Neutron capture cross section measurements on short-lived isotopes

PI: Sean Liddick

CoPI: Artemis Spyrou

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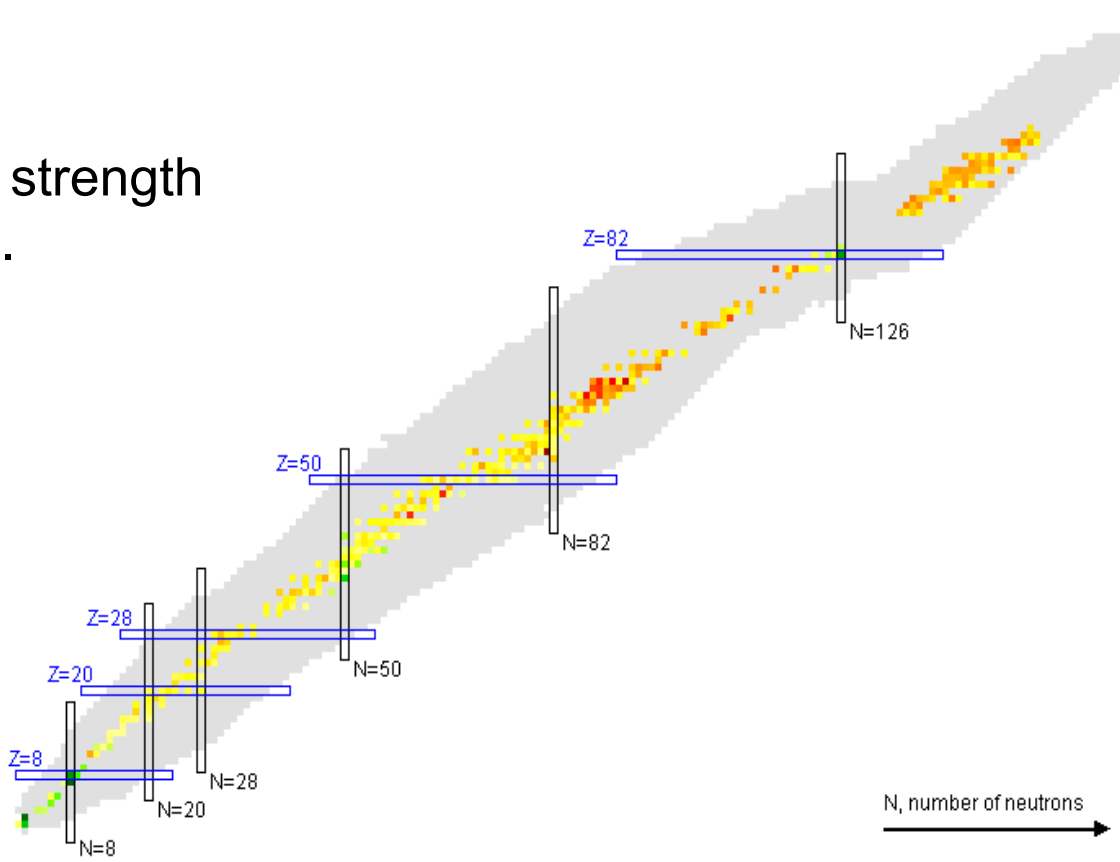
Scientific Challenge

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

- Goals
  - Investigate the spin dependence of the γ-ray strength function using the β decay of isomeric states.
  - Constrain neutron capture cross sections of interest for stockpile stewardship approaching ^{95}Zr and i-process nuclei
  - Train graduate students and postdoctoral researchers in nuclear science techniques and connect them with staff at the national laboratories.



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Neutron capture cross section measurements on short-lived isotopes

- PI: Sean Liddick
  Associate Prof. Facility for Rare Isotope Beams and Department of Chemistry
- Co-PI: Artemis Spyrou
  Professor Facility for Rare Isotope Beams and Department of Physics and Astronomy
- One graduate student and one postdoc supported:
  - Eleanor Ronning (MSU, graduate student)
  - Sivahami Uthayakumaar (MSU, postdoctoral researcher)
  - Debra Richman (MSU, graduate student)
  - Erin Good (MSU, postdoctoral researcher → PNNL postdoc)
  - Andrea Richard (MSU, postdoctoral researcher → LLNL postdoc)
  - Katherine Childers (MSU, graduate student → Texas A&M University 2021 → RSL)
  - Rebecca Lewis (MSU, graduate student → NNSA GFP Summer 2019 → startup)
  - Benjamin Crider (postdoctoral researcher → MissSU Assistant Professor)
  - Mallory Smith (MSU, postdoctoral researcher → staff NSCL)

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  Associate Prof. Facility for Rare Isotope Beams and Department of Chemistry

- Co-PI: Artemis Spyrou

  Professor Facility for Rare Isotope Beams and Department of Physics and Astronomy

- One graduate student and one postdoc supported:

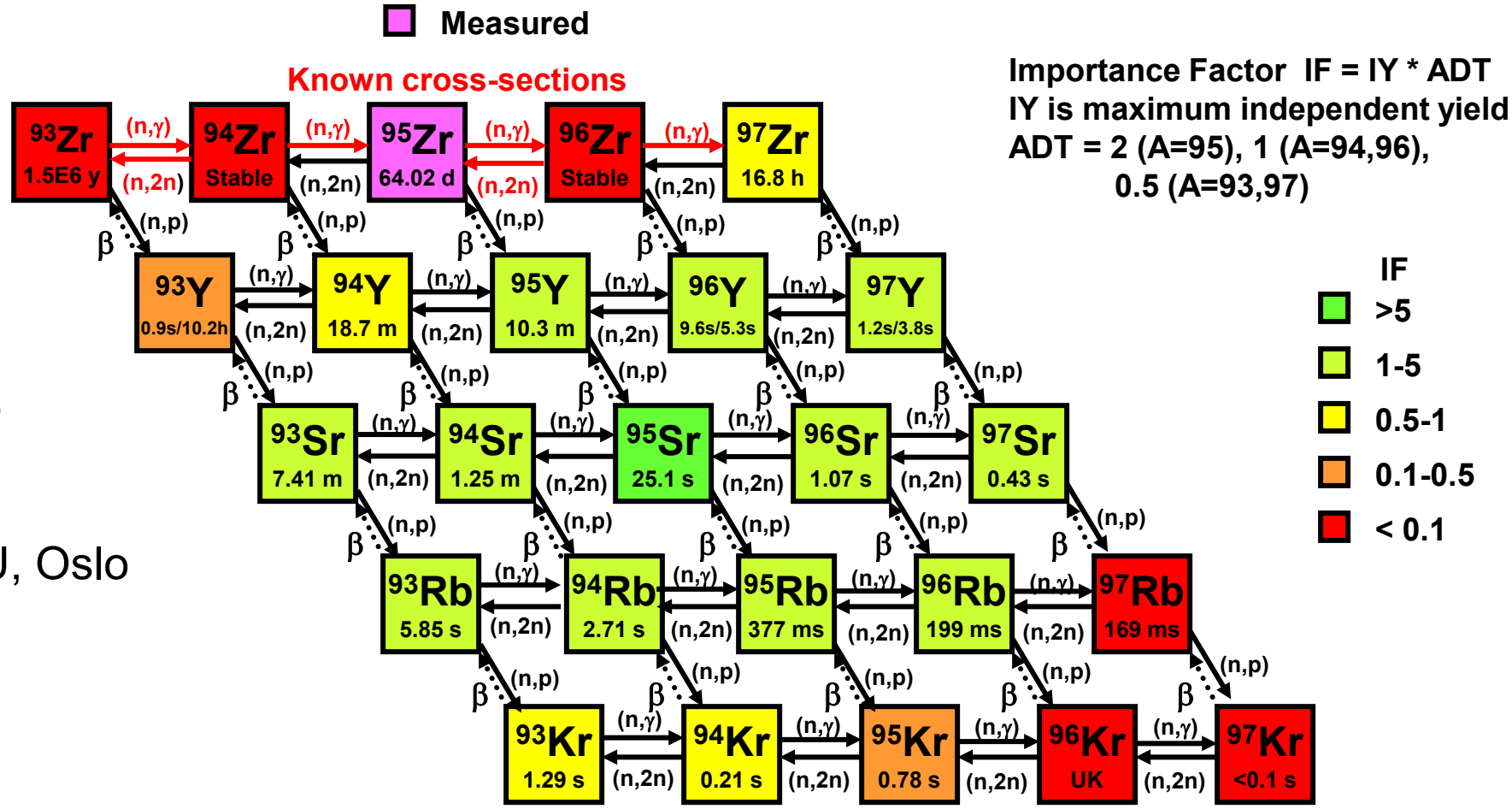
- Peer-reviewed papers

- R. Lewis *et al.*, Eur. Phys. J, 59, 42 (2023)
- D.Mucher et al., Phys.Rev. C 107, L011602 (2023)
- F. Naqvi *et al.*, Nucl. Phys. A **1018**, 122359 (2022)
- A. Tsantiri *et al.*, Phys.Rev. C 107, 035808 (2023)
- A.Palmisano-Kyle et al., Phys.Rev. C 105, 065804 (2022)
- A.C. Dombos *et al.*, PRC **103**, 025810 (2021)
- J. Gombas *et al.*, Phys. Rev. C **103**, 035803 (2021)
- C.F. Persch *et al.*, Phys. Rev. C **103**, 055808 (2021)
- M. Wiedeking *et. al.*, Phys.Rev. C **104**, 014311 (2021)
- M. Guttormsen *et. al.*, Acta. Phys. Pol. B**51**, 667 (2020)
- A. Spyrou, Annals of Physics **412**, 168017 (2020)
- W.J. Ong *et. al.*, Phys. Rev. Lett **125**, 262701 (2020)
- S.N. Liddick, *et al.*, Phys. Rev. C **100**, 024624 (2019)
- A. Voinov, *et. al.*, Phys. Rev. C **99**, 054609 (2019)
- R. Lewis *et. al.*, Phys. Rev. C **99**, 034601 (2019)
- A.C Dombos *et. al*. Phys. Rev. C **99**, 015802 (2019)
- A.C. Larsen *et al.*, Phys. Rev. C **97**, 054329 (2018)
- A.Spyrou, A.C. Larsen, S.N. Liddick *et al.*, J. Phys. G **44**, 044002 (2017)

Significant laboratory engagement on scientific program: one example - 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.

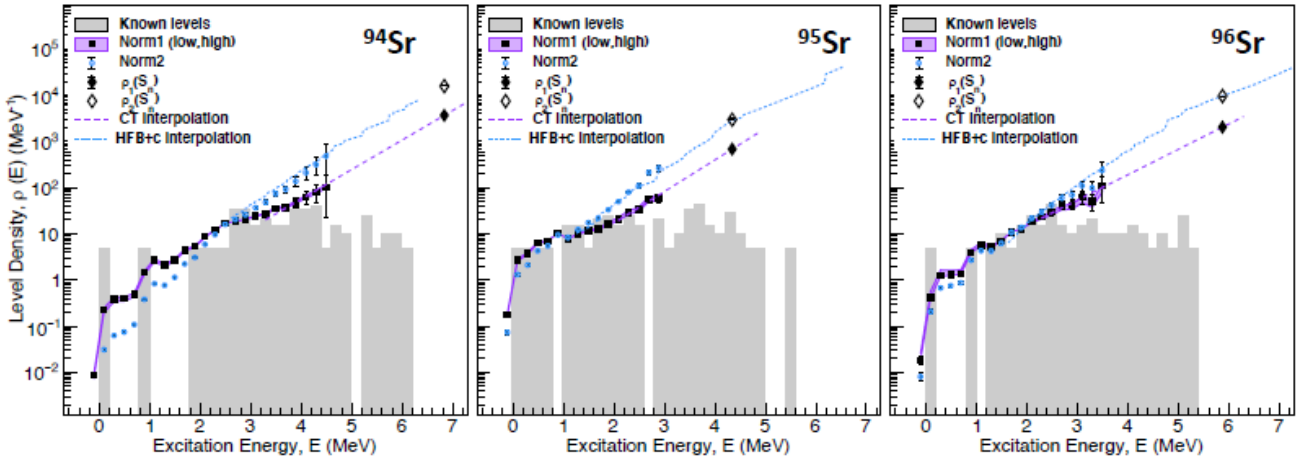
- UCB, LLNL, MSU, Oslo collaboration.



Courtesy M. Stoyer (LLNL)

Decay of ^{93,94,95}Rb: Providing (n,γ) for ^{92,93,94}Sr

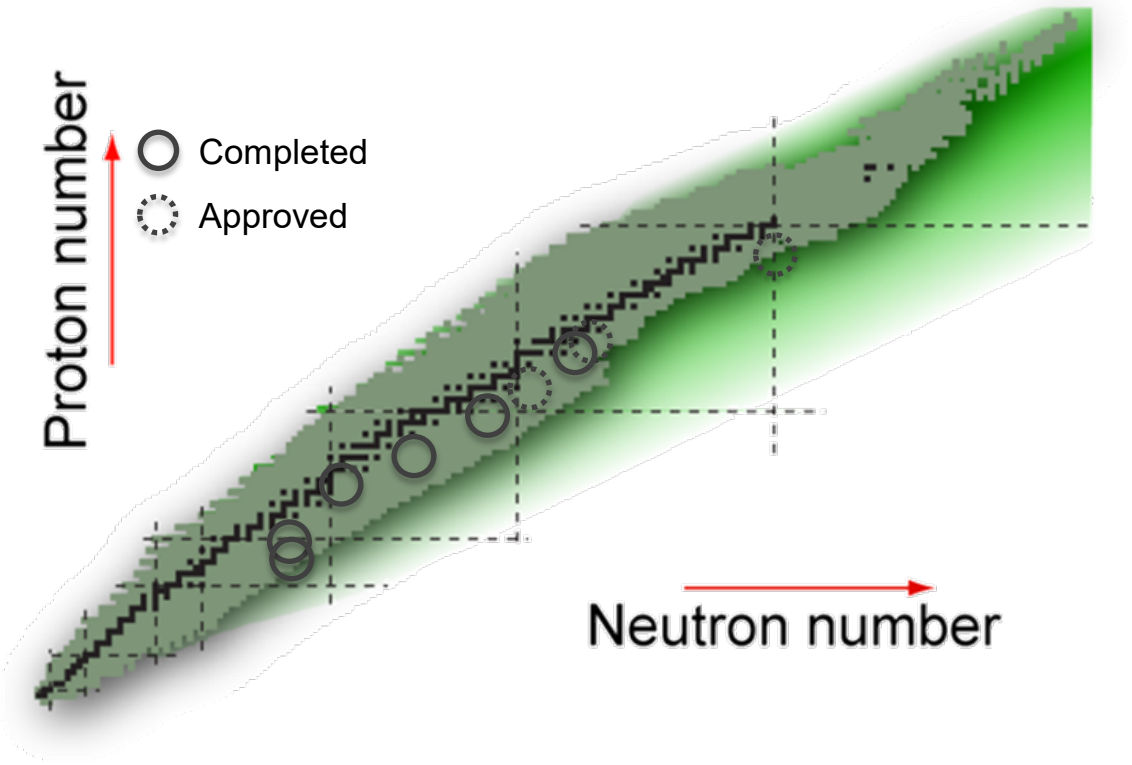
- Experiment to deliver thermal ^{93,94,95}Rb in Nov. 2021 at ANL CARIBU facility.
- Moving tape collector and interior plastic scintillator completed previously.
- High-intensity nearly pure beams of Rb isotopes enable high statistics TAS measurement of Sr isotopes
- β-decay populates above Sn and β-delayed neutron branch is significant (9-13%)
- Analysis ongoing by Adriana Sweet (LLNL). Previous analysis ^{92}Sr(n,γ) submitted



- NORM 1→Auxiliary data: Global systematics are fit to semi-empirical $\rho(S_n)$ for Rb, Sr, Y, & Zr nuclei
- NORM 2 → Microscopic approach to normalizing the NLD resulted in an estimated $\rho(S_n)$

Strong 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.



Approved

A. Spyrou (MSU): Constraints on neutron-capture reactions around N=82

A. Spyrou (MSU): Constraining neutron capture rates for r-process nuclei with the N=126 factory

A. Richard (LLNL): Constraining i-process nucleosynthesis in the Nb-Ru region

A. Richard (LLNL): Neutron capture constraints for the astrophysical i-process

S. Liddick (MSU): Neutron-capture cross section constraints in neutron-rich Sn and Sb isotopes

A.C. Larsen (Oslo): The rare-earth r-process peak: 156-159Sm(n,g) reaction rates constrained with the beta-Oslo method

H. Berg (MSU): Constraining neutron capture rates for the i-process around A=150

E. Ronning (MSU): The Last Piece of the Generalized Brink Axel Hypothesis Puzzle

Completed

S.Liddick (MSU): New technique for neutron capture cross section measurements on short-lived nuclei

A. Spyrou (MSU): Constraints on nucleosynthesis in the iron region

A. Spyrou (MSU) / S. Liddick (MSU): Constraining supernova models with SuN

N. Scielzo (LLNL): Determination of the ^{92}Sr neutron-capture cross section and fission product burn up. –

A. Spyrou (MSU): Study of Kr isotopes for astrophysical applications.

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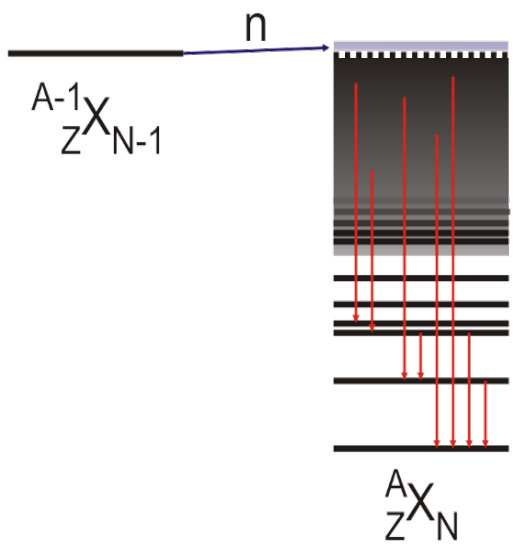
Nuclear level densities and γ-ray strength functions are the dominate uncertainties in (n,γ) calculations



Hauser – Feshbach

- Nuclear Level Density

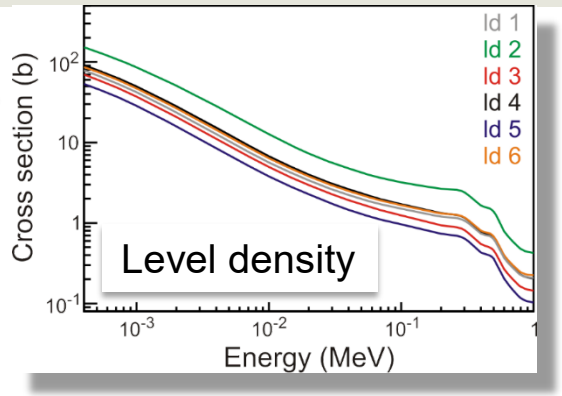
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

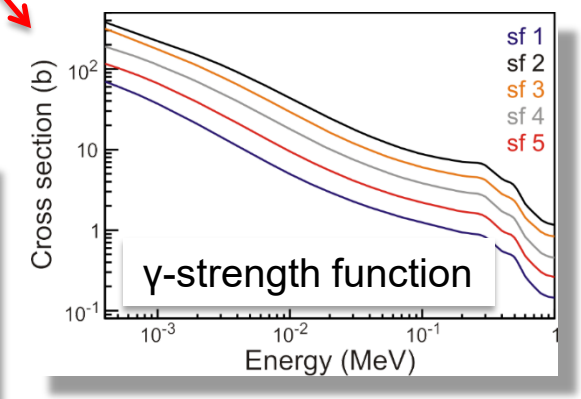
- γ-ray strength function

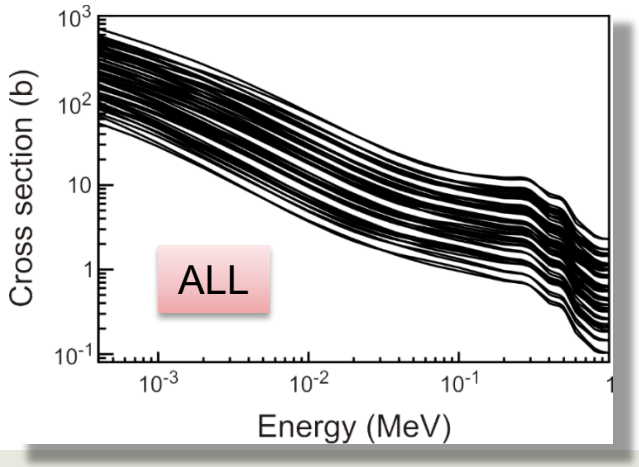
Generalized Lorentzian, Brink-Axel, various tables

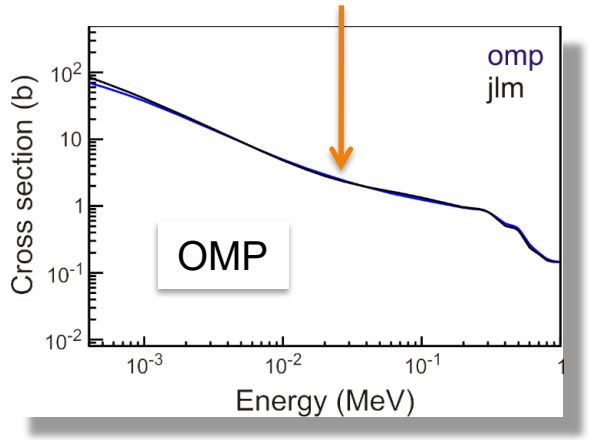
- Optical model potential

Phenomenological, Semi-microscopic









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

TALYS

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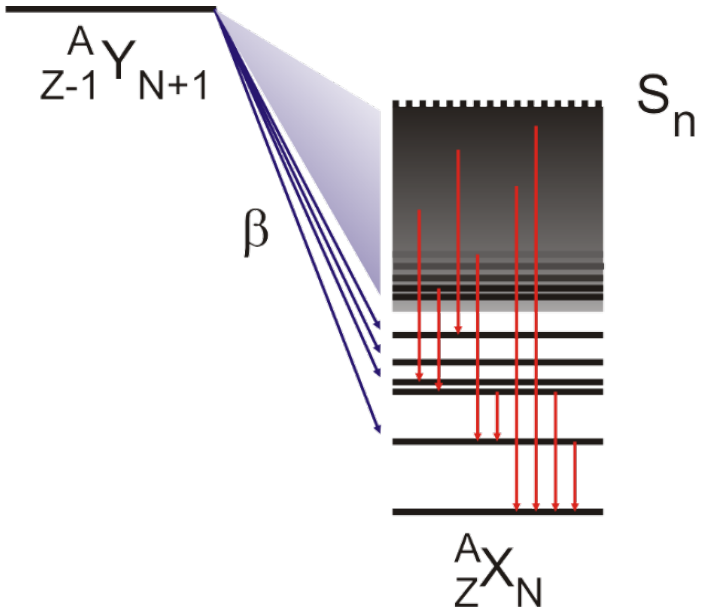
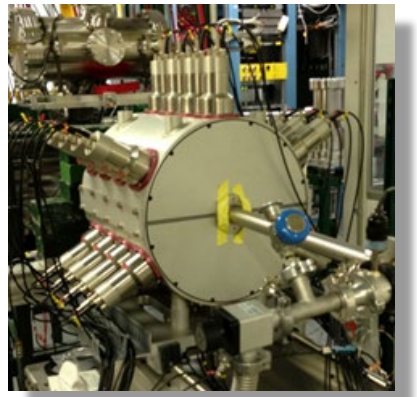
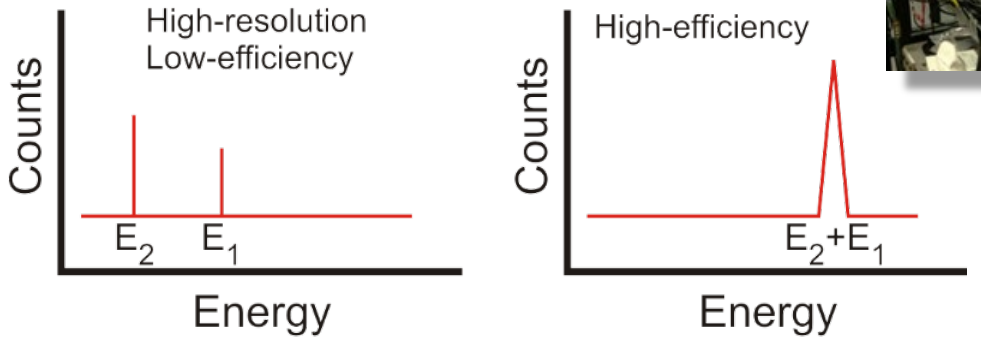
Using beta decay total absorption spectroscopy to infer neutron capture cross sections

- 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 γ-ray strength function.
- Insert both quantities into a statistical reaction model to constrain (n,γ) rate.

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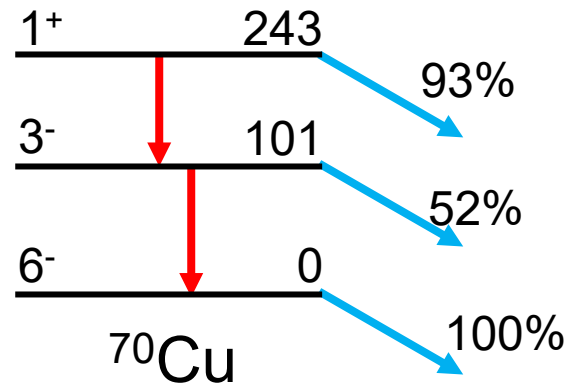
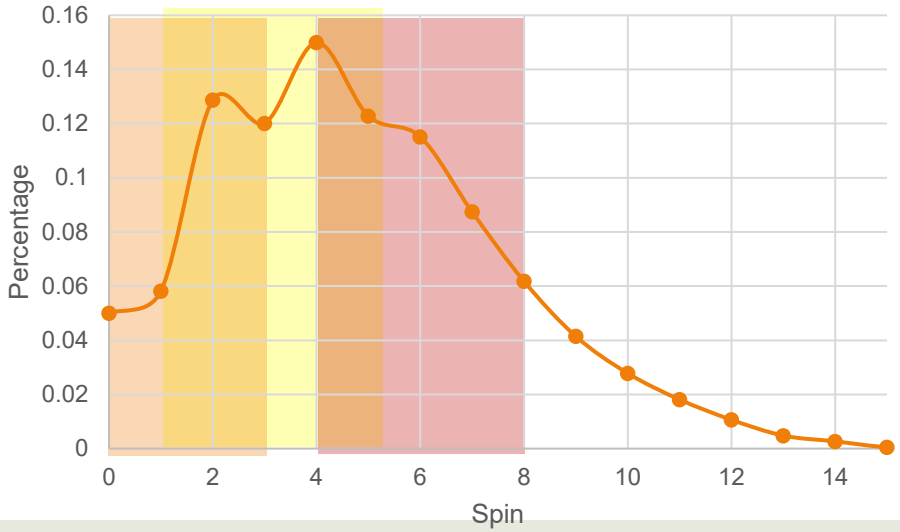
Testing Spin Independence of γSF: Decay of ^{70}Cu isomeric states over a wide spin range

- Test the independence of the γSF from different initial spin distributions.
- ^{70}Cu has three different isomeric states.
- Experiment completed Feb. 2024, analysis is ongoing.
- Work ongoing with funded student (E. Ronning).





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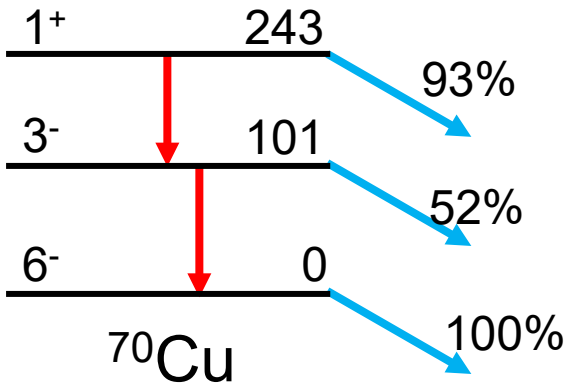
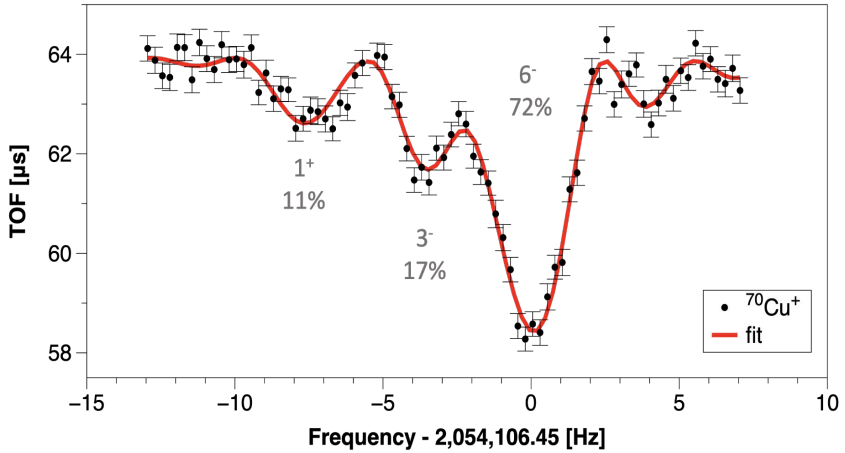
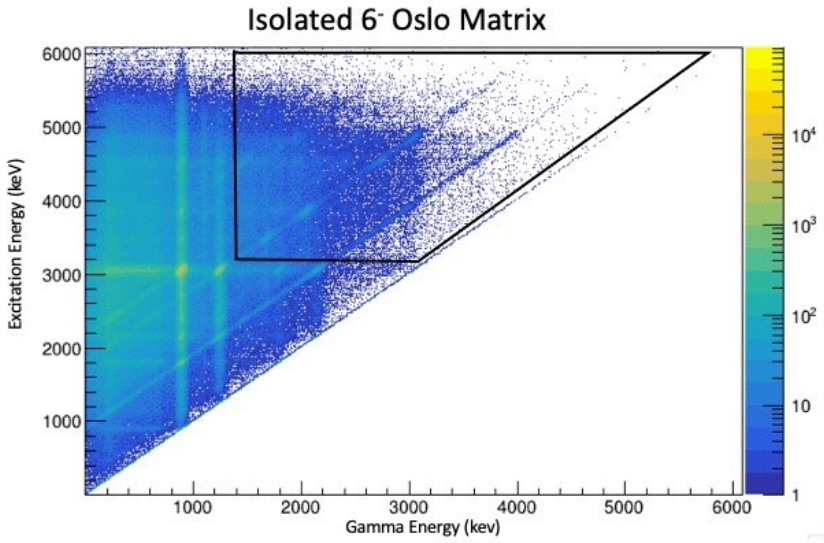
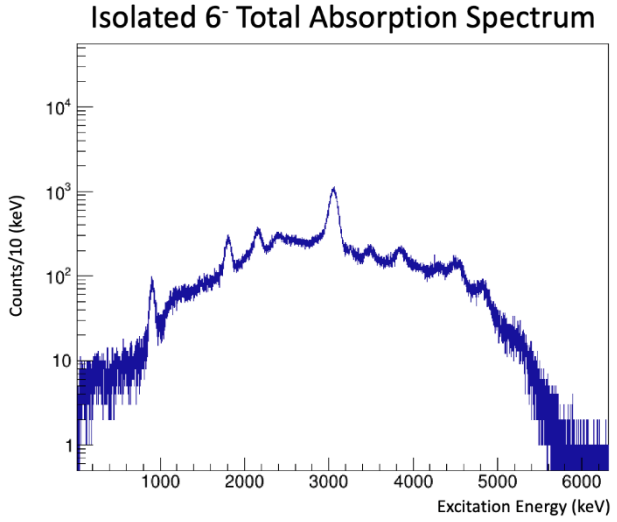
^{70}Cu beta decay as a probe of the spin independence of the γSF

- Multiple isomeric states produced.
- 6^- ground state cleanly separated
- Ran beam on/beam off cycle of 6/7 minutes









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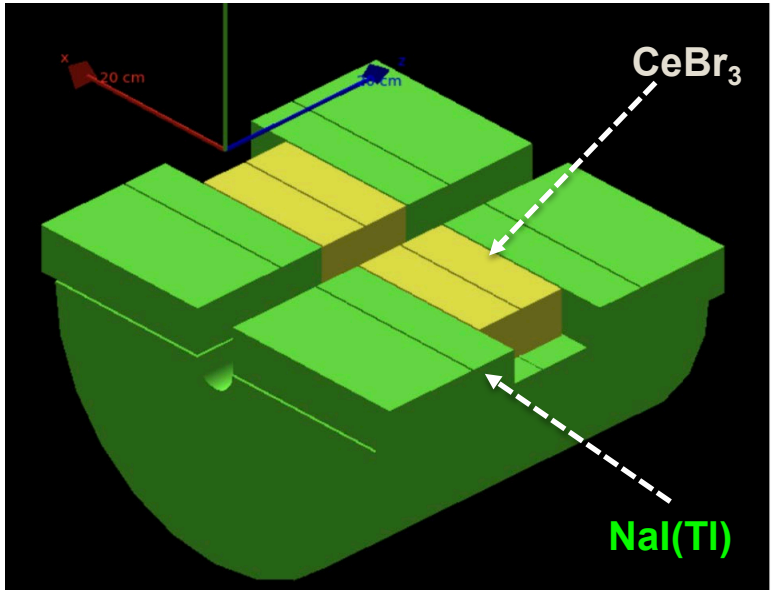
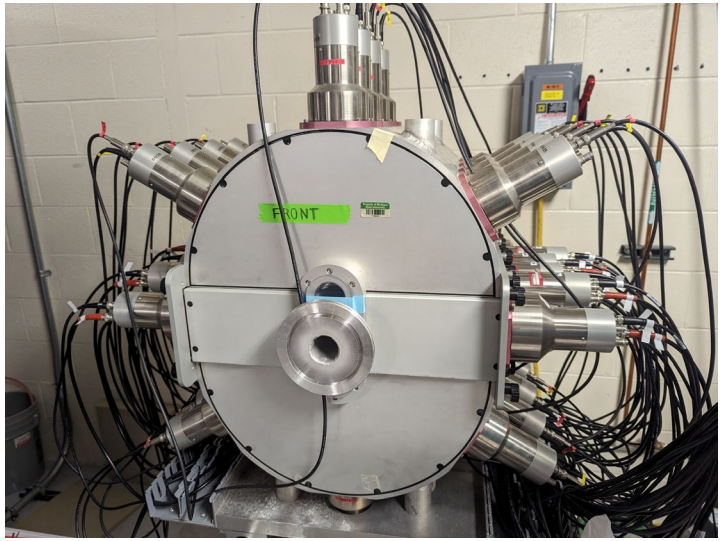
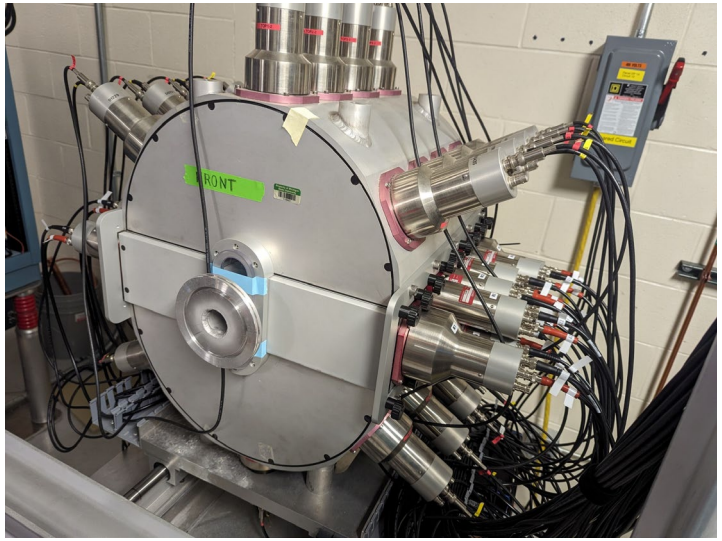
Upgrades to existing detector: SuN++







- SuN++ commissioned during last LEBIT experiment (20 new modules added to the existing detector (12 NaI and 8 $CeBr_3$).
- Smaller segments help to identify the direction of the electron and reduce electron background
- Better energy resolution with $CeBr_3$ segments to identify low-lying discrete levels without the need for an additional high-resolution experiment.

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, intermediate neutron capture process, slow-neutron capture process, and stewardship science.
  - Studies of sensitive i-process nuclei.
  - 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 supported one graduate student and one postdoctoral researcher strongly connected to the national laboratories.

Acknowledgements

S. N. Liddick, A. Spyrou, I. Yandow, R. Ringle, A. Chester, A. Hamaker, C. Harris, R. Lewis, K. Lund, J. Owens-Fryar, A. Palmisano, D. Puentes, M. K. Smith, C. Sumithrarachchi

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Questions?