Neutron capture cross sections for the astrophysical $r$-process

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Oslo, May 2015
Overview

• R-process nucleosynthesis
• Uncertainties
  o Neutron capture rates

• Experiment

• Results
• Future plans
Nucleosynthesis paths

Z

pp chain

rp / vp process

Stellar burning

56Fe

s process

p process

r process

N
Open questions: What is the site of the r-process?

Core Collapse Supernova?

Neutron Star Merger?

Credit: Erin O’Donnell, MSU

Credit: NASA Goddard
Abundance pattern is different for the different astrophysical scenarios.

• Does one of them reproduce the observed abundances best?
• Why can’t we tell?
r-process

- masses
- β-decay $T_{1/2}$
- Observations
- Nuclear theory
- Sensitivity studies
- Astrophysical modeling
- Neutron captures
- β-delayed neutrons
Monte-Carlo variations of \((n,\gamma)\) rates within a factor 100.

Surman and Engel PRC (2001)
Current \((n,\gamma)\) measurements
Neutron Capture – Uncertainties

**Hauser – Feshbach**
- **Nuclear Level Density**
  Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic
- **γ-ray strength function**
  Generalized Lorentzian, Brink-Axel, various tables
- **Optical model potential**
  Phenomenological, Semi-microscopic

\( (n, \gamma) \)
\( (A-1, Z) \)
\( \gamma \)
\( (A, Z) \)

\( ^{95}\text{Sr}(n,\gamma)^{96}\text{Sr} \)

TALYS
Traditional Oslo method

- Reaction based
- Applicable closer to stability
- Populate the compound nucleus of interest through a transfer or inelastic scattering
- Extract level density and γ-ray strength function
- Calculate “semi-experimental” (n,γ) cross section
- Excellent agreement with measured (n,γ) reaction cross section

T.G. Tornyi, M. Guttormsen, et al., PRC2014
Neutron Capture – β-Oslo

- Populate the compound nucleus via β-decay
- Spin selectivity – correct for it
- Extract level density and γ-ray strength function
- Advantage: Can reach (n,γ) reactions where beam intensity is 1 pps.

Experimental techniques

- Fast Beams
- Gas Stopper
- Stopped beams
- Reaccelerated Beams

- SuN β-decay experiments with fast beams
- SuN β-decay experiments with "stopped" beams

- K1200 Cyclotron
- A1900 Fragment Separator
- K500 Cyclotron
- ReA3 Hall
- ReAccelerator Facility

20 meter
Summing NaI - SuN

\[ E_x = E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3} + E_{\gamma 4} + \ldots \]

- 16x16 inch
- 45 mm borehole
- 2 pieces
- 8 segments
- 24 PMTs
- Efficiency > 85% for 1 MeV

Proof-of-principle: $^{75}\text{Ge}(n,\gamma)^{76}\text{Ge}$

$^{76}\text{Ga}$: $T_{1/2} = 32.6$ s  
$Q_{\beta^-} = 7.0$ MeV  
$S_n(^{76}\text{Ge}) = 9.4$ MeV


NSCL
National Science Foundation  
Michigan State University
Proof-of-principle: $^{75}\text{Ge}(n,\gamma)^{76}\text{Ge}$
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$$P(E_\gamma, E_x) = \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

Normalizations

• Functional form of level density and strength function

• Three normalization points
  – Low-energy level density.
  – Level density at $S_n$.
  – Average radiative width at $S_n$.

\[ \langle \Gamma_{\gamma} \rangle \]

\begin{itemize}
  \item Systematics
  \item Microscopic calculations
\end{itemize}

\[ \langle \mathcal{E} \rangle \text{ normalized from systematics} \]
Results: $^{75}\text{Ge}(n,\gamma)^{76}\text{Ge}$

$^{75}\text{Ge}(n,\gamma)^{76}\text{Ge}$

**Weak r-process measurements**

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**70Co:**  
- $T_{1/2} = 108$ ms  
- $Q_{\beta^-} = 12.3$ MeV  
- $S_n(70\text{Ni}) = 7.3$ MeV
Applicability

- Wide range of applicability
- Short lifetimes
- Low production rates
- Bounded by
  - Q values
  - Delayed neutron emission
A. C. L. and M. G. acknowledge financial support from the Research Council of Norway, project grant no. 205528. This work was supported by the National Science Foundation under Grants No. PHY 102511, and No. PHY 0822648, and PHY 1350234.