Constraining Neutron-Induced Reactions Through the Surrogate Reaction Method

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with B. Alan, J.E. Escher, J.T. Harke, R.O. Hughes, G. Potel, C. Reingold, and A. Richards

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How do we measure neutron-induced reactions on short-lived radioactive targets?

Option One: a neutron beam incident on a radioactive target ("normal kinematics")

- Neutron beam
- Radioactive target ($T_{1/2} < 100 \text{ d}$)
- Reaction product
- Proton
- Particle detector
- γ detector
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The background from the radioactive target is too high. We can’t do this.

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(gamma detector)

(proton)

(particle detector)

(reaction product)
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Neutrons are radioactive, too. And we can’t make a target out of them (yet).
How do we measure neutron-induced reactions on short-lived radioactive targets? – We can’t!

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We need a different approach!
Using the Surrogate Reaction Method to constrain neutron-induced reactions on radioactive targets

Desired Reaction: impossible to measure

\[ \sigma_{\alpha\chi}(E_a) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi) \]

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Surrogate Reaction: forms the “same” compound nucleus as the desired reaction.

\[ P_{\delta \chi}(E_{ex}) = \sum_{J, \pi} F^C_N(E_{ex}, J, \pi)g^{CN}_\chi(E_{ex}, J, \pi) \]

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Benchmarking \((d,p\gamma)\) as an \((n,\gamma)\) surrogate

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\(^{96}\text{Mo}\) levels from **RIPL-3** (R. Capote et al.)
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- Need to understand:
  - Reaction mechanism.
  - Entry spin distribution.

\(^{96}\text{Mo}\) levels from \text{RIPL-3} (R. Capote \textit{et al.})
Reaction Mechanism: (d,p) revisited for the FRIB era

G. Potel et al.

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)

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) – Potel et al., EPJ 53, 178 (2017)
- Application: Surrogate for $^{95}$Mo(n,γ) with Ratkiewicz, Cizewski, Escher, et al.: Measurements in regular and inverse kinematics, at Texas A&M and ANL, respectively

Thanks to Jutta Escher for this slide!
Correct theoretical description of the CN formation cross section and entry spin distribution are essential!

See G. Potel et al. PRC 92 034611 (2015)
The Experiment: $^{95}\text{Mo}(d,p\gamma)$
A. Ratkiewicz et al., PRL 122, 052502 (2019).

- 140 $\mu$m +1000 $\mu$m segmented telescopes at forward, backward angles.
- Beam energy of 12.5 MeV.
- 0.960 mg/cm$^2$ thick $^{95}\text{Mo}$ target (~97% $^{95}\text{Mo}$, 1.5% $^{96}\text{Mo}$).
- Four Compton-suppressed HPGe clovers at 90, 220, 270, 320 degrees (lab frame).

\[ P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex}) \epsilon_{\gamma}} \]
The Experiment: $^{95}$Mo(d,pγ)
A. Ratkiewicz et al., PRL 122, 052502 (2019).

$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_{\gamma}}$

$R = \left( E_1 + \Delta E_1 \right)\alpha - E_1^\alpha$

Energy Loss (MeV)
Total Energy (MeV)

En > 0
95Mo(d,pγ)
The Experiment: $^{95}\text{Mo}(d,\gamma)$

A. Ratkiewicz et al., PRL 122, 052502 (2019).

\begin{equation}
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$^{95}\text{Mo}(d,p\gamma)$

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The Experiment: $^{95}$Mo($d, p\gamma$)
A. Ratkiewicz et al., PRL 122, 052502 (2019).

Measure:

$$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_\gamma}$$

Calculate:

$$P_{\delta \chi}(E_{ex}) = \sum F_{\delta}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi)$$

$$\chi^2 = \sum_{i=1}^{N} \sum_{j=1}^{M} \left( \frac{P_{i}^{exp}(E_{ex}^j) - P_{i}^{calc}(E_{ex}^j)}{\Delta P_{i}^{exp}(E_{ex})} \right)^2$$

Minimize: (Bayesian MC)
The Experiment: $^{95}\text{Mo}(d,p\gamma)$
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The Experiment: $^{95}$Mo(d,\(p\gamma\))
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Measure:

\[ P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_{p}(E_{ex})\epsilon_{\gamma}} \]

Calculate:

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\[ \sigma_{\alpha\chi}(E_{a}) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi) \]

Does not depend on \(D_{0\gamma} \langle \Gamma \rangle\)!
The Experiment: $^{95}\text{Mo}(d,\gamma)$
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Successful Surrogate constraints are \textit{only} possible through close collaboration between theory and experiment.

Surrogate Reaction Method works on odd-odd & odd-even systems and with different reaction mechanisms:

- Same experimental apparatus.
- Surrogate reactions:
  - $^{89}$Y(p,d) for $^{87}$Y(n,γ)$^{88}$Y
  - $^{92}$Zr(p,d) for $^{90}$Zr(n,γ)$^{91}$Zr

- Includes full treatment of theoretical uncertainty in entry spin distribution.
- Requires two-step reaction mechanism.
- Agreement with data is good.


\[ \text{Branching points are powerful probes of the astrophysical environments of the } s\text{-process} \]

- The abundance of \(^{96}\text{Zr}\) in AGB stars is very sensitive to the neutron density during the \(s\)-process because of the \textbf{branching point at } \(^{95}\text{Zr}\).
- The \(^{96}\text{Zr}\) isotopic ratios derived from stellar models of AGB stars depend on the \(^{95}\text{Zr}(n,\gamma)\) cross section.

\[ \text{Measurements were performed at the Texas A&M Cyclotron Institute in Aug-Oct 2021} \]

- Measured \(^{95}\text{Zr}(n,\gamma)\) using the surrogate reaction \(^{96}\text{Zr}(p,p')\)
- Benchmark: measured \(^{93}\text{Zr}(n,\gamma)\) using the surrogate reaction \(^{94}\text{Zr}(p,p')\)
  - \(^{93}\text{Zr}(n,\gamma)\) cross section measured directly by Macklin (1985).
- Cave 4, K150 beamline
- Nominal 21-MeV-proton beam incident on target
- LLNL Hyperion detector array
  - Particles measured using 3 segmented double-sided silicon detectors in \(\text{dE-E1-E2} \) configuration
  - Gamma rays measured using 7 HPGe Clover detectors
Determining the n-capture rate for unstable $^{93}$Sr via the Surrogate Reaction Method

R.O. Hughes, A. Richards, et al.

- Very limited experimental data exist for n-capture rates off-stability but needed for applications & astrophysics.
- Early hints for n-rich strontium suggest possible enhancements of a factor of ten.
- We intend to constrain $\sigma(^{93}\text{Sr}(n,\gamma))$ with SRM and RIBs
- Experiment fielded at TRIUMF in Nov. 2021:
  - $^{93}\text{Sr}(d,p-\gamma)$ with TIGRESS & SHARC, 8MeV/A $^{93}\text{Sr}$.
  - Analysis underway led by LLNL postdoc Andrea Richard.

TIGRESS HPGe array & SHARC Si array @ TRIUMF

LLNL/TRIUMF experiment team

Doppler-corrected $\gamma$-rays in coincidence with protons from (d,p)
The surrogate method allows us to measure the cross section of unstable nuclei (ex: \(^{168}\text{Tm}(n,2n)\) which has never been measured)

J. Harke, et al.

**Desired Reaction**

\[
\text{Target} \quad \text{n} \quad \text{\^{168}Tm} \quad \text{\^{169}Tm} \quad \text{Decay} \quad \text{\^{169}Tm*}
\]

**Surrogate Reaction**

\[
\text{Target} \quad \text{\^{169}Tm} \quad \text{\^{169}Tm} \quad \text{Decay} \quad \text{\^{169}Tm*}
\]

\(^{168}\text{Tm}\) half-life = 93.1 days

100 milligram target

839 Curies or \(3 \times 10^{11}\) dps

OR

\(^{169}\text{Tm} =\) stable
NeutronSTARS: 3.7-ton active volume neutron detector

*J. Harke et al.*

NeutronSTARS is the largest neutron detector in the NNSA complex and the US. 3.7t liquid scintillator + Gd 0.25%. Fission neutron multiplicity (nu-bar), fission neutron distribution, surrogate (n,n') and (n,2n).

Commissioned January-April 2017
J.T.Harke, R.J. Casperson, R.O.Hughes, B.S. Alan, S.Fisher, O.Akindele, A.Tamashiro, A. Padilla

Courtesy S. Fisher

![Image of NeutronSTARS detector](image1)

Courtesy O. Akindele

![Image of Neutron capture and Gamma energy dep.](image2)
Using $^{90}\text{Zr}(p,d)^{89}\text{Zr}$ as a surrogate for $^{88}\text{Zr}(n,\gamma)^{89}\text{Zr}$

C. Reingold et al.

- Applications-driven measurement.
- Measured with StarLiTeR detector array, comprised of 6 Compton-suppressed HPGe clover detectors coupled to an S2 silicon telescope.
- Currently extracting the $(n,\gamma)$ cross section from the $(p,d)$ cross section (left) and $\gamma$-decay probabilities (right)

$S_n = 9.319$ MeV

$E_\gamma = 507.4$ keV
The Surrogate Method has been widely exercised.
Looking ahead to FRIB:
This is the opportunity with which we are presented

FRIB beam rates from LISE++ (Oleg Tarasov)
Looking ahead to FRIB:

This is the opportunity with which we are presented

Neutron capture rates from KADoNiS v0.3
Looking ahead to FRIB:
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Cold $r$-process path from Lippuner and Roberts APJ 815 2 (2015)
Looking ahead to FRIB:
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$r$-process $(n,\gamma)$ sensitives from Mumpower et al., PPNP 86 86-126 (2016)
Looking ahead to FRIB:
This is the opportunity with which we are presented
Looking ahead to FRIB and nuCARIBU:
This is the opportunity with which we are presented – maximizing it requires investments in theory and experiment.
Thanks to B. Alan, J.E. Escher, J.T. Harke, R.O. Hughes, and C. Reingold for slides and figures.

Thank you for your attention!