Theory for Indirect Reaction Studies

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Jutta E. Escher
Nuclear Data & Theory Group

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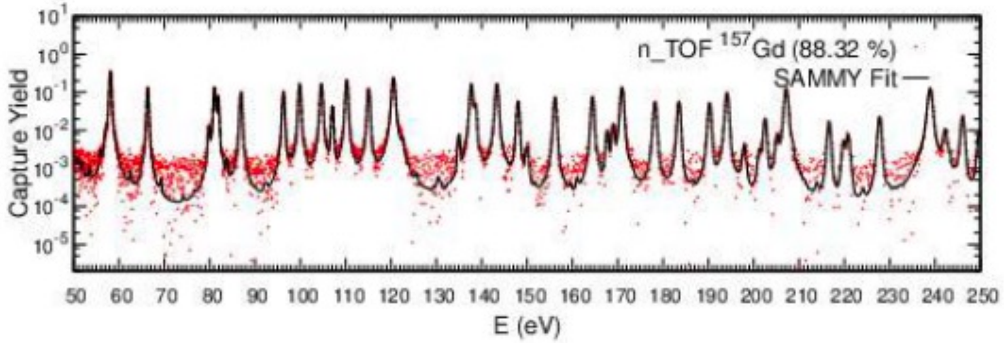
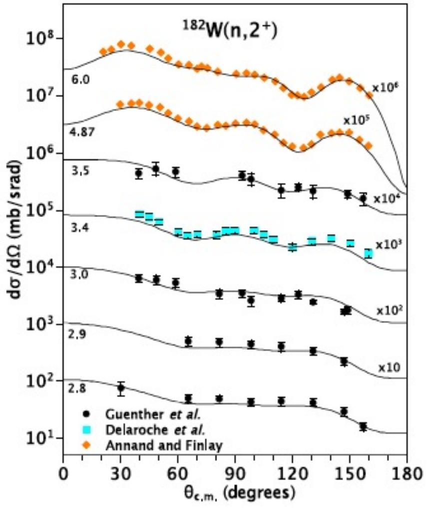
We have robust reaction theories and flexible data evaluation tools to describe a wide variety of reactions

- 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

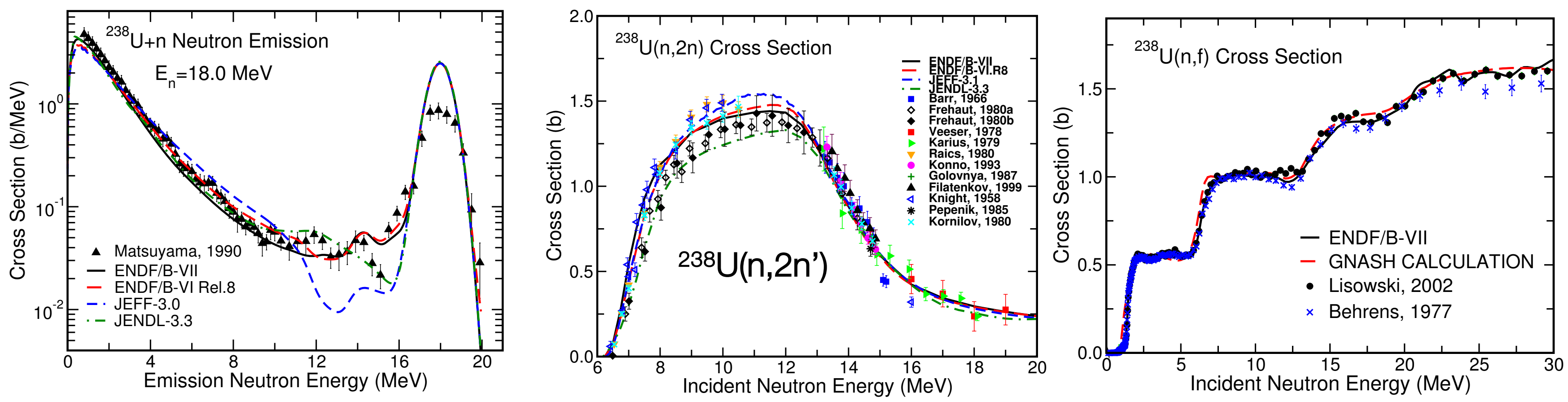


Leal, EPJ Conf 239, 11004 (2020)



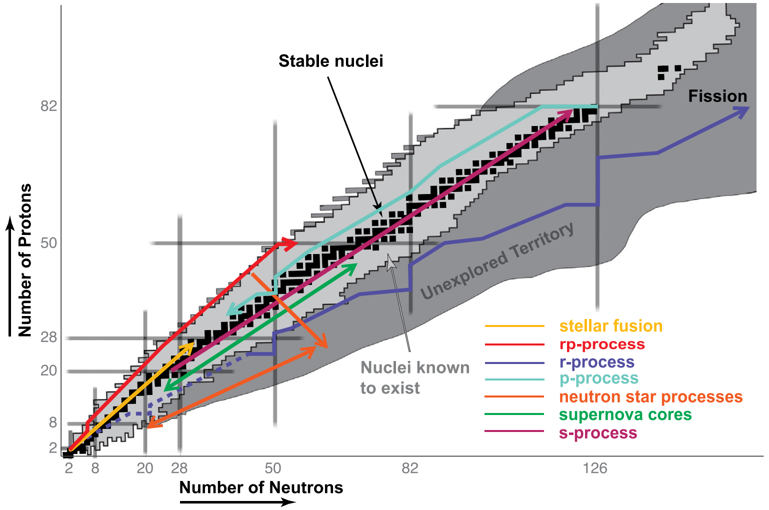
Nobre, PRC 91, 024618 (2015)

Young et al, NDS 108 (2007) 2589



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

- 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
- Opportunities with indirect reactions:
  - Provide specific ingredients for theory, constrain parameters and components of the theory
  - Provide new insights into reaction mechanisms and test our overall understanding of nuclear structure and reactions
- Examples:
  - charged-particle inelastic scattering and transfer reactions to determine n-induced CN cross sections



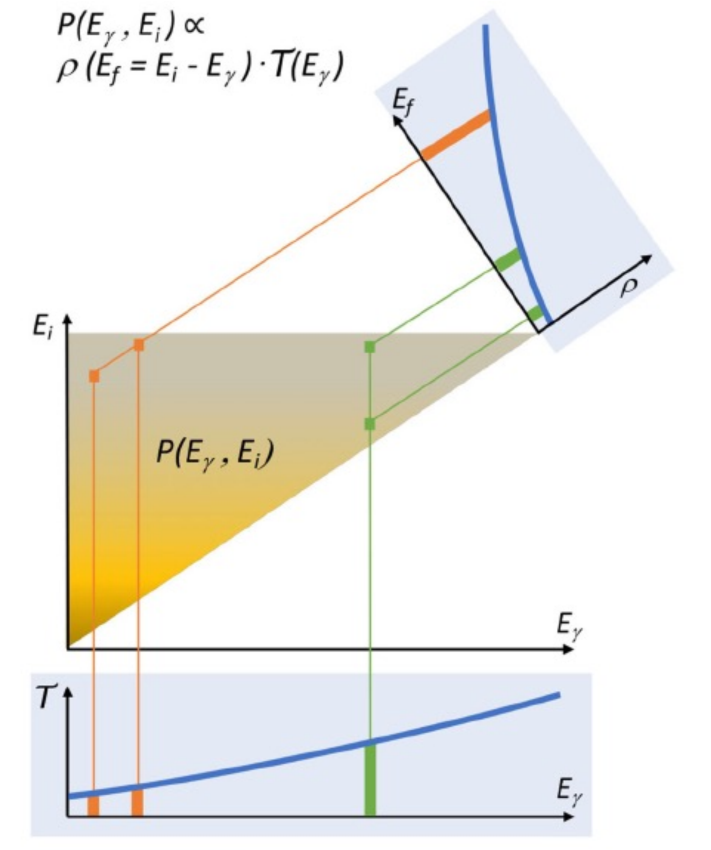
Oslo method produces compound nucleus and extracts γ strength function and level density from measured γ decay spectra

- Principle:
  - Transfer reactions and inelastic scattering produce compound nucleus (CN) of interest
  - Measure γ-decay probabilities
  - Establish connection to product of γ strength function (γSF) and level density (LD), then disentangle
  - Use γSF and LD in HF calculation of neutron capture reaction

- Challenges:
  - Separation of γSF and LD is ambiguous, requires auxiliary information
  - Electric and magnetic γSFs are not distinguished in the experiment
  - Effects of spin and parity on decay of compound nucleus (CN)
  - Does the system equilibrate?

- Theory developments:
  - Incorporating spin-parity predictions to improve analyses
  - Statistical uncertainty propagation
  - Needed: Auxiliary information to separate γSF and LD

γ emission probabilities in matrix form

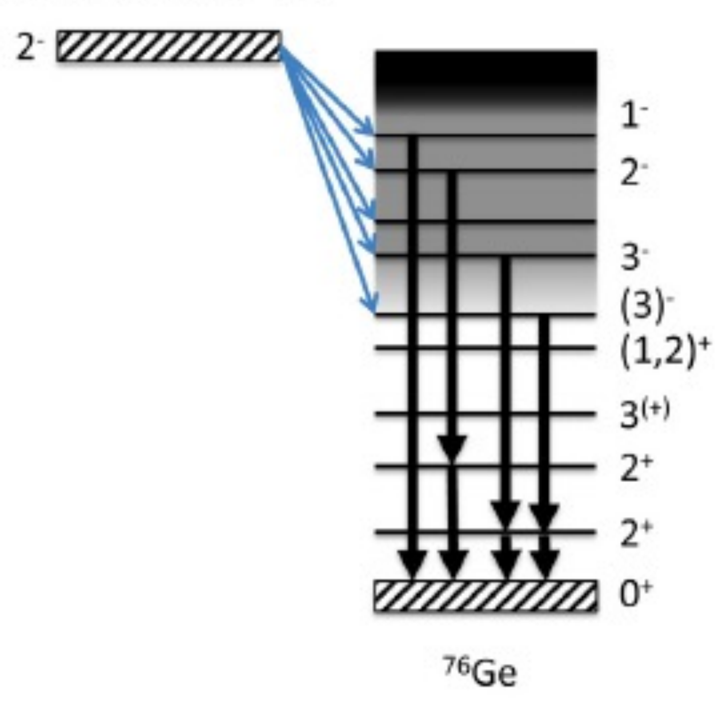


Goriely, EPJA 55, 172 (2019)

β-Oslo method measures β-delayed nucleus γ emission and extracts γ strength function and level density

- Principle:
  - Produce nucleus of interest via β decay
  - Analysis analogous to traditional Oslo method
  - Advantage: ability to reach nuclei far from stability
- Challenges:
  - Separation of γ strength function and level density is ambiguous, requires auxiliary information
  - β decay is very selective
  - Few spins populated
  - Does the system equilibrate?
- Theory developments:
  - Integrating β decay theory with γ emission description
  - Needed: Testing nuclear structure effects
  - Needed: Understanding compound-formation after β decay and signatures

β decay of ^{76}Ga, followed by γ emission



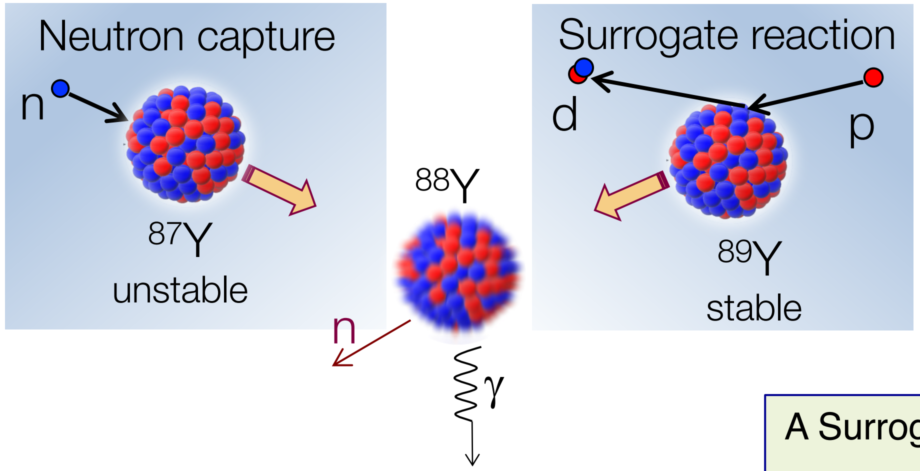
Larsen, PPNP 107, 69 (2019)

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

- Principle:
  - Transfer reactions and inelastic scattering produce compound nucleus (CN) of interest
  - Theory provides formation cross section for CN
  - Combine theory & experiment to obtain desired cross section
- Challenges:
  - Calculate spin & parity properties of doorway state in surrogate reaction
  - Does the system equilibrate?
- Theory developments:
  - Describe mechanisms for populating doorway states, for inelastic scattering and transfers
  - Integrate with decay modeling
  - Bayesian parameter inference

Problem: $^{87}Y(n,\gamma)$ calculations are highly uncertain

Solution: Constrain calculation with surrogate data



From theory

To be determined

A Surrogate experiment gives

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

From experiment

$^{87}Y(n,\gamma)$ cross section:

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

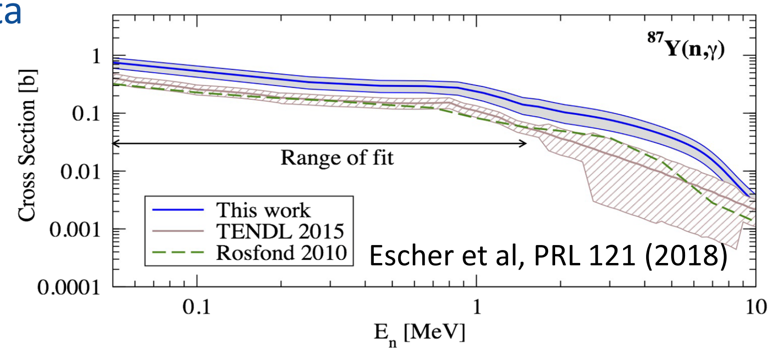
The new cross section we want

Well modelled from nuclear theory

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

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

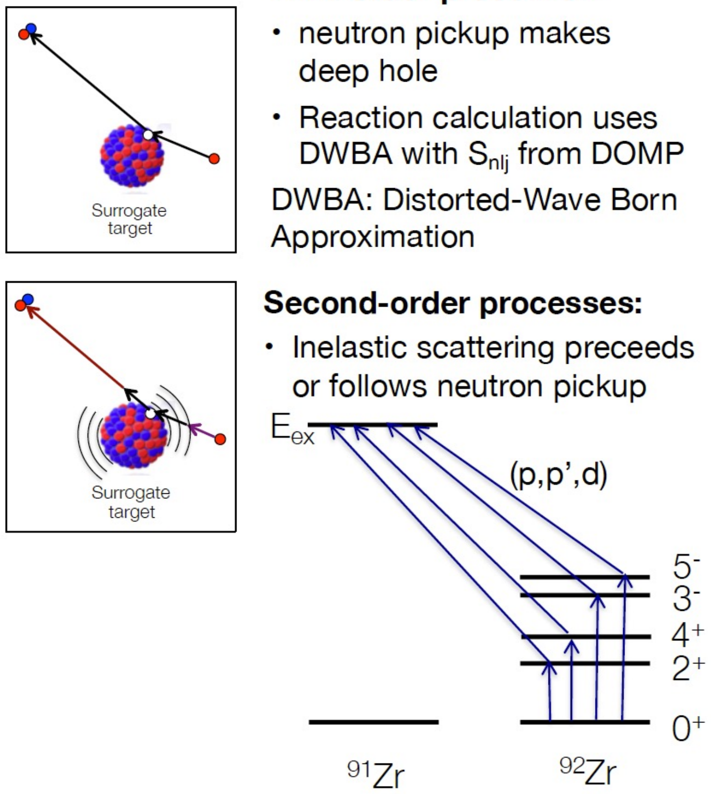
- Opportunities:
  - Important (n,γ) reactions become accessible
  - Wide range of 'equivalent neutron energy' is measured with fixed beam energy
  - Example: ^{87}Y(n,γ) from ^{89}Y(p,dγ) data
  - Isomer cross sections accessible



Escher et al, PRL 121 (2018)

- Challenges:
  - Nucleon removal produces holes deep in nucleus
  - Nucleon removal is accompanied by inelastic excitations
  - Experiments often measure decay signatures that require additional modeling
- Theory developments:
  - Leverage dispersive optical model parametrization to describe hole structure
  - Implement two-step reaction description to incorporate inelastic effects
  - Integrate nuclear decay scheme

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

^{89}Y(p,d) similarly

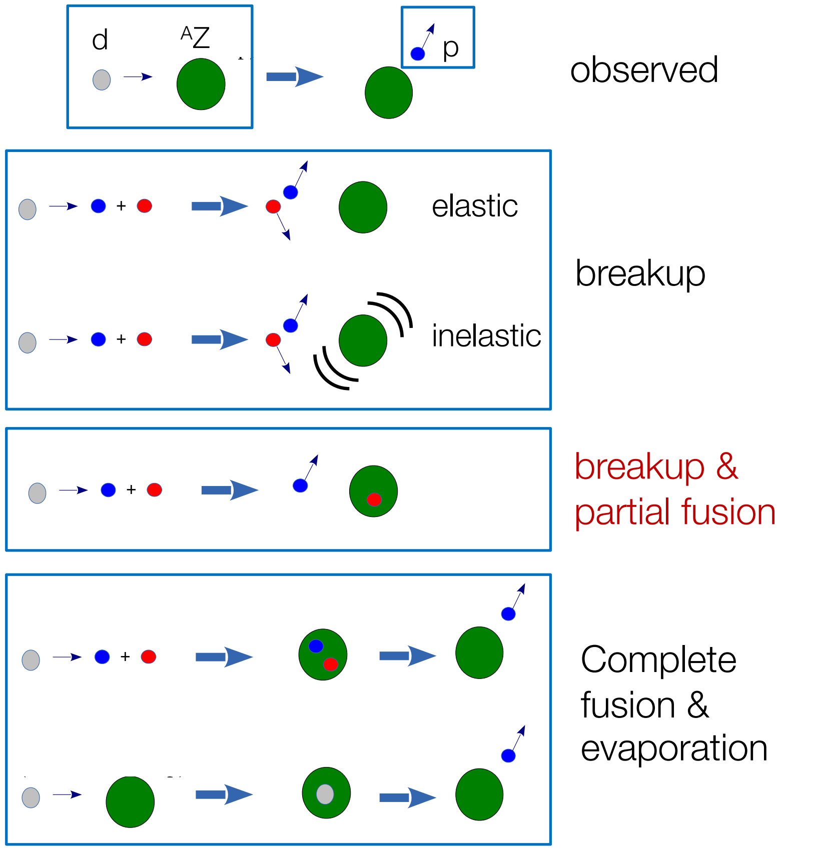
Surrogate (d,p) transfer reactions enable determination of unknown (n,γ) reaction cross sections

- Opportunities:
  - Important (n,γ) reactions become accessible.
  - Inverse-kinematics experiments at radioactive beam facilities
  - Examples: ^{95}Mo(n,γ), ^{95}Sr(n,γ)

- Challenges:
  - Multiple reaction processes lead to observation of proton, while only breakup-fusion is relevant
  - Decay modeling required

- Theory developments:
  - Describe deuteron breakup and propagation in nuclear field
  - Describe neutron absorption with optical model potential
  - Formalism to be extended to deformed systems

Surrogate (d,p) reaction

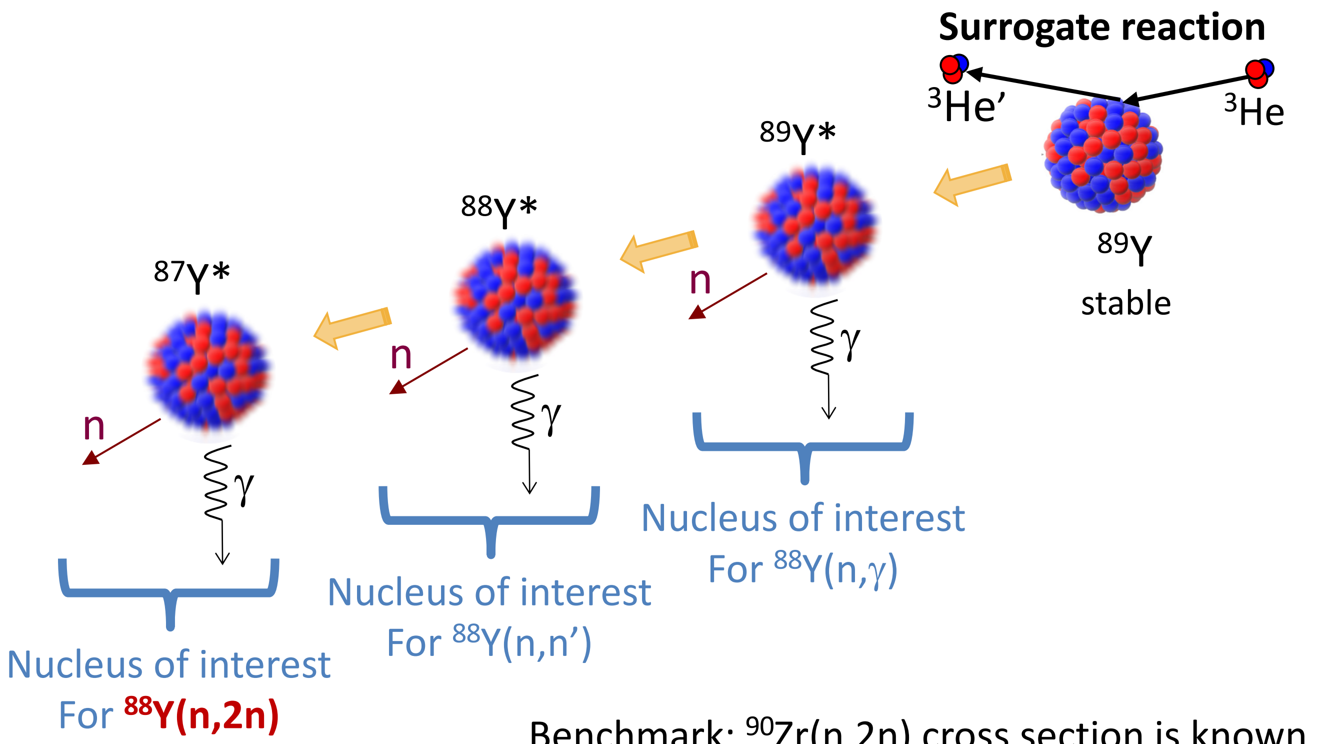


Application to ^{95}Mo: Ratkiewicz et al, PRL 122, 052502 (2019)

Surrogate reactions – Using inelastic scattering to determine unknown (n,n’) and (n,2n) reaction cross sections

- Opportunities:
  - Important (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
- Theory developments:
  - Integrate structure theory into description of surrogate reaction (QRPA, deformation, coupled channels)
  - Complement studies of (exotic) collective excitations
  - Study CN formation and pre-equilibrium emission
  - Opportunity: revisit fission applications

Unknown ^{88}Y(n,2n) cross section from inelastic scattering

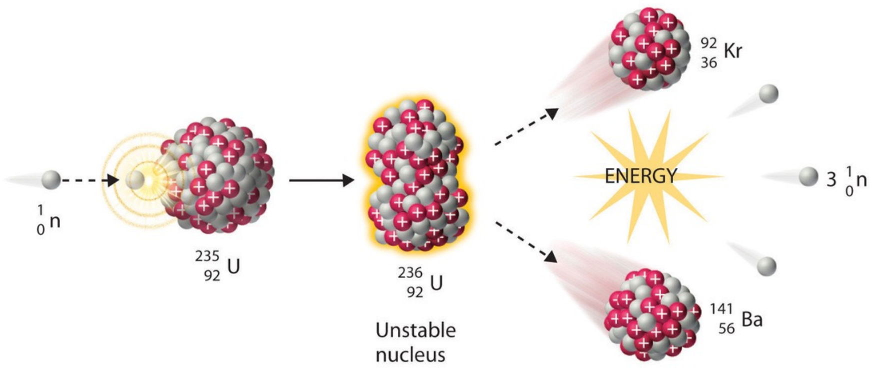


Benchmark: ^{90}Zr(n,2n) cross section is known

Inelastic scattering and transfer reactions provide insights into the fission process

Describing fission challenges theory (and experiment)

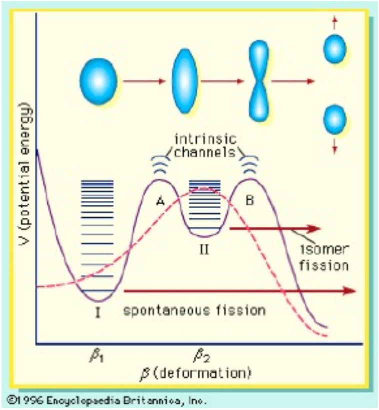
- Descriptions range from phenomenological to microscopic
- Lots of data needed to provide constraints



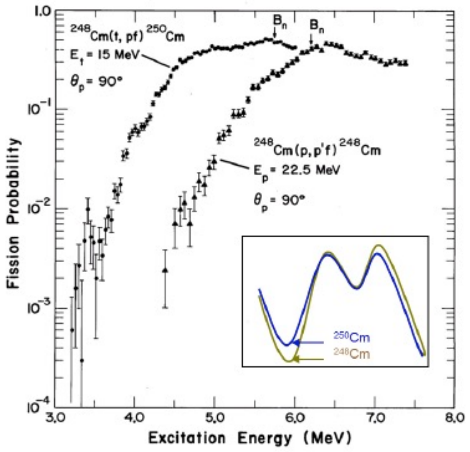
Opportunity: Surrogate fission measurements

- Observe fission properties in coincidence with surrogate ejectile
- Control over energy of fissioning nucleus, including sub-threshold
- Multiple surrogate reactions in one experiment
- Utilize new theory tools that track fission properties

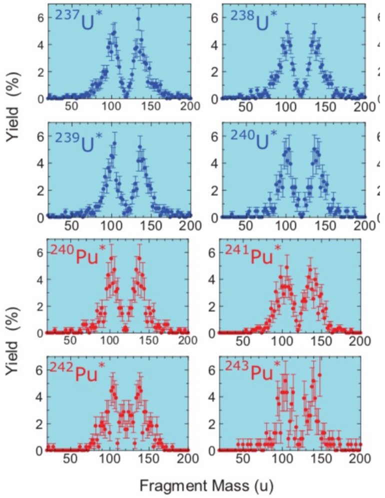
Schematic view of fission



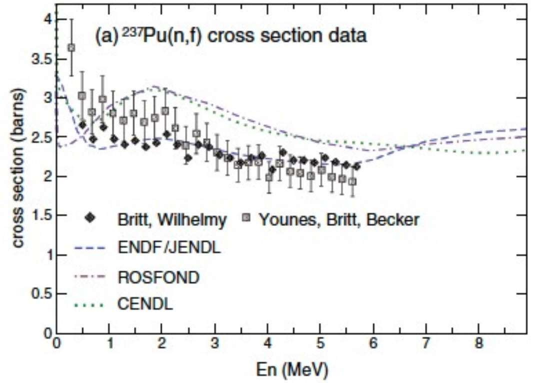
Fission barriers from surrogate data
Back, EPJConf. 232, 03002 (2020)



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

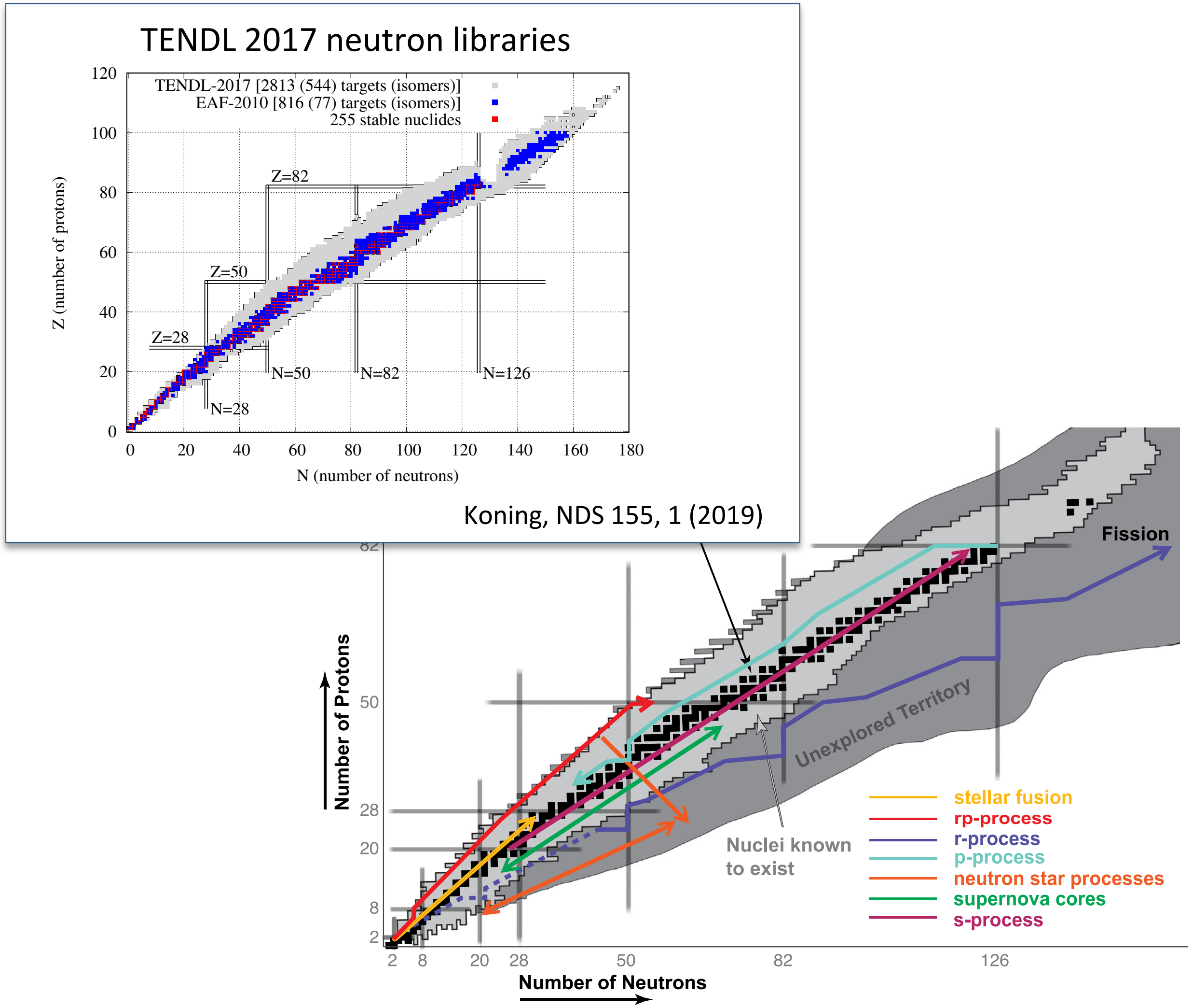


^{237}Pu(n,f) from surrogate measurement
Huges et al, PRC 90, 014304 (2014)



Moving far from stability brings additional challenges for theory

- Challenges away from stability:
  - Extrapolations become unreliable: optical models, γ strength functions, level densities
  - Uncertainties are unknown: need to go beyond ‘plugging in’ all different models supplied by HF codes
  - Statistical descriptions are limited to regions of high level density
- Opportunities:
  - Inverse-kinematics experiments at radioactive beam facilities
- Needs:
  - Develop and incorporate information from microscopic theories
  - identify suitable experiments to validate and inform theories

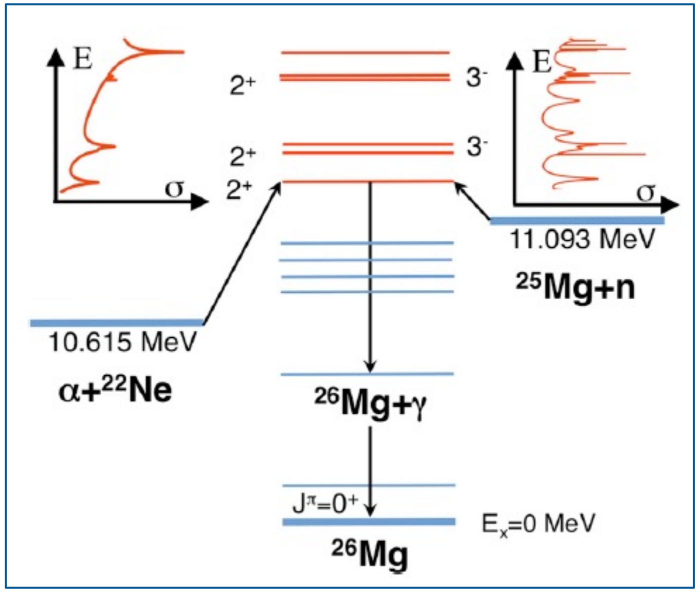


Koning, NDS 155, 1 (2019)

Indirect methods for direct and resonance reactions

- Challenges:
  - Cross sections for charged-particle reactions become vanishingly small at low energies
  - Screening effects in astrophysical environments and the lab are different
- Opportunities:
  - ANC method (Asymptotic Normalization Constant)
  - Trojan-Horse method
  - Coulomb dissociation
- Theory developments:
  - Reduce model dependence of results
  - Provide overall consistent descriptions
  - Optical models for nucleons and composite particles

Closer to drip lines, we will face situations similar to those we see now in lighter nuclei…



Massimi et al, PLB (2017)

…but with less structure knowledge!

Developing indirect reaction methods provides benefits for theory, experiments, and applications

- Theory and experiment are closely connected and rely on each other – this is particularly true for indirect reaction studies

- Having complementary indirect methods is important as no one approach covers all needs and cross-checks are needed

- Fully developing indirect methods will
  - test our nuclear structure and reaction theories
  - further our understanding of the underlying reaction mechanism
  - allow us to determine important unknown cross sections

A thank you to my collaborators:

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Thank you!

Hauser-Feshbach formalism for compound reactions

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

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

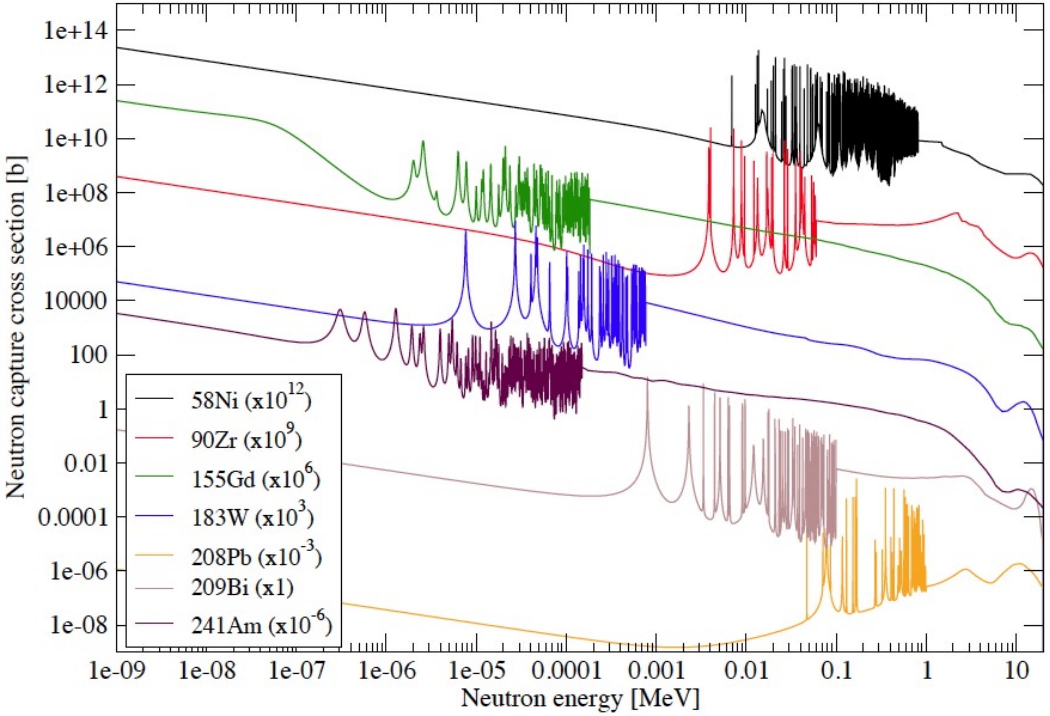
$$G_{\chi}^{CN}(E,J,\pi) = \frac{\sum_{l's'} T_{\chi l's'}^{J}\ \rho_{I'}(U')}{\sum_{\chi''l''s''} \int T_{\chi''l''s''}^{J}\ \rho_{I''}(U')\, dE_{\chi''}}$$

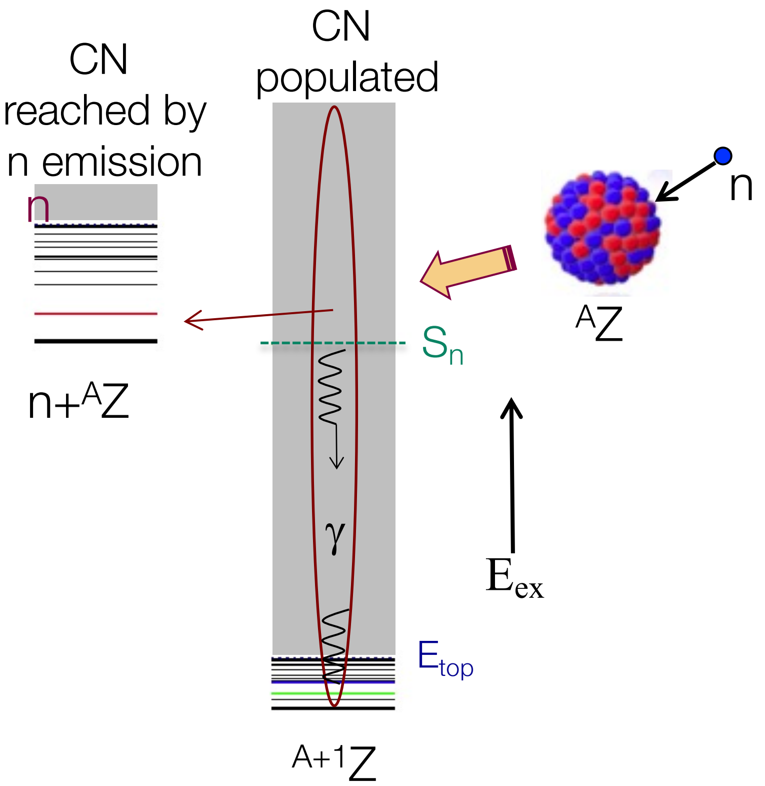
Need

- Transmission coefficients T_{χ} for all channels χ: neutron, proton, charged particles, γ, fission
- Level densities
- Discrete levels with J, π
- Width fluctuation correction WFC factors

Neutron capture reactions

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





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