Capability to address cross section needs for unstable isotopes

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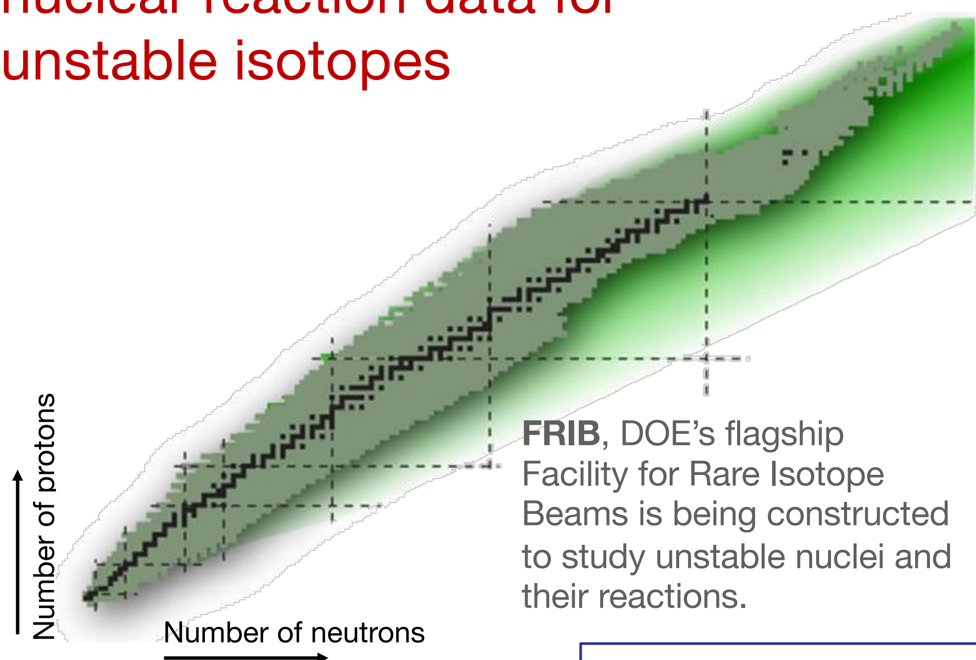
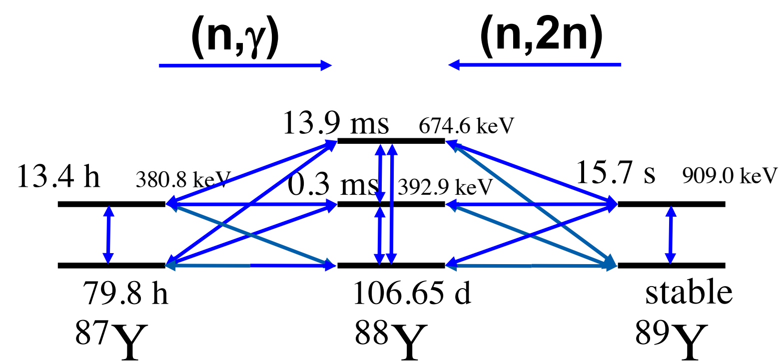
Cross-cutting need:
Cross sections for unstable nuclei

Formidable challenge:
nuclear reaction data for unstable isotopes



FRIB, DOE's flagship Facility for Rare Isotope Beams is being constructed to study unstable nuclei and their reactions.

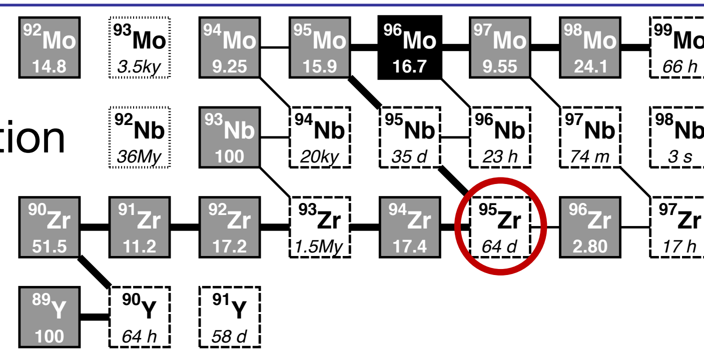
National security:



Understanding nuclear reaction networks involving RadChem tracers is critical to interpret past test results and predict performance.

Nuclear energy:
Cross sections are needed to simulate nuclear energy generation and waste.

Nuclear astrophysics:
Understanding the production of the heavy elements requires knowledge of neutron capture cross sections



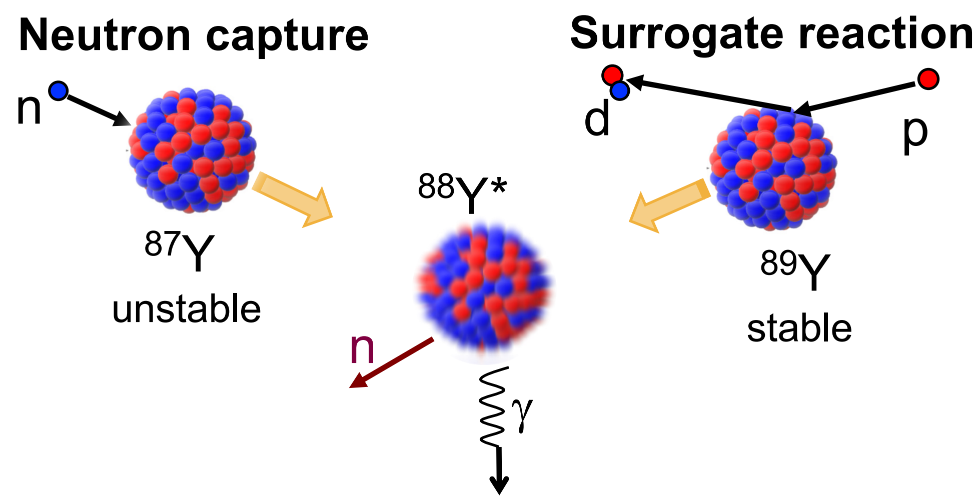
s-process path near ^{95}Zr

Addressing current reaction data needs requires theory & experiment

Capability: Determining challenging cross sections indirectly with surrogate reaction experiments and theory

Surrogate reactions method:

- Replace n + unstable target by a light-ion "surrogate" reaction on a stable target.
- Measure the decay of the compound (CN) nucleus.



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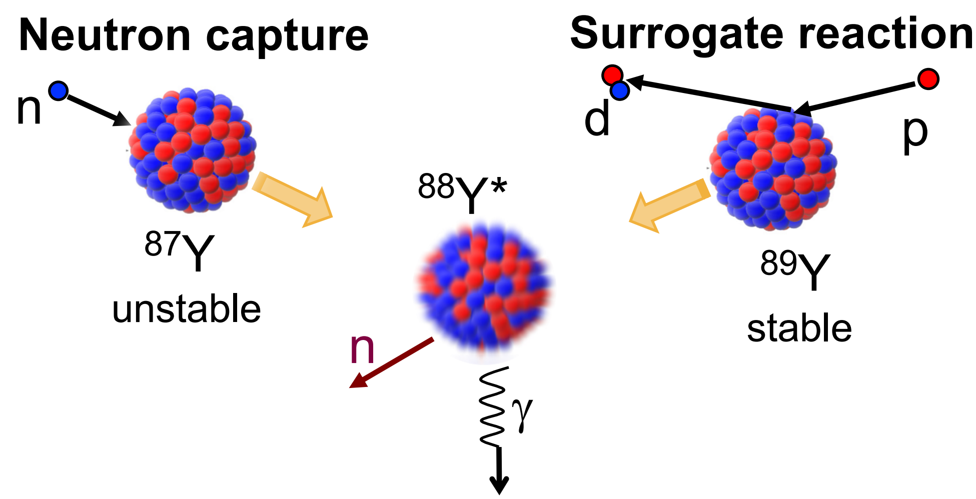

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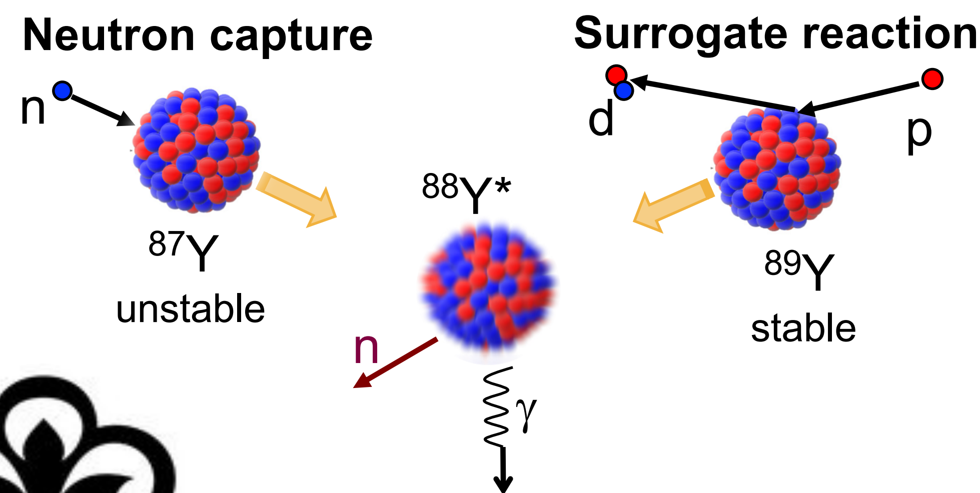
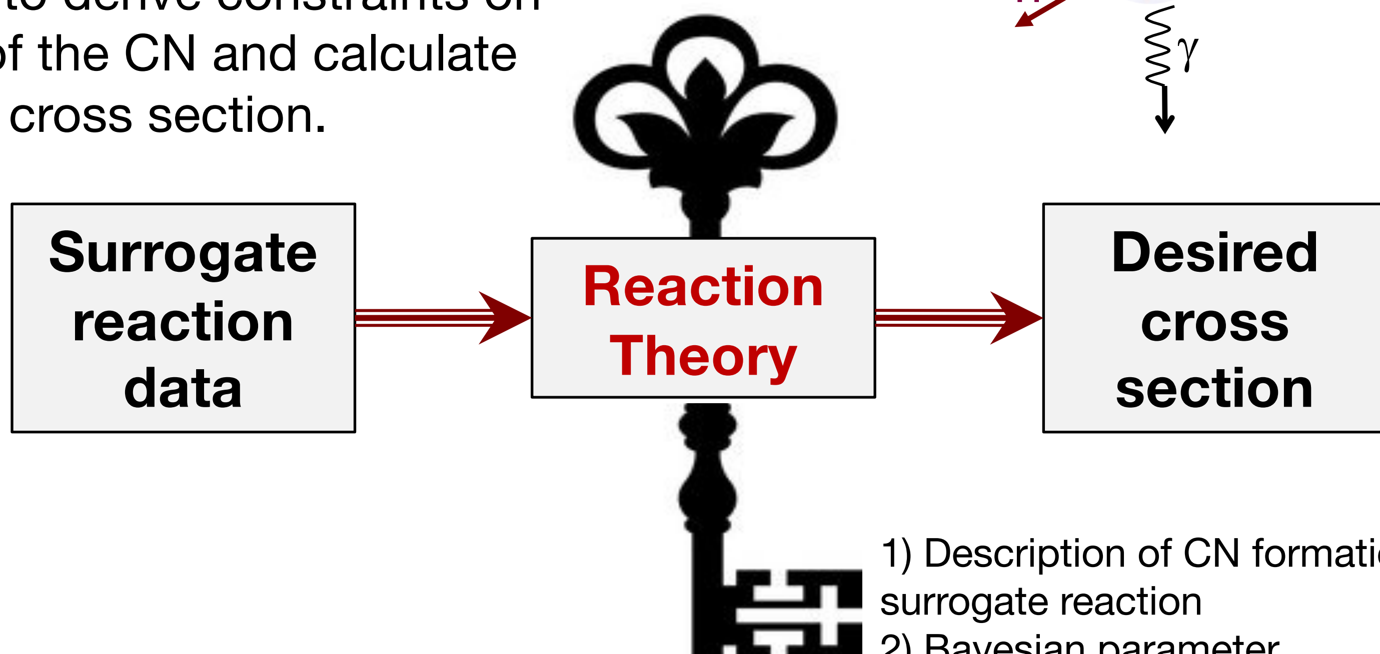
Surrogate reactions method:

- Replace n + unstable target by a light-ion "surrogate" reaction on a stable target.
- Measure the decay of the compound (CN) nucleus.
- Use theory to derive constraints on the decay of the CN and calculate the desired cross section.



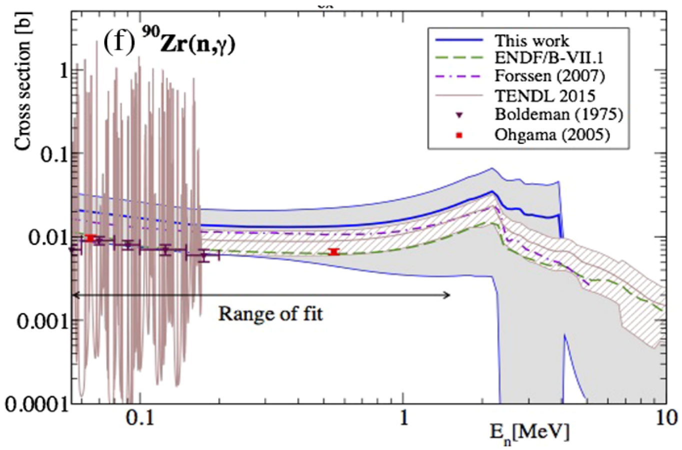


1) Description of CN formation in surrogate reaction
2) Bayesian parameter determination for decay model

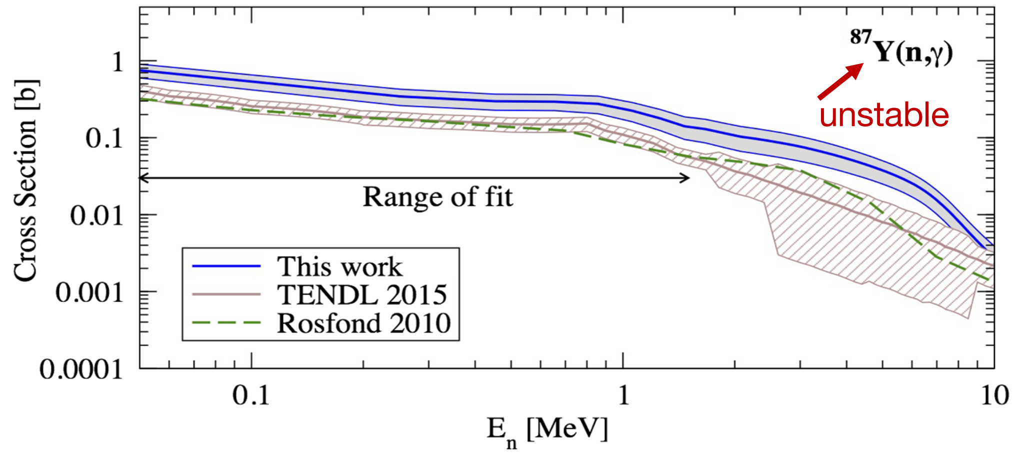
Reaction theory is key to determining reliable cross sections

Demonstrating the surrogate method for neutron capture

Escher et al. PHYSICAL REVIEW LETTERS **121,** 052501 (2018)



✓ **Benchmark:** ^{90}Zr(n,γ) from ^{92}Zr(p,dγ)



Application: ^{87}Y(n,γ) cross section from ^{89}Y(p,dγ)

Demonstrating the surrogate method for neutron capture

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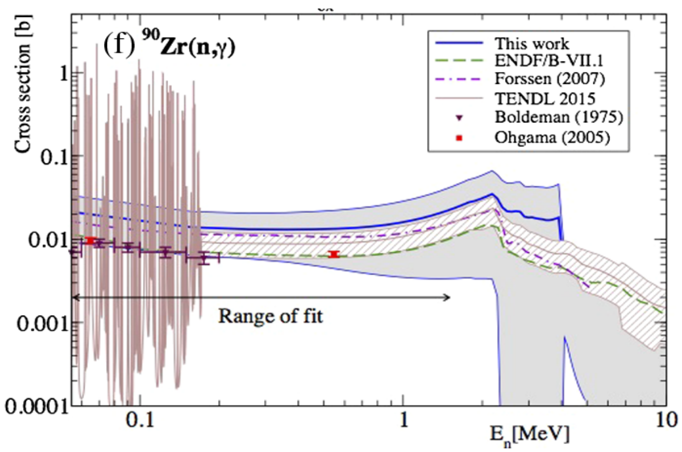
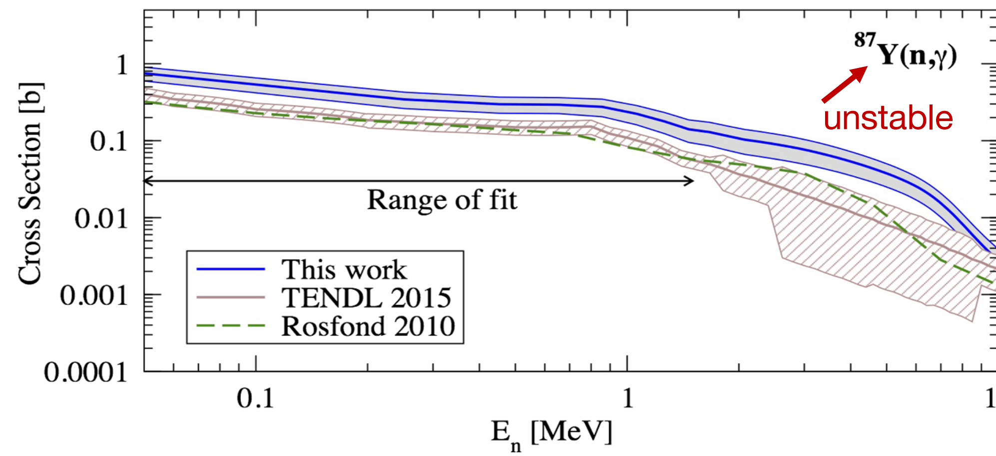
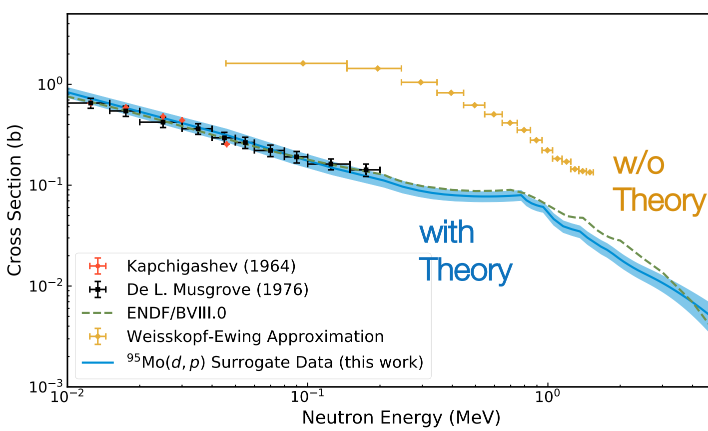




✓ **Benchmark:** ^{90}Zr(n,γ) from ^{92}Zr(p,dγ)

Application: ^{87}Y(n,γ) cross section from ^{89}Y(p,dγ)

PHYSICAL REVIEW LETTERS Ratkiewicz, Cizewski, Escher et al. (2019)



✓ **Benchmark:** ^{95}Mo(n,γ) cross section from ^{95}Mo(d,pγ)

Excellent agreement!

Key features:

- Advanced theoretical description of surrogate reaction mechanism.
- Bayesian parameter determination for decay model → UQ is built-in!
- The Surrogate method does not use auxiliary quantities which are unavailable for unstable isotopes.

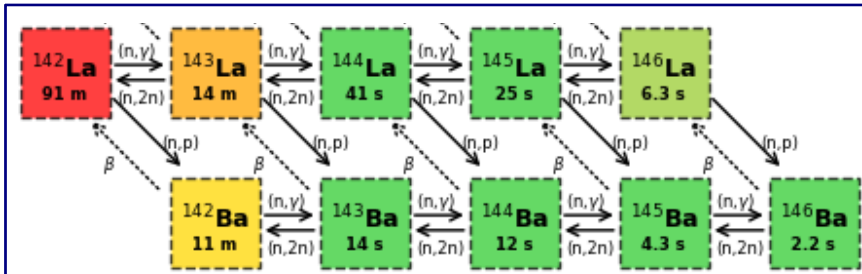
New developments in reaction theory enabled successful determination of neutron capture cross sections

Applying the surrogate method in inverse-kinematics experiments

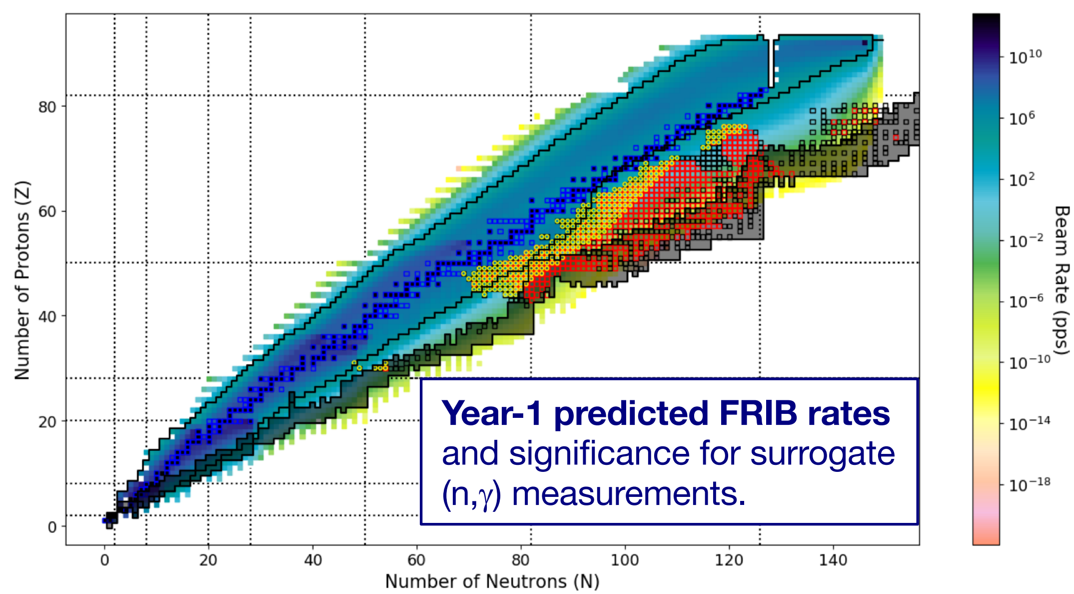
^{143}**Ba(n,γ)** from ^{143}**Ba(d,pγ)** inverse-kinematics measurement at Argonne/ATLAS with CARIBU/GODDESS (ORRUBA + Gammasphere)
Approved (Cizweski et al)

^{93}**Sr(n,γ)** from ^{93}**Sr(d,pγ)** inverse-kinematics measurement at TRIUMF with TIGRESS/SHARC
Submitted (Hughes et al)

^{117}**Cd(n,γ)** from ^{117}**Cd(d,pγ)** inverse-kinematics measurement at NSCL with ORRUBA + Gretina
Submitted (Ratkiewicz et al)



^{143}**Ba production and destruction**
Last stable Ba isotope is ^{138}Ba

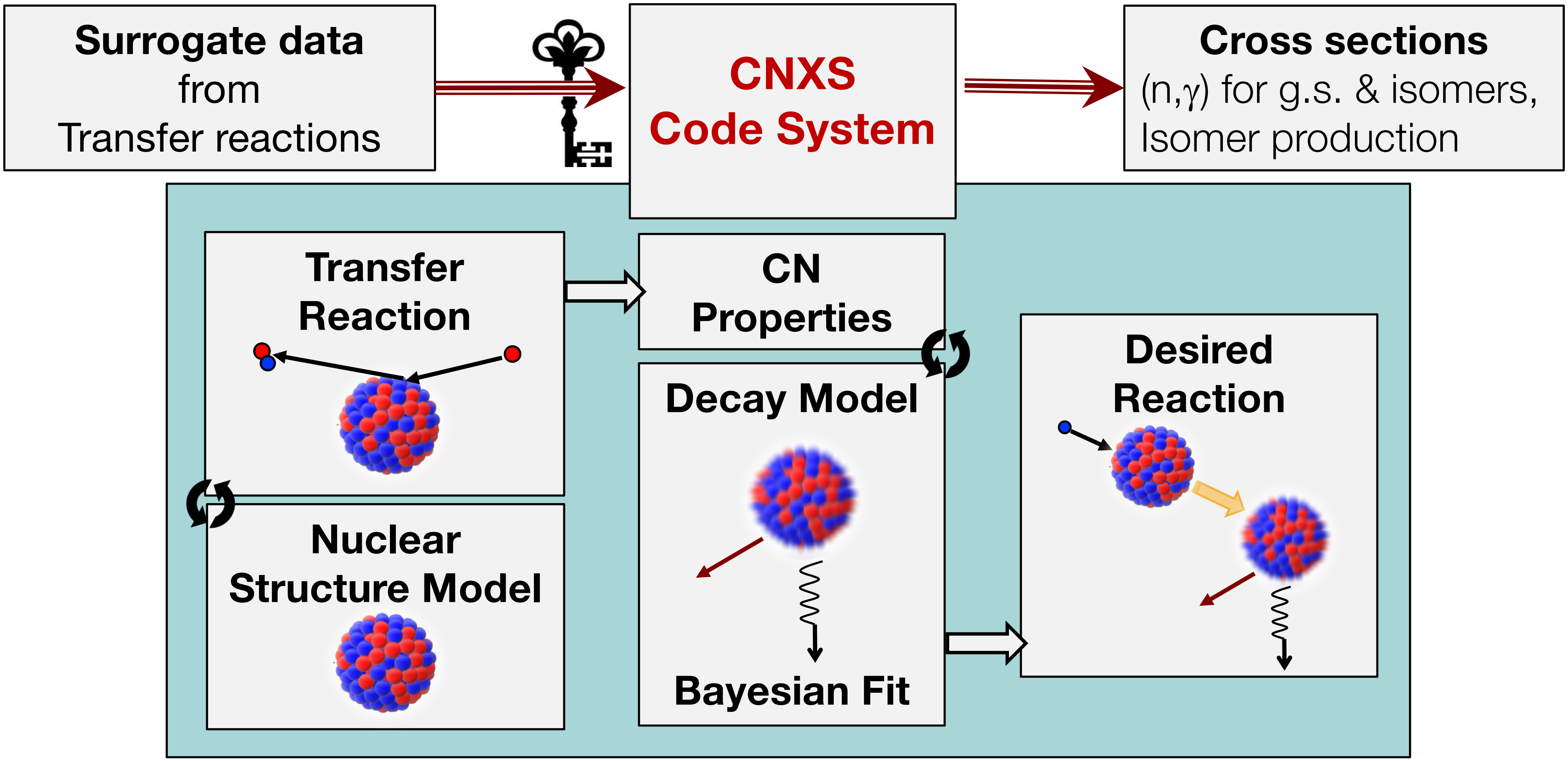


Year-1 predicted FRIB rates and significance for surrogate (n,γ) measurements.

Figures courtesy A. Ratkiewicz (LLNL).

We are building on our developments to determine cross sections from inverse-kinematics experiments with radioactive beams

How we accomplish the extraction of cross sections from surrogate reaction data



The (p,d) transfer reaction:

- Structure: Deep holes – Dispersive optical model
- Reaction: 2-step reactions

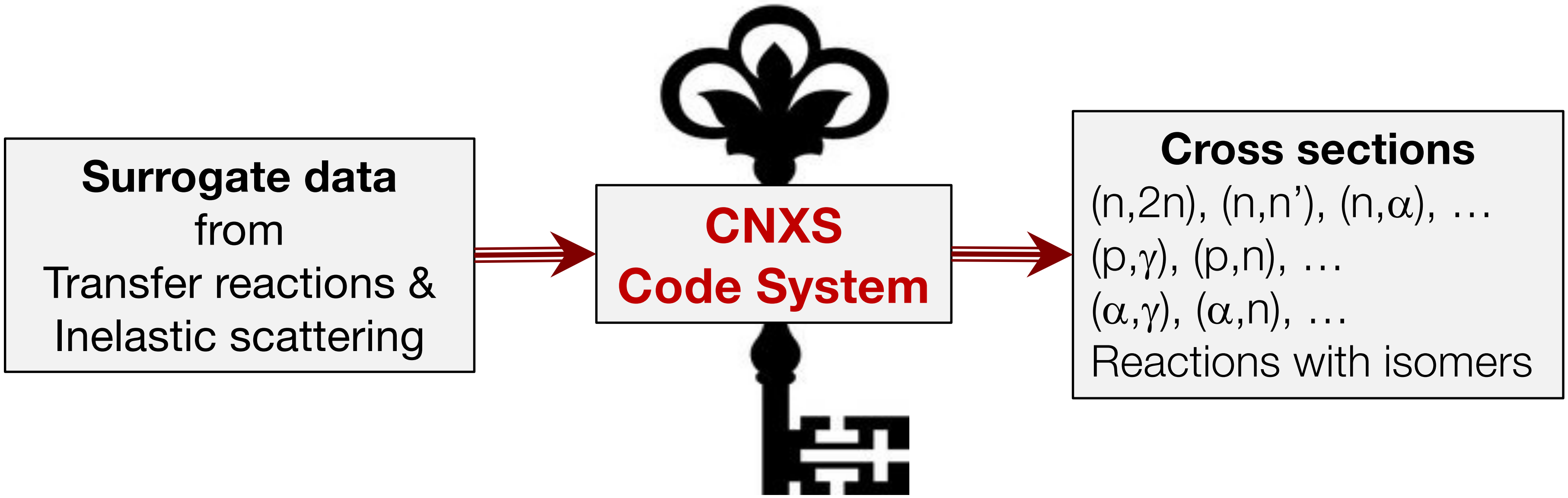
CN Decay:

- Level densities & γ strength parameters from Bayesian fits
- Method does not use D_0 or $\langle\Gamma_\gamma\rangle$

Final cross section:

- Optical model
- Best-fit Bayesian parameters w/uncertainties

Developing theory to address further cross section needs



Developing theory to address further cross section needs

Surrogate data
from
Transfer reactions &
Inelastic scattering

→

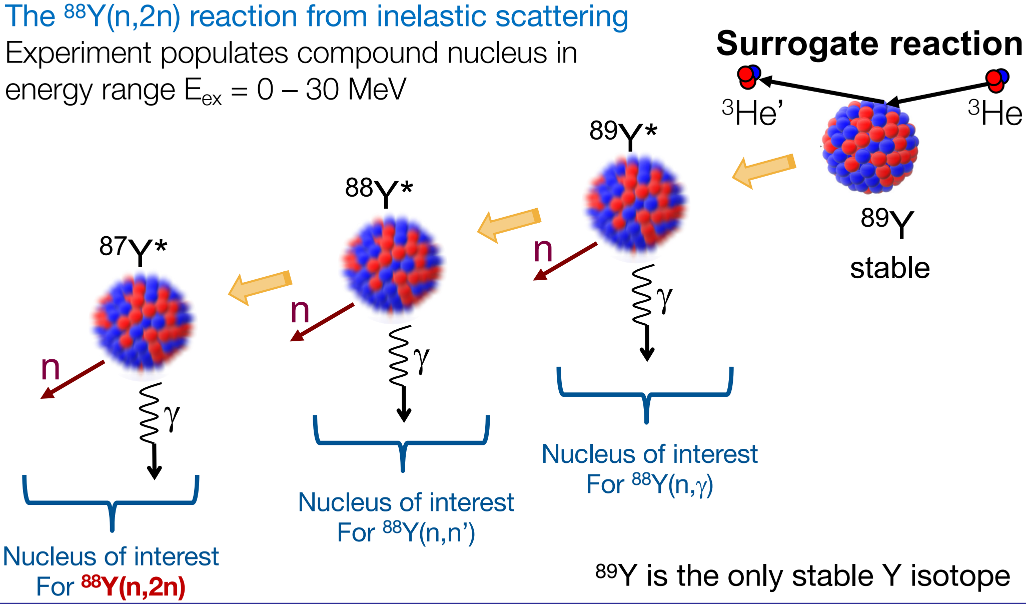
CNXS
Code System

→

Cross sections
(n,2n), (n,n’), (n,α), …
(p,γ), (p,n), …
(α,γ), (α,n), …
Reactions with isomers

Future Theory Developments

The ^{88}Y(n,2n) reaction from inelastic scattering
Experiment populates compound nucleus in energy range E_{ex} = 0 – 30 MeV



Inelastic scattering as surrogate
⇒ **Need:** Integrated structure and inelastic scattering description

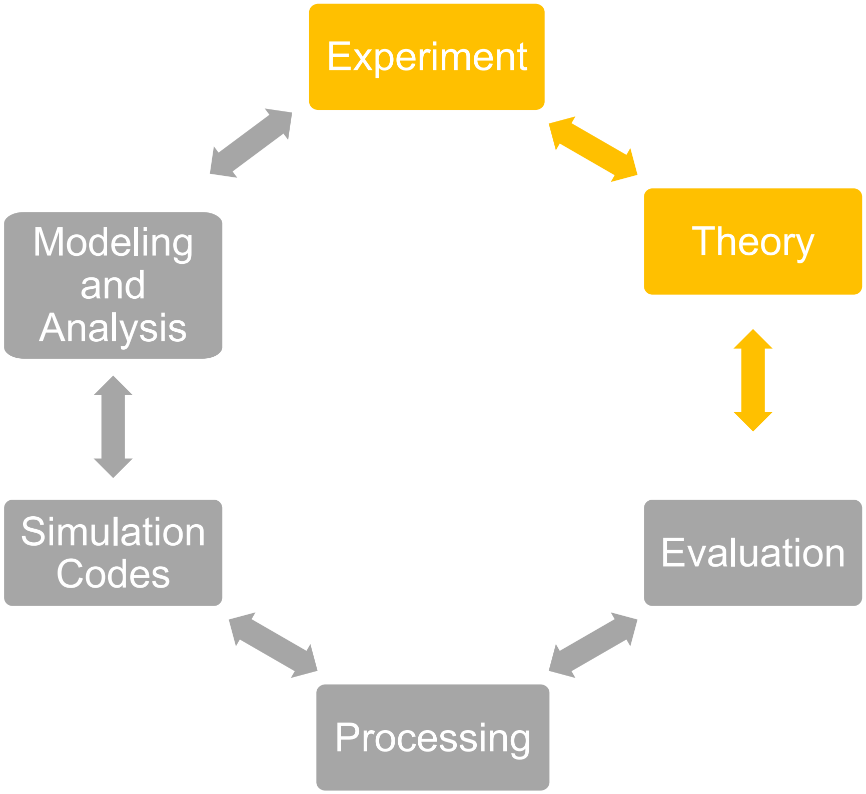
Reactions on deformed nuclei
⇒ **Need:** Extended reaction formalism and structure description

Utilizing other experimental observables
⇒ **Need:** updated CN decay model coupled to Bayesian parameter determination

Need: Full assessment of uncertainties.

With additional theory developments, we can generalize the surrogate approach into a powerful method for a wide range of reactions

How does this capability fit into the larger context?



Data pipeline:

Capability enables the production of important cross section data:

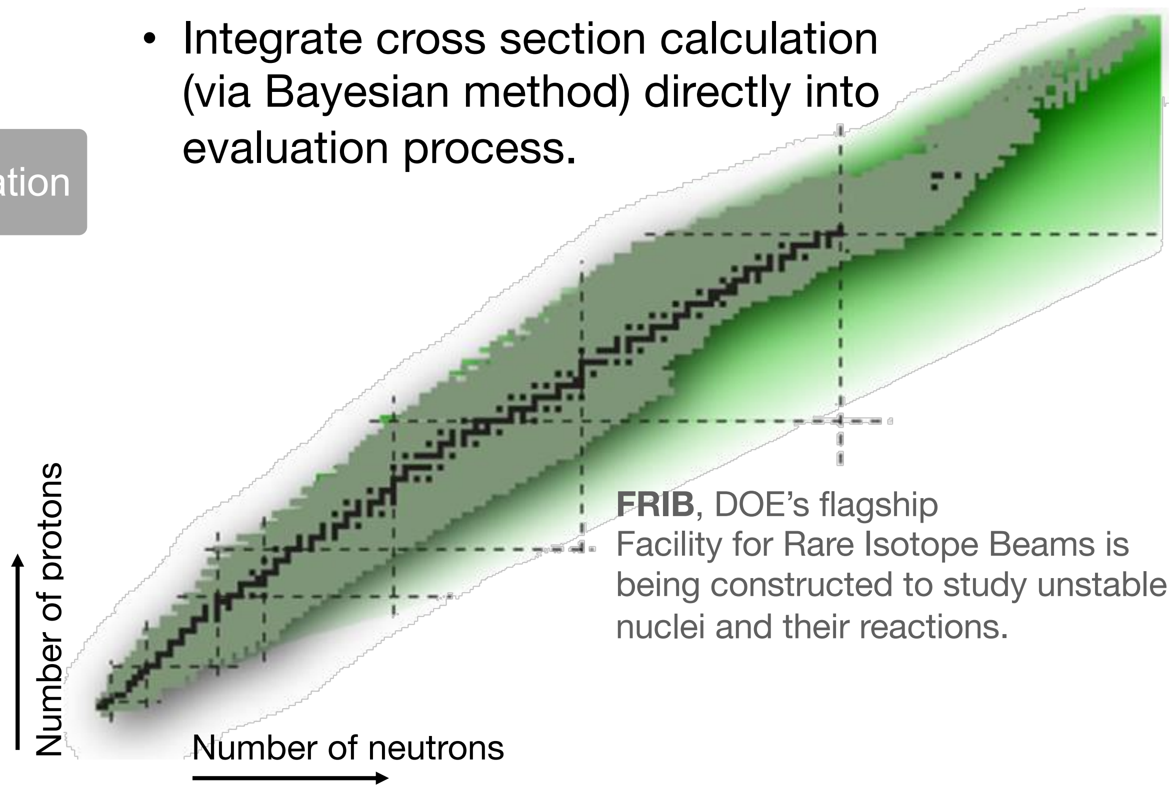
- Treat cross section + uncertainty like a new data set;

  or

- Integrate cross section calculation (via Bayesian method) directly into evaluation process.

Radioactive beam facilities:

Capability enables indirect measurements for radioactive isotopes currently not accessible



FRIB, DOE's flagship Facility for Rare Isotope Beams is being constructed to study unstable nuclei and their reactions.

New capability to fill critical gaps in reaction data and exploit opportunities for 'data harvesting' at FRIB

Thank you!

Summary

Obtaining reliable **data for nuclear reactions on unstable isotopes** remains an extremely important task and a formidable challenge. Cross sections for neutron-induced reactions are particularly elusive as both projectile and target in the reaction are unstable.

We have developed a **solution** for this problem: The **surrogate reaction method** uses an alternative, light-ion reaction to create the intermediate (compound) nucleus of interest and measures its subsequent decay. This data provides constraints for the models describing the decay of the compound nucleus, which dominate the uncertainties of the cross section calculations.

Key to a successful determination of the desired reaction cross section is a proper theoretical description of the surrogate reaction mechanisms.

We have **demonstrated the approach** for (p,d) and (d,p) transfer reactions in the Y-Zr-Mo region and determined cross sections for both known (benchmark) and unknown neutron capture reactions.

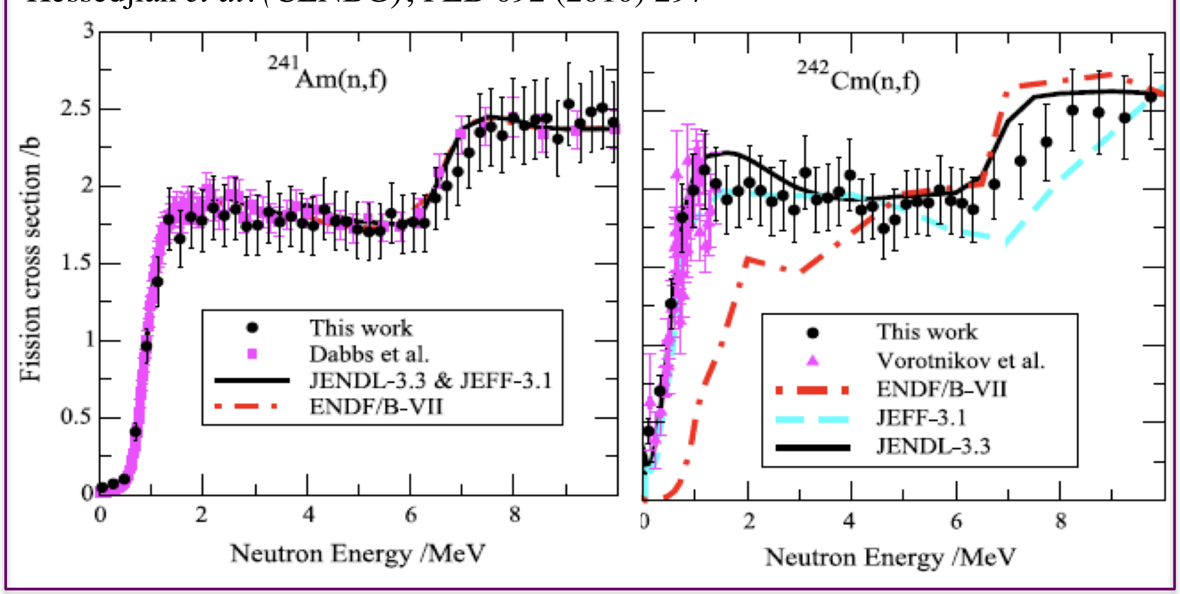
The method makes **no use of auxiliary constraining quantities**, such as neutron resonance data, or average radiative widths, which are not available for short-lived isotopes; thus is can be applied to isotopes away from stability using inverse-kinematics experiments.

The method can be used to determine cross sections of other reactions of interest, provided the commensurate theory is developed. **Uncertainty quantification is integrated** into the approach via Bayesian methods.

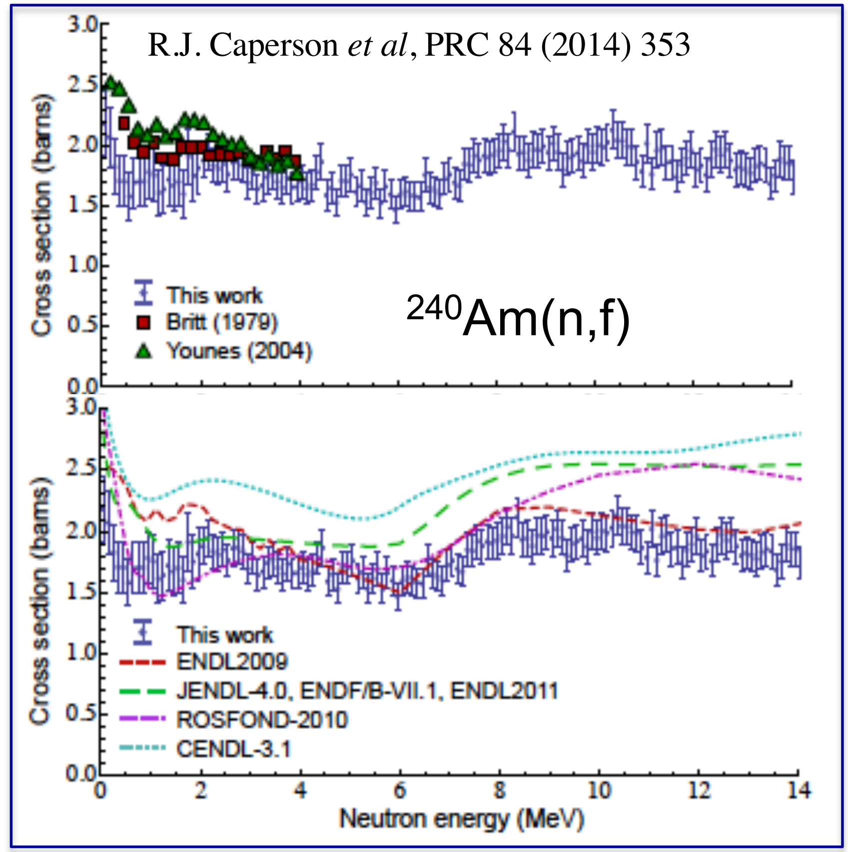
The approach developed represents a **new capability for filling critical gaps in reaction data** and **exploiting opportunities for 'data harvesting' at FRIB**.

(n,f) cross sections from surrogate measurements

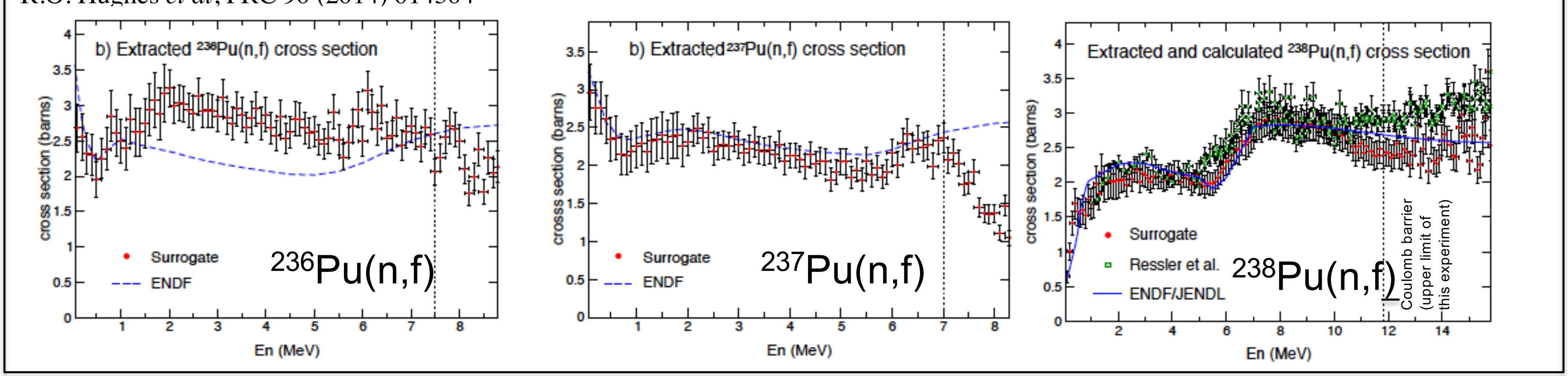
- ✓ Complement and extend indirect and direct measurements
- ✓ Typically agree within 10-15% with benchmarks
- ✓ Make use of approximation schemes



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



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



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

What is a surrogate reaction?

sur·ro·gate

ˈsərəgət,ˈsərəˌgāt/

noun

a substitute

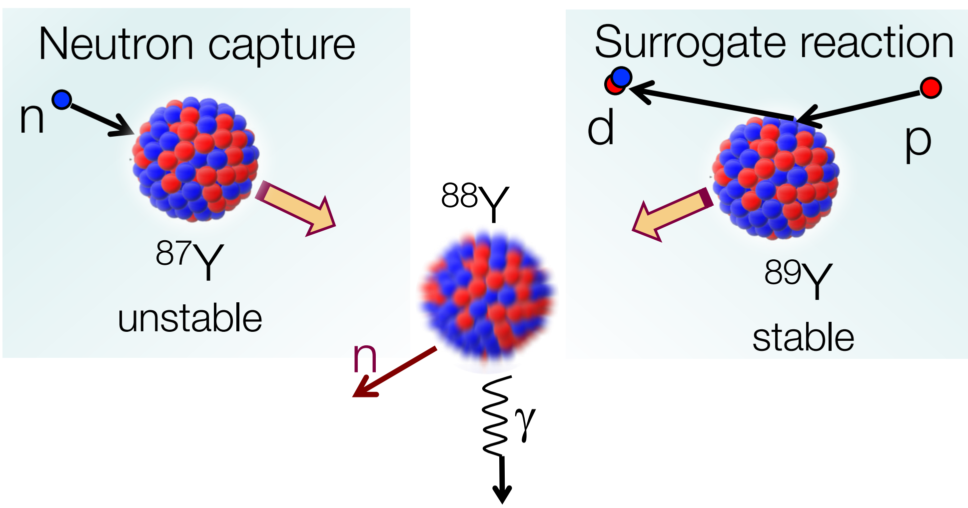
surrogate reaction

a nuclear reaction that is used in place of a more experimentally challenging (“desired”) reaction in order to indirectly infer properties of the desired reaction

We measure deuterons and gamma-rays in coincidence from the surrogate reaction

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

Solution: Constrain calculation with surrogate data



From experiment

$$P_{(p,d\gamma)}(E) = \frac{N_{(p,d\gamma)}(E)}{\varepsilon_\gamma N_{(p,d)}(E)}$$

From theory

To be determined

A Surrogate experiment gives

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

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

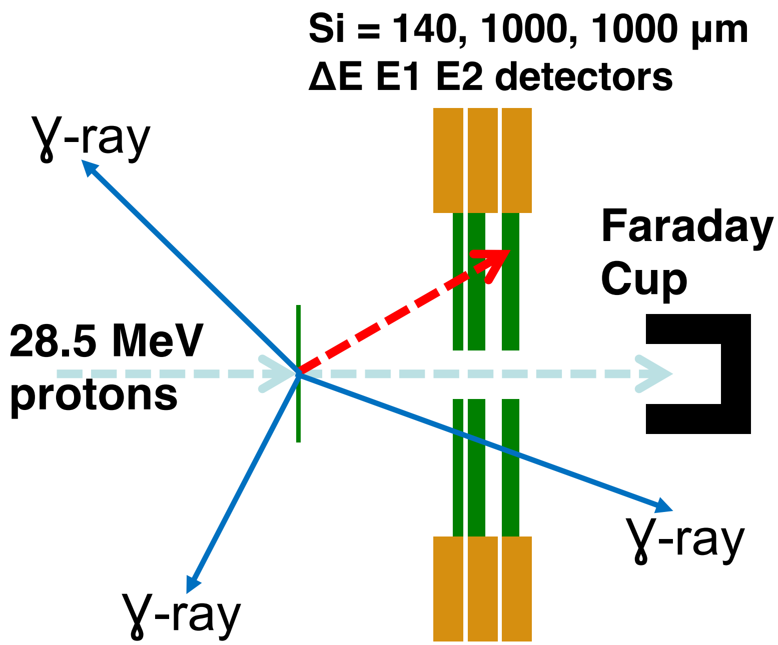
We use theory to extract the desired cross section

Surrogate experiment

$$P_\gamma = \frac{N_{d\gamma}(E)}{\varepsilon_\gamma N_d(E)}$$

Numerator: Number of particle-gamma coincidences

Denominator: Number of particle singles



Particle: energy, timing, angle and dE-E allows particle ID
Gamma-rays: energy, timing and angle

J.E. Escher, J.T. Burke, et al," *EPJ Web of Conf.* **146**, 12014 (2017)

Relevant Publications

Reviews:

J.E. Escher, J.T. Burke, F.S. Dietrich, N.D. Scielzo, I.J. Thompson, and W. Younes, “Compound-nuclear reaction cross sections from surrogate measurements,” *Rev. Mod. Phys.* **84**, 353 (2012)

B.V. Carlson, J.E. Escher, and M.S. Hussein, “Theoretical descriptions of compound-nuclear reactions: open problems & challenges,” *J. Phys. G* **41**, 094003 (2014)

A. Arcones,… , J.E. Escher et al. (43 authors), “White paper on nuclear astrophysics and low energy nuclear physics Part 1: Nuclear astrophysics,” *Progress of Particle and Nuclear Physics* **84**, 1 (2017)

Letters, regular journal articles, and refereed proceedings:

J.E. Escher, J.T. Burke, R.O. Hughes, N.D. Scielzo, R.J. Casperson, S. Ota, H.I. Park, A. Saastamoinen, and T.J. Ross, “Constraining neutron capture cross sections for unstable nuclei with surrogate reaction data and theory,” *Phys. Rev. Lett.* ***121***, 52501 (2018)

Ratkiewicz, J.A. Cizewski, J.E. Escher, G. Potel, J.T. Burke, R.J. Casperson, M. McCleskey, R.A.E. Austin, S. Burcher, R.O. Hughes, B. Manning, S.D. Pain, W.A. Peters, S. Rice, T.J. Ross, N.D. Scielzo, C. Shand, and K. Smith, “Towards Neutron Capture on Exotic Nuclei: Demonstrating (d,pγ) as a Surrogate Reaction for (n,γ),” *Phys. Rev. Lett.*, in press (2019)

G. Potel, G. Perdikakis, B.V. Carlson, M.C. Atkinson, W.H. Dickhoff, J.E. Escher, M.S. Hussein, J. Lei, W. Li, A.O. Macchiavelli, A.M. Moro, F.M. Nunes, S.D. Pain, and J. Rotureau, “Toward a complete theory for predicting inclusive deuteron breakup away from stability,” *Europ. Phys. J. A* **53**, 178 (2017)

Publications (cont.)

J.E. Escher, J.T. Burke, R.J. Casperson, R.O. Hughes, S. Ota, and N.D. Scielzo, “Capture cross sections from (p,d) reactions,” *EPJ Web of Conf.* **146**, 12014 (2017)

J.E. Escher, A.P. Tonchev, J.T. Burke, P. Bedrossian et al., “Compound-nuclear reactions with unstable nuclei: Con- straining theory through innovative experimental approaches,” *EPJ Web of Conf.* **122**, 12001 (2016)

J. Benstead, J.A. Tostevin, J.E. Escher, J.T. Burke, R.O. Hughes, S. Ota, R.J. Casperson, and I.J. Thompson, “Calculations of Compound Nucleus Spin-Parity Distributions Populated via the (p,t) Reaction in Support of Surrogate Neutron Capture Measurements,” *EPJ Web of Conf.* **122**, 12002 (2016)

R.O. Hughes, J.T. Burke, R.J. Casperson, J. E. Escher, S. Ota, J.J. Ressler, N.D. Scielzo, R.A.E. Austin, B. Abromeit, N.J. Foley, E. McCleskey, M. McCleskey, H.I. Park, T.J. Ross, and A. Saastamoinen, “Investigation of 88Y via (p,dγ) reactions,” *Phys. Rev. C* **93**, 024315 (2016)

S. Ota, J.T. Burke, R.J. Casperson, J.E. Escher, R.O. Hughes, J.J. Ressler, N.D. Scielzo, and I.J. Thompson, “Spin differences in the ^{90}Zr compound nucleus induced by (p,p′) inelastic scattering and (p,d) and (p,t) transfer reactions,” *Phys. Rev. C* **92**, 054603 (2015)

T.J. Ross, R.O. Hughes, J.M. Allmond, C.W. Beausang, C.T. Angell, M.S. Basunia, D.L. Bleuel, J.T. Burke, R.J. Casperson, J.E. Escher, P. Fallon, R. Hatarik, J. Munson, S. Paschalis, M. Petri, L.W. Phair, J.J. Ressler, and N.D. Scielzo, “Spectroscopy of ^{153}Gd and ^{157}Gd using the (p,d-γ) Reaction*,” Phys. Rev. C* **90**, 044323 (2014)

Publications (cont.)

R. Casperson, J.T. Burke, N.D. Scielzo, J.E. Escher, E. McCleskey, M. McCleskey, A. Saastamoinen, A. Spiridon, A. Ratkiewicz, A. Blanc, M. Kurokawa, and R.G. Pizzone, “Measurement of the ^{240}Am(n,f) cross section using the surrogate ratio method,” *Phys. Rev. C* **90**, 034601 (2014)

R.O. Hughes, C.W. Beausang, T.J. Ross, J.T. Burke, R.J. Casperson, N. Cooper, J.E. Escher, K. Gell, E. Good, P. Humby, M. McCleskey, A. Saastimoinen, T.D. Tarlow, and I.J. Thompson, “Deducing the σ(^{236}Pu(n,f)), σ(^{237}Pu(n,f)) and σ(238Pu(n,f)) cross sections using (p,t), (p,d) and (p,p) surrogate reactions,” *Phys. Rev. C* **90**, 014304 (2014)

J.E. Escher, J.T. Burke, F.S. Dietrich, J.J. Ressler, N.D. Scielzo, and I.J. Thompson, “Neutron-capture cross sections from indirect measurements,” *EPJ Web of Conferences* **21**, 01001 (2012).

J.E. Escher and F.S. Dietrich, ”Cross sections for neutron capture from surrogate measurements: An examination of Weisskopf-Ewing and ratio approximations,” *Phys. Rev. C* **81**, 024612 (2010)

J.E. Escher and F. S. Dietrich, “Determining (n,f) cross sections for actinide nuclei indirectly: An examination of the Surrogate Ratio Method”, *Phys. Rev. C* **74**, 054601 (2006)