Progress of the IS559 experiment

The $\gamma$-ray strength function and nuclear level density of $^{67}$Ni
Outline

• Motivation
• The IS559 experiments
• Preliminary results
• Summary
Nucleosynthesis – neutron capture process

- r- and s-process responsible for production of almost all elements heavier than iron\(^1\)
- r-process known to happen in kilonovas following neutron star mergers\(^2\)
- Abundance calc. needs accurate nuclear input
  - Neutron capture rates
  - Decay rates, masses, etc.

\(^2\) D. Kasen \textit{et al.}, Nature \textbf{551}, 80-84 (2017)

Figure credit: F. Timmes, http://cococubed.asu.edu/images/nuclide_chart/table_nuclei04.pdf
Nucleosynthesis – i-process

• First suggested in 1977 by Cowan & Rose\(^1\)
• Intermediate neutron flux
  \(\sim 10^{13} - 10^{16} \text{ cm}^{-3}\)
• Observed in post-AGB star
  Sakurai’s object (V4334 Sagittarii)\(^2\)
• Elemental abundance of HD94028: Cannot be explained with s- and/or r-
  process alone\(^3\)
  – Weak i-process

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The weak i-process

• Possibly initiated by ingesting of H into a convective He zone
• Terminates quickly
• The $^{66}\text{Ni}(n,\gamma)$ identified as a major bottleneck
  – Experimental measurements needed!

Figure 10. Isotopic abundances from the two additional ppa runs in which only the multiplication factor $f(^{66}\text{Ni})$ was switched between its maximum (top panel) and minimum (bottom panel) values constrained by the Hauser-Feshbach model computations.

Hauser-Feshbach model

\( \gamma \)-ray strength function

Nuclear level density

Optical model potential

Hauser-Feshbach calculations

\((n,\gamma)\) capture cross section
Hauser-Feshbach model

Oslo Method

- $\gamma$-ray strength function
- Nuclear level density
- Optical model potential

Hauser-Feshbach calculations

$(n,\gamma)$ capture cross section
\( \gamma \)-ray Strength Function

- Measure of the electromagnetic interaction of a nucleus
- Dominated by the E1 giant resonance (GDR)
- Low energy enhancement “upbend” (LEE)
- Scissors resonance
- Pygmy dipole resonance (PDR)
Effect of LEE on neutron capture

- Origin of LEE still not well understood
- The LEE can have a huge impact on \((n,\gamma)\) cross section
- Experimental data is needed to refine theoretical models

Figure credit: A. C. Larsen and S. Goriely, Phys. Rev. C 82, 014318 (2010)
The Oslo Method

- Simultaneous measurement of the $\gamma$-ray strength function and nuclear level density
- Starting point: $E_\gamma$ vs $E_x$ matrices
  - Reactions with light ions
  - TAS of beta-decay
  - Inverse kinematics
Experiment

- $^{66}$Ni beam @ 4.5 MeV/u
- $\approx 11$ pA for $\sim 140$ hours
- 669 ug/cm$^2$ C$_2$D$_4$ target
- Six Miniball clusters
- Six large volume (3.5x8") LaBr$_3$:Ce detectors
- C-REX particle array
- > 240k coincidences after BG subtraction
- First Oslo Method in inverse kinematics with radioactive beam!
Results

Bottom quadrant, ring 4

- Proton
- Deuteron
- Triton

Excitation energy [keV]

Δ E detector energy [keV]

E detector energy [keV]

γ-ray energy [keV]
Oslo Method Analysis - Unfolding

Raw

Unfolded
Oslo Method Analysis – First generation

Unfolded

First gen.
Oslo Method Analysis – extraction of gSF & NLD

\[ \Gamma(E_x, E_\gamma) \propto \mathcal{T}(E_\gamma) \rho(E_x - E_\gamma) \]

\[ \Gamma_{\text{theo.}}(E_x, E_\gamma) = \frac{\mathcal{T}(E_\gamma) \rho(E_x - E_\gamma)}{\sum_{E_\gamma = E_\gamma^{\text{min}}} \mathcal{T}(E_\gamma) \rho(E_x - E_\gamma)} \]

\[ f(E_\gamma) = \frac{1}{2\pi E_\gamma^3} \mathcal{T}(E_\gamma) \]

\[ \rho(E_x) = A \tilde{\rho}(E_x) e^{\alpha E_x} \]

\[ \mathcal{T}(E_\gamma) = B \tilde{\mathcal{T}}(E_\gamma) e^{\alpha E_\gamma} \]
The Oslo Method – normalization of NLD

- Known discrete levels
  - ENSDF
  - XNSDF
- NLD at $S_n$
  - Systematics
- Fixes slope parameter $\alpha$ and absolute value $A$
The Oslo Method – normalization of $\gamma$SF

- Slope $\alpha$ fixed by NLD
- Absolute value found by

$$\langle \Gamma_0 \rangle = \frac{B}{2\pi \rho(S_n, J_t^\pi)} \int_0^{S_n} dE_\gamma \mathcal{T}(E_\gamma) \rho(S_n - E_\gamma) \times \sum_{I = -1}^{1} g(S_n - E_\gamma, J_t + I)$$

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*Refereences*

Hauser-Feshbach calculations

Preliminary!
Summary

• Preliminary results for the $\gamma$SF and NLD for $^{67}$Ni
• We observe a strong low energy enhancement in the $\gamma$SF
• Will help our understating the weak i-process
• Oslo Method with inverse kinematics: An important tool for constraining (n,$\gamma$) cross sections of unstable nuclei
Acknowledgement

S. Siem\textsuperscript{1}, M. Wiedeking\textsuperscript{2}, K. J. Abrahams\textsuperscript{3}, K. Arnswald\textsuperscript{4}, F. L. Bello Garrote\textsuperscript{1}, T. Berry\textsuperscript{5}, D. L. Bleuel\textsuperscript{6}, J. Cederkäll\textsuperscript{4,7}, T. L. Christoffersen\textsuperscript{1}, D. M. Cox\textsuperscript{8}, L. Crespo Campo\textsuperscript{1}, H. De Witte\textsuperscript{9}, L. P. Gaffney\textsuperscript{7}, A. Görgen\textsuperscript{1}, C. Henrich\textsuperscript{10}, A. Illana Sison\textsuperscript{9}, P. Jones\textsuperscript{2}, B. V. Kheswa\textsuperscript{2,11}, T. Kröll\textsuperscript{11}, S. N. T. Majola\textsuperscript{2,12}, K. L. Malatji\textsuperscript{2,12}, T. Nogwanya\textsuperscript{2}, J. Ojala\textsuperscript{8}, J. Pekarinen\textsuperscript{8}, G. Rainovski\textsuperscript{13}, P. Reiter\textsuperscript{14}, D. Rosiak\textsuperscript{14}, M. von Schmid\textsuperscript{10}, M. Seidlitz\textsuperscript{14}, B. Siebeck\textsuperscript{14}, J. Snäll\textsuperscript{4}, K. Sowazi\textsuperscript{2}, G. M. Tveten\textsuperscript{1}, N. Warr\textsuperscript{14}, F. Zeiser\textsuperscript{1}

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06.12.2019
Acknowledgement

UiO: University of Oslo

Department of Physics
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NRF 20
National Research Foundation 1999-2019
Laboratory for Accelerator Based Sciences

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With funding from
The Research Council of Norway