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PNNL-39743

Detector calibration of β-decay into ^{136}Xe

August 2026

Lauren I. Miller
Stephanie M. Lyons

U.S. DEPARTMENT of ENERGY

Prepared for the U.S. Department of Energy
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Detector calibration of β-decay into ^{136}Xe

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(Dated: August 26, 2026)

Isotopes are versions of an element with the same number of protons but a different number of neutrons. Adding neutrons to a stable element usually makes it unstable, or radioactive, and these isotopes radiate particles or light to decay back into a stable form. ^{135}Xe (xenon-135) is a radioactive isotope of great interest to the nuclear physics community because it is produced by nuclear fission, which is how nuclear reactors generate electricity. In reactors, unstable ^{135}Xe often absorbs a neutron, making stable ^{136}Xe (xenon-136). This removes a neutron from the reactor fuel that could otherwise interact with other isotopes and sustain fission, making the fission reaction less efficient, so isotopes in reactors that commonly absorb neutrons to become stable are known as neutron poisons. ^{135}Xe is the biggest neutron poison known, so understanding it directly supports the U.S. Department of Energy's Office of Nuclear Energy mission to develop more efficient and safe advanced reactors. The ^{135}Xe + neutron reaction cannot be measured directly because neither ^{135}Xe nor neutrons live long enough, so we must use experimental nuclear physics techniques to determine whatever we can for this reaction. We performed an experiment at Argonne National Laboratory using their radioactive ion beam source to generate ^{136}I (iodine-136) and ^{136}Te (tellurium-136). These both decay into ^{136}Xe, and we studied this decay using a specialized detector. We can analyze this data to extract a lot of information, such as how long the isotopes live and how they decay. Information like this will be used to determine more about the key ^{135}Xe + neutron reaction. As part of my internship at PNNL, I started the data analysis by working on data calibration and comparing it to simulations. This internship allowed me to develop my coding and data analysis skills and expand my professional network significantly.

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I. INTRODUCTION

^{135}Xe is a very important isotope because of its significance for nuclear reactor design and nuclear safeguards. The ^{135}Xe$(n,\gamma)^{136}$Xe reaction is very common in nuclear reactors, as ^{135}Xe is a high-yield fission product of ^{235}U and ^{239}Pu fission, and this reaction has the largest known cross-section of any radioisotope. However, we rely on models for the cross section of this reaction, because it is so hard to measure directly due to ^{135}Xe's short half-life and noble gas properties. The cross section is very uncertain at energies above thermal due to differing model values (see figure 1), and this uncertainty affects the efficiency of reactors by increasing the safety margins engineers must follow. This experiment represents an effective way to indirectly measure the neutron capture cross section of ^{135}Xe, thereby reducing uncertainty greatly and improving the efficiency of next-generation nuclear reactors.

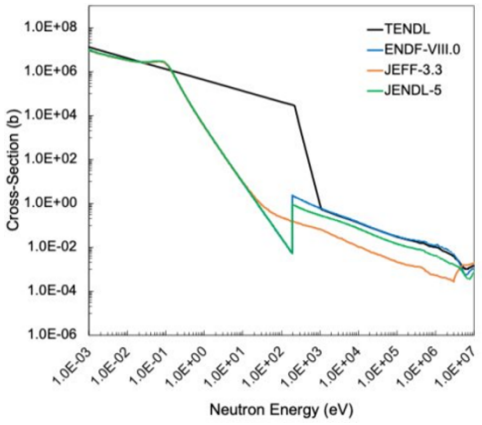

FIG. 1. ^{135}Xe$(n,\gamma)^{136}$Xe cross section measurements from TENDL (black), ENDF (blue), JEFF (orange), and JENDL (green).

Nuclear data for ^{136}Xe is also applicable to nuclear astrophysics. ^{136}Xe is produced by the r-process in neutron star mergers (kilonovae) and, less frequently, core-collapse supernovae.[123] There are many gaps in the nuclear data for Xe at high energies, one example of which is the ^{135}Xe$(n,\gamma)^{136}$Xe cross-section uncertainty. ^{135}Xe is a critical branching point in the i-process, so its cross section impacts the stellar abundance of many isotopes. The current model discrepancy therefore introduces uncertainty into astrophysical abundance calculations for many isotopes including barium and xenon isotopes.[4] The experiment we have performed also allows us to determine the nuclear level density and gamma strength function of ^{136}Xe, which will help determine the reaction rates and stellar abundance of this isotope.

II. EXPERIMENT

A. nuCARIBU

This experiment was part of a campaign that started on July 9 and continued until July 19 at Argonne National Laboratory in Chicago. ANL's ATLAS facility possesses nuCARIBU, which is a source of fission products from neutron-induced fission of ^{235}U. Protons are accelerated in a cyclotron and get fired at a target made of ^{7}Li. These protons undergo a p-^{7}Li reaction, producing neutrons, which hit the ^{235}U target and fission occurs. The fission products enter a sophisticated gas catcher, where they are funneled into a beam (see figure 2). This beam is mass separated by an isobar separator and further separated into packets by a radiofrequency quadrupole buncher.[5] This allows the beam to be composed of discrete packets, rather than a continuous stream.

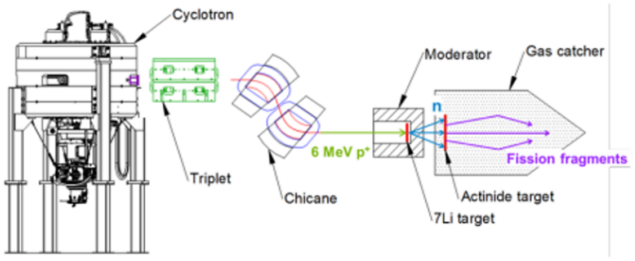

FIG. 2. Path of particles from the cyclotron to the gas catcher. Savard, G., Progress at the ATLAS facility, SSNET 2024 Conference.

B. SuNTAN

For this campaign, we used the SuN (Summing NaI(Tl)) detector as a segmented scintillator. The eight optically isolated segments allow for its use as a total absorption spectrometer.[6] Each of these segments contains three photomultiplier tubes (PMTs) for detecting gamma rays. The beam of ions from nuCARIBU traveled to the rare isotope source's stopped beam stations in the low-energy experimental area of the ATLAS facility, where SuN was placed. Figure 3 shows the layout of the ATLAS facility.

In addition to SuN was the Tape station for Active Nuclei (TAN), which is a system that allows us to observe decay of isotopes from a beam in addition to radioactive sources. It consists of a tape in the SuN beamline which is exposed to the beam and serves as a target. This long tape can be cycled inside the beamline at desired times to provide a fresh target for beam exposure. This allows for for the same isotopic decay pattern to be observed many times. The irradiated section of tape is cycled into a container, where isotopes will safely decay to stability

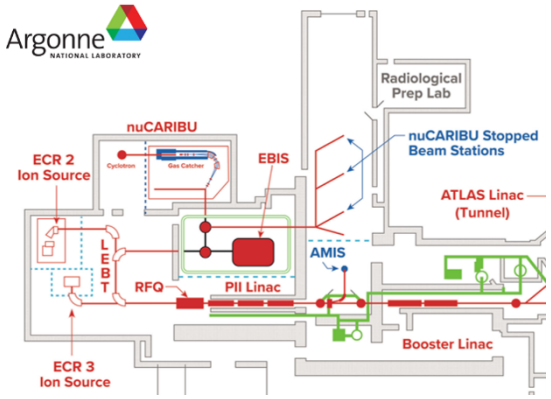

FIG. 3. ATLAS facility showing nuCARIBU, the rare isotope beam generator, and its stopped beam stations. SuNTAN was placed at the topmost beam station as seen on the map.

without excess radiation interfering with the measurement. A schematic of SuNTAN is shown in figure 4.

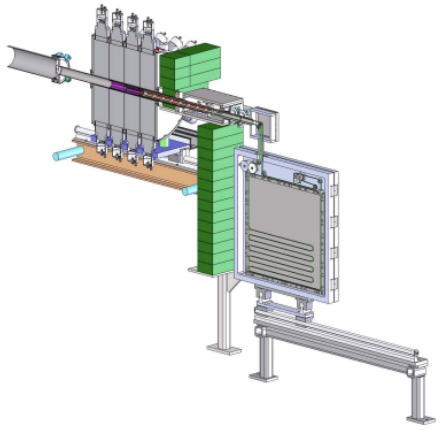

FIG. 4. Schematic of the SuNTAN setup, showing the tape storage container and the section extending into the SuN beamline.

Since the main isotope of interest is ^{136}Xe, we optimized the isobar mass separation to give us a beam of mostly ^{136g,m}I and ^{136}Te, the parent and grandparent isotopes of ^{136}Xe, respectively (see figure 5). This enabled us to examine the beta-decay of these isotopes into xenon, giving insight into the high-energy nuclear level density and gamma strength function of $^{135}\mathrm{Xe}(n,\gamma)^{136}\mathrm{Xe}$.

I was able to help with the data collection and processing at ANL, and I assisted in performing an approximate initial data calibration used to enable data visualization during the experiment.

III. ANALYSIS

Before this data is released to the collaborators, it must be calibrated. My main task for this internship was to

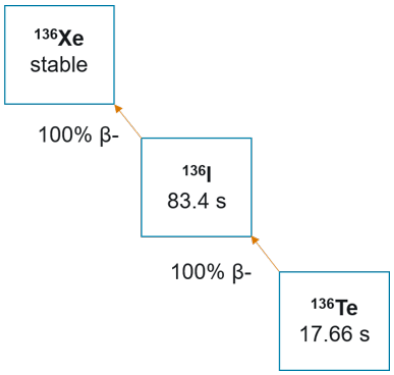

FIG. 5. Decay scheme of ^{136}I and ^{136}Te.

perform a precise calibration of the data gathered in July. This required a simulated dataset with which to match gamma-ray energy peaks to the experimental data we collected from calibration sources. The calibration sources we used were ^{60}Co, ^{137}Cs, ^{228}Th, and ^{241}Am. In order to artificially match the calibration data collected, I needed to simulate the emitted gamma rays from decays of each of these isotopes in different positions in the detector. To do this, I used a simulation of the SuN detector created using Geant4,[789] a high-energy physics detector simulation software developed by CERN. This simulation was already able to model the gammas emitted from a particle undergoing beta decay, meaning I could easily simulate ^{60}Co and ^{137}Cs decay. However, since ^{228}Th and ^{241}Am undergo alpha decay, they proved to be more of a challenge. I expanded the functionality of the simulation to include gammas emitted from alpha decay as well. To visualize this data, I used ROOT,[10] a data visualization framework also developed by CERN. Using ROOT's object browser, I was able to verify the simulated gamma spectra. I also used ROOT to examine the data collected using SuN.

IV. RESULTS AND DISCUSSION

When I visualized the gamma-ray spectra from the data we collected, they were not entirely as expected. For one, the pattern of gamma ray peaks we expected to see was not visible in all three photomultiplier tubes (PMTs) for each segment. It consistently was only clear in the middle PMT. Also, for ^{137}Cs, there seemed to be two peaks where there should only be one (see figure 6). We hypothesized that the spread in energy of the gammas detected by the edge PMTs was due to gammas reflecting off the sides of the segments and losing energy.

Each PMT needs to be gain matched, and I will do this by choosing a peak or feature of the spectrum at a specific energy and ensure that feature is at the same energy for all the PMTs. This provides a basis for accurate calibration. To begin calibration, I have fitted a Gaussian function to any observed peaks and recorded its

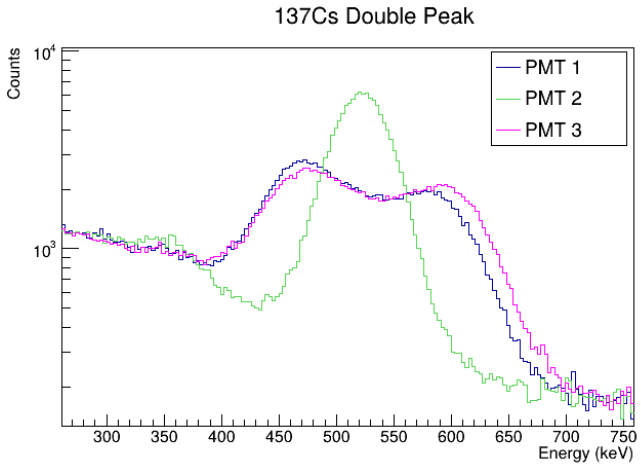

FIG. 6. Raw PMT spectra for 668 keV gamma peak emitted by ^{137}Cs. PMTs 1, 2, and 3 are all in the same segment.

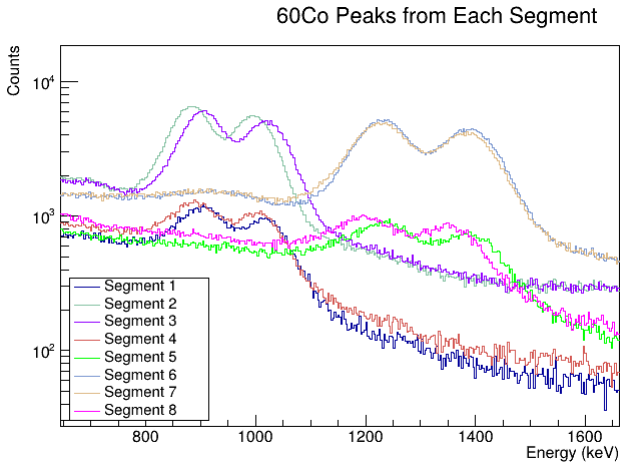

FIG. 7. Uncalibrated ^{60}Co 1173 and 1332 keV peaks from each segment of SuN. All data from central PMTs. Segments 1, 4, 5, and 8 are farther away from the source. Segments 2, 3, 6, and 7 are more central to the source.

centroid as well as the uncertainty. Once gain matched, I will be able to plot these points on a graph of expected energy – from a fit of the peaks from the simulation – versus observed energy. These points will form a line within uncertainty, the gradient and y-intercept of which will be the data needed to calibrate each PMT. Figure 7 shows the discrepancy between uncalibrated spectra of ^{60}Co from each segment, demonstrating the necessity of gain matching and calibration.

V. CONCLUSIONS

There is a lot of future work to be done analyzing this data. From β-Oslo analysis, we will be able to determine the nuclear level density of ^{136}Xe, which is extremely uncertain at high energies, yet very influential to nuclear astrophysics. We will also be able to calculate the gamma ray strength function (γSF). From total absorption spectroscopy (TAS) analysis, we will be able to see the β-feeding intensities and β-decay strength distribution, which will allow us to calculate the half-lives in a new way. All this analysis would not be consistent and reliable without a single, unifying calibration of all the data.

ACKNOWLEDGMENTS

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