Neutron capture cross section measurements on short-lived isotopes

PI: Sean Liddick
CoPI: Artemis Spyrou
Presenter: Andrea Richard
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Neutron capture cross section measurements on short-lived isotopes

• Scientific Challenge
  – Constrain neutron-capture cross sections of short-lived nuclei for stewardship science and astrophysical production of heavy elements.

• Goals
  – Constrain neutron-capture cross sections for influential reactions in r-process scenarios in the Co-Cu region.
  – Constrain neutron-capture cross sections of interest for stockpile stewardship approaching $^{95}\text{Zr}$
  – Train graduate students and postdoctoral researchers in nuclear science techniques and connect them with staff at the national laboratories.
**Neutron capture cross section measurements on short-lived isotopes**

- **PI:** Sean Liddick  
  Associate Prof. National Superconducting Cyclotron Laboratory and Department of Chemistry

- **Co-PI:** Artemis Spyrou  
  Professor National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy

- **Two graduate students and one postdoc supported:**
  - Rebecca Lewis (MSU, graduate student → NNSA GFP Summer 2019)
  - Debra Richman (MSU, graduate student)
  - Benjamin Crider (postdoctoral researcher → MissSU Assistant Professor)
  - Mallory Smith (MSU, postdoctoral researcher → staff National Superconducting Cyclotron Laboratory)
  - Andrea Richard (MSU, postdoctoral researcher)

- **Peer-reviewed papers**
Significant laboratory engagement by supported graduate students

- **Rebecca Lewis**
  - 3-month placement at LANL in 2017.
  - Performed work with neutron science experimenters and theorists at LANL including A. Couture and T. Kawano
  - Manuscript on $^{73}\text{Zn}(n,\gamma)$ PRC 2019.
  - Completed thesis in 2019
  - NNSA GFP Summer 2019!
Significant laboratory engagement by supported graduate students

• Debra Richman
  – Permanently placed at Los Alamos National Laboratory working within the P-27 group with A. Couture and S. Mosby.
  – Performing analysis to extract neutron-capture cross section of $^{59}$Fe, a key reaction rate in the astrophysical s-process.
  – Analysis in progress
  – First results presented at Nuclear Astrophysics winter school Russbach 2017, NASA Laboratory Astrophysics 2018, DNP 2019
Scientific program focused on rapid-neutron capture process, slow-neutron capture process, and stewardship science.

- Inferring neutron capture cross sections on short-lived nuclei receiving strong support from NSCL and ANL Program Advisory Committee.

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- A. Spyrou (MSU): Study of Kr isotopes for astrophysical applications.
- N. Scielzo (LLNL): Determination of the $^{92}$Sr neutron-capture cross section and fission product burn up.
- S. Liddick (MSU): Neutron-capture cross section constraints in neutron-rich Sn and Sb isotopes
- Approved
- S. Liddick (MSU): Constraints on nucleosynthesis in the iron region
- A. Spyrou (MSU): Constraints on neutron-capture reactions around $N=82$
- A. C. Larsen (Oslo): The rare-earth r-process peak: $^{156-159}$Sm(n,$\gamma$) reaction rates constrained with the beta-Oslo method
- Approved
- A. Spyrou (MSU): Constraining supernova models with SuN
- N. Scielzo (LLNL): Study of Kr isotopes for astrophysical applications.
Nuclear level densities and $\gamma$-ray strength functions are the dominate uncertainties in (n,$\gamma$) calculations

**Hauser – Feshbach**

- **Nuclear Level Density**
  Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

- **$\gamma$-ray strength function**
  Generalized Lorentzian, Brink-Axel, various tables

- **Optical model potential**
  Phenomenological, Semi-microscopic

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

**TALYS**
Using beta-decay total absorption spectroscopy to infer neutron capture cross sections

- Measure beta decay of nucleus.
  - Extract level densities and gamma-ray strength function
- Need total excitation energy of the daughter isotope.
  - Can’t use beta-decay electron (three body process)
- Instead, measure total emitted photon energy.

- Require high detection efficiency.
- Extract nuclear level density and $\gamma$-ray strength function.
- Insert both quantities into a statistical reaction model to constrain $(n,\gamma)$ rate.
$(n,\gamma)$ uncertainties impact the rapid-neutron capture process for heavy element creation.

Monte-Carlo variations of $(n,\gamma)$ rates within a factor $100 - 10 - 2$ (light – darker – dark bands)
Sensitive \((n,\gamma)\) rates in the neutron-rich Ni region

- Inferred neutron capture rates of \(^{68,69}\text{Ni}\) and \(^{73}\text{Zn}\) have already been performed.
- Extract neutron capture rates of \(^{71,72,73}\text{Ni}\).
- Strong local impact on astrophysical abundance predictions.
- Covers a number of high sensitivity reactions.
- Provides systematics across a chain of five Ni isotopes.

Nuclear level densities and gamma-ray strength functions in the neutron-rich Ni region

- Constrained nuclear levels densities, gSF, and neutron capture cross sections on $^{71,72,73}$Ni
- Combined with prior results provides systematics across a chain of five Ni isotopes.
- Impact on astrophysical abundance predictions underway.
Neutron capture needs for diagnostics: $^{95}$Zr

- $^{95}$Zr can be used as a yield indicator.
- However, $^{95}$Sr is short lived and can’t be made into a target.
- UCB, LLNL, MSU, Oslo collaboration.
Decay of $^{93}\text{Rb}$: Providing ($n,\gamma$) for $^{92}\text{Sr}$

- Experiment to deliver thermal $^{93}\text{Rb}$ within last year to perform stopped beam $\beta$-decay with $^{93}\text{Rb}$.
- Moving tape collector and interior plastic scintillator completed previously.

$^{93}\text{Rb}$

$t_{1/2} = 5.84(2)$ s

$t_{1/2} = 7.43(3)$ m

$t_{1/2} = 10.18(8)$ h

$^{93}\text{Sr}$

$^{93}\text{Y}$

$\beta -$

Analysis in progress; working on response function of plastic scintillator within SuN.

Total Absorption Spectra

Production Runs $^{93}\text{Rb}$

Daughter Runs $^{93}\text{Y}$

Only levels in $^{93}\text{Y}$

Count $\times 10^3$
Testing Spin Independence of $\gamma$SF: Preliminary beam test with $^{70}$Cu isomeric states

- Test the independence of the $\gamma$SF from different initial spin distributions.
- $^{70}$Cu has three different isomeric states.
- Experiment completed summer 2019, analysis is ongoing.
Conclusions

- Application of technique to infer neutron capture cross sections on short-lived neutron-rich nuclei ongoing.
- Applicable to studies of rapid-neutron capture process, slow-neutron capture process, and stewardship science.
  - Cross section constrained for a range of neutron-rich Ni isotopes.
  - Neutron-rich $^{59}$Fe analysis in progress
  - Stockpile stewardship analysis on neutron-rich Sr isotopes in progress
- Investigation of spin dependence of strength function using isomeric states in $^{70}$Cu – analysis in progress
- Funding supports two graduate students and one postdoctoral researcher strongly connected to the national laboratories.
- One graduate student has taken a position with the NNSA GFP.
Thanks

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<th>Michigan State University</th>
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Questions?