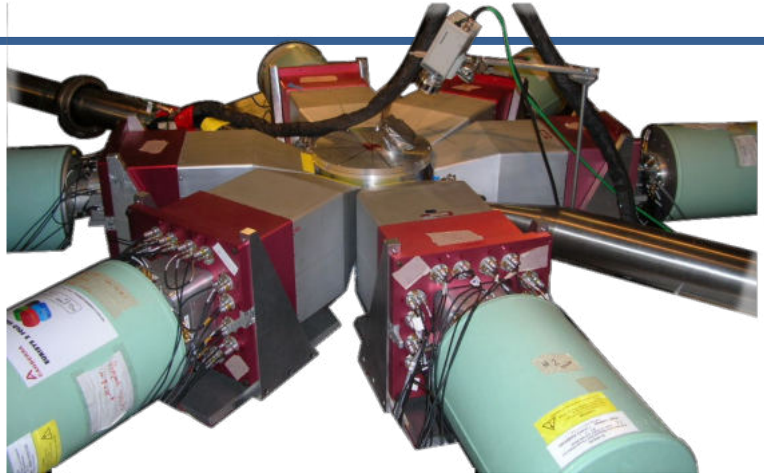
^{90,91,92}Zr(^{3}He,^{3}He') and ^{90,91,92}Zr(^{3}He,α)

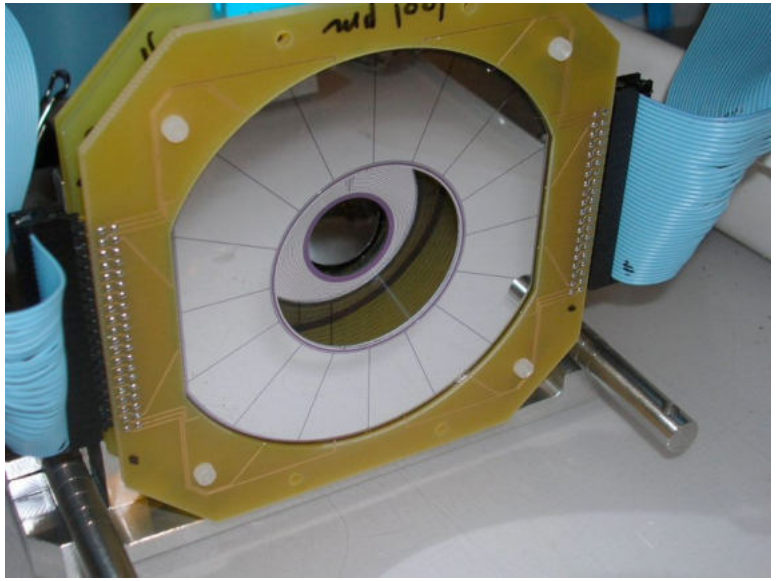
^{89}Y(^{3}He,^{3}He') and ^{89}Y(^{3}He,α)

Scielzo et al.





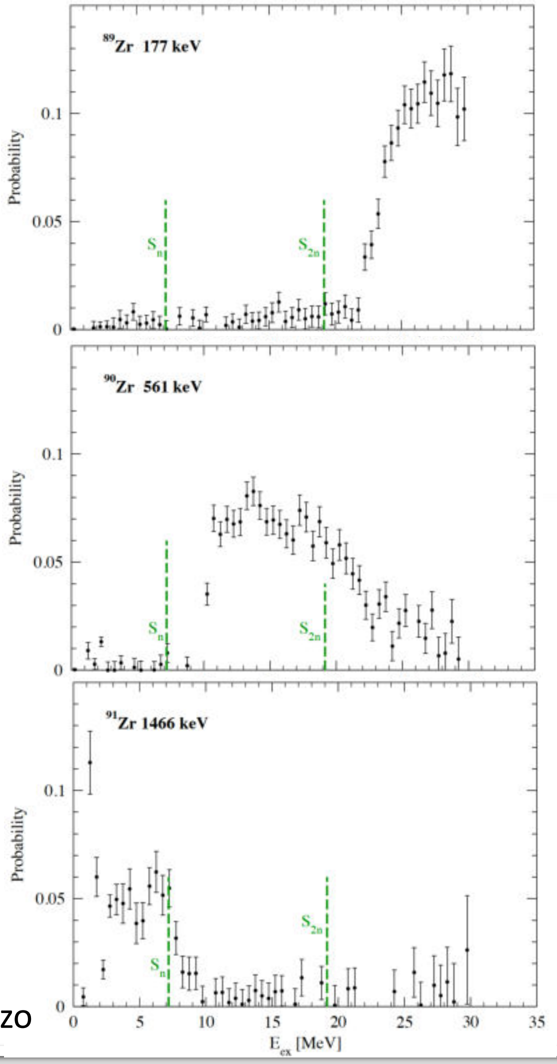




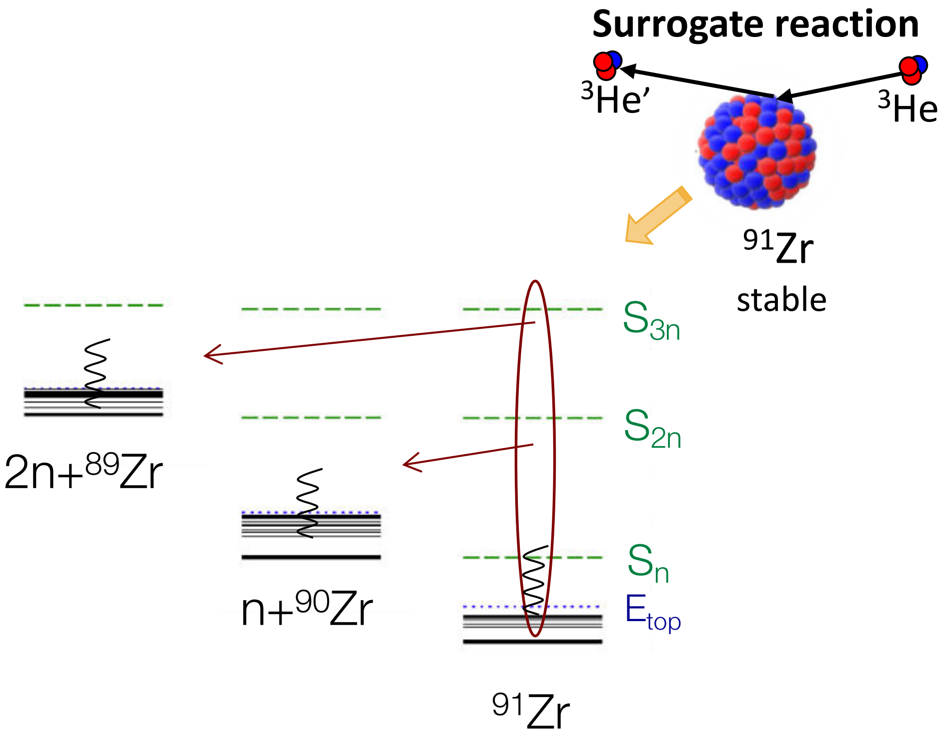
Surrogate reactions method for (n,n') and (n,2n)

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 distribution
  - 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

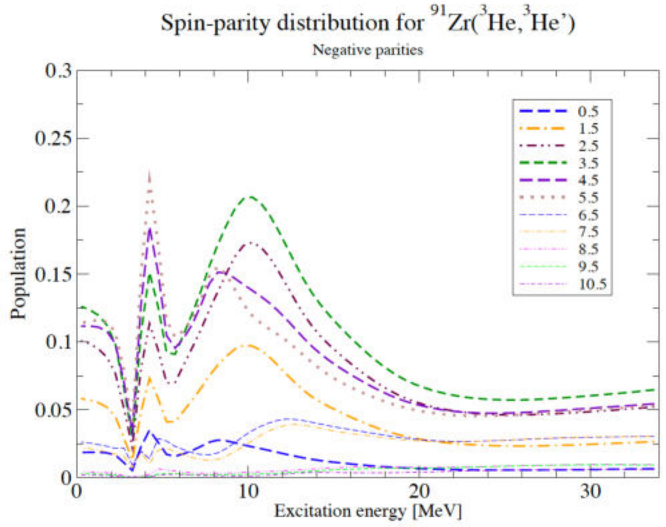
Escher et al., WIP (2023)

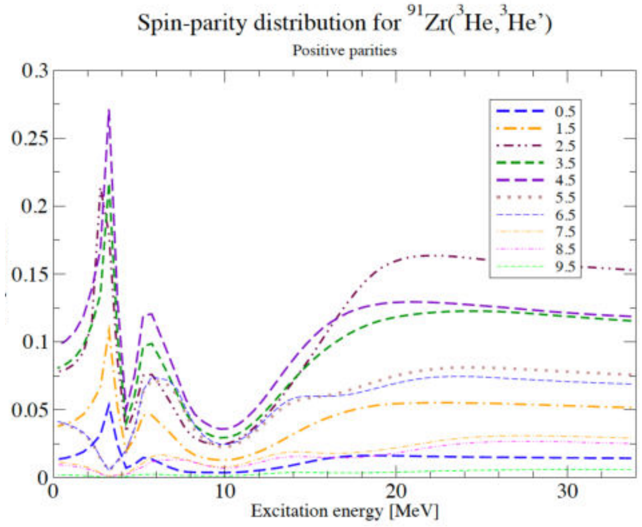
Coincidence probabilities from surrogate experiment

Surrogate coincidence probabilities

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

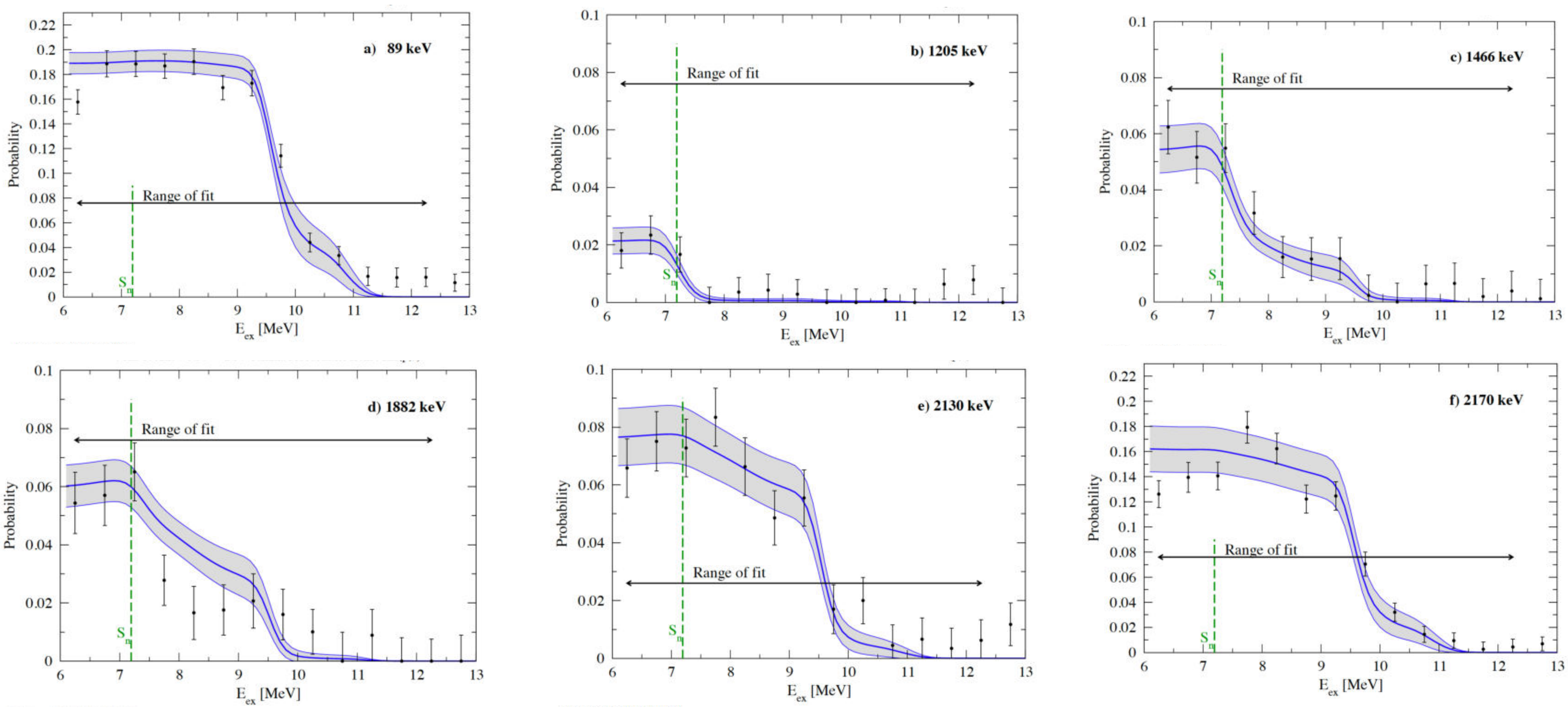
Spin-parity distribution from direct-reaction theory





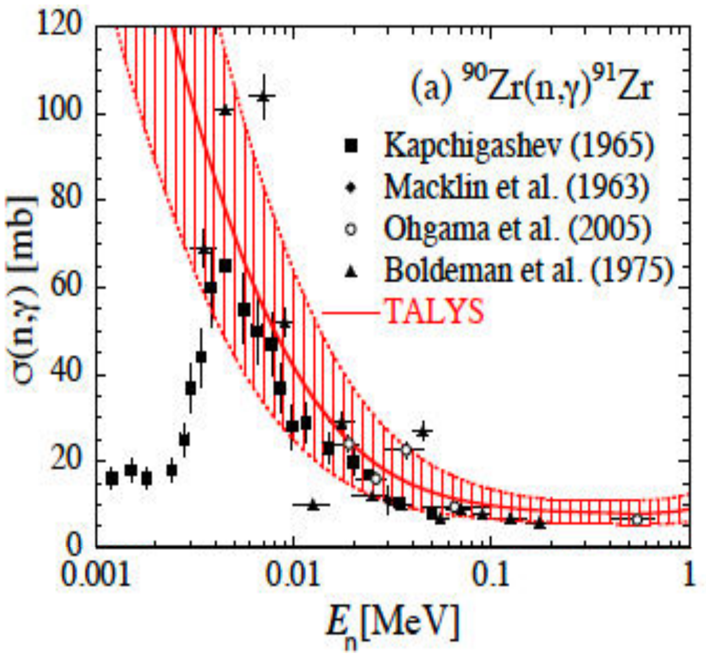
Fits to gamma transitions in ^{91}Zr → constrain LDs and γSF in ^{91}Zr

Escher et al., WIP (2023)

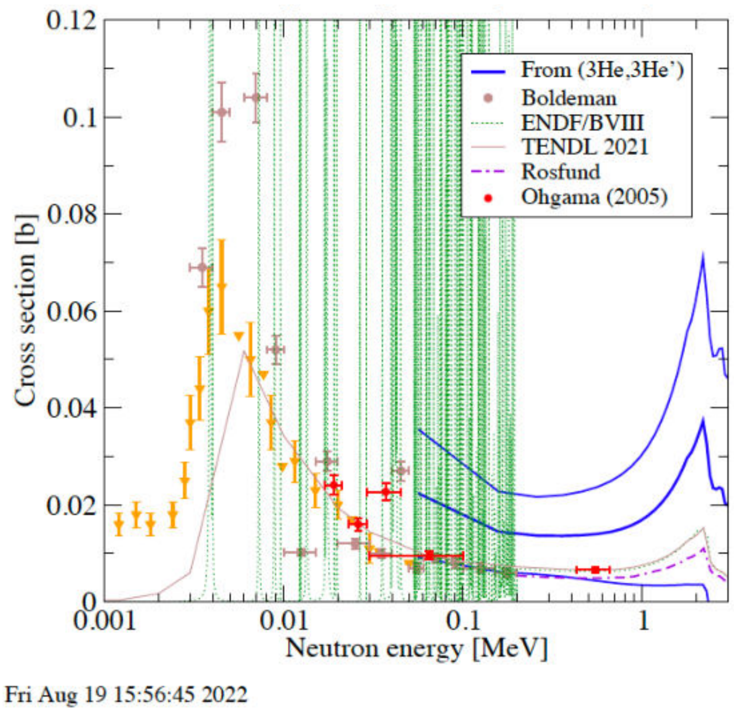


Neutron capture cross section from $^{91}Zr(^{3}He,^{3}He')$ surrogate data compared to results from other indirect measurements

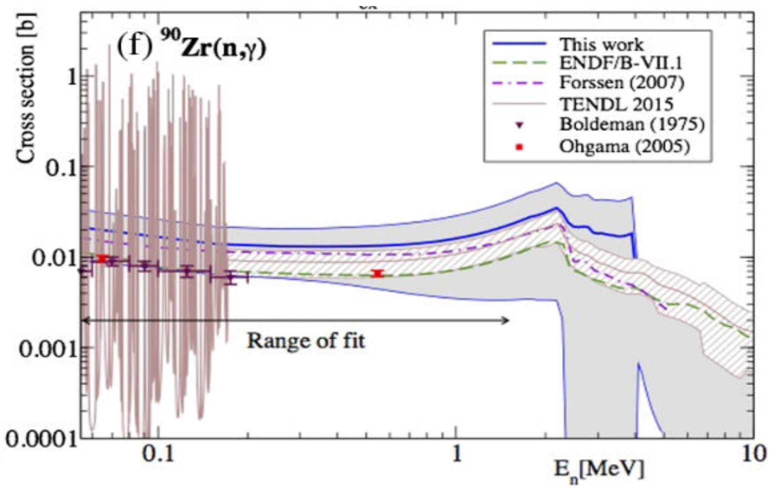
Escher et al., WIP (2023)



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



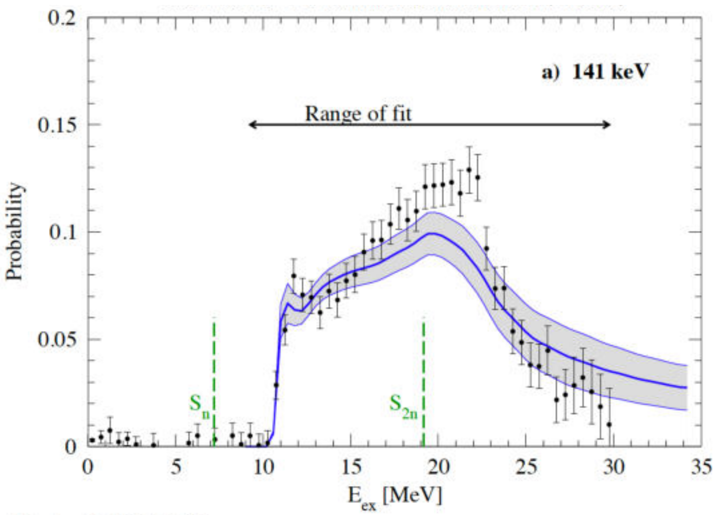
This work
(preliminary)

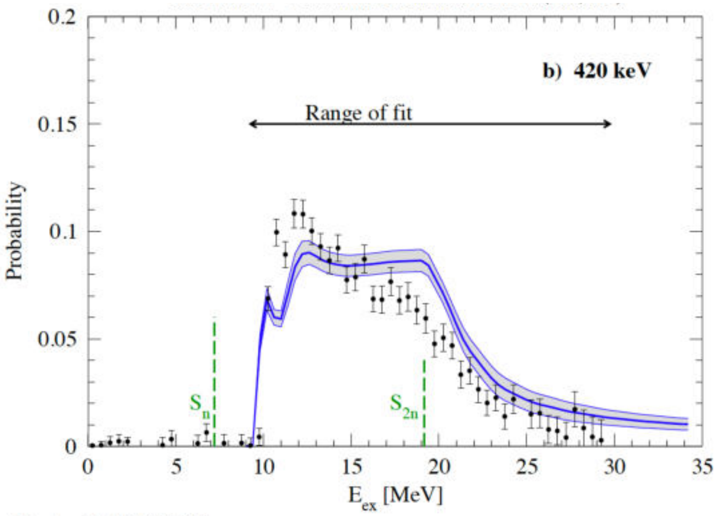


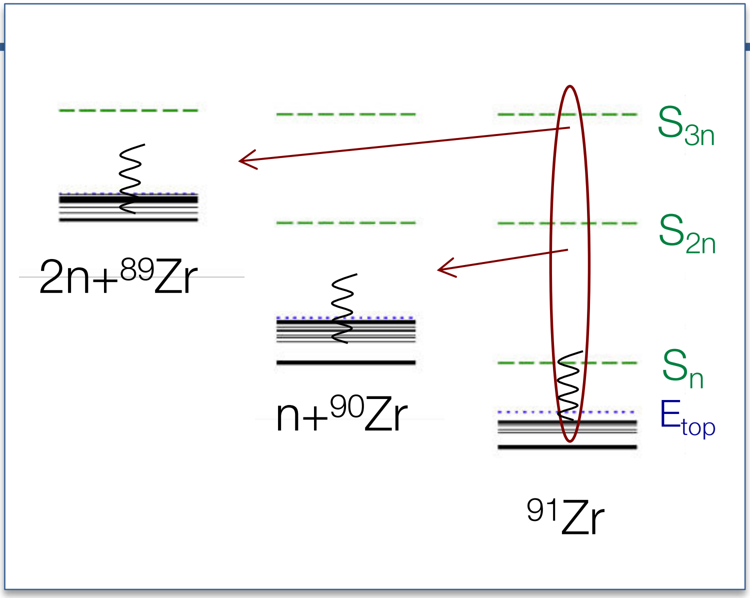
Escher et al, PRL 2019
Surrogate method, $^{92}Zr(p,d)$

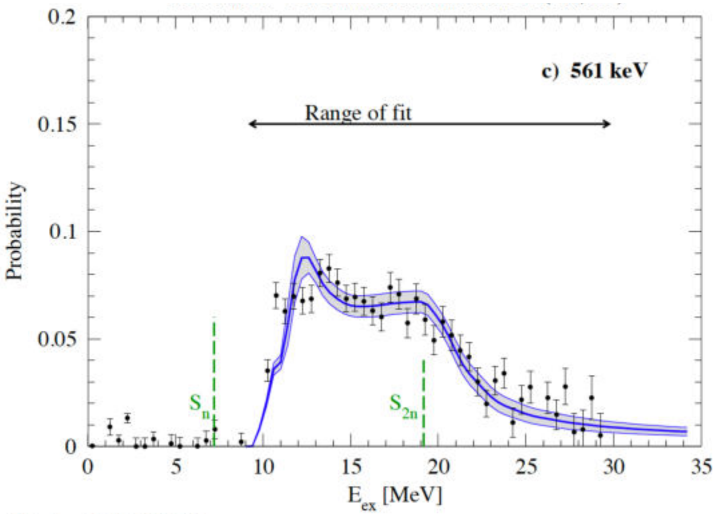
Simultaneous fit to gammas in ^{90}Zr and ^{89}Zr

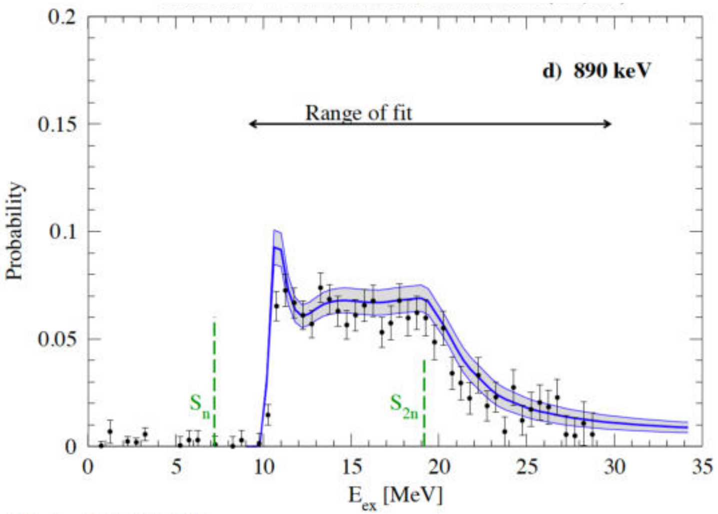
Escher et al., WIP (2023)

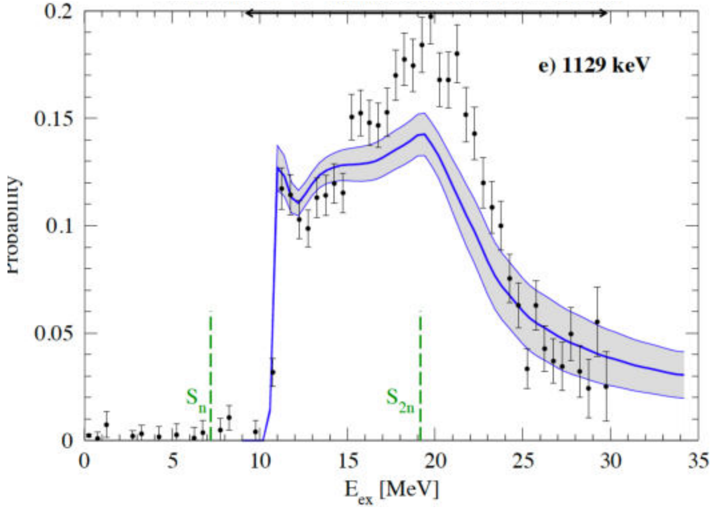






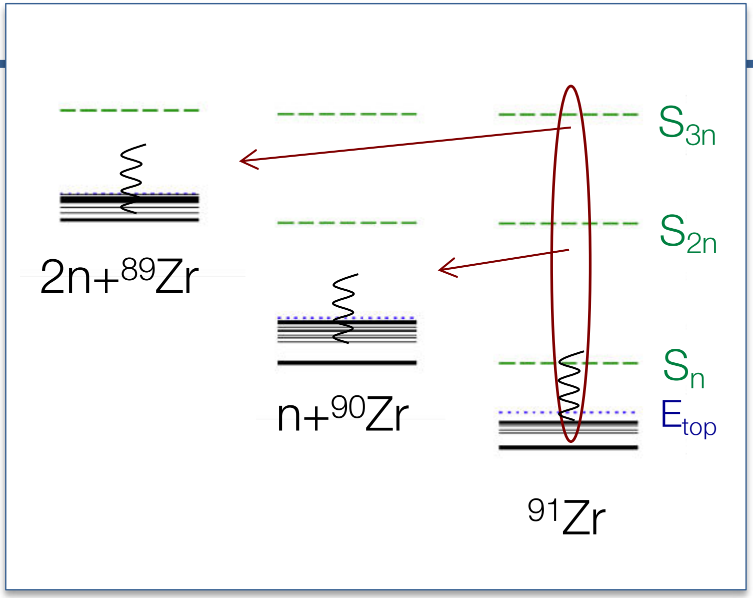


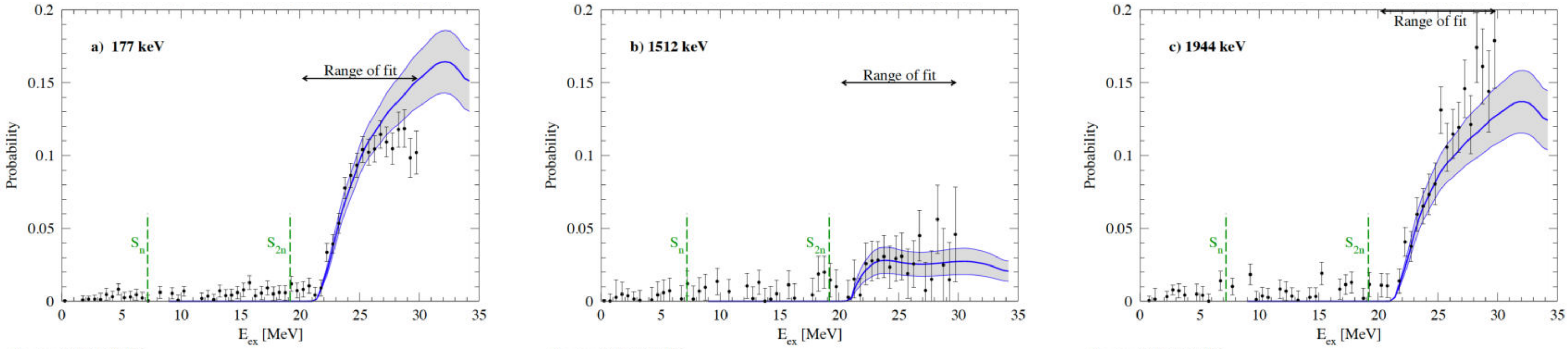




Simultaneous fit to gammas in ^{90}Zr and ^{89}Zr

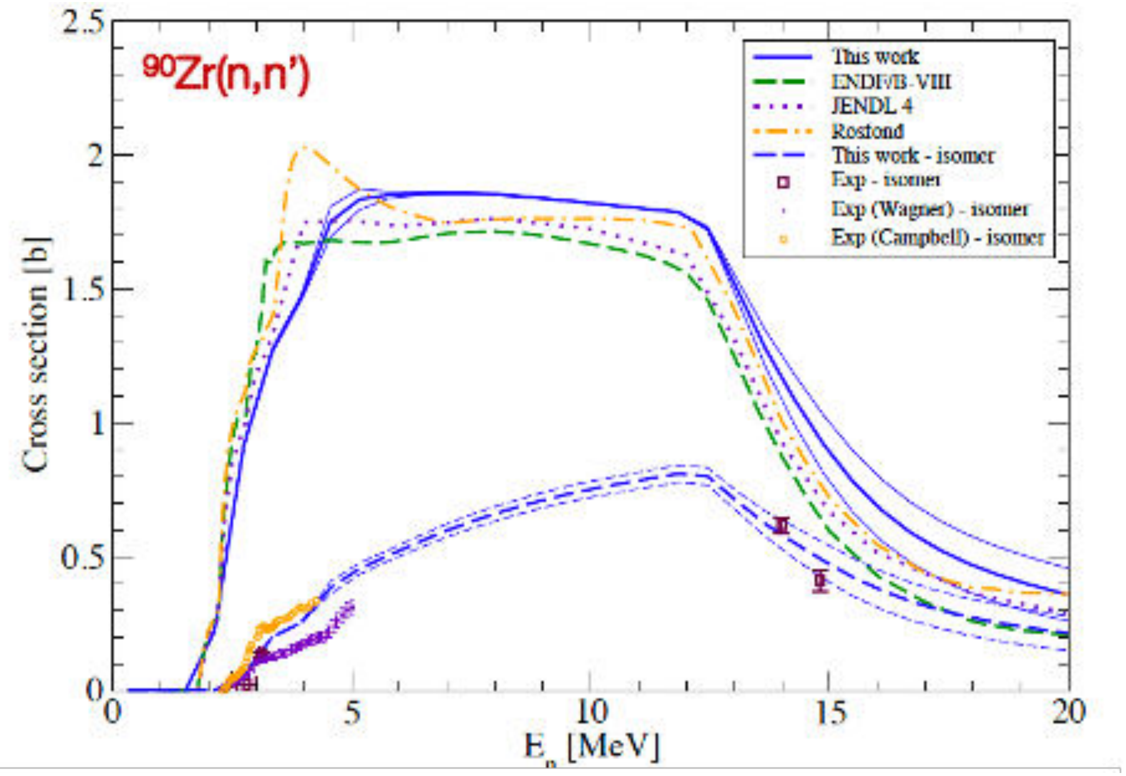
Escher et al., WIP (2023)

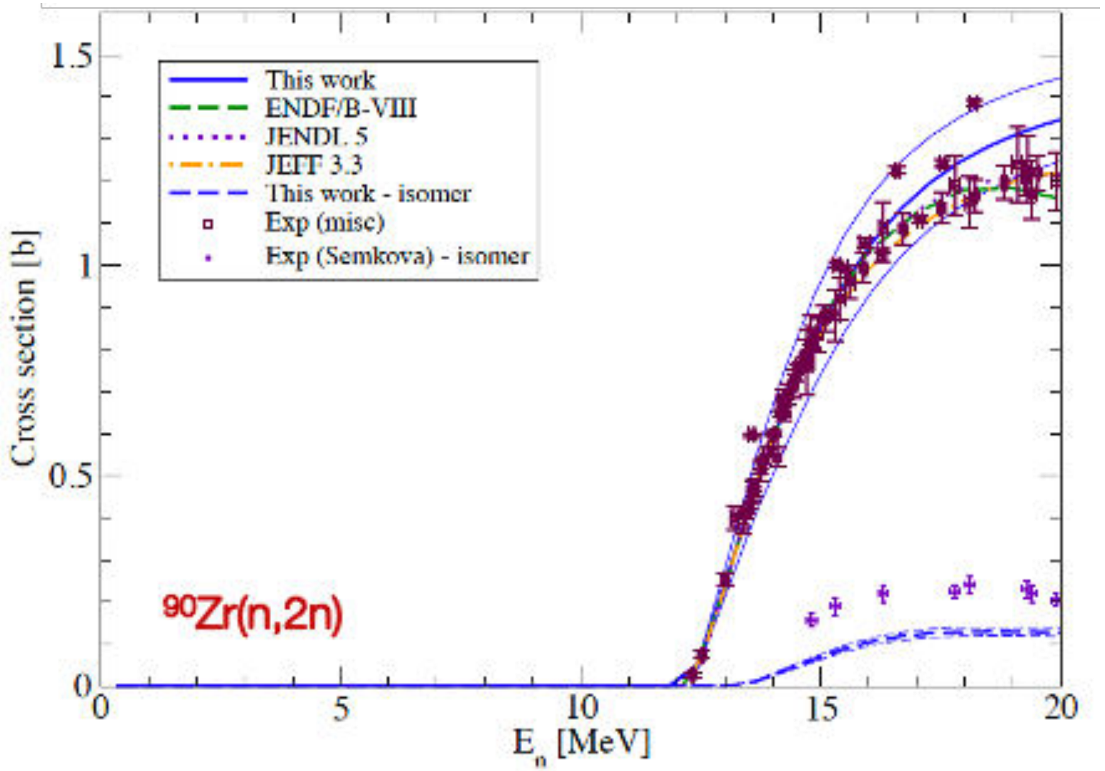




^{90}Zr(n,n') and (n,2n) cross sections from ^{91}Zr(^{3}He,^{3}He') data and theory

Escher et al., WIP (2023)



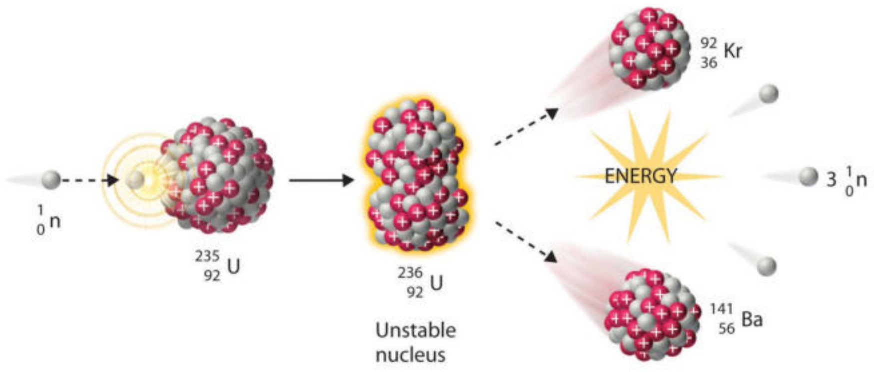


(preliminary)

Full circle: We plan to revisit the surrogate reactions method to obtain (n,f) cross sections and insights into the fission process

Describing fission challenges theory (and experiment)

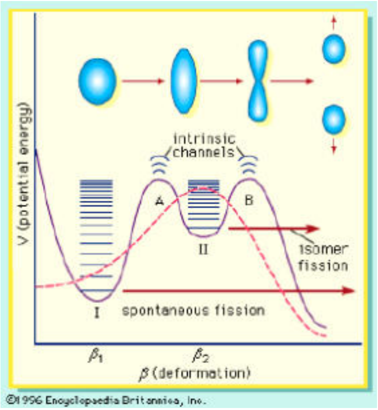
- Descriptions range from phenomenological to microscopic
- Lots of data needed to provide constraints



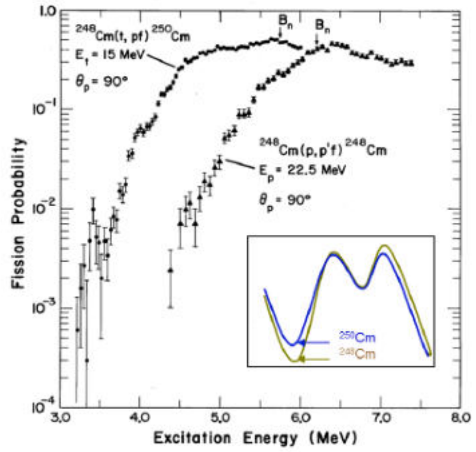
Opportunity: Surrogate fission measurements

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

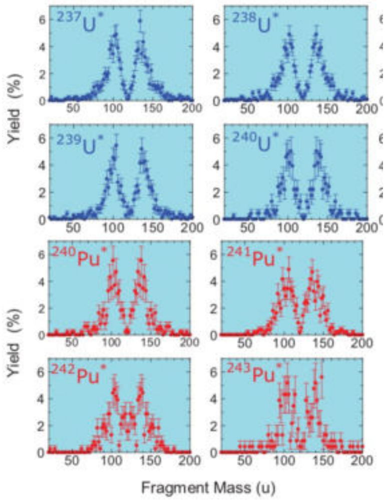
Schematic view of fission



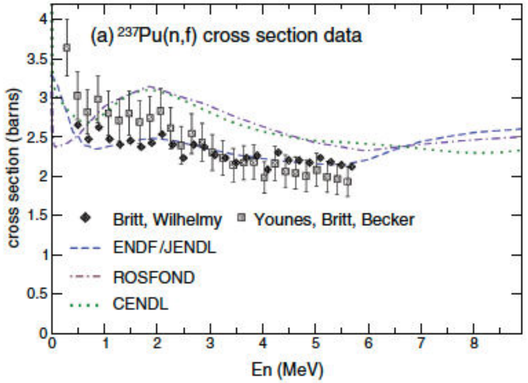
Fission barriers from surrogate data
Back, EPJConf. 232, 03002 (2020)



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



^{237}Pu(n,f) from surrogate measurement
Huges et al, PRC 90, 014304 (2014)



Concluding remarks

1. Nuclear astrophysics requires information on multiple reaction types for many isotopes. We will not be able to measure all. Predictive theory is indispensable.

2. Substantial progress has been made integrating structure and reaction theory for light nuclei. Symmetry-adapted bases promise to extend advances to medium-mass nuclei.

3. For heavy nuclei, efforts are underway to integrate sophisticated structure theory into reaction calculations:
   - Optical models are being extended off-stability
   - Shell-model and DFT-based theories are used to calculate LDs and γSFs
   - Consistency and UQ need to be implemented

4. Measurements are needed to validate and complement theory

5. Surrogate reactions method constrains cross section calculations for compound reactions by combining an indirect measurement with theory
   - Method uses inelastic scattering or transfer reactions in regular or inverse kinematics
   - Theory provides important information on population of doorway states and extracts desired cross section

A thank you to my collaborators:

LLNL: J. Berryman, O. Gorton, E. In, K. Kravvaris, S. Perrotta, G. Potel, C. Pruitt, A. Thapa, I.J. Thompson, W. Younes, B. Alan, R. Casperson, J. Harke, R. Hughes, A. Ratkiewicz, N. Scielzo, BNL: E. Chimanski; FRIB: G. Sargsyan; SDSU: C. Johnson ORNL: S.Pain; Rutgers U.: J. Cizewski, Ohio U: A. Richard CEA/France: M. Dupuis, S. Peru

This summer in Vienna……

Compound-Nuclear Reactions and Related Topics (CNR*24)

- Nuclear reaction mechanisms (direct, compound, pre-equilibrium, other)
- Nuclear fission
- Statistical Hauser-Feshbach theory
- Surrogate methods
- Optical model
- Level densities and photon strength functions
- R-matrix theory
- Nuclear structure for nuclear reactions
- Measurements relevant to compound-nuclear reactions (direct and indirect)
- Nuclear data evaluation and dissemination (including Machine Learning, Statistics, Bayesian Inference)
- Applications in nuclear astrophysics, energy, waste management, nonproliferation, medical physics, etc.
- Experimental facilities

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