XENONnT and Kr-83m Calibration
REU Program at Columbia University - Nevis Labs

Chloe Liebenthal¹

¹Rice University

August 4, 2022

Contents

1 Introduction 2
2 Background 2
3 Goals 3
4 The Calibration Process 3
5 Methods 5
6 Results and Discussion 6
7 Conclusion 8
8 Acknowledgements 9
1 Introduction

About 85 percent of all matter in the universe cannot be observed via conventional methods, and this ‘dark matter’ is one of the central problems in modern physics. The XENON Dark Matter Project represents an international effort to directly detect dark matter. The current XENON detector, known as XENONnT, is calibrated via a process involving the radioactive decay of the metastable isotope Kr-83m. My research goal this summer has been to analyze XENONnT data from Kr-83m calibration runs to establish a methodology for making Kr-83m data selections, visualizing Kr-83m decays as a physical process, and analyzing the distribution of Kr-83m in the detector throughout the calibration process. The findings from this research can be used to calibrate detector response to light and charge signals and to optimize the calibration process.

2 Background

The evidence for the existence of dark matter dates back to 1933, when the physicist Fritz Zwicky proposed the existence of dark matter (and coined its original name, dunkle materie) to explain a discrepancy in galactic velocities. In the 1970s, the astronomer Vera Rubin proved her observation that galactic rotational velocity curves are significantly different from what we’d expect in a universe without dark matter. This is direct observational evidence that astrophysical objects are affected by some unidentified matter. More recently, physicists have worked backwards from the Cosmic Microwave Background data, which shows us how radiation is distributed in the universe, to determine dark matter density during early universe formation. Dark matter provides a strong explanation for Cosmic Microwave Background anisotropies. Ultimately, the existing evidence provides a lot of information about what dark matter is like and how physicists should conduct their search.

From this evidence, we know about some of the attributes of dark matter. For it to have influenced the Cosmic Microwave Background, it would need to have been created early in the universe’s lifespan. It is electrically and color neutral. It also travels at non-relativistic speeds, so we call it ‘cold’. Dark matter is functionally collisionless, meaning it does not interact with itself very much. Furthermore, it exhibits mass-based gravitational attraction. There are many proposed theories about a particle constituting dark matter, such as neutrinos or a hypothetical particle called an axion, but one of the theories that best fits the evidence is a Weakly Interacting Massive Particle, or WIMP.

In addition to fulfilling all of the other conditions for a dark matter particle, WIMPs would have a significantly higher mass than the standard particles in our universe. They would interact via the electroweak and gravitational forces. WIMPs are an ideal candidate for dark matter because of their consistency with existing evidence for dark matter., For example, the hypothetical WIMP density in the early universe would be consistent with Cosmic Microwave Background data. Furthermore, WIMPs are consistent with proposed extensions to the Standard Model of particle physics, such as supersymmetry. This summer project focuses on the XENON experiment’s search for WIMPs.

The XENON experiment is the most sensitive search for dark matter in the world. Since 2006, the experiment has used a series of increasingly-sensitive particle detectors known as Time Projection Chambers to search for WIMPs. The experiment is located at LNGS (Gran Sasso National Laboratory), an underground research facility under a mountain in Italy. The mountain shields experiments from outside radiation, making LNGS an ideal location for this highly-sensitive particle search. The current XENON detector is XENONnT, which was built during the earliest months of the COVID pandemic. Despite the additional challenges, construction was a success and the first science run took place in 2021. XENONnT searches for WIMPs using a volume of 8.5 tons of xenon; this is 5 tons more than XENON1T, the previous detector. XENONnT also greatly improves the detector’s
3 Goals

The purpose of this summer research project is to study the XENONnT Kr-83m calibration process. The experiment uses the radioactive decay of Kr-83m to characterize the detector’s response to light and charge signals. By using data from the well-understood Kr-83m decay process as a control group, researchers learn about how the light and charge yields translate to recorded detector signals and can use this information to calibrate the detector and their experimental methods in order to refine the hunt for WIMPs.

This project’s main goal is to analyze the physical process of mixing Kr-83m into the detector and determine how its distribution in the detector changes over time. It is important to ensure even and homogeneous distribution in order to calibrate the TPC accurately.

4 The Calibration Process

XENONnT is a time projection chamber consisting of a cylindrical tank of xenon, with liquid xenon (LXe) on the bottom and gaseous xenon (GXe) on the top. When a particle enters the detector and interacts with a xenon atom, the interaction releases a photon and creates scintillation light with photons at a wavelength of 175 nm. Photomultiplier tubes, or PMTs, record the photon signal, also called an S1 signal. Next, due to an electric field applied to the detectors, electrons released by the interaction will drift towards the gaseous xenon. Once the electrons hit the gas, they also begin creating light, which the PMTs record as an S2 signal. Each interaction provides information such as its location in the detector (z-position is reconstructed from how long it took for the electron to drift upwards and create an S2, and XY-position is reconstructed based on which PMTs recorded the signal), whether the particle interacted with the nucleus or electron of a xenon particle based on the relative size of the S1 and S2, and how much energy the incoming particle deposited in the detector.

Kr-83m is a metastable isotope soluble in liquid xenon. When it decays, it emits two energy conversion electrons at 9.4 and 32.1 keV, as seen in Fig. 1. The half-life of the 9 keV state is 154.4 ns. Kr-83m is used for calibration because only an internal radiation source will be effective. The detector is heavily shielded from outside radiation, and xenon further attenuates radiation, so the radiation needs to come from inside the detector. Kr-83m mixes uniformly into the detector in time, which is essential for ensuring that all spots in the detector volume record events in the same way. Furthermore, Kr-83m releases low-energy signals that are easily distinguishable from background events in the detector. Its half-life is 1.83 hours, which is fast enough that it is useful for calibration but does not linger for long enough that it creates problematic background decays after the calibration period. After decaying, the resulting Kr-83 is not radioactive and therefore not a problem when recording detector events.

Kr-83m for XENONnT is generated from the radioactive decay of a Rb-83 source, then added to the detector through a process visualized in Fig. 2. GXe on its way to the detector is flushed through the Rb-83 source to mix gaseous Kr-83m into the xenon volume. Most of the GXe is liquefied with a heat exchanger and is guided straight into the liquid volume of the detector, while a small remaining GXe fraction is directed into the GXe volume of the detector at the top. Once it reaches the xenon volume, it begins mixing into the TPC and eventually achieves near-homogeneity within the volume.

Because Kr-83m emits two energy conversion electrons, a recorded Kr-83m event is more like two events occurring with one very soon after the other. The two S1s, referred to as the main and
Figure 1: The decay scheme for Kr-83m, from Ref. [3].

Figure 2: Kr-83m mixes with xenon before entering the detector.

alternate S1 or as S1a and S1b, occur on the scale of nanoseconds apart. The amount of time between the S1s is called the center time difference. In most events the two signals can be differentiated from each other, and show up as a 9keV event and a 32 keV event, but in cases where the S1s have a very small center time difference, they are recorded as a single 41 keV event. The two S2s usually merge
5 Methods

Raw Kr-83m data needs to be corrected. A major source of error within the data comes from the loss of S2 signals from events deep in the detector. The further down an event takes place, the higher its likelihood of not being recorded, because the electrons hit an impurity and are lost before making it to the PMTs to be recorded.

The procedure begins by selecting relevant data from Science Run 0, the first science run conducted with XENONnT. Several Kr-83m calibrations were performed during SR0 to monitor the detector performance over time. It is necessary to apply a cut to select the Kr-83m events. This cut is based on center time difference and detector location. Events that take place at the very top or bottom of the detector, or right next to the walls, are recorded because these locations do not always provide valid data. By applying a cut on all remaining events based on center time difference, it is possible to select only those events that follow the Kr-83m decay scheme, as indicated in Fig. 3. Events with very low center time differences occur when the main and alternate S1s are recorded at nearly the same time and merge into one 41 keV signal; to avoid introducing additional variables into the dataset, this project does not investigate these events. A Kr-83m cut difference also excludes high center time differences, because these are likely to be background events.

Once these cuts are finished, the amount of data has been greatly reduced due to background events being filtered out. What remains should consist of useful Kr-83m events, as seen in Fig. 4. Minimizing the impact of background events is one of the most important steps for conducting an analysis on any TPC data, so being able to differentiate Kr-83m events and their background is an extremely important part of this procedure.

Next, fitting the remaining Kr-83m data to a theoretical model is necessary to statistically confirm the validity of the cut. This is accomplished via the Chi-squared goodness of fit test and by residual analysis. To ensure that the fit describes the data well, a histogram of the residuals, which represent the discrepancy between a data point and its predicted value, should follow a Gaussian distribution.

Finally, once the relevant events are selected, they can be visualized over time in three-dimensional space to investigate their physical distribution in the detector. The results from this stage of the analysis form the most significant results from this project. Although Kr-83m enters the detector both from the GXe on top of the detector and from an entry point on the wall of the liquid phase,
Figure 4: Cutting based on center time difference and detector location greatly reduces the number of selected events.

it does not immediately become homogeneous in the TPC volume. This time evolution will indicate where Kr-83m events first appear, how long it takes for them to become homogeneous, and if any locations in the detector record an unusual amount of Kr-83m events.

6 Results and Discussion

Figure 5: Selected Kr-83m events fit an exponential decay curve.

The cut resulted in a selection of Kr-83m events that aligns well with predicted values for an exponential decay fit, in Fig. 5. Notably, the half-life derived from the fit is within the error parameters
for the true value, 154.4 ns. The chi-squared and residual analysis also corroborate the effectiveness of the cut. The residuals follow a Gaussian distribution, which indicates that the fit describes the data well. This cut limits the data to events with a center time difference between 500 and 1500 ns, though the later cuts in this project further restrict the cut to those with a center time difference between 500 and 800 ns to select an even narrower range of events.

Figure 6: The cut separates Kr-83m events from background events in the detector.

After selecting Kr-83m events, they can be visualized in S1/S2 space. By comparing the energy of their S1a/S1b and S2 signals, both the 9.4 keV and 32.1 keV decays can be clearly derived from the existing event data. Fig. 6 visualizes how the cut filters out background events and preserves data about Kr-83m events. Instead of background noise, the cut preserves only the Kr-83m events that are useful for calibration. Fig. 7 displays plots of the two Kr-83m decay peaks. Although this cut overlooks the third peak that would normally be generated by events with a very small center time difference, the main decays are preserved clearly.

Figure 7: The two peaks formed by S1as and S1bs represent the double-decay scheme of Kr-83m’s radioactive decay.

The final stage of the project involves creating a time-evolution animation of the location of Kr-83m events in the detector over time in order to analyze how Kr-83m spreads through the detector. The visualization features histograms of events in the detector along two sets of axes: z and r, a side view of the TPC, and x and y, a view of the TPC from above. As described by the time evolution (Fig. 9), in which the Kr-83m valve opens in the first five minutes, Kr-83m events occur at the very top of the detector. This indicates that they arrived in the xenon volume via the GXe phase. After about 80 minutes, events begin to occur in the LXe phase. LXe Kr-83m events are distributed homogeneously throughout the detector in 3-dimensional space, indicating that the Kr-83m mixes with the liquid almost instantly due to the liquid constantly cycling through the detector.
Figure 8: At 97.0 minutes into the run, most events are at the top of the detector, but some are appearing at random locations throughout the LXe volume.

Figure 9: At 110.0 minutes into the run, events are distributed homogeneously throughout the LXe volume.

7 Conclusion

Applying cuts to XENONnT data based on detector location and center time difference is an accurate and effective way to select useful Kr-83m events. The effectiveness of these cuts is confirmed by the comparison of the Kr-83m data and the theoretical exponential decay fit. Furthermore, visualizing these events in S1/S2 space clearly indicates that the selected events represent 9.4 keV and 32.1 keV decays. Making these cuts allows us to learn about how Kr-83m propagates in the detector.

Continuing this research would involve refining the data selection process. The parameters of the cut could be expanded to select low-center time difference events representing merged S1as and S1bs, which are overlooked in the existing scope of this project. Furthermore, the cut could be further tuned to ensure that it excludes as many background events as possible. Comparing SR0 and SR1 data would also be necessary for future research, since this could eliminate any time dependencies in the SR0 data that were preserved in the analysis.

After refining the data selection, it could be used to create a method of correcting Kr-83m data for factors such as losing electrons during the drift period. This will prepare the data for use in other future analyses.
This project’s conclusions about Kr-83m’s physical distribution and propagation through the xenon volume are also useful for optimizing future calibrations. Knowing when the events have reached the point of homogeneity, how long it takes for Kr-83m to stop being present in the detector, and other sorts of time-based information are essential for an effective calibration. Ultimately, the results from this project will be useful in future XENONnT data collection and analysis.

8 Acknowledgements

Thank you to Professor Elena Aprile for welcoming me into the XENON group at Columbia University and supervising this research project.

Thank you to Dr. Michael Murra for supervising this research project.

This material is based upon work supported by the National Science Foundation under Grant No. PHY/1950431.
References


[1] [2] [3]