Neutron capture cross sections for short-lived nuclei from surrogate reaction data and theory

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6th International workshop on Compound-Nuclear Reactions & Related Topics (CNR*18)

Berkeley, CA
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Bring together theory, experiment, and data/application communities

https://indico.bnl.gov/e/CNR2018
Neutron capture reactions

\[ \frac{d\sigma_{\alpha \chi}^{HF}(E_a)}{dE_{\chi}} = \pi \lambda_\alpha^2 \sum_{J\pi} \omega_\alpha^J \sum_{\ell \ell' s' s''} T_{\alpha \ell s}^J T_{\chi \ell' s'}^J \rho_{I'}(U') W_{\alpha \chi}(J) \sum_{\ell'' s''} T_{\chi'' \ell'' s''}^J \sum_{\chi''} \int T_{\chi'' \ell'' s''}^J (E_{\chi''}) \rho_{I''}(U'') dE_{\chi''} \]
(n,γ) cross sections for unstable isotopes

Neutron capture reactions

Hauser-Feshbach formalism:

\[
\frac{d\sigma_{a\chi}^{HF}(E_a)}{dE_\chi} = \pi \chi^2 \sum_{J\pi} \omega_\alpha \sum_{\ell s' l' s} \sum_{\chi'' s''} T^J_{\alpha \ell s} T^J_{\chi' \ell' s'} \rho_{I'}(U') W_{\alpha \chi}(J) \frac{T^J_{\chi'' \ell'' s''} + \sum_{\chi'' s''} \int T^J_{\chi'' \ell'' s''}(E_{\chi''}) \rho_{I''}(U'') dE_{\chi''}}{\sum_{\ell s' l' s} \sum_{\chi'' s''} T^J_{\chi'' \ell'' s''} \rho_{I''}(U'') dE_{\chi''}}
\]
Capture cross sections for unstable isotopes

**Challenge:** uncertainties increase dramatically with distance from stability

**Figure:** Calculated $(n,\gamma)$ cross sections for Sn isotopes


**Hauser-Feshbach formalism:**

\[
\frac{d\sigma_{H^F}^{a\chi}(E_a)}{dE_\chi} = \pi\lambda^2 \sum_{J\pi} \omega^J_{\alpha} \sum_{\ell s' s'\ell'} T^J_{\alpha \ell s} T^J_{\chi \ell' s'} \rho_{I'}(U') W_\alpha(J) \\
\sum' \sum'' \sum'' \sum'' \sum'' \int T^J_{\chi'' s'' I''} (E_\chi'') \rho_{I''}(U'') dE_\chi''
\]
Modeling of astrophysical processes requires neutron capture cross sections

Scientific challenge: Origin of the heavy elements?
Reliable nuclear physics required to validate nucleosynthesis models against observations

Practical challenge: Measuring cross sections involving short-lived nuclei
- New facilities, e.g. Facility for Rare Isotope Beams (FRIB), produce unstable nuclei
- Innovative indirect techniques needed
Capture cross sections from surrogate \((p,d)\) reaction

Capture cross sections from surrogate \((p,d)\) reaction

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

A Surrogate experiment gives

\[ P_{(p,d\gamma)}(E) = \sum_{J,\pi} F_{(p,d) \, \text{CN}}(E,J,\pi) \cdot G_{\text{CN} \gamma}(E,J,\pi) \]

**Turning measurement into cross section**

1. Use theory to describe Surrogate reaction, predict \( F_{(p,d) \, \text{CN}} \)
2. Develop rough decay model \( G_{\text{CN} \gamma} \)
3. Fit uncertain parameters in \( G_{\text{CN} \gamma} \) to reproduce \( P_{(p,d\gamma)} \)
4. Use best-fit parameters to calculate desired \( \sigma_{(n,\gamma)} \)

**Result:** Experimentally constrained cross section calculation.

Escher et al, RMP 84 (2012) 353
Theory Challenge #1: Neutron hole structure relevant to \((p,d)\) reaction?

- What is the structure of deep neutron holes?
- Location?
- Fragmentation?

\[ \text{92}^\text{Zr} \text{(p,d) reaction} \]

\[ \gamma \rightarrow S_n \text{ populated} \]

\[ \text{91}^\text{Zr} \]

\[ \text{neutrons} \quad \text{protons} \]

<table>
<thead>
<tr>
<th>Excitation energy (MeV)</th>
<th>Counts per 80 keV</th>
</tr>
</thead>
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<tr>
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<tr>
<td>12</td>
<td>3000</td>
</tr>
<tr>
<td>14</td>
<td>3500</td>
</tr>
</tbody>
</table>

\[ \times 10^3 \]

\[ \text{Zr}^{92}\text{(p,d) particle singles spectra} \]

- Surrogate \((p,d)\) reaction

\[ \text{neutron hole made in reaction} \]
Theory Challenge #1:
What is the structure of deep neutron holes?
Location?
Fragmentation?

Structure of deep neutron holes

Dispersive Optical Model
• Connects OMP for scattering to nuclear mean field:
  Empirical scattering information yields OMP at positive energies
  Mean field gives energy-averaged nuclear properties: single-particle $E_{nlj}$, spectral functions $S_{nlj}$, etc.

• DOMP of renewed interest for obtaining reliable potentials for scattering calculations


Gives energy-averaged nuclear properties
Theory Challenge #1
What is the structure of deep neutron holes?
Location?
Fragmentation?

Structure of deep neutron holes

Dispersive Optical Model

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Spectral functions $S_{nlj}$

- Zr hole structure

Spectral function for n states in $^{92}$Zr for multiple $nlj$ orbitals, normalized to spectral strength, exp. width $D=0.080$ MeV

Gives energy-averaged nuclear properties

Theory challenge #2: Reaction mechanism includes higher-order processes

First-order processes:
- neutron pickup makes deep hole
- Reaction calculation uses DWBA with $S_{nlj}$ from DOMP

DWBA: Distorted-Wave Born Approximation

Theory Challenge #2:
Standard DWBA (p,d) calculations insufficient
Two-step mechanisms important
Theory challenge #2: Reaction mechanism includes higher-order processes

**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 precedes or follows neutron pickup

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**Theory Challenge #2:**
Standard DWBA (p,d) calculations insufficient
Two-step mechanisms important

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$^91\text{Zr}$

Excitation energy (MeV)

Counts per 80 keV

$^92\text{Zr}$

$(p,p',d)$ analogously
Theory Challenge #2:
Standard DWBA (p,d) calculations insufficient
Two-step mechanisms important

CN formation involves 2-step processes

- Include (p,p')(p',d) and (p,d')(d',d)
- Philosophy of pre-equilibrium theories: forward coupling, spectator approximation, no interference
- Structure information on inelastic states from experimental literature
- Couple all angular momenta explicitly

Second-order processes:
- Inelastic scattering proceeds or follows neutron pickup

Wide range of angular momenta possible: 0.5 to 11.5
Result: Compound-Nucleus Formation via (p,d)

High energies (region of interest):
- absolute cross section approximately reproduced, no normalization!
- 2-step processes dominate
- measurement and calculation agree, model assumptions valid
Result: Compound-Nucleus $J^\pi$ Distribution

Spin-parity distribution:
- As function of excitation energy of $^{91}\text{Zr}$
- Calculated from relative contributions of final $J^\pi$ to total (p,d) cross section
- Contributions from spins up to $\sim J=10$

$$P_{(p,d\gamma)}(E) = \sum_{J,\pi} F_{(p,d)}^{\text{CN}}(E,J,\pi) \cdot G_{\gamma}^{\text{CN}}(E,J,\pi)$$
Select relevant $^{91}$Zr $\gamma$ transitions

- Fit to data from 0.5 MeV below $S_n$ to 1.5 MeV above $S_n$

Fit yields best set of parameters & uncertainty estimate.

$$P_{(p,d\gamma)}(E) = \sum_{J,\pi} F_{(p,d)}^{CN}(E,J,\pi) G^{CN,\gamma}(E,J,\pi)$$
\( ^{90}\text{Zr}(n,\gamma) \) cross section from surrogate \((p,d)\) data

- Surrogate data constrains cross section up to \(E_n=1.5\) MeV
- Result in agreement with direct measurements & evaluations
- Result includes experimental & theoretical uncertainties

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

Surrogate method does not use \(D_0\) or \(\langle \Gamma_{\gamma} \rangle\)

Using best set of parameters to calculate \( ^{90}\text{Zr}(n,\gamma) \)

\(0.0001\quad 0.001\quad 0.01\quad 0.1\quad 1\quad 10\)

\(E_n [\text{MeV}]\)

\(0.0001\quad 0.001\quad 0.01\quad 0.1\quad 1\quad 10\)

Cross section [mb]
$^{89}\text{Y}(p,d)$ singles results

- Procedure is analogous to the Zr case
- Special feature: Isobaric Analog States (IAS)
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- Special feature: Isobaric Analog States (IAS)

\[ P_{(p,d\gamma)}(E) = \sum_{J,\pi} F_{(p,d)}^{CN}(E,J,\pi) \cdot G_{\gamma}^{CN}(E,J,\pi) \]
\(^{87}\)Y\((n,\gamma)\) cross section from surrogate \((p,d)\) data

Surrogate data constrains cross section up to \(E_n=1.5\) MeV
Result differs from evaluations (based on regional systematics)
Result includes experimental & theoretical uncertainties

\[ ^{87}\text{Y}(n,\gamma) \]

Cross section determined from surrogate experiment compared to prior evaluations

Result includes experimental & theoretical uncertainties

Surrogate method does not use \(D_0\) or \(<\Gamma_{\gamma}>\)

Cross section from surrogate \((p,d)\) data

\(E_n \) [MeV]

\( \text{Cross Section [b]} \)

This work
TENDL 2015
Rosfond 2010

Fri Apr 27 10:56:44 2018
Escher et al, PRL 121, 025501 (2018)
Towards inverse-kinematics applications with RIBs…
…the (d,p) reaction
The (d,p) reaction – revisited for the RIB era

(d,p) reaction: ideal substitute for n+A?
The (d,p) reaction – revisited for the RIB era

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

$^{96}$Mo spin distribution

Surrogate ($d,p\gamma$) data

Data by A. Ratkiewicz, J. Cizewski, et al.

Spin distribution calculated by G. Potel
$^{95}$Mo(n,$\gamma$) cross section from surrogate (d,p$\gamma$) data, reaction theory, and decay modeling

Excellent agreement of cross section with benchmark. This is encouraging for inverse-kinematics (d,p) measurements.
Excellent agreement of cross section with benchmark. This is encouraging for inverse-kinematics \((d,p)\) measurements. The theoretical description of \((d,p)\) is critical to obtaining \((n,\gamma)\).
Can we use inelastic scattering for \((n,\gamma)\)?

**Advantages:**
- Option for s-process branch points
- Potentially useful in inverse kinematics
- Recent progress in nuclear structure calculations: (Q)RPA transition densities for many isotopes now available
- Reaction populates wide range of \(E_{\text{ex}}\)

![Diagram showing s-process path and r-process region]

S-process path at branch point \(A\)
Often isotope \(A+1\) is long-lived

- \[ Z+1 \rightarrow (n,\gamma) \rightarrow A+1 \rightarrow Z+1 \]
  - \((\beta^-)\)
- \[ A-1 \rightarrow (n,\gamma) \rightarrow A \rightarrow (n,\gamma) \rightarrow A+1 \]
  - \((\beta^-)\)

Inelastic scattering:
Currently studied as indirect method to determine \((n,2n)\) cross sections.
The $^{90}$Zr(n,2n) reaction from inelastic scattering

Benchmark case:
Experiment populates compound nucleus in energy range $E_{ex} = 0 – 30$ MeV

Surrogate ($^3$He,$^3$He') reaction

$^{91}$Zr

$^{3}$He

$^{3}$He'
Using inelastic scattering to determine \((n,\gamma)\)?

**Experiment at LBNL:**
- \(^{90,91,92}\text{Zr}(^3\text{He},^3\text{He}')\) and \(^{89}\text{Y}(^3\text{He},^3\text{He}')\)
- Measured by N.D. Scielzo et al
- Goal: determine \((n,2n)\) cross section
- Observed \(\gamma\)-rays in 3 isotopes, corresponding to \((n,\gamma), (n,n'), (n,2n)\)
- Inelastic scattering calculations using (Q)RPA transition densities
- Decay calculations simultaneously reproduce observed \(\gamma\)

Data from N.D. Scielzo

\[ P_\gamma(E) \text{ for 2170 keV in } ^{91}\text{Zr} \]

Predictions vs. data

\[ P_\gamma(E) \text{ for 890 keV in } ^{90}\text{Zr} \]

Predictions vs. data

\[ P_\gamma(E) \text{ for 1512 keV in } ^{89}\text{Zr} \]

Predictions vs. data

For \((n,\gamma)\)

For \((n,n')\)

For \((n,2n)\)
Concluding remarks

General:

• Capture cross sections for unstable isotopes are important & difficult to obtain
• Indirect methods are critical & need further development
• Complementary methods are needed to reach large number of isotopes and to cross-check

Light-ion surrogate reactions:

• Different target-projectile combinations possible, method can be used at RIB facilities in inverse kinematics
• Method does not use $D_0$ or $<\Gamma_\gamma>$
• Understanding CN formation is important to account for spin-parity mismatch (inelastic scattering, pickup, stripping)
• Concept also applicable to other reactions: $(p,\gamma)$, $(n,2n)$, etc.

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J. Burke, R. Casperson, R. Hughes, A. Ratkiewicz, N. Scielzo (LLNL)
S. Ota (Texas A&M), J. Cizewski (Rutgers), G. Potel (MSU/FRIB)
Extras
Selected Publications - 1

Reviews:


Letters, regular journal articles, and refereed proceedings:


Selected Publications - 3


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)

