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שביב

כיול של שפורפרות מכפילות-פוטונים בשביל פרויקט הDireXeno

Calibration of photomultiplier tubes for the DireXeno Project

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אב ה'תשע"ט

Abstract

Photomultiplier tubes (PMTs) are used in many practical experiments due to their low-noise, high-gain, ultra-fast response, and accurate readings. This means they can detect single photons if properly used. Due to the fact that each PMT sends a signal to the computer at a different rate, the time at which a signal is measured on the computer is different by a few nanoseconds. Knowing exactly when a signal is captured by the PMT to the resolution of the nanosecond scale is essential for many operations (notably photon radiation from Xenon when dark matter interacts with it, which will be the focus of this paper). Therefore, the calibration of PMTs is required. Calibrating PMTs requires looking at when their signal is highest, the offsets between each PMTs respective signal peak, and a signal which shows when the photon was released, and then calculating the time offset of each PMT from the source. This information can later be factored in when making calculations using results from those PMTs. During the project, we wrote a python code that calibrates PMTs and took data about 50,000 events from 19 PMTs.

Introduction

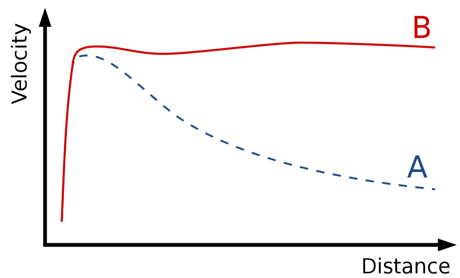
Although PMTs have many other uses[1], this paper will focus on their use for discovering dark matter, as this was the focus of the mentor's (Gera Koltman) study during the time of this project.

Dark Matter

Evidence of existence

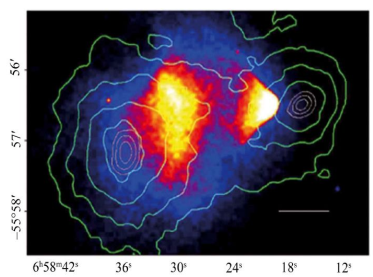
DM was introduced as a scientific theory for three main reasons:

1. The disparity between masses and contradiction between Kepler's law[2] and rotation speed [1].



[5]

2. About 90% of the galaxy cluster's mass is in the plasma [2]. In some galaxy clusters (e.g. the Bullet cluster) it was found that the luminous mass is separated from the center of gravity during merging with another cluster, a possible explanation for this phenomenon is DM [3].



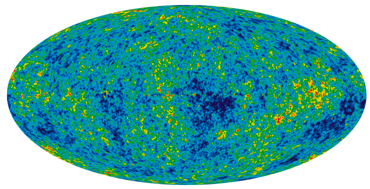
Plasma mass (shown in blue, red, yellow, and white) is not in the same place as the gravitational force (shown in green lines). [6]

3. Cosmic microwave background anisotropy- the radiation from the early universe is shown to be very homogenous, but not perfectly; at the fifth decimal point, slight discrepancies arise in the temperature. While it would be easy to explain this phenomenon using baryonic matter, there isn't enough

[1] low light level spectroscopy, Raman spectroscopy, radar jamming, fluorescence spectroscopy, astronomy, medical diagnostics including blood tests, nuclear and particle physics, confocal microscopy, medical imaging, and high-end image scanners known as drum scanners

[2] Kepler's law defines the rotation velocity of galaxies according to their mass. The expected rotation velocity of some galaxies is lower than in reality, showing some other factor is affecting their mass, thought to be dark matter.

of it in our universe to explain these discrepancies fully, so one must turn to cold DM to explain and describe these anisotropies.



Radiation is different in different parts of Earth[5]

WIMPs (Weakly interacting massive particles) - Dark Matter Candidate

Wimps are theoretical particles that are thought to exist everywhere. WIMPs have negligible interaction, don't react with other particles, and they interact using weak interaction. WIMPs' mass ranges from 10 GeV to 10 TeV, about 10,000 times the mass of a proton. WIMPs are called "cold particles" since most of their energy is in the form of mass making them non-relativistic.

Searching methods

DM can be searched for in a multitude of ways:

1. Indirect detection - astronomical observations (e.g. dark matter particles might decay into standard model particles, producing gamma rays which could be detected.
2. Production at colliders - production of DM in a laboratory, notably the collision of LHC proton beams [4]
3. Direct detection - Measure the interaction of DM with particles on Earth using sensitive equipment. We took part in the DireXeno project. The project is motivated by direct detection.

Xenon & DireXeno project

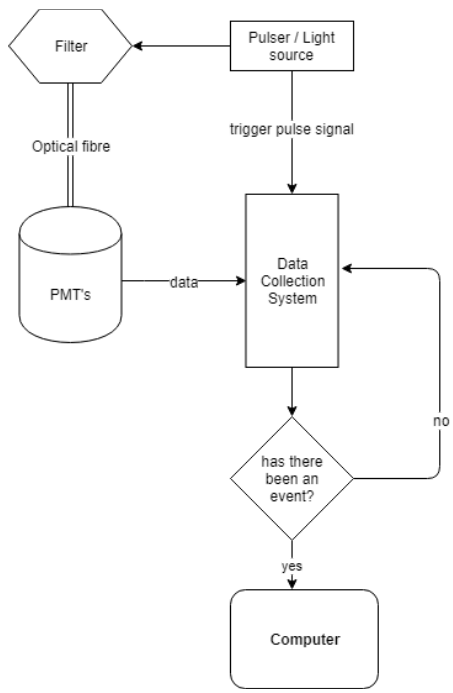
The XENON project is an international cooperation between 16 universities and research facilities around the globe who are conducting an experiment aiming to detect DM. Weizmann institute is part of this project. The experiment is taking place in Gran Sasso-Italy to detect collisions of WIMPs with gaseous and liquid Xenon via electronic and nuclear recoils.

The experiment works with a container of liquid xenon and gaseous xenon, and two arrays of photomultiplier tubes. Since it is assumed that there is dark matter in our galaxy, the earth should experience DM interactions. The Xenon project works by detecting when the dark matter particles interact with our apparatus; When the DM interacts in the detector, photons are emitted. These photons are detected by the PMTs. One of the challenges with this experiment is how to differentiate between the WIMPs and other subatomic particles; this is what they're working on at Weizmann institute with the DireXeno project.

DireXeno (Directional Xenon) is the experiment that is conducted in Weizmann Institute. The main purpose of the project is to find and detect the distribution of the direction and time of photons when they are emitted from liquid Xenon. The project motivation is to find superradiance[3] in Xenon. Superradiance in Xenon can lead to the differentiation between NR (nuclear recoil)[4] and ER (electronic recoil)[5]. Superradiance in Xenon might improve significantly DM detection.

Methods

Lab Structure



Although the lab includes other experimental setups motivated by DM detection, the main part that this paper is focused on is the photon gun and PMTs, *see figure above*. A photon gun will usually shoot more than one photon, however, in order to calibrate the PMT response to single photons, a filter is put in place to reduce the number of photons to either zero or one. This means calculations must be put in

[3] Superradiance is a phenomenon that occurs when a group of excited atoms are in a high density, in which they emit photons only in a certain direction.
[4] In nuclear recoil, a particle without charge penetrates into the middle of an atom and interacts with its nucleus, releasing a few electrons and either a proton or a neutron.
[5] In electron recoil, a particle with charge or high energy photon interacts with the electron shell of an atom, releasing an electron

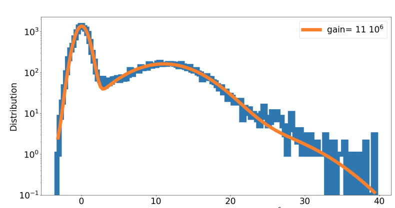
place to discard non-events but allows for more accurate (similar to what would actually be detected using PMT) calibration.

Safety

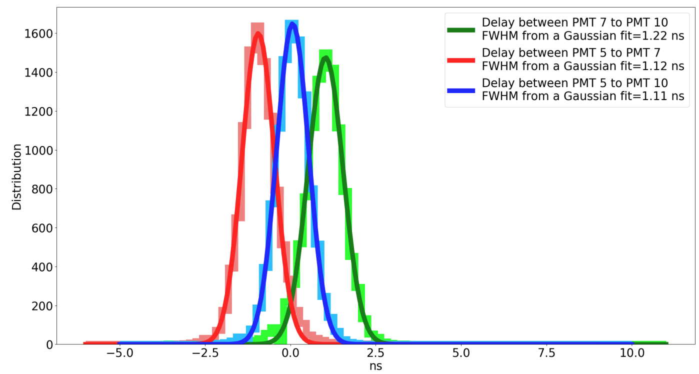
Some safety procedures are implemented in the lab, notably the need for a keycard to enter, as well as safety loops on critical parts of the system including the PMTs and the High Purity Fused Silica (HPFS) Sphere used to hold the Xenon. Additionally, a system is put in place to send an SMS message to the lab members when the cooling system put in place is in danger of being destroyed. Lab members can disable the cooling system remotely. These safety procedures help prevent human error from affecting the experiment.

Code

In order to properly calibrate the PMTs, code had to be written to analyze previous readings. Sample readings were taken prior to writing the calibration code to provide test data. This data was stored in a '.dxd' file, a file type that was written to allow the storage of large sets of PMT data. This file needed to be converted into a suitable format for analysis, so a function was written to convert the information. Afterwards, the data is saved into a '.csv' (comma-separated values) file to allow for easy reading both by the software and by Excel (for debugging purposes). Another advantage of saving the information into a CSV file is that it doesn't need to be read in order to be written to. Instead, information can be appended to it, saving computing time. Additional calculated information is saved with the raw data, including noise baseline, the height of the peak, start and end of the peak, and the area of the peak. Additionally, the trigger pulse sent by the photon gun is stored. Next, the information is filtered to only allow events that have a high likelihood of containing photons to move on to the next stage of analysis. This is done by looking at the $peak's\ start\ point\ -\ trigger\ point$ of each PMT, and then manually finding in which range most photon events occur, e.g. ±2ns, then discarding the rest of the information as non-events. This means that most non-photon events are discarded, and only some remain. Looking at a single PMTs information now as a histogram of the number of charge carriers in each event, we can see some non-events (close to zero) and some events (close to 10^6 charge carriers). There are many more non-events than events.



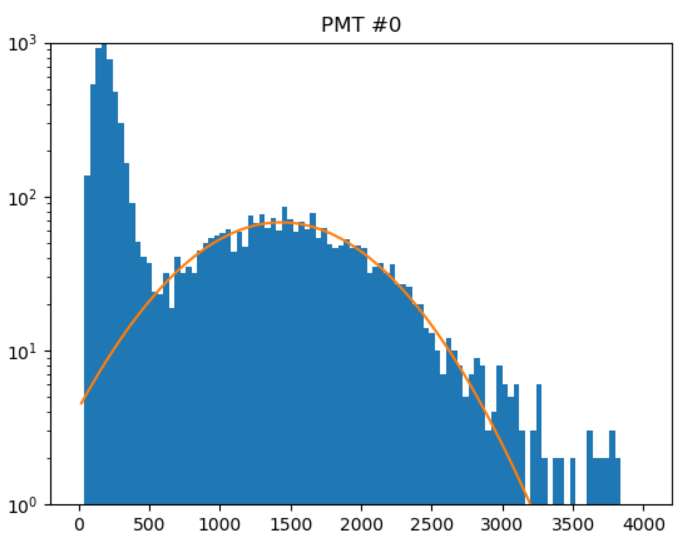
We can now cut out the beginning 15% of information to discard of the non-events, and use the event information, when coupled with the trigger pulse, to figure out exactly what is the time disparity between the trigger pulse and the event sighting. Doing this over all the PMTs allows us to find the time disparity between each respective PMT and include that in later calculations.



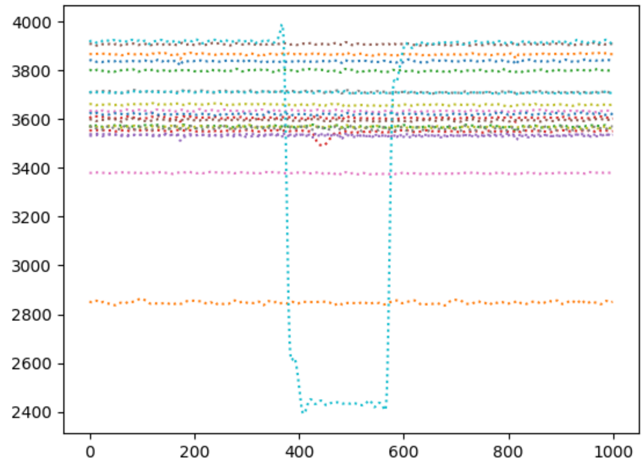
Going to the lab and obtaining actual information allowed the testing of this program (*see Results)*.

Results

Running the code described previously on data obtained in the lab presented the following information.



Using the figure above, we can see a spike around 0, with many PMTs not registering events. Then, we can see a gradual rising around the 1500 mark, showing the spread of events over the area.



In the figure above (cyan blue shows trigger, all other colors are PMTs) you can see the difference between different PMTs as well as the time delay between the trigger and the PMT capture.

Discussion

In the continuation of this project, a higher level of accuracy will be needed when detecting and analyzing photons. One of the main problems in this system is that humans are needed to analyze the output data. First of all, this slows down the process of gathering information. Secondly, it leads to inconsistent and unreliable information because the boundaries are subjective. Two methods that can be used to solve this are to write an algorithm that will find a close approximation of the boundaries, or to create a machine learning program that learns where the point is based on the input of all points on the histogram.

Another goal would be to analyze the information about the photons even farther in order to learn more about the Nuclear recoil. Using this knowledge we could figure out how to use super radiance to only detect specific particles; we would then set it to only record information by those that we suspect are WIMP's, when the project will be run in Italy.

Acknowledgments

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