A Study of Electron Lifetime in the Large Underground Xenon Dark Matter Detector

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Abstract

Computer algorithms were developed to determine the electron lifetime in the Large Underground Xenon (LUX) detector. The electron lifetime was determined for seven data sets obtained from metastable Krypton 83 calibration runs and the lifetimes were then compared to analyse fluctuation over time.

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1 Introduction

1.1 Dark Matter

Direct detection of dark matter is the primary goal of the Large Underground Xenon (LUX) experiment. Evidence for the existence of dark matter has been derived from observations of phenomena in the universe that are seemingly caused by unseen matter, including the rotational curve of galaxies and weak gravitational lensing. One candidate for dark matter is the weakly interacting massive particle (WIMP). The LUX detector aims to detect WIMPs through their interaction with regular matter. [1]

1.2 LUX

1.2.1 Detector Structure

The LUX detector is a dual-phase (liquid-gas) time projection chamber (TPC) located 4850ft underground at the Sanford Underground Research Facility in Lead, South Dakota. The TPC measures 47cm across and 48cm tall and contains 370kg of liquid xenon. At each end of the TPC there is an array of 61 photomultiplier tubes (PMTs). The detector is submerged in a cylindrical water tank measuring 7.6m across and 6.1m tall. In addition to the water tank, several layers of different materials provide the detector with shielding necessary to minimize background, an obstacle for WIMP detection. [2]

1.2.2 Detector Function

When a particle enters the TPC, its interaction with the liquid Xenon results in emitted scintillation light and ionization of the Xenon. The light signals are detected by the PMTs located at the top and bottom of the detector. This primary scintillation is measured by the detector as an S1 signal. PMTs located closer to the impact sight detect a stronger light signal. This information is used during analysis to help pinpoint the horizontal position at which the initial interaction took place.

An applied electric field causes the electrons that were freed by the initial interaction to drift to the top of the detector where they interact with the gaseous

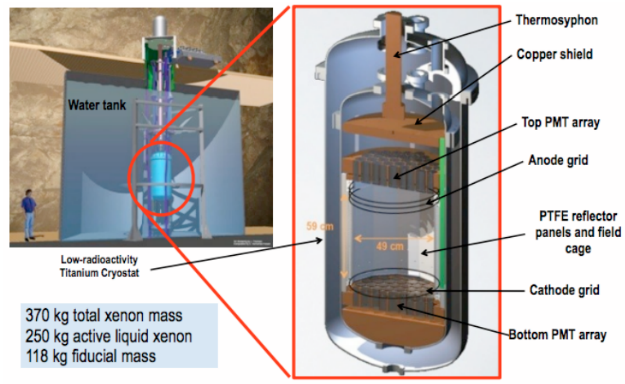


Figure 1: A schematic of the LUX detector, including water tank and shielding material layers surrounding the TPC.

Xenon and produce more scintillation light, which is recorded as an S2 signal. This light signal is measured primarily by the top PMTs and the variation in intensity is again used to pinpoint the location of the interaction.

The vertical distance between the S1 signal and the S2 signal, measured as the time between the pulses, allows for determination of the depth at which the initial interaction occurred. [1]

1.3 Electron Lifetime

In order to obtain an S2 signal, electrons must reach the top of the detector from the initial interaction site. The distance the electron must traverse is measured in the time it takes the electron to make the journey. This is called the drift time.

As the electrons make their way to the top of the detector, impurities in the liquid Xenon threaten their ascent. The amount of time that a free electron can remain in the detector before it is swallowed up by an impurity is called the Electron Lifetime. Ideally the Electron Lifetime will at least be equal to the maximum drift time possible given the dimensions of the detector. The goal of this project was to determine the Electron Lifetime of the detector through analysis of data obtained from ^{83m}Krypton calibration runs and analyse it over an extended period of

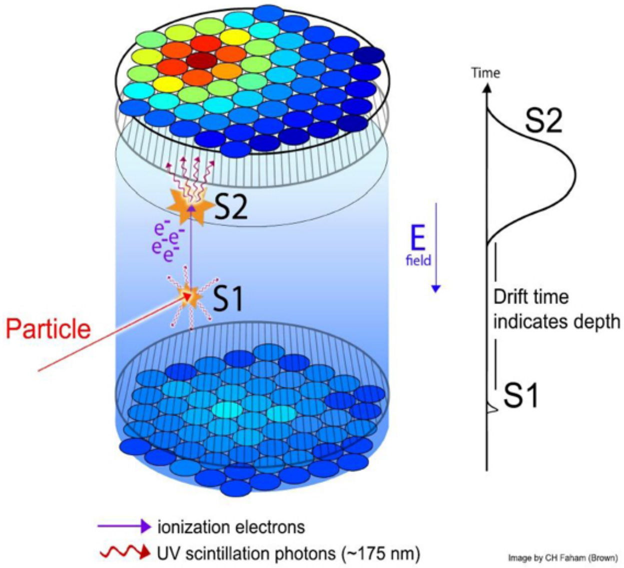


Figure 2: A depiction of the S1 and S2 signals produced within the detector. S2 signal intensity, shown as different colors at the top of the detector, enables pinpointing of the x-y position of the initial interaction, while distance between the S1 and S2 pulses, measured as drift time, enables calculation of the z position.

time.

1.4 Krypton Calibration

In order to monitor parameters such as Electron Lifetime, metastable Krypton 83 (^{m83}Kr) was periodically injected into the detector for the runs analysed. Once injected, the Krypton uniformly mixed into the liquid Xenon. ^{m83}Kr has a two-step decay process. With a half-life of 1.8 hours, ^{m83}Kr undergoes its first decay and emits a 32keV gamma ray. The intermediate Krypton state (^{83}Kr*) has a half-life of only 154ns and its decay produces a 9keV gamma ray. In the data this translates to two S1 pulses, a characteristic that was used to select data points for analysis. [3] A schematic of the gamma ray emission of ^{m83}Kr is shown in Figure 3.

Using a known and constant source for incident rays minimized the amount of influences on the Electron Lifetime, making the distance the electrons must travel, and by extension the amount of impurities they can come across, the only variable and the focus of analysis.

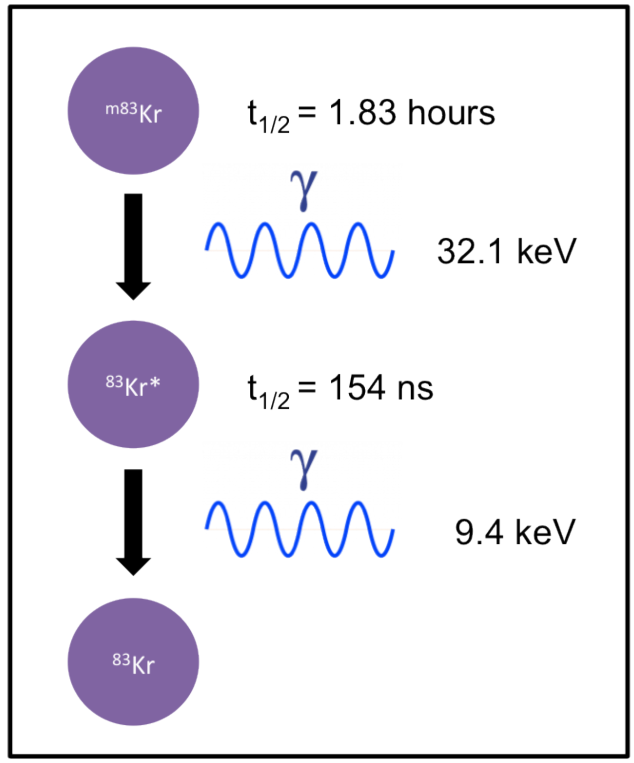


Figure 3: Depiction of the double gamma ray emission property of metastable Krypton 83.

1.5 Motivation

When an event occurs in the detector it falls into one of two categorizes, nuclear recoil and electron recoil. Each of these categorizes has a distinct value range for the ratio of the S2 pulse area to the S1 pulse area as shown in Figure 4. WIMP events fall under the nuclear recoil category, therefore the ratio of S2 pulse area to S1 pulse area is used to identify an event as a potential WIMP event. For this reason it is essential that the electrons successfully reach the

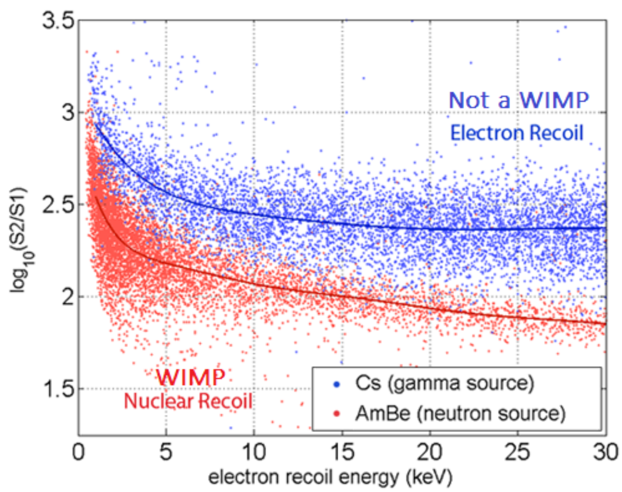


Figure 4: A plot showing the different ranges or S2 area vs S1 area that correspond to nuclear recoil events and electron recoil events for known incident ray sources.

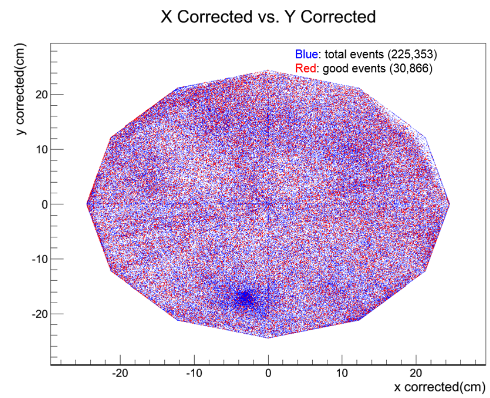
top of the detector, as this determines the size of the S2 pulse. In other words the Electron Lifetime for the detector must be longer than the maximum drift time the electrons can potentially travel for. Given the dimensions of the TPC, the maximum drift time of the LUX detector is 350μs. The LUX detector must have an Electron Lifetime well above 350μs to ensure a proper S2 pulse reading. The data analysis done in this project hopes to confirm that that is the case.

2 Discussion

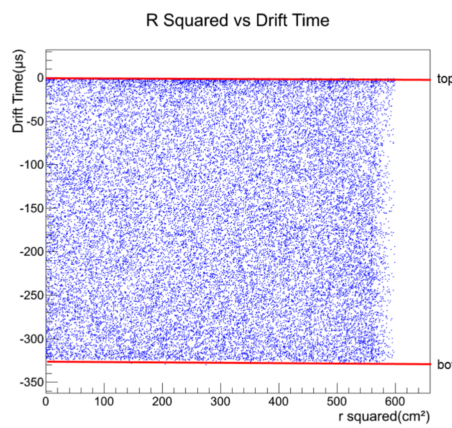
2.1 Procedure

2.1.1 ROOT

ROOT is an object-oriented program developed by CERN. ROOT is written in C++ and was originally designed for particle physics data analysis. With functionality for histogramming, curve fitting, mathematical functions, and the like it is the language of choice for dozens of particle physics experiments. Data analysis and plot generation for this project was done primarily in ROOT.



(a) x-y correction



(b) z correction

Figure 5: Events chosen for analysis based on position corrections are shown. The red events in (a) are shown in (b). (b) shows the even distribution of events throughout the detector and shows the allowed range of depth from 0μs to 330μs.

2.1.2 Data and Algorithm

Analysis was performed on seven data sets obtained from ^{m83}Kr calibration runs. Each data set contained several hundreds of thousands of events. Out of those events, only ones that occurred within the physical parameters of the detector were valid. A valid event also needed two S1 pulses to precede the S2 pulse given the double decay property of ^{m83}Kr. The first step was to impose a cut on the data to select only those events that fit this criteria.

Following the cut, the area of the S2 pulses for the remaining events were plotted as a function of drift time. The plots showed that the area of the S2 pulses decreased over drift time, meaning that the longer the electrons traveled the less of them reached the gaseous Xenon to produce the second pulse. In order to quantify this behavior and obtain the Electron Lifetime an exponential function was fit to the plot. The slope of the exponential function represents the decay constant, and the Electron Lifetime is the inverse of the decay constant. Once a value for the Electron Lifetime was calculated for each data set the values were plotted as a function of time to show the behavior of the Electron Lifetime over the span of several months.

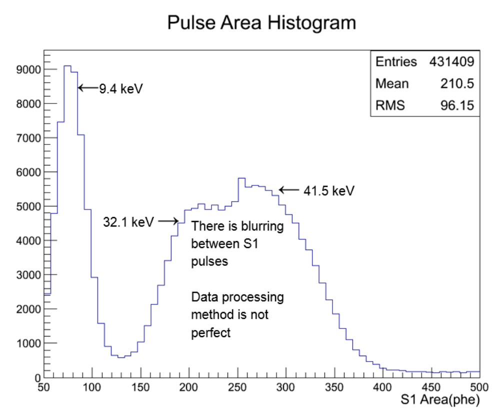


Figure 6: A histogram showing the S1 pulse areas. The combining of the two expected pulses into a single larger pulse is depicted by the blurring that occurs between the 32.1keV pulse and the 41.5keV pulse.

2.2 Analysis

Part of the event selection process involved a cut to select only those events with two S1 pulses before the S2 pulse, one corresponding to the 9 keV gamma ray emitted by the ^{m83}Kr and the other to the 32keV gamma ray. A histogram of the pulses was created and in doing so a discrepancy was discovered. Figure 6 shows the histogram of the S1 pulse areas.

In the plot there are three discernible peaks, one corresponding to the 9keV gamma, one to the 32keV gamma, and a third that corresponds to a nonexistent 41keV gamma ray emission. This third peak indicates that the data processing methods used to produce the S1 pulse areas are combining the two S1 pulses into a single larger pulse, and this occurred often enough to appear clearly on the histogram. Only the events with two distinct S1 pulses remained after the cut was applied.

The S2 pulse areas were plotted as a function of drift time for the remaining events. The plot shows that as drift time increased the pulse area decreased. In other words, the further the electrons had to travel the more of them were lost to impurities encountered along the way. To determine the decay constant, the rate at which the pulse area decreased, an exponential function was fit to the plot using the ROOT function FitSlicesY.

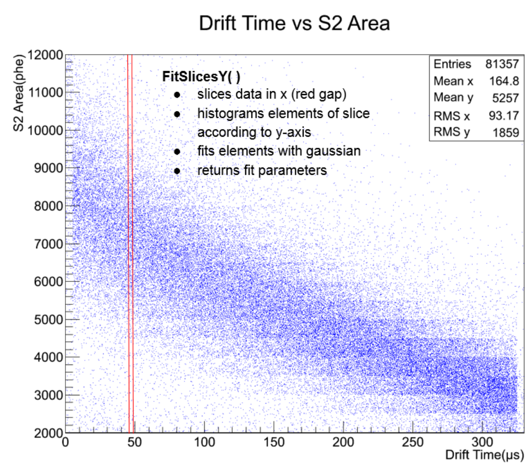


Figure 7: A plot of S2 pulse area as a function of drift time for one of the data sets. As expected, the area decreases as drift time increases.

FitSlicesY created the exponential function by taking slices of the data, fitting the points in the slice to a gaussian distribution and returning the fit parameters. The exponential function for the points in Figure 7 is shown in Figure 8.

The exponential function shows a decrease in area as drift time increases. The slope of the function is the decay constant in units of $1/\mu$s. The inverse of the decay constant is the Electron Lifetime, which for the March 20, 2013 data set was 324μs, less than the maximum drift time of 350μs. Such a low Electron Lifetime suggests that impurities were abundant in the detector at the time this data was collected.

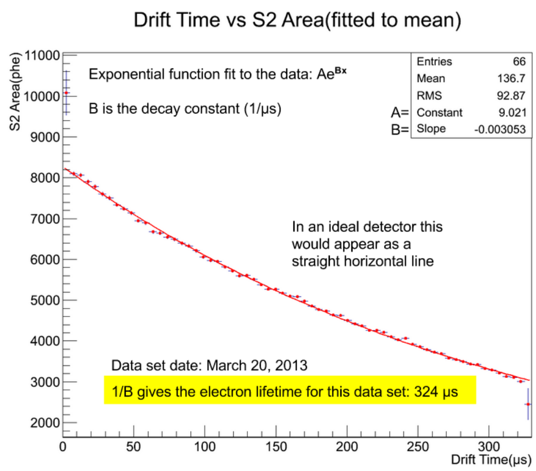


Figure 8: The exponential function fit to the data in Figure 7 is shown. The slope of the exponential is the decay constant B. The inverse of B gives the Electron Lifetime for the data set.

Figure 9 shows the Electron Lifetimes for all seven data sets, collected from March 20th to November 4th 2013, as a function of time. The Electron Lifetimes for the March 20th and November 4th data sets were below 350μs. This was caused by a lack of circulation on those days. Constant circulation of the detector filters out impurities that can interfere with the electrons' ascent. A temporary cease in circulation enables impurities build up in the detector. These impurities reduce the electron lifetime of the detector until circulation, and by extension filtration, restart. For the other five data sets, the detector was circulating properly and impurities were being filtered out. This resulted in Electron Lifetime values well above the maximum drift time. The results suggest that proper circulation and filtration of the detector is essential to maintaining a high Electron Lifetime.

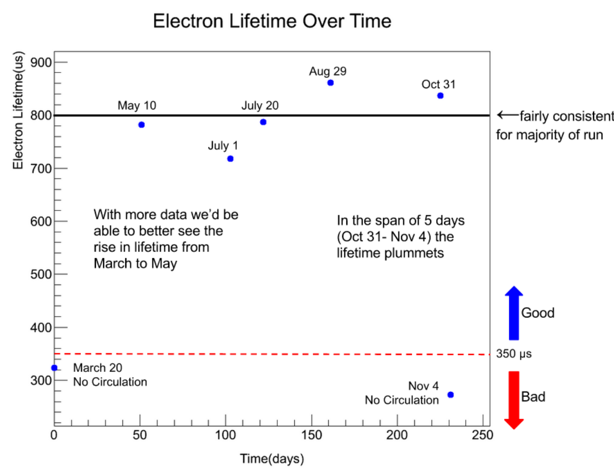


Figure 9: A plot showing the Electron Lifetime computed for the seven data sets analysed, spanning from March to November 2013.

3 Conclusion

From the analysis done on the seven sets of data obtained from the Krypton calibration runs we are able to conclude that electrons are being lost to impurities in the detector, though these losses are minor so long as the detector maintains proper circulation. A lapse in proper circulation of the detector causes a significant decrease in the electron lifetime with potential to influence S2 data obtained from the run. This points to the importance of z-position corrections for the data.

A second conclusion drawn regards the method used to distinguish S1 pulses. Analysis of the data from the calibration runs suggests that the current method for separating multiple S1 pulses is not working optimally, as the two distinct S1 pulses expected were recorded as a single larger pulse with noticeable regularity.

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[3] Attila Dobi. Lux krypton-83m position dependent corrections, 2013.