A Study of the Low Mass WIMP Discovery Potential of the Large Underground Xenon Dark Matter Detector

Jamison Blanchard
Advisor: Mani Tripathi

Abstract

A Monte Carlo simulation of the Large Underground Xenon (LUX) detector has been developed and is being used to model the detector response in the presence of hypothetical dark matter particles in the form of Weakly Interacting Massive Particles (WIMPs). The motivation for a low mass WIMP search (~5-10 GeV) is explained as well as simulation procedures and analysis.

1 Introduction

1.1 Dark Matter

The dark matter hypothesis was proposed in an attempt to account for several cosmological observations, including gravitational lensing and galactic rotations caused by unseen matter. Current estimates attribute roughly five times more of the mass-energy content of the universe to dark matter than to regular matter.[1] It is conjectured that one type dark matter candidate may interact with matter via the weak nuclear force. These particles, know as Weakly Interacting Massive Particles (WIMPs), are the prominent candidates for dark matter searches.

1.2 LUX

1.2.1 Detector Function

The Large Underground Xenon (LUX) experiment is one of several direct detection experiments looking for WIMPs. A fundamental assumption in this experiment is that WIMPs will interact with matter via nuclear recoils (NRs).

The LUX detector is a dual phase time projection chamber. Inside the detector is 350kg of highly purified liquid xenon with gaseous xenon above. When a WIMP enters the detector and causes an NR with a xenon nucleus, γ-ray scintillation light and ionized electrons are emitted. The initial scintillation (called S1) is detected with PMT arrays at the top and bottom of the chamber (Figure 1). Two mesh lattices at the top and bottom are kept at a potential difference in order to drift the electrons to the gaseous xenon. The electrons produce a secondary scintillation (S2) from an electron-electron recoil with valence electrons in the gaseous xenon which is also recorded by the PMTs. The difference in arrival time between S1 and S2, along with the known electron drift velocity in liquid xenon, permits calculation of an event's height (z position) in the detector. Similarly, the relative intensities recorded by the PMT arrays allow us to reconstruct the x-y position of an event.

It is crucial to maximize the probability of this interaction which is related to the target atom's elastic scattering cross section, σ. The cross section goes as $\sigma\sim$ A^2, where A is the number of nucleons of the target nucleus. To determine the sensitivity of a detector to attributes of unknown particles, particle experiments measure the ability of the detector to span a parameter space. Parameter space is the set of all possible combinations of unknown parameters in the model being tested. For WIMPs, the probability of interaction is dependent on the spin-independent elastic scattering cross section, σ_{SI}, and particle mass.

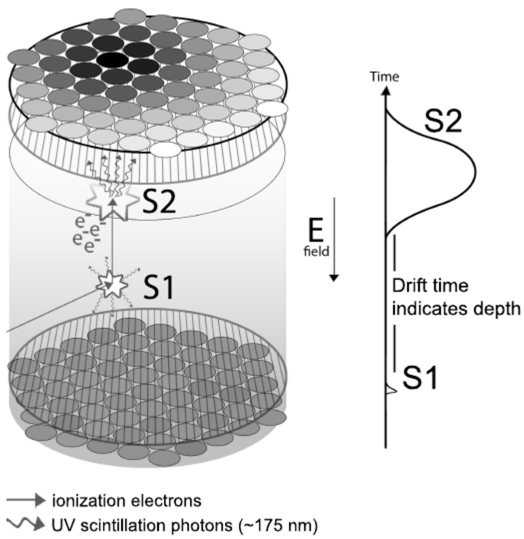

Figure 1: A depiction of the basic function of the detector. Note the relative intensities of detection at the top of the schematic which is used used to track the x-y position of the interaction. The sketch of the S1 and S2 signals, separated by the electron drift time, allow us to calculate the z position of the interaction.

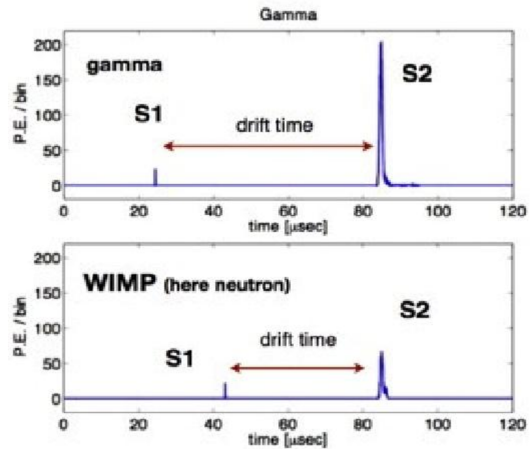

Figure 2: Illustration of how different drift times for different particles (in this case γ-rays and neutrons) allow us to differentiate them. Once distinguished, we can cut out much of the detector response that does not have WIMP-like behavior.

1.2.2 Detector Background

The detector is 4850 feet underground in order to eliminate enough cosmic background to make it negligible in comparison to internal background and background from the containment mine[1]. The detector is also encased in a water shield to filter out γ-ray and muon background.

The largest sources of background come from within the detector, mainly from the components of the PMTs. These materials emit neutrons due to fission and α-decays. Neutrons can produce NRs that can be mistaken for WIMPs, so extremely low neutron backgrounds is essential. Similarly, a considerable amount of low energy background is produced when background light excites electrons in the liquid xenon and light is reemitted. These events are called electron recoils (ERs).

The other main source of internal background is from impurities in the liquid Xe, namely ^{85}Kr which is a β-emitter. Impurities could also absorb scintillation light and cause deficiencies. Therefore, high xenon purity is important in decreasing the detector's internal background. To this end, liquid xenon is incrementally boiled off and run through a getter, which is a substance that reacts with and removes impurities. The xenon is then re-condensed and put back into the detector.

There are several methods used to account for the remaining background after the data are taken. Cuts on the data can be made to filter out signals that are not WIMP-like in nature. For example, we can discriminate between gamma and neutron interactions (the latter of which will have similar signals as WIMPs) by looking at the difference in their drift time through the liquid xenon (Figure 2).

Due to the large nucleus of the xenon atom, the outermost liquid xenon absorbs the majority background, leaving a smaller internal mass with few background interactions. Because of this, the experiment defines an interior fiducial mass in the detector and disregards all events outside of this mass. The observed background will decrease as we discriminate against events outside of the fiducial mass; however, particles that have low probability of interaction will be affected less, including WIMPs. Simulations accounting for all of these background were run to determine the best possible fiducial cut for the purpose of background discrimination cuts. The main problem then becomes distinguishing between NRs and ERs caused by background for similar cuts. The ratio of S2 to S1 is higher for electron recoils which allows a filter to be applied between NRs and ERs. In S2-only analysis, this ratio can no longer be used, so a detailed simulation of ER sources will be needed to proceed (Section 2.3).

1.3 Motivation

Recently, experiments including CoGeNT (Contact Germanium Neutrino Technology) and CDMS (Cryogenic Dark Matter Search) have reported excesses of low mass interactions that they interpret as possible dark matter candidates with m ~ (6.5-10 GeV) and σ_{SI} ~ (2-6)$\times 10^{-41}\mathrm{cm}^2$.[2] It was also found that a careful change of assumptions could alter the Xenon100 experiment constraints in a feasible way that would change their parameter space constraint to include the region of parameter space to include the low-energy event region to which CoGeNT and CDMS attribute their dark matter signals.[2] These recent developments have motivated an S2-only analysis project for the LUX collaboration. My project in this analysis concerns using a Monte Carlo simulation developed for LUX (LUXSim) to determine the discovery potential for the LUX detector for a WIMP in this region of parameter space. This project will also help estimate the event frequency of these low mass WIMPs, and what detector response we should expect to see if these dark matter candidates prove to be valid.

2 Discussion

2.1 Procedures

2.1.1 LUXSim

Geant4 is a powerful Monte Carlo particle simulation package written in C++. This simulation software is equipped with the ability to set physics parameters in a simulation environment and build geometries of detectors. An extension to Geant4 called the Noble Element Simulation Technique (NEST) has also been developed to account for the scintillation yield having a non-linear behavior. LUXSim is a simulation built in Geant4 that accounts for the geometries of the LUX detector as well as extensions developed with NEST. LUXSim was used to produce the Monte Carlo simulated data throughout this paper.

2.1.2 Automation

Geant4 has the capabilities of working with scripting macros which are files that contain a series of Geant4 commands to be procedurally executed. The simulations I ran involved altering minor parameters in these macros and running them in succession. Doing this using the Geant4 loop mechanism proved difficult and potentially unreliable, so instead I learned some basic bash scripting. Bash scripts are programs written for the UNIX operating system, or any system built off of the UNIX shell. Knowing some basic technique allowed me to edit parameters in Geant4 macros and run them in order, as well as process the outputs of the simulation to convert them into usable files. This, in effect, minimized the time spent running the simulation.

2.1.3 ROOT

ROOT is a data analysis framework written in C++ by CERN for handling large amounts of real world and simulated particle experiment data. ROOT, like Geant4, has the capability of using macros in which large numbers of C++ commands can be written and compiled in order. This proved particularly helpful in processing many different simulation outputs in the

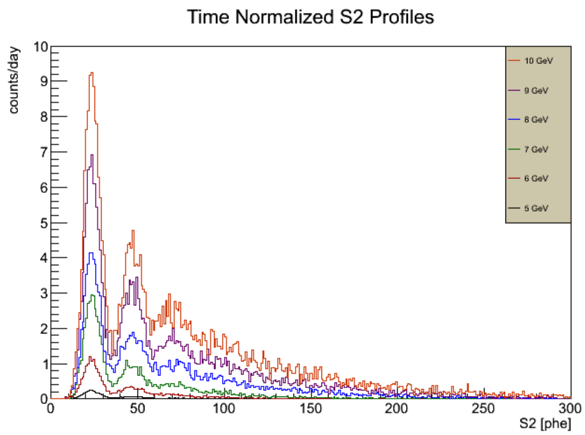

Figure 3: A plot of simulated counts per day of photoelectrons expected from the PMTs as the result of nuclear recoils from WIMPs of integer mass from 5-10 GeV.

same way. All of the data processing done for this project was done in ROOT.

2.2 S2-Only Analysis

S2-only analysis becomes important in the low mass region of the parameter space. Lower masses correspond to smaller nuclear recoil energies. As a result, the S1 scintillation, which is significantly smaller than the S2, decreases to negligible levels. Similarly, the S2 signal decreases, but as it is larger that the S1, we are left with an analyzable signal. To determine the detector response for the low mass spectrum of the detector, a simulation of 2 million WIMP particles was conducted at integer masses from 5 to 10 GeV. The simulations of the S2 signals are done for a set number of particles, irrespective of the amount of real world time it would take for that many particles to actually interact with the detector. So in order to get a more coherent scale, the counts of photoelectrons are normalized to a one day interval. The results of this simulation are expressed in Figure 3. There are several interesting properties of this plot that need explanation.

During the nuclear recoil interaction, different numbers of electrons will ionize depending on how much energy the WIMPs impart on the xenon atom. It is important to note that this number of electrons is an integer number so when they reach the gaseous xenon, they should produce integer multiple amounts of S2 scintillation depending on the integer number of electrons involved. The S2 produced in LUX from this effect is given by [2]:

$$S2 = E_{nr} Q_y(E)\, Y, \tag{1}$$

where $\mathrm{E_{nr}}$ is the nuclear recoil energy from the WIMP interaction with the detector, $\mathrm{Q_y}$ is the charge yield (or free electrons per unit energy), and Y is the ratio of photoelectrons (phe) to ionized electrons. For LUX, the average Y is 23 phe per ionized electron, fit to a normal distribution. Because integer numbers of electrons are produced in ionization, we expect to see peaks of S2 around integer multiples of 23 phe. Figure 4 demonstrates this effect with peaks of photoelectrons centered about 23, 47, and 70 phe.

Also notice the diminishing response as the mass of the simulated WIMPs decreases. This also confirms our expectations. The simulation assumes an equal velocity distribution for the particle of varying mass, so the kinetic energy of the WIMPs scales linearly with the mass. Because NRs occur when WIMPs transfer their kinetic energy to the liquid xenon nuclei, nuclear recoil energies are proportional to the mass of the incoming WIMPs. As a result, the S2 we see, which is also proportional to the recoil energy (Equation 1), increases with increasing mass.

These simulations were conducted in the absence of background solely for the purpose of determining the S2 response for the detector. In order to get a realistic response, a detailed spectrum of the background must also be generated.

2.3 Low Energy Background Simulation

The S2 profiles are simulated independent of the detector background. In order to correct the simulated profiles, a background simulation must be conducted, normalized, and added into the simulated data to produce a realistic detector output. This process is

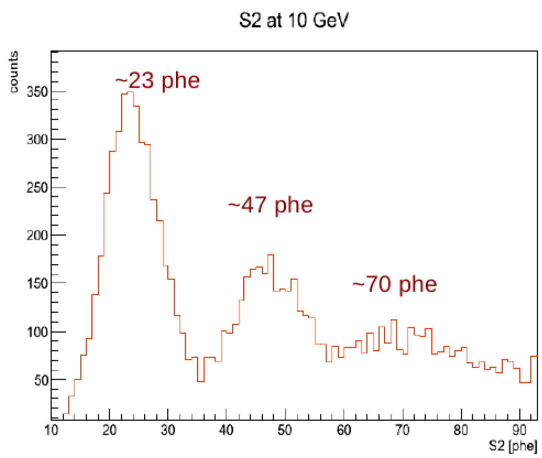

Figure 4: This is an unnormalized version of the 10 GeV plot in Figure 3. The peaks are roughly around integer multiples of the ratio of photoelectrons to ionized electrons. This occurs because only integer numbers of ionized electrons can be produced from a nuclear recoil. Notice that the number of counts decrease for larger numbers of phe; this corresponds to an increasing ionization energy for each successive electron that decreases the likelihood of ionization.

difficult because the detector was built to minimize background, so in order to build up significant statistics in the low electron recoil energy region, millions or even billions of background sources must be simulated. These simulations are still in progress.

Like the S2 signals, these simulations are run for a certain number of particles. We are more interested in the expected behavior with respect to a normalized time, so the real world time is used to ascertain the average behavior per day. In a similar fashion, we want to normalize the background against the fiducial mass and the particular energy binning used so that we have the amount of background scaled to events per keV*kg*day. Normalizing the background is important because it will give us a normalized environment in which to compare the background and the S2 signals, which otherwise would be on completely different scales.

3 Conclusion

The future goal of this project is to finish the high statistic low energy detector background and superimpose it with the simulated S2 response to determine the discovery potential for an S2-only analysis. This will establish a new lower limit for the low mass area of the parameter spaces and allow us to gauge the response we should expect out of the detector for a continuous run.

In the mean time, my research on the behavior of this background is ongoing. As the statistics build up, we can find the trending form of the background. A previous project assumed the background at the very low energies was flat, something these simulations will be able to verify or dismiss.

Acknowledgements

I would like to acknowledge Mani Tripathi and Matthew Szydagis, the latter of whom facilitated my education on the LUX experiment and guided me through many of the details of my project. I would also like to thank Rena Zieve for organizing the research group at UC Davis this year.

References

[1] D.S. Akerib, et al., arXiv:1211.3788v2 [hep-ex].

[2] Dan Hooper, arXiv:1306.1790v1 [hep-ph].

[3] J. Mock, et al., arXiv:1310.1117v1[physics.ins-det].