Dual Phase Detection of Dark Matter and the Uniformity of Photomultiplier Tubes (PMT)

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The search for dark matter has produced a multitude of innovative experiments in an effort to find the missing mass of our universe. Recently, theoretical evidence that the unseen matter permeating space is a supersymmetric weakly interacting massive particle (WIMP), has inspired a number of low background detection methods in an effort to observe a WIMP signal. In order to detect the faint signals of WIMPS, photomultiplier tubes (PMT) have been used in experiments such as XENON 10 and XENON 100. At the moment, the XENON collaboration uses a standard 1" PMT in their experiment located at the Gran Sasso Underground Laboratory in Italy. However, in an effort to reduce the background radiation originating from radioactive isotopes in PMTs, Katsushi Arisaka, in collaboration with Hamamatsu Photonics Inc., has developed the QUartz Photon Intensifying Detector (QUPID). However, to utilize QUPID in dark matter experiments, several characteristics must be tested and compared to other standard PMTs. One such characteristic is the uniformity and collection efficiency of PMTs. From these tests, it has been concluded that QUPID uniformity is comparable to other standard PMTs, however improvements can be made.

1. Introduction

A. Dark Matter

The existence of dark matter has been inferred from several cosmic observations. Fritz Zwicky first predicted the existence of dark matter in 1963 by using the virial theorem to show that galactic velocities of the Coma cluster were too high for the amount of visible matter observed [1].

The case for dark matter was strengthened with the observations of velocity curves of spiral galaxies. Most of the visible matter of spiral galaxies resides in a thin disk where stars and dust rotate the galactic center on nearly circular orbits. The velocity of stars, if following Newtonian mechanics, should be inversely proportional to the square root of the radius. However, it was found that the velocity stays constant after about a maximum of 5kpc [2]. Therefore, most of the mass of the galaxy must reside in a dark halo surrounding the galaxy.

Dark matter has also been inferred through the process of gravitational lensing. The most famous of this example comes from observations of the Bullet cluster. By using gravitational lensing to probe the collision of two galaxy clusters, scientists were able to deduce the geometry of the collision. Although a majority of the visible matter was located at the center of the Bullet cluster, observation indicated that most of the matter was distributed in a halo surrounding the cluster.

The final evidence for dark matter came from the study of the cosmic microwave background (CMB). By studying the fluctuations in the CMB, it was seen that normal baryonic matter could not account for evolution of structure in the universe seen today [2].

B. XENON 100

In an effort to detect WIMPs, UCLA has teamed up with a number of institutions as part of a worldwide collaboration known as XENON. XENON is aimed to detect low energy signals emitted through interactions of WIMPS with liquid Xe nuclei via the weak force. XENON relies on a dual phase time projection chamber to detect dark matter particles [3]. A theoretical WIMP, traveling at a speed of 10^-3 m/s, deposits a certain amount of energy in a Xe nucleus [4]. This interaction produces scintillation light at a wavelength of 178nm as well as ionized electrons, which subsequently interact with Xe gas to produce another light signal. The process is illustrated in Figure 1.

Detecting dark matter requires an experiment that is sensitive to the rare interactions of dark matter (interacts via gravity and the weak force). To improve the event rate of XENON, liquid Xe is used due to its high atomic number, which is directly proportional to the cross section interaction of WIMPs. Also, to detect the faint signals of the WIMP/nuclei interaction, a 1" photomultiplier tube is used.

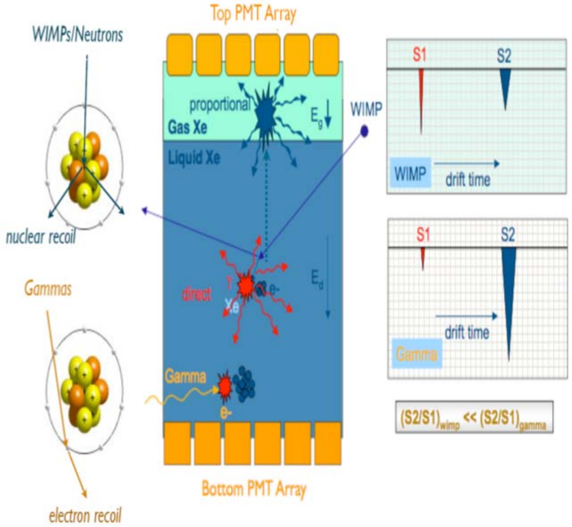

Fig 1: Diagram of Dual Phase Time Projection Chamber (TPC)

B. Photomultiplier Tubes

Photomultiplier tubes offer a wide range of applications in the scientific and technological communities. One application is in the amplification of a photon signal. XENON uses the R8520 1" PMT developed my Hamamatsu, Inc. This

PMT is designed to detect the faint signal of dark matter (signal energy ~10keV) [4]. The basic operation of a PMT is illustrated in Figure 2. A photon hits the surface of the PMT, which is coated with a photocathode material designed to have a low work function. After this collision, a photoelectron is emitted and accelerated to a dynode via a potential gradient. Through secondary emission, another electron is emitted when the dynode is struck by the photoelectron, producing a gain. The process continues throughout the remaining dynodes, until a net gain produces a current, which is collected by an anode and read as a signal.

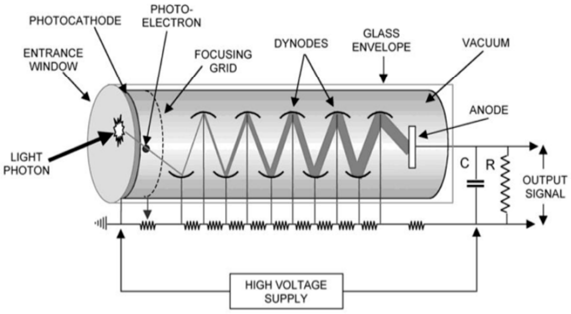

Figure 2: PMT schematic

C. QUPID

The Quartz Photon Intensifying Detector is a single photon sensor that operates with low radioactivity. It consists of a bialkali photocathode, an indium ring and an avalanche photodiode.

QUPID operates slightly different than conventional photomultiplier tubes. Instead of using dynodes set at varying voltages to produce electron gain, QUPID uses an avalanche photodiode (APD). An APD produces a gain through electron bombardment and by creating electron hole pairs in an avalanche process.

A negative high voltage of -6kV is applied to the photocathode while the indium ring is grounded. A bias voltage of -200V is placed on the APD. The schematic of this can be seen in Figure 3.

Although QUPID offers low radioactivity there are still other characteristics that must be compared with standard PMTs to decide if QUPID is the optimal choice in dark matter experiments. One of these characteristics is uniformity. Uniformity has two aspects, Cathode uniformity and anode uniformity.

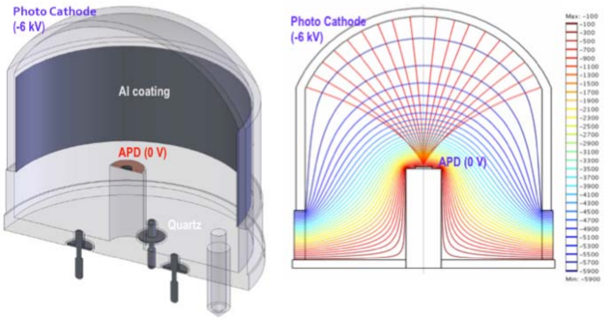

Figure 3: QUPID schematic showing equipotential lines and electric field lines.

D. Cathode Uniformity

Cathode uniformity is a measure of position dependence on the photocathode current and is dependent on quantum efficiency. The lack of uniformity can be due to fluctuations in the photocathode on the face of the PMT.

Three conventional PMTs were measured in the lab: R8520 1”, R8778 2” and R11065 3”. The flat scan uniformity system to scan the PMTs was designed to provide optimal focusing. A v-block holds the PMT in place as the face of the PMT sits perpendicular to an LED light source. The LED light source then does a 2D scan over the entire face of the PMT while the picoammeter reads the current output at each point in the scan. A picture of the flat scan system can be seen in Figure 4.

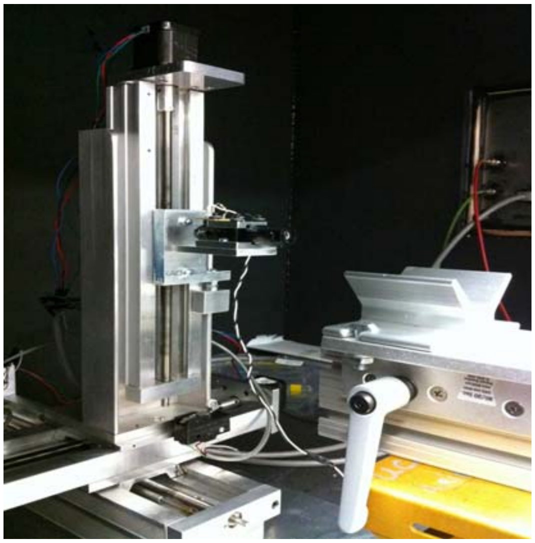

Figure 4: Flat scan uniformity system

To conclude the proper PMT voltage and LED voltage to be used, prior 1D scans were made over the radius of each PMT to be tested. From the data, it is conclude that the proper PMT voltage lies in the range of 100-300V, as above this range, the current becomes saturated. The LED can be operated in the voltage range of 4-7V. As each PMT produced the same trends, only the 1” PMT graphs are shown in Figures 5-6.

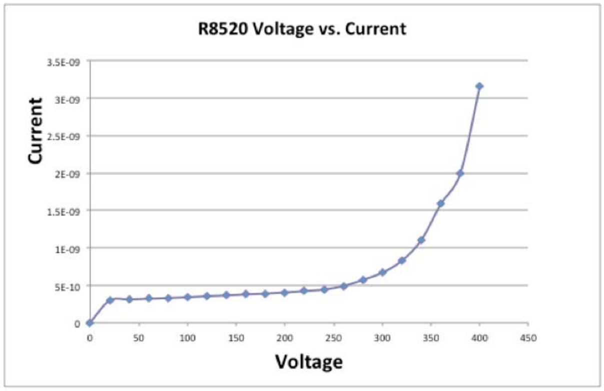

Figure 5: Voltage vs. Current of 1” PMT.

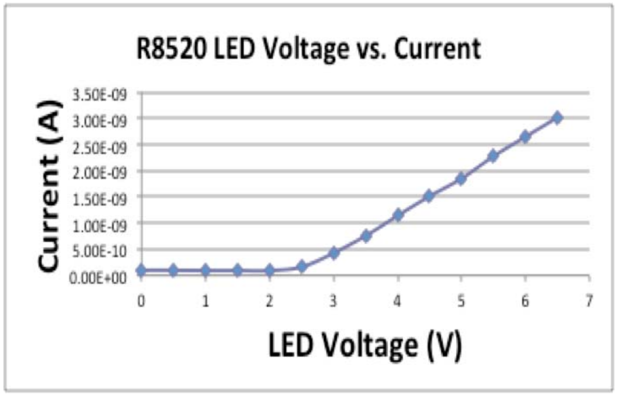

Figure 6: LED Voltage vs. Current of 1” PMT.

To measure cathode uniformity, a voltage of +200V was applied to the dynodes and anode of the PMT. The photocathode was then connected to a picoammeter to measure the current output. An LED light was focused onto the face of the PMT at 4V.

The scan of each PMT was then plotted using a color contour graph. Taking the max current reading from each data set and dividing the other current readings by that quantity normalized the current of each graph.

A 1D slice was also plotted for each PMT. The uniformity was calculated by averaging the normalized currents. See Figure 7-9.

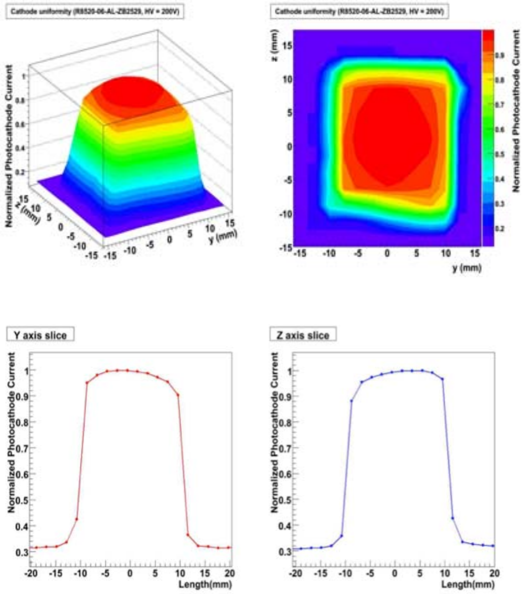

Figure 7: R8520 cathode uniformity~80% across the face.

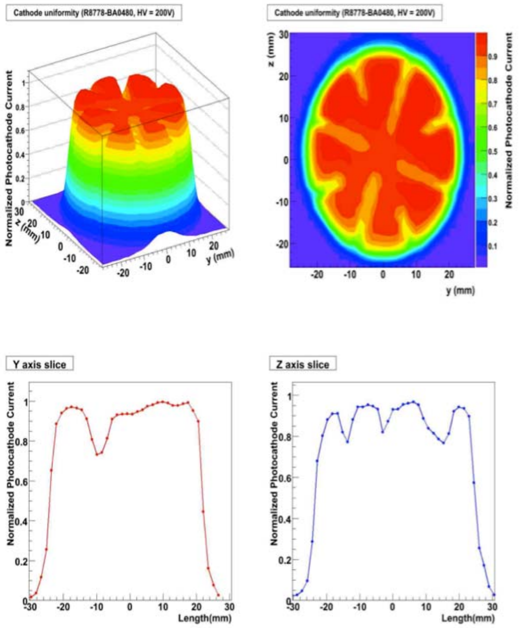

Figure 8: R8778 cathode uniformity~80% across the face.

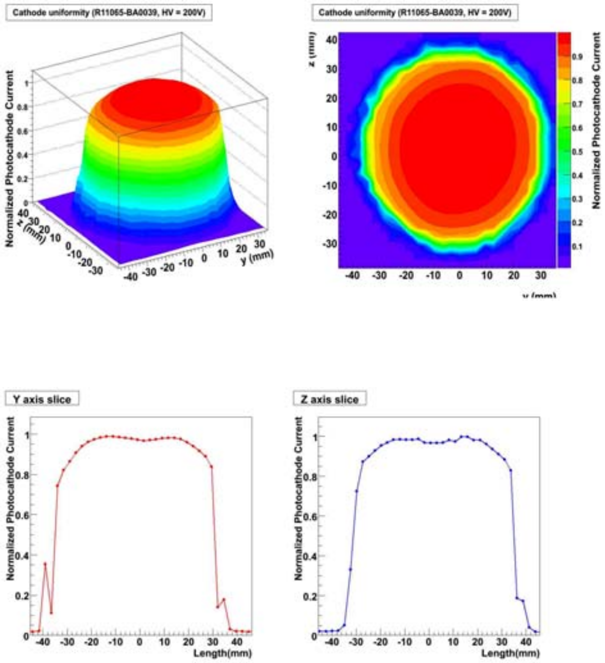

Figure9: R11065 cathode uniformity~85% across the face.

E. Anode Uniformity

Anode uniformity was measured slightly differently than cathode uniformity. A negative high voltage of -800V was applied to the photocathode while the anode was connected to a picoammeter. The anode current was then normalized in the same method as the cathode current. The 1" and 3" PMTs were scanned. From the measurement of anode uniformity, one can calculate collection efficiency. Collection efficiency is the probability that a photoelectron ejected from photocathode will reach the first dynode. To calculate the collection efficiency, anode uniformity is divided by cathode uniformity. The results are seen in Figures 10-11.

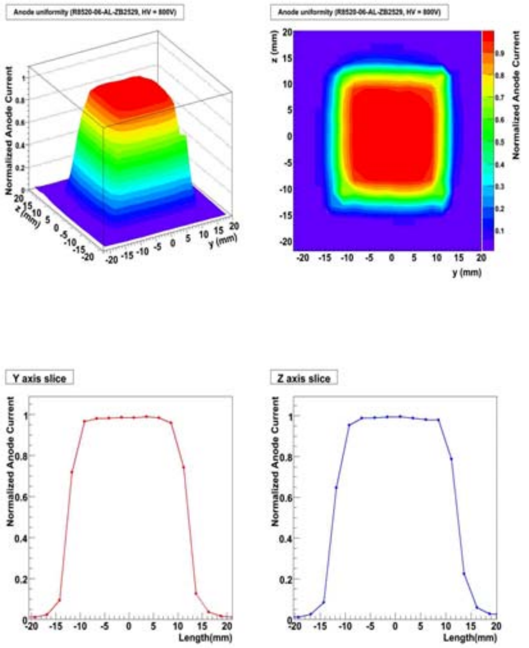

Figure 10: R8520 collection efficiency~85%

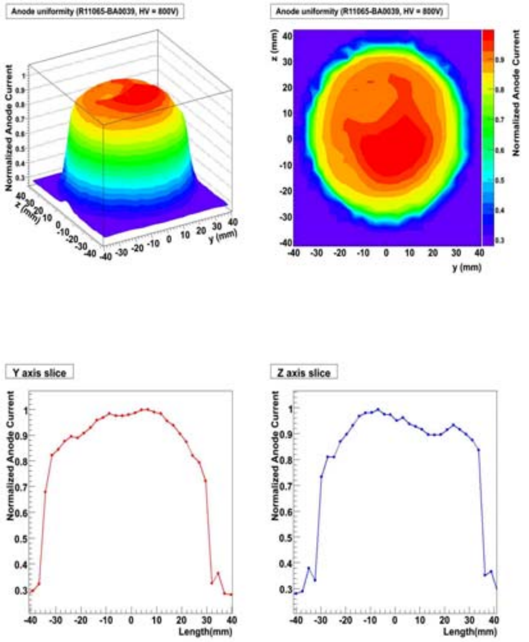

Figure 11: R11065 collection efficiency~75%

F. QUPID Uniformity

QUPID uniformity was measured using a system designed at UCLA by an undergrad student. The details of this system can be read in the QUPID paper [5]. The results of these measurements are shown here in Figures 12-13 so the reader can compare the results with standard PMT uniformity graphs.

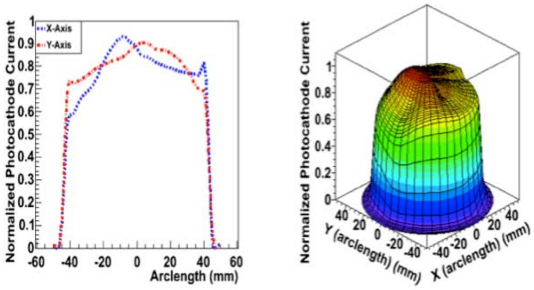

Figure 12: QUPID cathode uniformity. Uniform up to ~80% across the face.

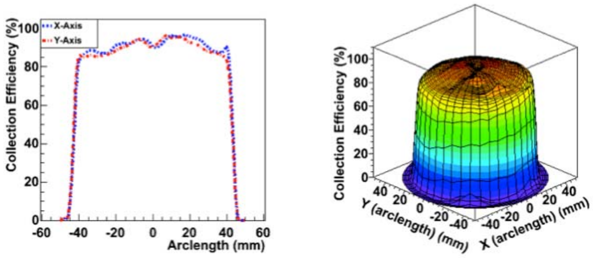

Figure 13: QUPID collection efficiency. Collection efficiency measured to be >80%.

G. Conclusion

The results of the uniformity graphs offer varying conclusions. The cathode uniformity of the 1” PMT used in XENON 100 is identical to the QUPID uniformity, leaving room for improvement in QUPID. However, the 3” PMT showed superior cathode uniformity (See Figure 9). The anode uniformity measurements of QUPID were superior to all other PMTs. In conclusion, QUPID uniformity and collection efficiency is nearly equivalent to conventional PMTs, although improvements can be made.

H. Acknowledgements

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