Capability to address cross section needs for unstable isotopes

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Workshop for Applied Nuclear Data Activities (WANDA)
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Cross-cutting need: Cross sections for unstable nuclei

Formidable challenge: nuclear reaction data for unstable isotopes

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

Addressing current reaction data needs requires theory & experiment

Cross sections for unstable nuclei

Number of protons

Number of neutrons

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

National security:

\((n,\gamma)\) \hspace{1cm} \((n,2n)\)

13.9 ms \hspace{1cm} 13.9 ms

13.4 h \hspace{1cm} 380.8 keV

0.3 ms \hspace{1cm} 392.9 keV

674.6 keV \hspace{1cm} 909.0 keV

79.8 h \hspace{1cm} 106.65 d

87 Y \hspace{1cm} 88 Y \hspace{1cm} 89 Y

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

Nuclear astrophysics:

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

s-process path near \(^{95}\text{Zr}\)
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.

\[
n + 87\text{Y} \rightarrow 88\text{Y}^* \\
88\text{Y}^* \rightarrow 89\text{Y} + \gamma
\]
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.

![Diagram of neutron capture and surrogate reaction]
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.
- Use theory to derive constraints on the decay of the CN and calculate the desired cross section.

Neutron capture

$\text{Surrogate reaction data} \xrightarrow{\text{Reaction Theory}} \text{Desired cross section}$

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

Benchmark: $^{90}\text{Zr}(n,\gamma)$ from $^{92}\text{Zr}(p,d\gamma)$

Application: $^{87}\text{Y}(n,\gamma)$ cross section from $^{89}\text{Y}(p,d\gamma)$
Demonstrating the surrogate method for neutron capture

**Escher et al.**

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

**Benchmark:** $^{90}\text{Zr}(n,\gamma)$ from $^{92}\text{Zr}(p,d\gamma)$

**Application:** $^{87}\text{Y}(n,\gamma)$ cross section from $^{89}\text{Y}(p,d\gamma)$

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**Ratkiewicz, Cizewski, Escher et al. (2019)**

**Benchmark:** $^{95}\text{Mo}(n,\gamma)$ cross section from $^{95}\text{Mo}(d,p\gamma)$

**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

$^{143}\text{Ba}(n,\gamma)$ from $^{143}\text{Ba}(d,p\gamma)$ inverse-kinematics measurement at Argonne/ATLAS with CARIBU/GODDESS (ORRUBA + Gammasphere)
Approved (Cizweski et al)

$^{93}\text{Sr}(n,\gamma)$ from $^{93}\text{Sr}(d,p\gamma)$ inverse-kinematics measurement at TRIUMF with TIGRESS/SHARC
Submitted (Hughes et al)

$^{117}\text{Cd}(n,\gamma)$ from $^{117}\text{Cd}(d,p\gamma)$ inverse-kinematics measurement at NSCL with ORRUBA + Gretina
Submitted (Ratkiewicz et al)

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

$^{143}\text{Ba}$ production and destruction
Last stable Ba isotope is $^{138}\text{Ba}$

Figures courtesy A. Ratkiewicz (LLNL)

Year-1 predicted FRIB rates and significance for surrogate $(n,\gamma)$ measurements.
How we accomplish the extraction of cross sections from surrogate reaction data

Surrogate data from Transfer reactions → CNXS Code System → Cross sections \((n,\gamma)\) for g.s. & isomers, Isomer production

Transfer Reaction → CN Properties → Desired Reaction

Nuclear Structure Model → Decay Model → Bayesian Fit

The \((p,d)\) transfer reaction:
- Structure: Deep holes – Dispersive optical model
- Reaction: 2-step reactions

CN Decay:
- Level densities & \(\gamma\) strength parameters from Bayesian fits
- Method does not use \(D_0\) or \(<\Gamma_\gamma>\)

Final cross section:
- Optical model
- Best-fit Bayesian parameters w/uncertainties
Developing theory to address further cross section needs

**Surrogate data**
from
Transfer reactions &
Inelastic scattering

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**CNXS**
Code System

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**Cross sections**
(n,2n), (n,n’), (n,α), …
(p,γ), (p,n), …
(α,γ), (α,n), …
Reactions with isomers
Developing theory to address further cross section needs

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

**Surrogate data** from Transfer reactions & Inelastic scattering

**Cross sections**
- $(n,2n)$, $(n,n')$, $(n,\alpha)$, ...
- $(p,\gamma)$, $(p,n)$, ...
- $(\alpha,\gamma)$, $(\alpha,n)$, ...

Reactions with isomers

**CNXS Code System**

**Future Theory Developments**

- **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.

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The $^{88}\text{Y}(n,2n)$ reaction from inelastic scattering

Experiment populates compound nucleus in energy range $E_{\text{ex}} = 0 - 30$ MeV

$^{89}\text{Y}$ is the only stable Y isotope

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

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

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

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

R.J. Caperson et al, PRC 84 (2014) 353
What is a surrogate reaction?

**sur·ro·gate**
'sərəgət, 'sərəˌɡāt/
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:** $^{87}\text{Y}(n,\gamma)$ calculations are highly uncertain.

**Solution:** Constrain calculation with surrogate data.

A surrogate experiment gives

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

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

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

The new cross section we want.

Well modelled from nuclear theory.

We use theory to extract the desired cross section.
Surrogate experiment

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

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

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

Relevant Publications

Reviews:


Letters, regular journal articles, and refereed proceedings:


Publications (cont.)


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 $\sigma(^{236}$Pu(n,f)), $\sigma(^{237}$Pu(n,f)) and $\sigma(238$Pu(n,f)) cross sections using (p,t), (p,d) and (p,p) surrogate reactions,” *Phys. Rev. C* **90**, 014304 (2014)

