Neutron capture cross sections constrained in β-decay experiments

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**Research Focus Areas:** Nuclear and particle physics, radiation detection and instrumentation, nuclear data

**Mission Relevance of Research:** Providing neutron capture cross sections of interest for nuclear astrophysics, stockpile stewardship, and nuclear energy

Some of the SuN group at Argonne National Laboratory
NNSA Connections

- Basic Science
  - Neutron capture cross sections
  - Nuclear statistical properties
- Nuclear Astrophysics
  - Nuclear reaction network inputs
- Nuclear Power
  - Reactor monitoring

Most neutron-rich nuclei are made in the r- and i-processes
  - Weak r-process, main r-process, and i-process

These processes can be modeled with nuclear network calculations that require precise inputs:
  - Masses
  - Beta-decay rates
  - Neutron capture cross sections

Surman et al have identified which abundances are most sensitive to changing neutron capture cross sections in the weak r-process
  - $^{75,76}$Zn neutron capture cross sections

Measuring reaction network inputs

- Direct measurements are ideal, but difficult
  - Neutron and short-lived isotope targets aren’t practical due to short half-lives
  - Neutron-rich nuclei are difficult to create as isotope beams with high enough intensity
- Indirect techniques can avoid these pitfalls: one of these is the $\beta$-Oslo method

\[ F = 100 \times \sum_{A} |X(A) - X_{\text{baseline}}(A)| \]

The outcome of each sensitivity study is thus a set of sensitivity measures $F$ for each of the 300 nuclei whose capture rates were varied.

The final abundance pattern for this baseline simulation is a good match to the solar $A \sim 80$ region and above as shown in Fig. 2, plotted with the red line. This case is a 'true' $r$ process, in that we see the establishment of ($n, \gamma$)-($\gamma, n$) equilibrium, and the behavior of the nuclei flows and through the $N = 50$ closed shell is similar to that in the $N = 82$ and $N = 126$ regions in a main $r$ process, with the $r$-process path as shown in the top panel of Fig. 3. Thus, we expect the evolution of neutron capture rates to be similar to that identified for the $N = 82$ region in a main $r$ process, as described in detail in Refs. 19 and 20. Indeed, the pattern of sensitivity measures for this example follows the $N = 82$ region results, with the greatest sensitivity measures $F$ found for nuclei above and to the left of the closed shell, along the $\beta$-decay pathways of the closed shell nuclei, as seen in Fig. 3.

Ref. 19 and 20 identified two mechanisms by which neutron capture rates in the $A \sim 130$ region influence the final $r$-process abundance pattern: an early-freezeout photodissociation effect and a $\beta$-Oslo method uses the decay of these isotopes as a tool.

- $\beta$-Oslo method does not require high rates of radioactive beams

Ref. 19, 20, 75, 76
Indirect calculations of neutron capture cross sections

- Hauser-Feshbach statistical model codes like TALYS can be used to calculate neutron-capture cross sections using these inputs:
  - Neutron-nucleus optical model potential (nOMP)
  - Nuclear level density (NLD)
  - γ-ray strength function (γSF)

- Main uncertainties in these calculations come from NLD and γSF

- Experimental determination of the NLD and γSF can greatly reduce uncertainties
SuN: Segmented NaI detector

- Segmented, high-efficiency NaI detector
  - $\gamma$-ray resolution at 1 MeV: 6%
  - $\gamma$-ray efficiency at 1 MeV: 85%
- Capabilities:
  - Total absorption $\gamma$ spectroscopy: gives excitation energy of nuclei
  - Segmentation provides individual $\gamma$-ray energies

Figure 4: Experimental setup at the new low energy area showing a potential location for SuN and the tape system.

Figure 5: a) The SuN detector installed on a beam-line at the NSCL. b) The fiber detector during installation so that the plastic scintillator and fibers are visible. The bottom picture shows the tape being installed at the center of the fiber detector.

## Experimental quantities determined in SuN measurements

### Beta decay properties
- Beta feeding intensities
- B(GT) values

**Uses:**
- Average gamma, electron, and neutrino calculations

**Applications:**
- Reactor decay heat calculations
- Anti-neutrino reactor anomaly

### Statistical properties
- Nuclear level densities
- Gamma ray strength functions

**Uses:**
- Neutron capture cross section calculations

**Applications:**
- Nuclear astrophysics models
- Stockpile stewardship
The β-Oslo Method: matrices from β-decay of $^{77}$Cu

1. Create $E_γ$ v $E_x$ matrix from experimental data

2. Extract first generation $γ$-ray from each $γ$-cascade to create primary matrix
The β-Oslo Method: statistical properties and normalization

3. Use the Oslo method to extract statistical properties from the primary γ-ray matrix:
   - Nuclear level density (NLD)
   - γ-ray strength function (γSF)

4. Normalize statistical properties with three normalization points:
   - Level density of low-energy discrete states
   - Level density at neutron separation energy \( \rho(S_n) \), which can be found from neutron resonance spacings \( D_0 \)
   - Average radiative width \( (\Gamma_\gamma) \) at \( S_n \)

   • Must take selective spin population of beta decay into account

G.S. of \(^{77}\)Cu is \( \frac{5}{2}^- \)
First results for $^{76}\text{Zn}(n,\gamma)$

The Olso method has been used to extract the nuclear level density and gamma ray strength function for $^{77}\text{Zn}$, which is used to calculate $^{76}\text{Zn}(n,\gamma)$
Experimentally determined NLD of $^{77}$Zn has been compared with TALYS’s six standard NLD models.
Future work:

- Use these experimentally determined NLD and γSF to reduce uncertainties in theoretical (n, γ) cross sections
- Also working on total absorption spectroscopy (TAS) for both isotopes to determine their beta decay feeding intensities
- More β-Oslo measurements planned at FRIB and ANL!

\(^{74}\text{Zn}(n,\gamma)\) from Lewis et al. Phys Rev C (2019)
My NSSC Experience

• University Program Review, September 2021

• Various NSSC-hosted online talks and workshops during COVID

• Collaborations with national laboratory partners:
  - Lawrence Livermore National Laboratory
  - Pacific Northwest National Laboratory

• Ongoing experimental campaign at Argonne National Laboratory
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