

GEANT4 Simulation Of Light Collection Efficiency For The XENON1T Demonstrator

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Abstract

The XENON group focuses on the search for evidence of dark matter. Currently, they are working on the XENON1T experiment, which is the next generation of direct detection. In order to test the systems which will be utilized by XENON1T, the group has created the XENON1T demonstrator, which is a prototype of the XENON1T detector. This summer, I used GEANT4 to create a basic model of the demonstrator which utilized a simplified model of the demonstrator geometry and incorporated the reflectivity of the PTFE container. The data from this simulation will allow us to model the light collection efficiency of the demonstrator for different reflectivities of PTFE, and can be easily modified to model many other physical processes in the demonstrator.

1 Introduction

1.1 What is dark matter?

Dark matter is a form of non-baryonic matter that is theorized to account for approximately 75% of the mass in the universe. It neither emits nor absorbs electromagnetic radiation, which makes it very difficult to observe. First theorized by Fritz Zwicky in 1933 based on his observations of the Coma galaxy cluster, dark matter is now a widely acknowledged phenomenon. We have confirmed its presence by observing the gravitational effect of dark matter on the rotation velocity of matter at the edges of galaxies. The virial theorem allows the total kinetic energy of a complicated system such as a galaxy to be calculated. For a galaxy, the virial theorem predicts that the total kinetic energy T is equal to:

$$2T = nV(R)$$

where the force between any two particles results in an average potential of the form $V(R) = \alpha R^n$. Also, since we know that the average potential energy is approximately:

$$V(R) \simeq -\frac{1}{2}G\frac{M_{tot}^2}{R_{tot}}$$

It is possible to solve the virial theorem to find the relationship between the mass of the galaxy and the average velocity v of the individual objects in the

galaxy.

$$\begin{aligned}T &= -\frac{1}{2}V(R) \\ \frac{1}{2}M_{tot}v^2 &= +\frac{1}{4}G\frac{M_{tot}^2}{R_{tot}} \\ M_{tot} &\simeq 2\frac{R_{tot}v^2}{G}\end{aligned}$$

However, observation has shown that this relationship is not obeyed at the edges of galaxies. It is possible to determine the mass of a galaxy based on its gravitational effects on nearby galaxies, and the velocity of matter on the edges of the galaxy can be measured using Doppler shifts and other techniques. These discrepancies can best be explained by the presence of a spherically symmetric distribution of dark matter within the galaxies.

1.2 What Are WIMPs

There are several theories which try to explain the nature of this mysterious dark matter. One of the most appealing theories is that dark matter is made up of particles called WIMPs (weakly interacting massive particles). Based on calculations and observations, scientists expect this particle to be cold, have an energy of approximately 100 GeV, and have interactions on the weak scale. They believe that WIMPs formed in the very early universe, and that their rate of annihilation dropped steadily with the expansion of the universe. Most super symmetric extensions of the standard model provide at least one candidate which fulfills all of these requirements, which is one reason why WIMPs are such appealing candidates for dark matter. The problem with testing this theory is that the WIMPs interact only very weakly with normal matter, making them extremely difficult to detect.

1.3 Methods of Detection

There are three methods that scientists are using to try to detect these elusive particles: creation of WIMPs, indirect detection and direct detection. Given a particle accelerator of sufficient energy, it should be possible to create WIMPs as the result of a particle collision. Since the particles are weakly interacting, we would likely not be able to directly detect the WIMPs formed in this way, but would instead see a characteristic amount of energy from the collision go unaccounted for. This method has three main challenges: since we don't directly detect the WIMPs, the missing energy from the reaction could be from a number of other sources. It would be difficult in this case to be sure that we had found a WIMP candidate. The second problem is that we do not know for sure what the mass of the WIMP is. It's possible that our colliders are not currently at high enough energy to create this particle. Lastly, since WIMP events are very rare, it may take many runs to collect enough data to be able to say anything definitive about the WIMPs.

Indirect detection methods tend to use space-based telescopes to measure the by-products of WIMP interactions such as gamma-rays. Such searches mostly focus on finding the characteristic gamma rays which would result from WIMP-WIMP annihilation. Some searches also look for characteristic gamma rays

emitted from the decay of WIMPs. Using this method, it is very difficult to determine whether any individual event is a dark matter event, and that it is again difficult to gather enough data points to definitively say anything about the nature of dark matter.

Direct detection attempts to capture evidence of WIMP-nucleus interactions using a ground-based apparatus. Commonly, direct detection techniques will depend on the WIMPs interacting a scintillating material, which will produce heat, scintillation photons and ions as a result of a nucleus-WIMP event. Though the WIMP-nucleon interaction cross section is small, it is non-zero. This means that with a large enough mass of scintillator and a long enough observation of events, the detection of WIMP events becomes more and more likely. However, this method also poses some unique challenges. Direct detection demands a very large scintillating volume which operates for a long time. Though it is possible to determine the nature of each individual event (a capability currently unique to the XENON detector), it is still difficult to collect enough data to make any definitive statements about the nature of dark matter. In order for the community to make confident statements about the nature of dark matter, all three methods must be combined and used to check one another.

2 The XENON Collaboration

The XENON experiment is multistage project which hopes to directly detect WIMPs interacting with a large volume of ultra pure liquid xenon. The experiment is currently in its third and final stage: the XENON1T experiment. The first two stages of the XENON experiment used smaller volumes of liquid xenon (25 kg for XENON10 and 161 kg for XENON100) as the scintillating material, and XENON1T uses 2200 kg of liquid xenon. The XENON experiments are located in an underground lab at Gran Sasso, Italy underneath more than 1400 m of solid rock, which helps to shield the experiment from background radiation. The progressively larger volumes of liquid xenon allow us to get better statistics, increasing the chances that we will be able to capture rare events and making it easier to exclude background events.

2.1 XENON100

A key feature of XENON100 is its ability to localize events with millimeter resolution in all spatial dimensions, enabling the selection of a fiducial volume in which the radioactive background is minimized. The simultaneous detection of charge and light signals provides discrimination between the expected WIMP-induced nuclear recoil signal and interactions from the electromagnetic background in the form of electronic recoils. XENON100 recently completed its first full data run which consisted of 100.9 live days of data recording. The collaboration has recently released some of its preliminary data. Of the 161 kg of liquid xenon used in the experiment, 99 kg are used as the active scintillator veto, which completely surrounds the optically separated 62 kg target. An interaction in target (which is 30 cm in height and 30 cm in diameter), an incoming particle will, upon reaching the liquid xenon volume, interact with the xenon and create scintillation light and ions. The vuv photons from the scintillation light will be detected by the bottom PMT array. The signal generated

by the vuv photons in the liquid xenon is denoted as S1. The ions resulting from the initial reaction will be moved by the drift field toward the top of the liquid xenon volume. Upon reaching the top of the liquid volume, the ions will be accelerated by a strong electric field. When the charged particles are accelerated, they will emit photons which will be picked up by the top PMT array. This signal is denoted as S2. The x and y positions of the initial interaction can be found from the hit pattern of the S2 signal on the PMT arrays. To find the depth of the interaction, we simply look at the time difference between the S1 and S2 signals. Since we know the magnitude of the drift field, we can then fairly easily find the distance between the initial interaction and the top PMT array.

2.2 XENON1T

An upgrade to the larger XENON 1T detector from the XENON100 project presents some technical issues. Notably, it is important In order to address these challenges, the XENON group at Columbia University has created the XENON1T demonstrator, which has been created as a prototype for the XENON1T system. It allows the group to test the cryogenic system, xenon purification method, and time projection chamber methods that will be used in XENON1T.

3 Demonstrator

3.1 Experimental Setup

The XENON1T demonstrator is a two phase, position sensitive time projection chamber, consisting of three main parts: a detection chamber, a cooling tower, and a heat exchanger. The main purpose of the demonstrator is to test the xenon purification and circulation methods which will be used in XENON1T, but it is also important to thoroughly understand the light collection of the time projection chamber, which is the main focus of my research this summer. However, the amount of light collected by the PMT arrays has some dependence on the depth of the initial interaction. In theory, all radiation detectors will record some pulse for each quantum of energy which reacts within the detector. However, gamma rays must undergo a significant reaction within the detector to create a signal large enough to be detected. This, combined with the fact that the gamma rays and their products can travel large distances between interactions means that we must have a good model for the detection efficiency in order to have a good idea of the relationship between the number of pulses that we see and the number of photons incident on the detector.

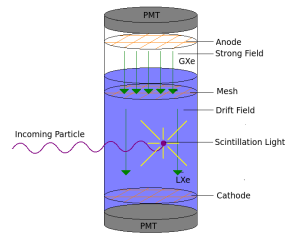


Figure 1: TPC Sketch

4 Detection Calibration

For calibration of the detector, it is common to observe how the detector reacts to a mono-energetic source of radiation. However, even a mono-energetic source of photons does not deposit an equal angular distribution of vuv photons or ionization in the detector. Depending on the type of particle and its energy, the interaction of the incident particle with the scintillating material will result in a characteristic angular distribution of vuv photons. In order to accurately determine the detector's response, it is necessary to understand this angular distribution. Commonly, Cs-137 is used as a gamma ray source for this sort of calibration. Below, we discuss the types of interactions that gamma rays can have within the scintillating volume and derive the angular distribution that results from the Compton scattering of Cs-137 gamma rays within the scintillating volume.

4.1 Gamma-Ray Interactions

There are three important types of interactions that gamma rays can undergo: photoelectric absorption, Compton scattering, and pair production. All of these processes transfer energy from the gamma ray to an electron. They result in large changes to the gamma ray energy and path through the absorber.

4.1.1 Photoelectric Absorption

In this process, the incident photon is completely absorbed. All of its energy is transferred to one of the electrons of the absorber atom, which is subsequently ejected from the atom. For incident photons of sufficient energy, it is most likely that the photoelectron will originate from the innermost shell. The photoelectron appears then with energy:

$$E_{e^-} = h\nu - E_b$$

Once the photoelectron escapes, the original absorber atom is left in an excited state, which will cause it to emit characteristic X-rays or an Auger electron, as described in chapter 1. In most cases the X-rays are reabsorbed close to the source.

4.1.2 Compton Scattering

This type of interaction is the most common for the energies typical of radioactive γ sources. In Compton scattering, the incoming photon is scattered through some angle θ with respect to its original direction. The photon transfers some of its energy to the electron, which is then known as a recoil electron. Based on the angle and energy of the incoming photon, it is possible to determine the distribution of energies given to the recoil electron. The probability of scattering through a certain angle can be found using the *Klein-Nishina formula*. The probability of Compton scattering in the absorber depends on the number of electrons available as targets and thus

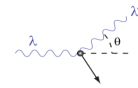


Figure 2:
Compton Scattering Diagram

increases linearly with Z . However, the chances of Compton scattering occurring goes down significantly with increasing Z .

4.1.3 Pair Production

If the energy of the incident γ -ray is greater than 1.02MeV (twice the rest mass energy of an electron), then pair production is possible. Usually this doesn't actually occur until the energy of the incident photon is several times higher than this value. If pair production occurs (it must occur in the coulomb field of the nucleus), the photon will turn into a positron-electron pair. All excess energy above 1.02MeV will go into the kinetic energy of the positron and electron. Since the positron will annihilate once it runs out of energy, two more annihilation photons usually occur.

4.1.4 Compton Spectrum

Using conservation of energy and momentum, it is possible to find the energy of the Compton scattered photon in terms of the energy of the incident photon and the scattering angle, theta. It can be shown that, for a photon of energy E_γ incident on an electron at rest:

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos(\theta))}$$

In order to find the angular distribution of scattered photons, we must also use the Klein-Nishina formula. This formula was one of the earliest results from the study of quantum electrodynamics. It was derived by Oskar Klein and Yoshio Nishina in 1928 and takes into account both relativistic and quantum mechanical effects. This equation describes the differential angular cross section of the compton scattered photons. The Klein-Nishina equation is shown below, with r_0 standing for the classical electron radius:

$$\frac{d\sigma}{d\Omega}(\Theta) = \frac{r_0^2}{2} \left(\frac{E'_\gamma}{E_\gamma} \right)^2 \left(\frac{E_\gamma}{E'_\gamma} + \frac{E'_\gamma}{E_\gamma} - \sin^2(\theta) \right)$$

If we substitute in from the first equation and define $\epsilon \equiv \frac{E_\gamma}{m_e c^2}$, we can rewrite the Klein-Nishina formula as:

$$\frac{d\sigma}{d\Omega}(\Theta) = \frac{r_0^2}{2} \left[\frac{1 + \cos^2(\theta)}{1 + \epsilon(1 - \cos(\theta))^2} \right] \left[1 + \frac{\epsilon^2(1 - \cos(\theta))^2}{(1 + \cos(\theta))^2(1 + \epsilon(1 - \cos(\theta)))} \right]$$

We can now denote this equation as:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{\sin(\theta)d\theta d\phi} \equiv f(\theta)$$

We then can find the differential energy distribution since:

$$\frac{dN}{dE'_\gamma} = 4\pi m_e c^2 \frac{d\sigma}{d\Omega} \left(\frac{1 + (\epsilon(1 + \cos(\theta)))^2}{E_\gamma} \right)^2$$

From this expression, we can easily get a graph of the differential energy distribution for a given incident photon energy. Below, I have included a graph which shows this distribution for several incident photon energies. These results are well-known, and those obtained from the derivation agree well with those presented in literature.

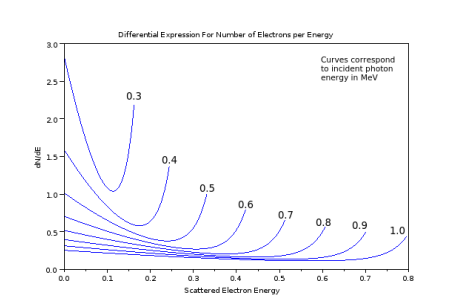


Figure 3: Compton Spectrum

5 Light Yield Simulations

5.1 Detection Efficiency

In theory, all radiation detectors will record some pulse for each quantum of energy which reacts within the detector. However, particles must undergo a significant reaction within the detector to create a signal large enough to be detected. This, combined with the fact that the incident particles and their products can travel large distances between interactions means that we must have a good model for the detection efficiency in order to have a good idea of the relationship between the number of pulses that we see and the number of particles incident on the detector.

There are basically two measures of efficiency: absolute efficiency and intrinsic efficiency. The absolute efficiency depends on the detection geometry as well as the detector properties, while the intrinsic efficiency does not take into account the detector geometry. They are defined in the following ways:

$$\epsilon_{abs} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta emitted by source}}$$

$$\epsilon_{int} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta incident on detector}}$$

There is another distinction between efficiency values for certain detectors. If the efficiency of detection is calculated over the entire energy spectrum, it is called the total efficiency. For gamma ray detectors, these values are calculated using the well known gamma ray spectrum which was discussed in the previous section. For different types of particles or particles of the same type but different energies, the value of the efficiency can be different. Many factors impact the efficiency of the detector, and so it is necessary to make several calibration measurements to determine the efficiency of the detector. It is important to verify these measurements with simulations. To this purpose, I have created a simulation of the detector and its light collection efficiency. This will not only allow us to determine the collection efficiency of the detector, but also to see the dependence of the efficiency on the z position of the initial interaction.

5.2 GEANT4

GEANT4 is a object oriented simulation package which allows the user to easily create Monte Carlo simulations of the interaction and passage of particles through matter. It is most commonly used in high energy physics, as well as many other branches of physics. The program allows the user to have considerable control over the simulation - it includes capabilities for the creation of complicated geometries, the tracking of the passage of particles through the geometry, and the creation of a customized list of physics processes.

GEANT4 allows the user to define customized detector geometries and materials. For our simulation, we have chosen to implement a simplified version of the demonstrator geometry. This geometry consists of five distinct components: a simulation world which is in vacuum, a PTFE cylinder, a sensitive volume of scintillating liquid xenon, a volume of gaseous xenon, and a PTFE volume which is sensitive to vuv photon radiation. A schematic of the geometry which I created for this simulation is pictured to the right. In addition to the definition of a volume, one must define which volumes are sensitive to the passage of particles. In this simulation, the bottom of the teflon cylinder is sensitive to the passage of vuv photons. This allows us to extract information such as the position of the creation event for these photons without having any extra events which may come from other sources (such as electrons, alpha particles, or high energy gamma rays).

Furthermore, each of the materials in these objects was defined and customized within the code. This gives the user a lot of flexibility to add or change the basic properties of the materials to better match the behaviors of materials in the demonstrator. It also allows the user to easily change the materials and their responses as the materials in the demonstrator are added or replaced.

Lastly, I had to create my own physics list to tell the simulation which physics processes to implement. GEANT4 does not inherently include any physics processes, so it is very important to properly define which physics processes take place in the simulation. It was especially important to define the scintillation processes for this simulation, since the exact details of the scintillation process can have a large impact on the characteristics of the interaction.

5.3 Results

Initially, we wanted to test only for the z dependence of the photon collection efficiency. Therefore, we randomly generated an alpha particle with energy of 0.66 MeV within the scintillating volume. Since alpha particles have a very short interaction length, these particles interacted very close to the position in which they were generated and deposited their full energy into the detector. This resulted in the generation of 990 optical photons with an angular distribution characteristic of an alpha interaction event. Initially, we assumed that the PTFE had a reflectivity of 0%. We then randomly generated 50000 alpha events and recorded the z position of optical photon creation as well as the number of vuv photons incident on the bottom of the teflon tube. Our results for this simulation are pictured below.

The color scale on the right simply indicates the number of events which are in any particular bin. We can see from this distribution that the closer the alpha interaction event is to the sensitive volume, the more photons are detected.

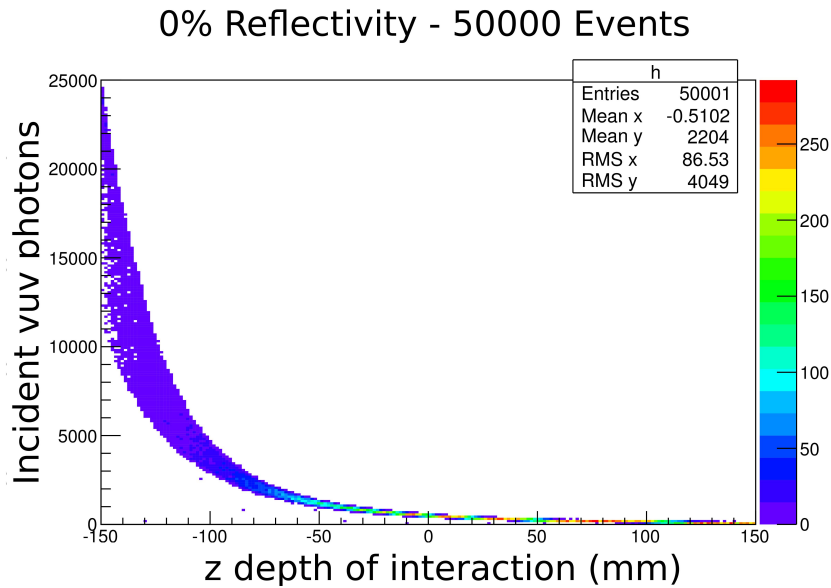


Figure 4: 0% Reflectivity Spectrum

This makes sense, since the volume takes up more of the solid angle of the interaction for events closer to it. Since we were sure that we had the basics of the detector working, we then wished to add some more complexity to the simulation, allowing it to more accurately model the response of the demonstrator. We then added to the simulation the reflectivity of the PTFE housing. When we initially simulated the event at reflectivities of 100%, 95%, 90%, and 85%, we saw no noticeable difference between the different reflectivities. In order to test whether the reflectivity was being implemented in the simulation at all, we simulated 5000 events at 0% and 100% reflectivity. I then created a histogram of the number of hits for different depths of the initial alpha interaction (z). These histograms are pictured at the top of the next page.

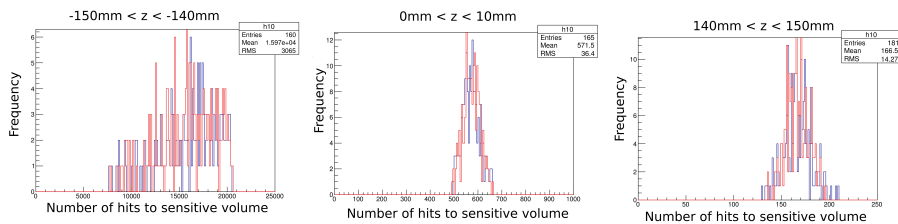


Figure 5: Hits Per Depth Histogram

We can clearly see from this graph that the reflectivity was not being properly implemented, since otherwise the number of vuv photons incident on the detector would have some dependence on the reflectivity of the container. There-

fore, we went back to debug the code. After some minor corrections, we managed to get the reflectivity working. Below is a histogram of our preliminary results:

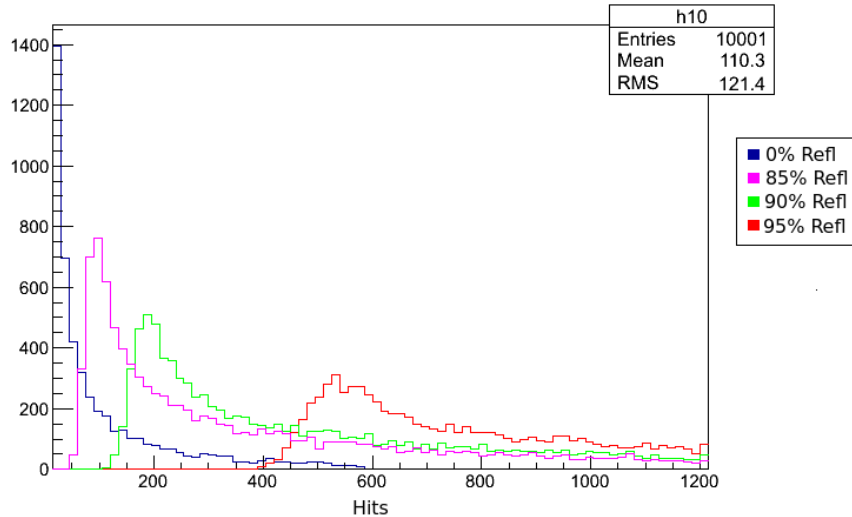


Figure 6: Hits Histogram

We can clearly see that the number of hits incident on the sensitive volume goes up as the reflectivity goes up, which is in accordance with what we have measured and would predict. At this point, the results are still preliminary and have not been thoroughly analyzed, but they suggest that the simulation is running properly and that it is ready to have more detail added to it.

6 Summary

The XENON group hopes to directly detect WIMP-nucleus interactions via direct detection methods. The group is currently in the process of creating the next generation of detector, and they are currently developing and testing the new systems which will be used in the XENON1T experiment. In order to test these systems, they have created the XENON1T demonstrator, which is a prototype of the XENON1T detector. This summer, I used GEANT4 to create a basic model of the demonstrator which utilized a simplified model of the demonstrator geometry and incorporated the reflectivity of the PTFE container. The data from this simulation will allow us to model the light collection efficiency of the demonstrator for different reflectivities of PTFE, and can be easily modified to model many other physical processes in the demonstrator. While the current measurements of light collection efficiency are valuable in and of themselves, the GEANT4 simulation is very flexible and will allow the team to model many other facets of the detector behavior.

References

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