Gamma-Ray Cascade and Detector Characterization for Indirect Neutron-Capture Measurements

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ABSTRACT

Neutron-capture reactions on unstable nuclei play a key role in the production of heavy elements in the universe and provide vital diagnostics for reaction networks related to fission products. However, these reactions cannot be measured directly because they involve radioactive nuclei. We have performed an indirect measurement of ^{93}Sr(d,pγ) at TRIUMF using radioactive beams of ^{93}Sr and charged particle and γ-ray detector systems. In order to interpret our data, we need to use simulations of our detector coupled with simulations of γ-ray cascades. Though we have detector simulations, a reliable γ-ray cascade simulation has not been performed. We are attempting to create a gamma-ray cascade simulation that mimics the experiment data using the simulation tool RAINIER [1]. Our results will enable us to better understand and interpret our data and will ultimately aid in the calculation of the neutron-capture reactions.

https://www.esa.int/ESA_Multimedia/Videos/2017/10/Neutron_star_merger

INTRODUCTION

- One of the major questions in science is the origin of heavy elements in the universe, or nucleosynthesis.
- So-called neutron-capture reactions are responsible for producing most elements heavier than iron, and involve reaction networks of neutron-capture and β decay.
- Neutron-capture reaction rates are crucial for understanding these processes, and provide information about the reaction networks of fission products.
- Neutron-capture rates for unstable elements are unfeasible to measure directly, and there is little data.

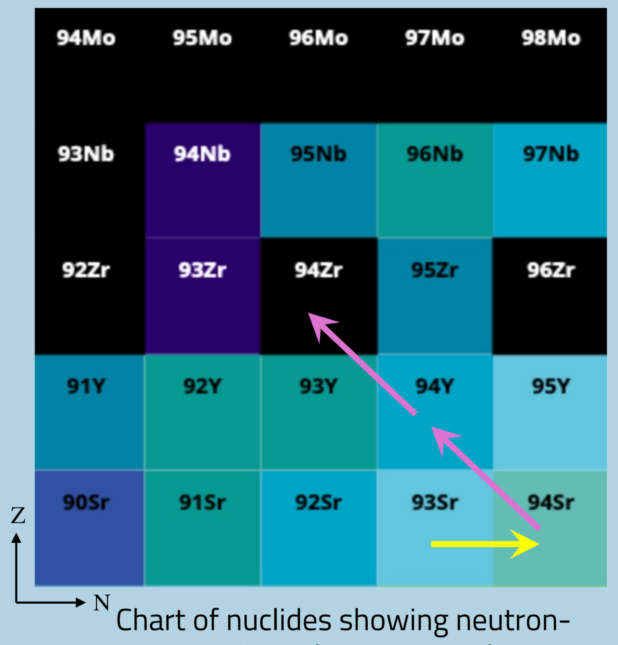


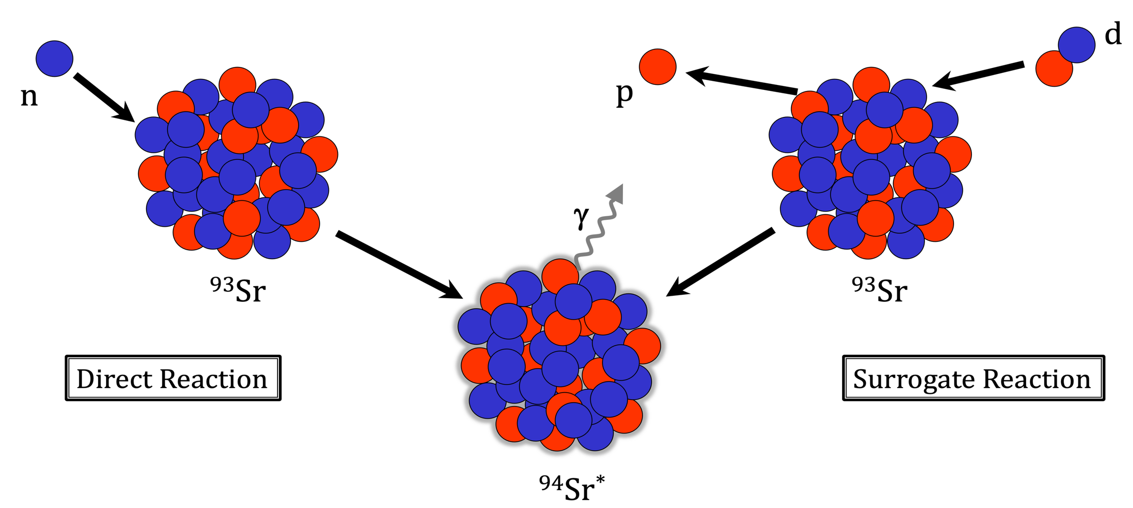
Chart of nuclides showing neutron-capture of ^{93}Sr (yellow arrow) and beta decay paths of ^{94}Sr (pink arrows).

MOTIVATION

- We are interested in measuring the neutron-capture rate of ^{93}Sr(n,γ), which has no experimental information known.
- ^{93}Sr(n,γ) reaction plays a role in the formation of the stable Nb and Zr elements that we observe in nature.
- Understanding the reaction network that produces these elements adds to our knowledge regarding the origin of the elements in the universe and for fission products that may be used as a diagnostic tool.

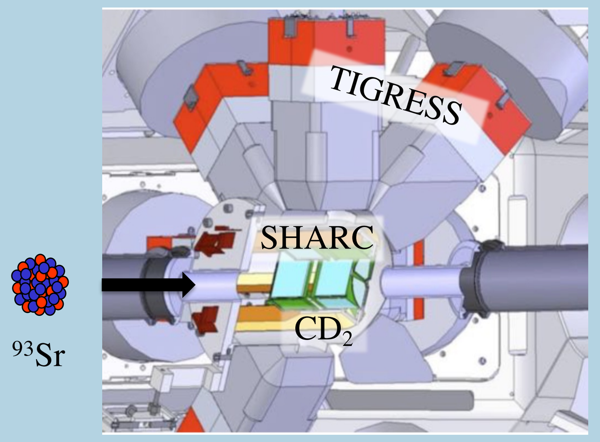
SURROGATE REACTIONS

- We deduce neutron-capture reactions by measuring the gamma-rays emitted by the excited product nucleus.
- Experiments to deduce (n,γ) rates directly are not feasible for short lived radioactive nuclei.
- Instead, we use an indirect "surrogate reaction" measurement with a (d,pγ) reaction, which mimics (n,γ).



EXPERIMENT

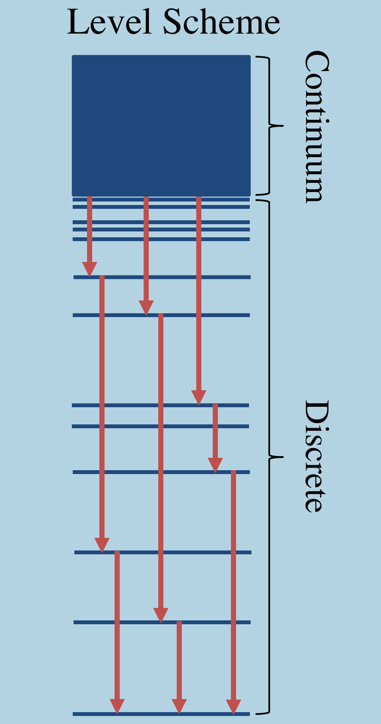
- The measurement of ^{93}Sr(d,pγ)^{94}Sr was conducted at TRIUMF, which is a particle accelerator in Canada that provides a range of rare isotope beams.
- Radioactive ^{93}Sr was shot at a target of CD_2.
- The expelled protons and gamma-rays were detected using SHARC and TIGRESS.
- The measured γ-ray spectrum is used to understand the reaction rate.
- In order to interpret our spectrum, we need to understand how ^{94}Sr de-excites via γ-ray emission.



Experiment diagram of ^{93}Sr(d,pγ) measurement at TRIUMF.

SIMULATION

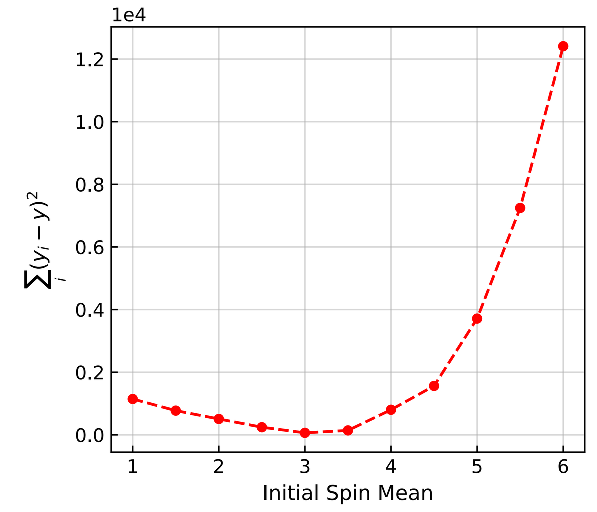
- We are attempting to mimic the experimental γ-ray spectrum using the simulation tool RAINIER [1].
- RAINIER is a Monte Carlo code which uses nuclear data and statistical models to simulate γ-ray cascades of excited nuclear states.
- Our goal is to simulate γ-ray cascades from the continuum region of the excited ^{94}Sr.
- We are starting with well known test cases to benchmark our simulation.



Orange arrows are possible γ-ray cascade pathways.

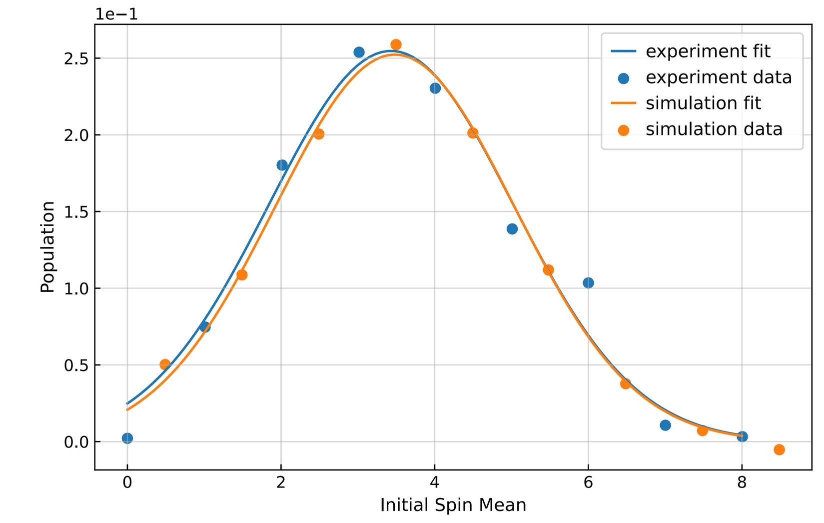
TEST CASE

- We use available ^{95}Mo(d,pγ)^{96}Mo data because it uses a stable target, a similar reaction, and is well documented [2].
- We modify simulation parameters to match the peak locations, widths, and intensities of the experiment.
- We fit the peaks in the simulated and experimental spectra to quantitatively compare them.
- Additionally, we performed the least squares method to determine the best fit spin distribution, and compared the spin distribution with the experimental distribution [2].



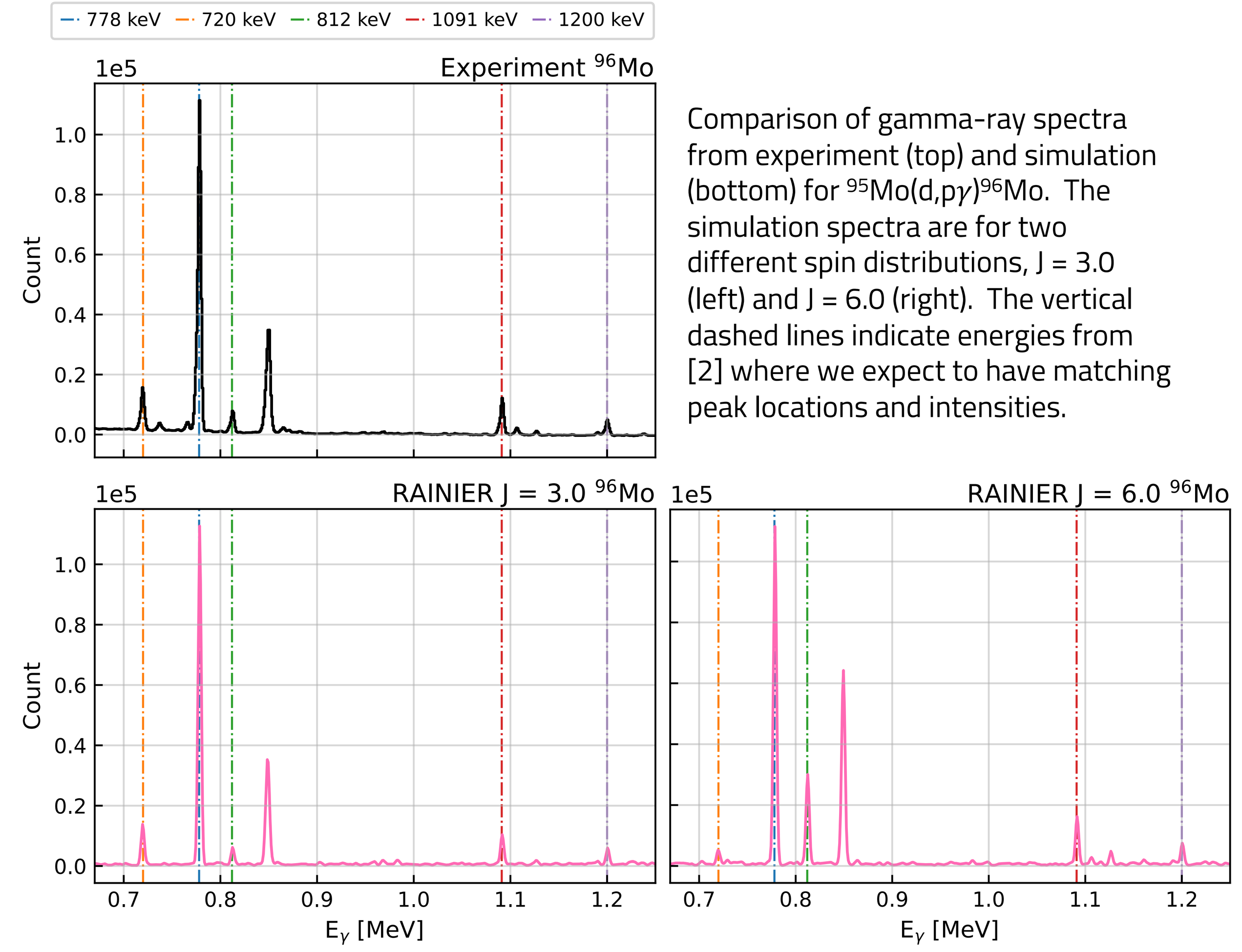
Left: We use the sum of the squares of the residuals for a variety of spins to determine the best fit spin distribution, which is identified by the minimum.

Bottom: Comparison of the spin distribution from the experiment and simulation.



BENCHMARK RESULTS

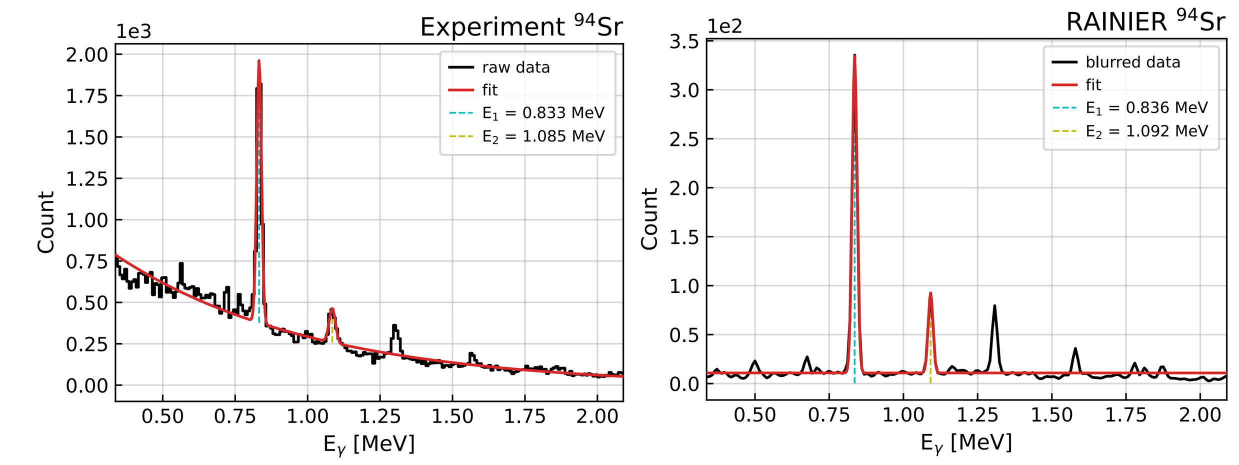
- Comparing our simulation results with the experiment and [2], we have determined that the simulation reasonably matches the experimental data.



Comparison of gamma-ray spectra from experiment (top) and simulation (bottom) for ^{95}Mo(d,pγ)^{96}Mo. The simulation spectra are for two different spin distributions, J = 3.0 (left) and J = 6.0 (right). The vertical dashed lines indicate energies from [2] where we expect to have matching peak locations and intensities.

FUTURE WORK

- With RAINIER validated in our simulation of ^{96}Mo, we now plan to simulate the ^{93}Sr(d,pγ)^{94}Sr case.



Experiment (left) and simulation (right) gamma-ray spectrum of ^{93}Sr(d,pγ)^{94}Sr. Both spectra where fit using a two-peak gaussian function and account for the offset.

REFERENCES

- [1] Kirsch, L. E., & Bernstein, L. A. (2018). RAINIER: A simulation tool for distributions of excited nuclear states and cascade fluctuations. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 892, 30-40.
- [2] Ratkiewicz, A., Cizewski, J. A., Escher, J. E., Potel, G., Harke, J. T., Casperson, R. J., ... & Smith, K. (2019). Towards Neutron Capture on Exotic Nuclei: Demonstrating (d, p γ) as a Surrogate Reaction for (n, γ). Physical Review Letters, 122(5), 052502.

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