Columbia - Nevis Labs REU 2008
XENON Dark Matter Experiment at Laboratori Nazionali del Gran Sasso
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Introduction

This paper encompasses several aspects of the research experience I had during my stay at Laboratori Nazionali del Gran Sasso with the several members of the Xenon Dark Matter Experiment. It will begin with the 'why' behind the experiment, then briefly describe the 'how' of the experiment and this paper ends focusing on what I did this summer.

I. What is Dark Matter?

Dark matter is the non-luminous, non-baryonic matter that is said to compose about 23% of the universe. Meanwhile, 73% of the universe is composed of dark energy and only 4% is composed of baryonic matter. Dark Matter is considerd to be cold and non-baryonic because it is postulated that dark matter greatly aided in the large structure formation of the universe by being slow moving, or cold, so that it clumps together to produce large graviational effects that cause galaxies to cluster and also hold single galaxies intact by a galactic halo.

While there are many astronomical examples that point towards the existence of dark matter, some of the more popular examples come from Freidrich Wilhelm Bessell, Fritz Zwicky, Vera Rubin and the CMB anisotropies.

The first prediction for dark matter came from Freidrich Wilhem Bessell in 1844 as he studied the sinusoidal displacement of the star Sirius and noted that there must be an invisible companion to cause such a trajectory. In 1864, however, this invisble companion was discovered as Sirius B, the white dwarf (Sirius). Later in 1933, US/Swiss astronomer Fritz Zwicky used the Virial Thereom to calculate the mass of a region of galaxies on the periphery of the Coma Cluster. He found that the amount of mass needed was much greater than what could be calculated from the brightness of the galaxies in the cluster. However, very few people in the scientific community believed him until other theories also began to point to the existence of something like dark matter. In the 1960's Vera Rubin also concluded that the velocity on the outer arms of the galaxy to do not follow the Newtonian dynamics of centripal acceleration. As the radius increases the velocity should slow down, but in fact on the outer arms of spiral galaxies the velocity was equal to the inside and sometimes even greater! Velociy dispersion in galaxies at large radii is probably the most promising evidence for dark matter (Ni, 15).

Figure 1.1: Image Galaxy cluster CL 0024+17 from Hubble Space Telescope depicts a ring of dark matter.

The polarization of the cosmic microwave background is another example pointing to the existence of dark matter. The CMB is the radiation resulting from the big bang and exists throughout the universe. Generally the CMB spectrum (Figure 1.2) has the likeness of a black body spectrum, however, with small anisotropies, or irregularities, that point to fluctuations in matter density. These anisotropies can be used to study the initial conditions of cosmic structure formulation. Various details in this analysis results in the favored existence of dark matter.

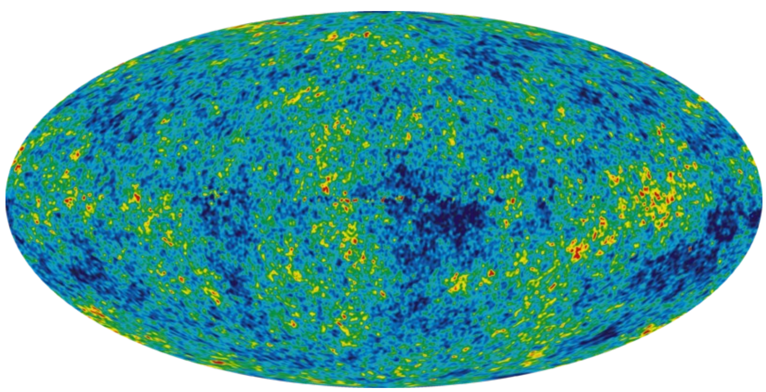

Figure 1.2 Temperature fluctuations in the cosmic microwave background

While there is much theoretical evidence pointing to the existence of dark matter, experimental evidence has yet to be discovered. There are many experiments across the globe that are trying to detect dark matter directly and even indirectly. WIMPs (Weakly Interacting Massive Particles) are one of the candidates for dark matter, but the nature of these particles is still unknown. The most favored candidates under this category are nuetralino from supersymmetry (SUSY), the Kaluza Klein particle and the axions (Ni, 10). WIMPs from the dark halo of our galaxy should elasctically interact with ordinary matter nuclei via the weak force and gravity and induce nuclear recoils. They also have a large mass compared to standard particles. By detecting experimental evidence for these WIMPs, scientist expect to find a new realm of physics in need of further discovery.

II. The Xenon Dark Matter Experiment

Starting in 2002, Xenon has developed through various stages of R&D up to Xenon100 today. The Xenon collaboration hopes to continue it's direct detection of dark matter by increasing to the Xenon 1 Ton which will contain 10 identical 100kg Liquid Xenon time projection chambers (TPCs).

Xenon100 is a dual phase time projection chamber that enables the direct detection of dark matter through scintillation and ionization of LXe by WIMPS. With over 200 PMT's arrayed over the top and bottom of the detector to catcth the scintillation light produced in the Xenon, Xenon100 holds 100kg of LXe in a tank that also has a gaseous xenon layer above it.

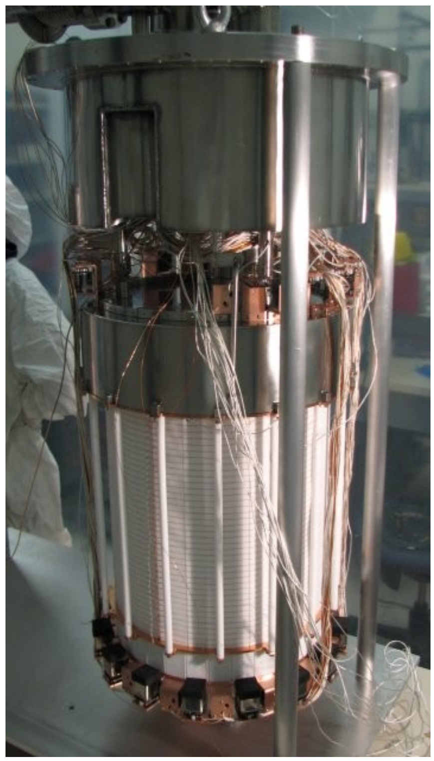

Figure 2.1: Xenon TPC

As well as the rare WIMP, many other high particles can bombard the detector, but since Xenon100 is only ineterested in collecting data from low energy nuclear recoils the detector must be shielded from as many of these high engergy particles as possible. Firstly, this explains the location of the experiment 1400 meters underneath Gran Sasso. The rock provides a lengthy shield that can slow down many high energy particles and reduce some from coming into the detector. Lead shields are also placed around the detector to reduce the number of high energy muons going into the detector. This greatly reduces the amount of electron recoils that the detector will see. On the other hand, the problem with detecting nuclear recoils for WIMPS is that neutrons also produce nuclear recoils. Discerining between the two particles isn't difficult when the neurtons have a high energy; in this case the neutrons will scatter multiple times and the recoils will stand out from those expected from WIMPS. To reduce the number of low energy neutrons, a plastic shield made of polyethylene was set in place to slow down neutrons and ideally prevent them from entering the detector. Only a small fraction of nucelar recoils produced by neutrons is known to occur. The rest would ideally be caused by WIMPS scattering off the nuclei of the LXe.

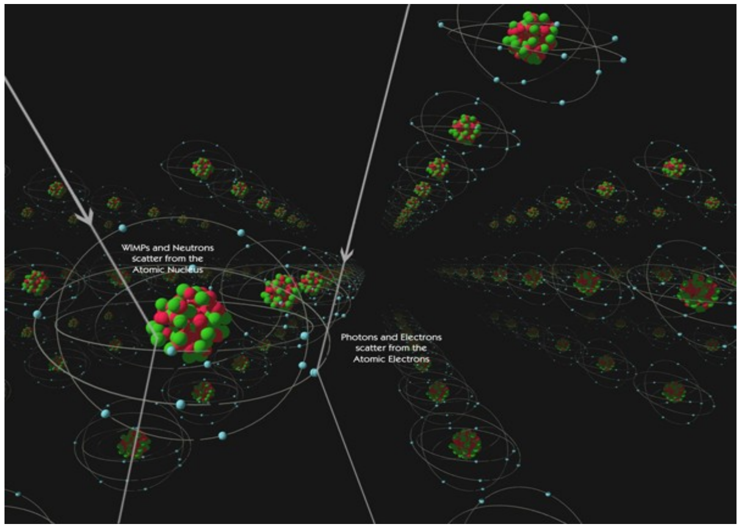

Figure 2.2 Illustration of nucelar recoils and electron recoils

A cathode and anode are postioned at either end of the detector to produce an electric field that drift electrons from the ionized liquid into the gas. By electroluminescence, the drifting electrons are able to recombine with Xe gas and produce photons through this interaction. The collaboration collects data in forms of signals from the ionization of the LXe (called the S1 signal) and the proportional scnitillation produced in the gas Xenon (called the S2 signal). The key to differentiate between nuclear recoils and electron recoils is in the comparison of the S2 signal to the S1 signal. Ideally, the proportinal scintillation produced by a nuclear recoil will be much less than the primary scintiallation. The reverse is true for an electron recoil event where the S2 signal will be much greater than the primary S1 signal. Comparing these ratios will show the electron recoil ratio to be much larger than that of the neutron recoil (Ni, 50).

III. REU

The detection of WIMPS requires equipment that is sensitive to low thresholds of energy. Since radiation is everywhere it is necessary to take good measurements of background radiation in order to subtract uninteresting events that the detector will pick up. Xenon must be concerned with all radiation types - gamma, beta and alpha – and also be on the lookout for nuclear recoils caused by neutrons as well as WIMPS. Background comes from outside the detector as well as from the inside of the detector. From the outside, most background radiation is caused by the decay chain of 238-U and 232-Th and decay of 40-K. These chains can produce gamma rays through their decays. They can also emit alpha and beta particles that can interact with the surrounding rock to produce high energy neutrons. Additional background radiation is caused by cosmic rays, such as high energy muons, which can interact with the LXe to produce neutrons inside the detector (Ni, 52).

XENON has already gone to great lengths to reduce the detectors intake of outside background radiation with lead shielding to block penetrating gamma ray, beta and alpha particles and polyethylene shielding to block most low energy neutrons. With much of the outside radiation blocked, the collaboration is able to focus their attention on the background caused by the various equipment pieces inside the detector. This involves testing as many of these objects as possible with their available germanium detector named ‘Gator’ and making sure they only place the lowest activity instruments inside the detector.

I spent the beginning of my summer reading papers about Dark Matter and the XENON experiment. Later in the summer I got to work with PMT's and the blackbox, but the majority of my summer was spent learning ROOT by recreating data gathered by Alfredo Ferella using the ‘Gator’ germanium detector. Germanium detectors are semiconductor detectors and, in this case, Gator is a coaxial high purity germanium detector. Semiconductor detectors function similar to the Xenon TPC in the sense that high energy particles come into the detector and excite the element inside. In the event that a gamma ray comes into the germanium detector, the photon can deposit energy into an electron, thereby exciting it so the electron creates a hole by moving from the valence band to the conduction band. An electric field is applied across the crystal volume and moves the free electrons to one end of the electric field and the holes produced move to the other end of the electric field. When the electrons and holes are gathered at the contacts they create a signal that is sent to a preamplifier and other necessary modular electronics. This detector produces good energy resolution and timing resolution, but it must be cooled to liquid nitrogen temperatures so that the valence electrons can only be excited by high enegy particle ineteractions. Warmer temperatures allow thermal excitations to occur inside the detector causing poor resolution for high energy particle interactions.

The following data is from a background run conducted in March 2008 by Alfredo Ferrella. The first two graphs are the steps taken to normalize the raw data collected from Gator. The raw data consisted of channel numbers and counts for each channel corresponding to energy depositions for the Gator background.

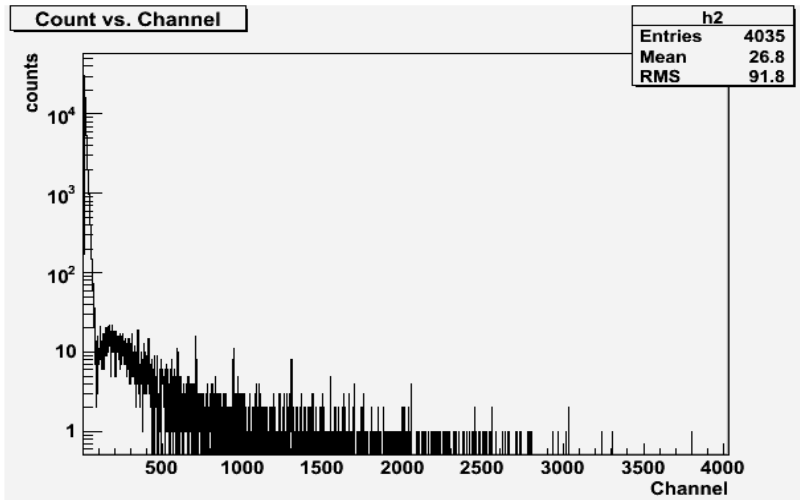

Figure 3.1: Raw data, background spectrum

I calibrated the peaks using a linear fit. The slope of fit, as well as the livetime of the run and the mass of the detector allowed me to calculate the differential rate unit (DRU) which normalizes the spectrum.

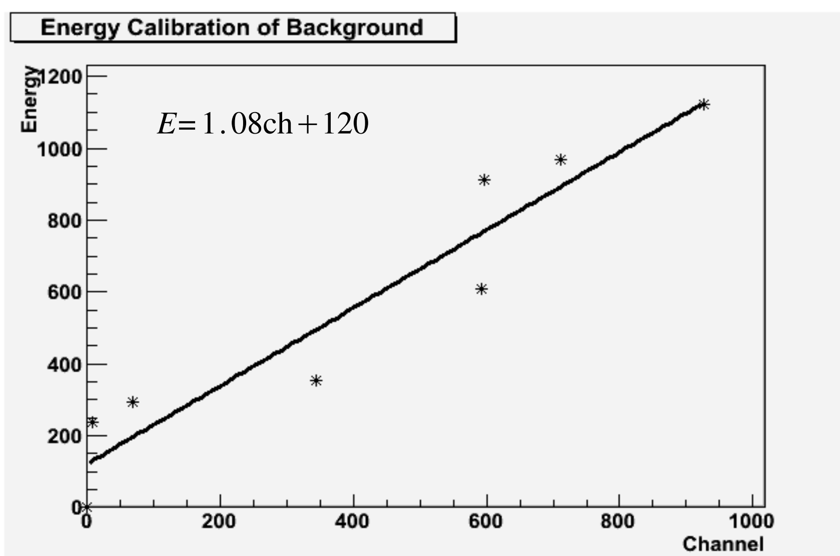

Figure 3.2: Energy calibration using linear fit.

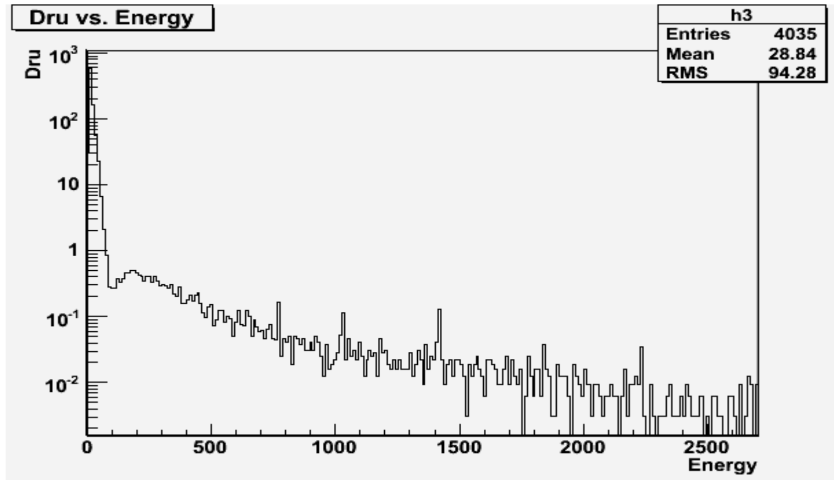

Figure 3.3: Normalized background spectrum

Similar to the background data, the following data consisted of channel numbers and counts for each channel corresponding to energy depositions for several PMT bases used for the Xenon100. This data was taken in November 2007 by Alredo Ferrella. I found energy deposits corresponding to the decay chain or Uranium-238 and Thorium-232 in this sample, namely: 1120 keV, 1765 keV, 352 keV, 295 keV, 609 keV from the 238U chain and 239 keV, 911 keV, and 969 keV from the 232Th chain because they have the highest probability of emitting these types of gamma rays.

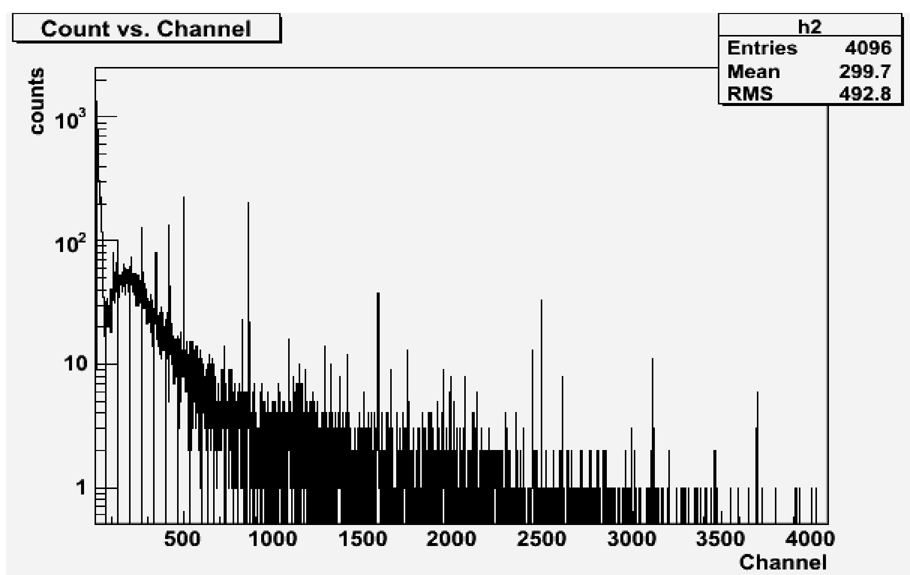

Figure 3.3: Histogram plotting the the counts and channels from the raw data

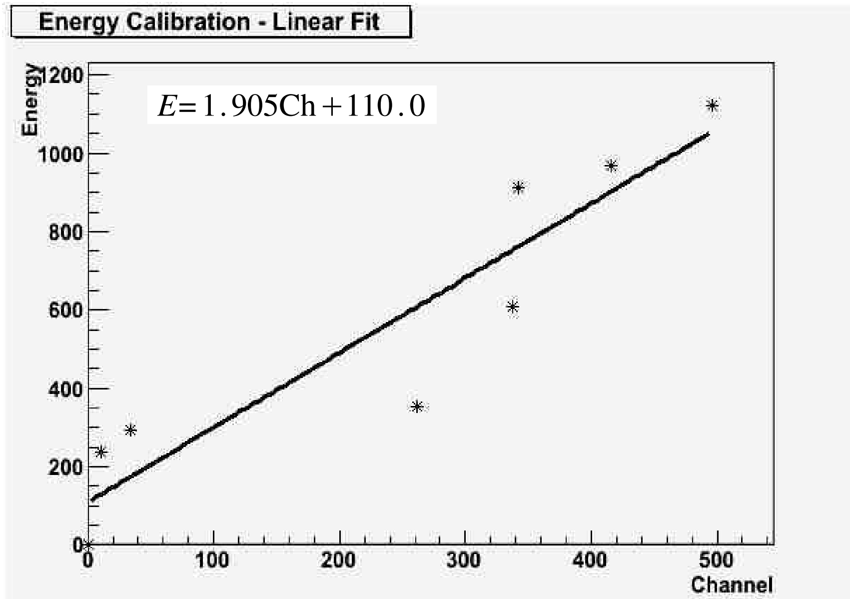

Figure 3.5: Energy cailbration for PMT Bases

Calibrating the energies produced a linear fit which can be used to find all the corresponding energies from the spectrum. This equation also helps when graphing Dru (counts/(kg*energy/bin*days)) against the energy; this produces a normalized spectrum that can be compared with other spectrums plotted in this fashion.

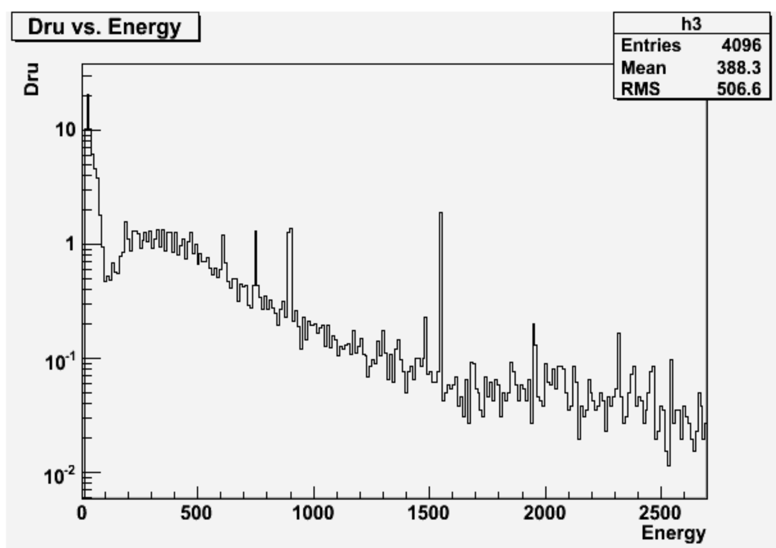

Figure 3.6: Normalized plot of PMT bases count rate vs. energy

Using Figure 3.6 and Figure 3.3 I can determine the amount radioactivity the PMT bases produced by first deteriming the efficiency of the detector and then subtracting the background data from specific peaks produced by the PMT bases spectra.

This would give me the number of counts/sec for each peak. Then, multiplying this by the efficiency allows me to see a more precise contribution from these PMT bases.

Actually, I was unable to determine the efficiency of the detector so the results calculated from Alfredo's GEANT4 simulation of the Ge detector would have sufficed. In this simulation he created a detector of similar geometry to that of Gator. A simulation makes this efficiency calculation easier because the user allows a known number of gamma ray events occur and lets the simulation count how many events would be recorded by the detector.

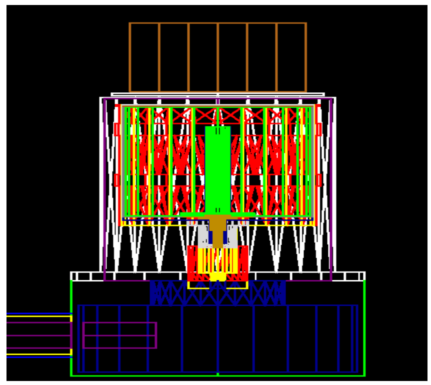

Figure 3.7: GEANT4 simulation of Gator

IV. Conclusions

As far as determining the background contribution of these PMT bases. I was unable to determine them due to time constraints, among other things. However, whatever results I would have found would serve as a comparison to the results concluded by Alfredo Ferrella. The measurement of the activities of the equipment inside the detector is extremely important as it contributes to the scintillations gathered by Xe100 and these signals must be sorted out in order to lower the energy threshold for detecting WIMPS.

Of course, the summer can not end properly without showing my appreciation to those who were involved in my summer. My gratitude goes to Dr. John Parsons and Dr. Elena Aprile for allowing me to be involved in this REU. My appreciation also goes to the National Science Foundation (NSF) for alotting the funds for this program to function. However, I believe the biggest thanks should go to those directly involved in my experience and that includes all those here at LNGS this summer, especially my house mates Kaixuan, Bin, Tae-Hyun, Kyungeun “Elizabeth”, and Andrew. Also, thanks goes to Alfredo for his help, and the rest of the Xenon collaboration for the enjoyable and memorable experience.
Grazie mille!

Sources

Ni, Kaixuan. Development of a Liquid Xenon Time Projection Chamber for the XENON Dark Matter Search. Columbia University, 2006.

Sirius: history. http://www.obspm.fr/actual/nouvelle/bobi_hist_en.html