Katsushi Arisaka

Dark Matter Detection
Characterization of Photomultiplier Tubes for Dark Matter Experiments

Terrance White
Department of Physics and Astronomy, University of California, Los Angeles, USA

Dark matter has become a major topic of research as the attempt to described the gravitatioinal interactions between some unknown substance and the stars that make up the galaxacy has been approached. Photomultiplier tubes are used in the observation of Weakly Interacting Massive Particles (WIMPs) in dark matter detection experiments, such as the Xenon 10 and Xenon 100 experiments conducted at the Gran Sasso National Laboratory by the Xenon Collaboration.[1] In previous experiments the conventional PMT, R8520, has been used as the standard PMT in various laboratory investigations. However, one of the leading challenges in detecting WIMPS in the Xenon experiments is reducing the radioactive background, originating from the radioactive isotopes in the conventional PMT, to a level in which the rare occurrences of dark matter can be observed. As a result, Katsushi Arisaka with the collaboration of Hamamatsu Co. developed the Quartz Photon Intensifying Detector (QUPID) to solve the radioactivity issue. The QUPID has been assessed with single photo electron gain measurements and measurements of the radioactive contaminants. Furthermore, there have been many laboratory investigations concerning the uniformity of the QUPID's photocathode and charge collection. As a result, it can be concluded that on the matter of the uniformity of the Qupid there is indeed room for improvement.

1. INTRODUCTION:

A. Dark Matter

By observing the rotational movement of the stars that makeup the galaxies, one would notice that the velocity is constant throughout. This phenomenon can only be described by a gravitation interaction between the visible matter of the universe and some invisible matter known as dark matter. Dark matter is an invisible substance that only reveals its presence through gravitational effects and is known to make up 26 percent of the mass in the universe.[2]

Also, the velocity of the stars and the gases allows astronomers to weigh and make accurate measurement of the universe. As a result,the mass that the astronomers predict is roughly five times larger than what the galaxy clusters can account for.[3] In addition, gravitational lensing produces the same results. Gravitational lensing uses the deflection of light in a gravitational field to measure the mass of a cluster of galaxies. Through gravitational lensing, there has also been spottings of insufficent mass reading in the universe. This leads towards an indication that there is some unknown matter that accounts for the rest of the mass.

Furthermore, the Wilkinson Microwave Anisotropy Probe map of the cosmic macrowavable background justifies an indication of dark matter. The WMAP was a NASA explorer mission that was launced in 2001 to measure the anisotropy of the CMB. By taking this measurement of the fluctuation of hot and cold spots in the sky, WMAP was able to make a conclusion that our universe is composed of different types of matter. Therefore, it showed that there must be a new kind of dark matter particle that exist.[4]

When discussing what dark matter actually is, there are a number of candidates that are percieved to acknowlege such a question. First, there is a hypothesis that dark matter is in the form of Brown Dwarfs. Brown Dwarfs,also known as MACHOS, have the same characteristics of dark matter. They tend to only interact through gravitational means and they cannot be detected through visible light sightings. Also, the other two candidates for dark matter have surfaced in the forms of Supermassive Black Holes and new forms of matter called Weakly Interactive Massive Particles. .[3]

B. Xenon 100 detector

In the detection of dark matter, The Xenon collabaration has relied on the particle physics theory that dark matter is the lightest of supersymmetric particles in the detectioin of WIMPS. They have depended on the observation of Weakly Interacting Massive Particles (WIMPs) by measuring the amount of energy they create through nuclear recoils during its interaction with Xenon. Xenon was used in this experiment due to its high mass number of A-131, high atomic number and density, low radioactivity, and the life span of its isotopes. When observing the interaction between the WIMPs and the Xenon, one looks to measure the amount of energy in the form of photons deposited through the nuclear recoil. However, since dark matter only emits photons in the ultraviolet spectra, composing of a wavelength of 175 nm, the Xenon 100 experiment had to use Photomultiplier Tubes in order to complete the measurement of energy emitted.[1]

Also, since Dark Matter mostly interacts through gravitational effects and rarely interacts with any other sources, there is a need for low background. Therefore,

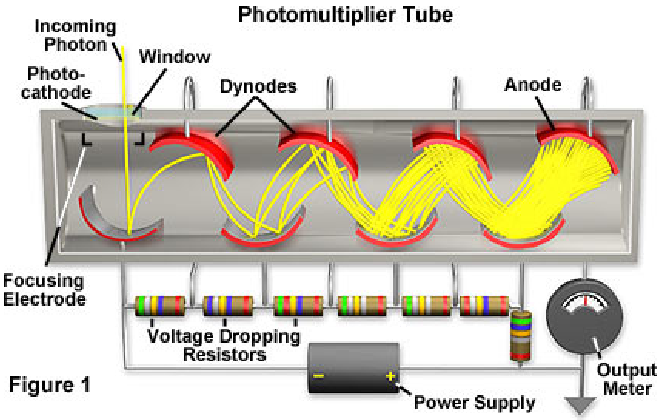

FIG. 1: Conceptional View of photomultiplier tubes http://micro.magnet.fsu.edu

[6]

the most effective PMT must not emitt an abundant amount of radiation. This is a major challenge found in most dark matter detection experiments.

C. Photomultiplier Tubes

Photomultiplier Tubes are light detectors that convert photons to electrical signals. They are ideal in the dark matter detection experiments because they can convert low light signals with wavelengths between 115 nm to 1700 nm to large pulses of current. Also, PMTs consist of photomassive cathode material, electron multipliers, and electron collectors.[5]

2. R8520

In the Xenon 100 experiment a conventional PMT, R8520, was utilized in the detection of photons. The R8520 consists of a photocathode and dynodes set at different potential differences as shown in Figure 1. As a result, when a photon hits the PMT the photo cathode emits a single photoelectron and sends it towards the first dynode. As the electron reflects off of each dynode, it multiplies by a factor of ten giving a total gain of approximately one million. The amplification of this process is sufficient that the signal of the nuclear recoil can be easily read by standard electronics.

A. Gain

The gain of a PMT is noted as the amount of electrons it outputs for every one single photo electron we input. In order to calculate the gain of the R8520, a high voltage is applied upon the base of the PMT which acts as a voltage divider and places different voltages upon the dynodes and photocathode. Furthermore, a small LED light is shined upon the R8520 in order to direct photons towards the photocathode. However, the light must be calibrated to a dim enough source to only allow one single photo electron to eject off of the photocathode. This is regulated and determined by an oscilloscope connected to the R8520. Most of the time, the oscilloscope will only read out noise which is very ideal since the chances for photocathode to emit one single photoelectron is slightly low.

On the other hand, there will be few instances where the oscilloscope will read out short pulses with a pulse width of 10ns and amplitude of 15mV; this is a representation of one single photoelectron being emitted from the photocathode. Once the output is read on the oscilloscope, a certain window is chosen for the waveform, which includes the noise and the single pulse, and is integrated. This process is completed 10,000 times and the true area values are taken and placed into a histogram as shown in Figure 2.

The histogram is composed of two peaks. The largest peak is a representation of the area of the noise, while the smaller peak is the representation of the area of pulses created by the single photoelectron. Furthermore, the gain can be represented by below:(Z is the impedance)

$$V = IZ \tag{1}$$

$$[V] = \left[\frac{C \cdot \Omega}{s}\right] \tag{2}$$

$$Output = V \cdot t = Q \cdot Z \tag{3}$$

$$Charge = Q = \frac{Output}{Z} \tag{4}$$

$$Numberofelectrons = \frac{Charge}{1.60217646 \cdot 10^{-19} coulombs} \tag{5}$$

The gain is already calculated in Figure 2. Therefore, it shows the number of electrons outputted in each Gaussian curve. As a result, when the means of both curves are subtracted, we are able to get a total gain of 1.05e+6 electrons. Thus, the justification of the gain of the R8520 being a factor of one million is valid.

B. R8520 Application

By producing a gain of one million electrons, the R8520 proves to be a valid light detector in the detection of dark matter. It has the ability to magnify the signal of the dark matter source to one that can be read out. However, impurities in the R8520 emit radiation that is a

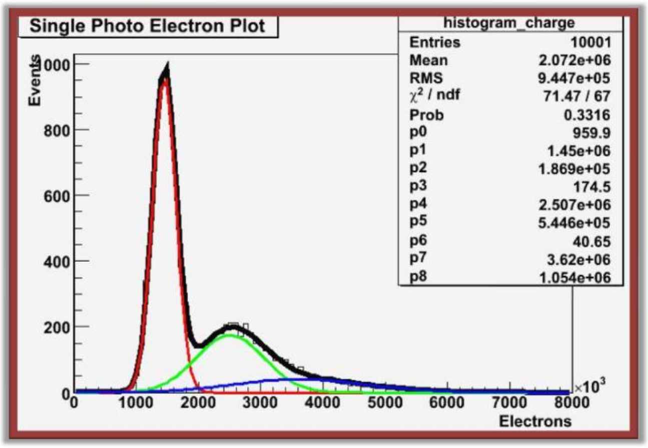

FIG. 2: Single Photoelectron Gain Measurement Response of R8520, which is used to measuer a gain of 1.05e+6

major source of background in the dark matter detector. As a result, a new design of a photomultiplier tube had to be designed in order to reduce the background to a level in which rare observances of dark matter could be seen.

3. QUPID

The Quartz Photon Intensifying Detector (QUPID) is a single photon sensor that operates with low radioactivity. It consists of a bialkali photocathode, avalanche diode for electron bombardment, and quartz (Figure 3 Outline of the QUPID). Quartz is utilized in the constructionof the QUPID because it has a low intrinsic radioactivity.

Also, it is known to be very transparent to ultraviolet light. Therefore, it solves the problem of background radioactivity that is presented by the conventional PMT. The QUPID operates differently from a regular PMT. Instead of using dynodes set at different voltages to create a multitude of electrons, it uses an avalanche photo diode that amplifies the number of electrons in two ways, initial electron bombardment and an avalanche effect. [7]

Therefore, when a high voltage ranging from -1kV to -6kV is applied to the photocathode and a voltage is placed upon the APD ranging from -100V to -200, an electric field is created within the QUPID. This electric field allows for a single photo electron, derived from the interaction between a photon and the photocathode, to be directed towards the APD and multiplied by a gain of 100,000. Ideally, the QUPID is designed to be uniform throughout. Thus, no matter where a photon impacts the Qupid the same results should happen throughout as shown in Figure 4.

However, there are two things that can effect the uniformity of the QUPID. Discrepencies can be caused first by fluctuations in the actual photocathode. Also, electron collection on the APD can cause nonuniformity. For example, when the electrons come out of the photocathode they may not reach the APD. As a result, in order to justify the uniformity of the QUPID we must test photocathode fluctuations through Cathode Uniformity and electron collection through Anode Uniformity.

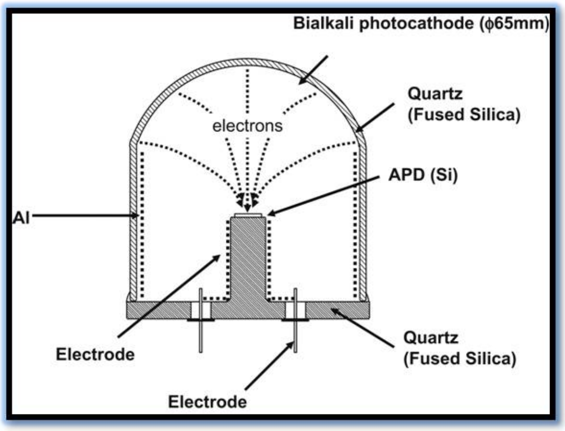

FIG. 3: Diagram of the QUPID

[7]

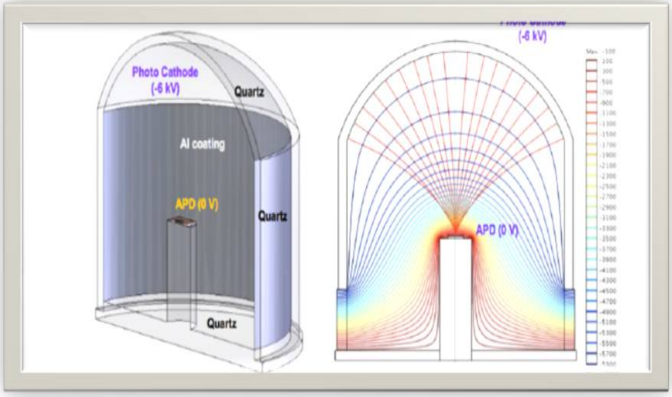

FIG. 4: QUPID Uniformity Diagram

[8]

4. CATHODE UNIFORMITY

Cathode Uniformity is a measurement of the position dependence of the photocathode current. In order to test this characteristic of the photocathode there must be a voltage ranging from +100V to +200V placed upon the APD and all the material surrounding the photocathode. This creates an electric field within the QUPID that attracts electrons out of the photocathode and directs them towards the APD. Also, the photocathode is connected through a pico ammeter to ground.

Thus, when a program written in C plus plus and root

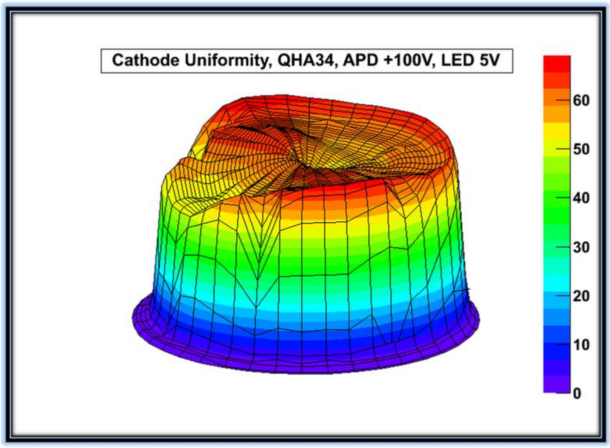

FIG. 5: QUPID Cathode Uniformity Diagram
The discrepencies and the uneven surface tendencies of the plot justifies that the photocathode has some areas of non-uniformity

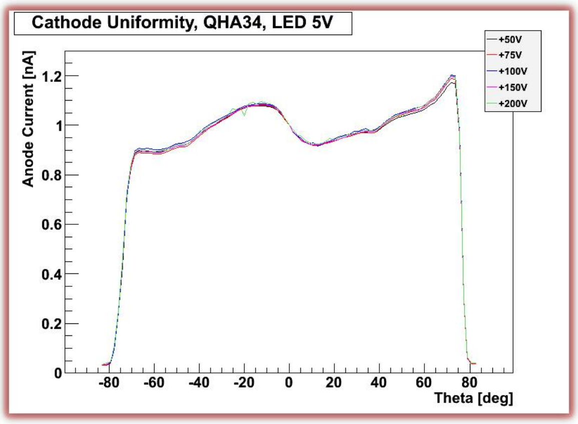

FIG. 6: QUPID Cathode Uniformity Diagram
Bias Voltage:
This plot indicates the changes in the uniformity for different Bias voltages set upon the APD

scans over the QUPID using a PLP pico second laser of 402 nm, the photocathode pulls electrons from ground in order to replace the electrons that were emitted and directed towards the APD. The pico ammeter then measures the flow of the electrons that are pulled from ground to the photocathode.

In an ideal situation, the amount of current measured at every point along the photo cathode should be equivalent. However, when taking measurements along 93 points, the amount of points for one slice, and 1860 points, the amount of points for an entire 2D scan, for different voltages and LED light settings there was an indication for some discrepancies in the uniformity of the photocathode. The representation of some of these nonuniformiteis can be seen in Figures 5,6, and 7.

Figure 5 shows a 2D representation of the Cathode Uniformity of the QUPID. It can be noticed that some areas of the QUPID experience some non-uniformity. Furthermore, Figure 6 tells us that it is justifiable to conclude that the APD voltage has no effect upon the uniformity of the QUPID. Figure 7 tells us that the voltage placed upon the LED also does not have an effect upon the uniformity. In addition, by taken a closer look at Figure 7, one will notice that the QUPID begins to saturate at 8 and 9 volts placed upon the LED. As a result, the ranges of light voltages that can be placed upon QUPID can be noted.

5. ANODE UNIFORMITY

AAnode Uniformity is a measurement of the postion dependence of the APD current, which includes both the effects of the photocathode non-uniformity and the electron collection efficiency. The set up for anode uniformity is slightly different. There still is a bias voltage ranging from -100V to -300V connected to the APD. However, a pico ammeter connected to ground is also connected to the APD. Also, a high voltage ranging from 1kV to

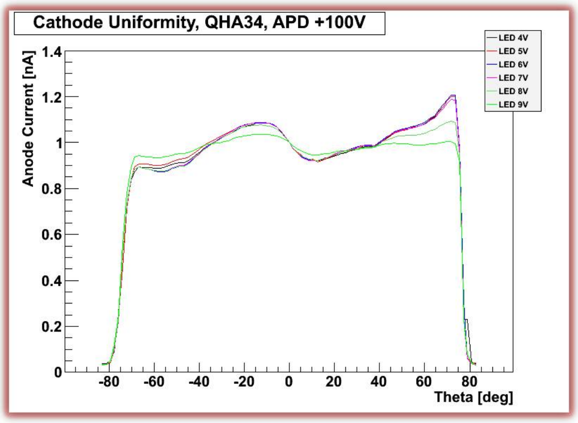

FIG. 7: QUPID Cathode Uniformity Diagram
LED Voltage:
This plot indicates the changes in the uniformity for different voltages set upon the LED
Also there is an indication of saturation at 8v and 9v

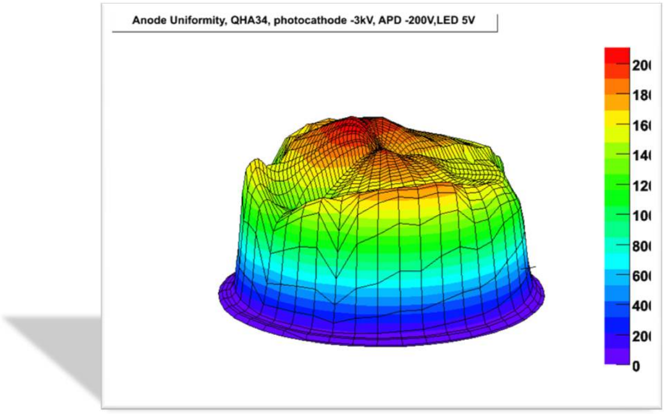

FIG. 8: QUPID Anode Uniformity Diagram
The discrepencies and the uneven surface tendencies of the plot justifies that the APD is not very uniform

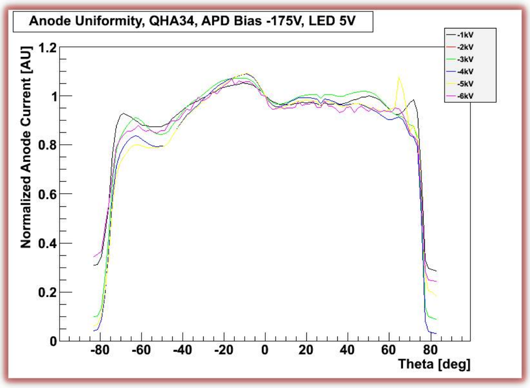

FIG. 9: QUPID Uniformity Diagram
High Voltage on Photocathode:
This plot shows one slice of the QUPID at different high voltages upon the photocathode. It is indicated that the amount of voltage upon the photocathode does not effect the uniformity of the QUPID

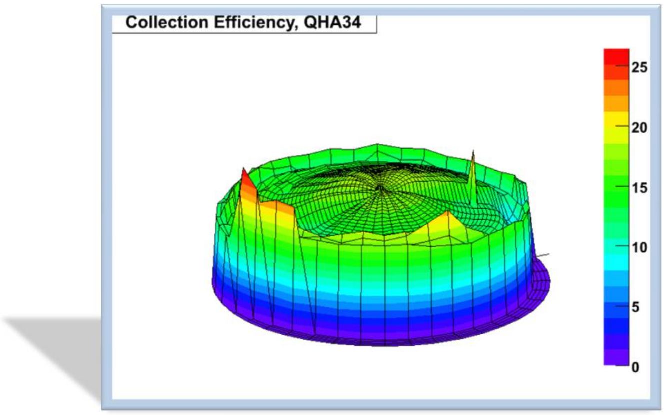

FIG. 11: Collection Efficiency
This diagram shows a compiliation of both the Anode and Cathode Uniformity. As a result, we are able to get a better view of the uniformity of the QUPID as a whole

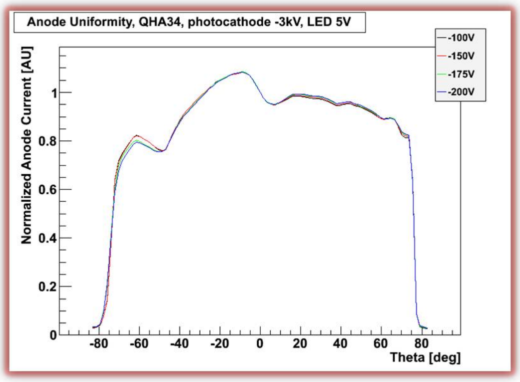

FIG. 10: QUPID Uniformity Diagram
LED Voltages:
This plot shows one slice of the QUPID at different LED voltage settings. As a result of this plot, it is justifiable to conclude that the LED voltage does not effect the uniformity of the APD

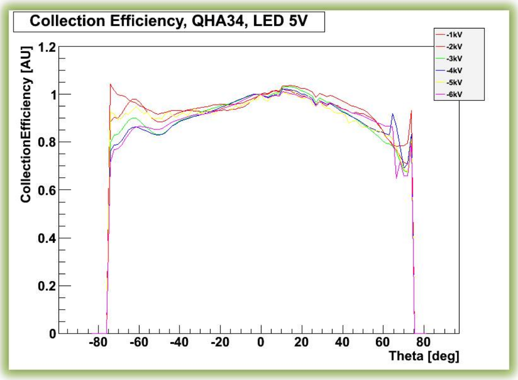

FIG. 12: Collection Efficiency Slice
This diagram shows a compiliation of both the Anode and Cathode Uniformity. As a result, we are able to get a better view of the uniformity of the QUPID as a whole

6kV is applied to the photocathode in order to create an electric field inside of the QUPID.

The same program that is used for Cathode Uniformity is utilized, however, instead of reading the current out of the photocathode, the amount of current is read out of the APD. Thus, at every point scanned throughout the QUPID the amount of current flowing out of the APD should be equivalent. However, there were also some discrepancies in the uniformity of the APD current as shown in Figures 8,9 and 10. Figures 9 and 10 also indicate that the uniformity of the QUPID is not dependent upon the voltage of the LED or the High Voltage placed upon the photocathode.

6. CONCLUSION

The evaluation of the gain output of one million electrons for the R8520 photomultiplier tubes proved to be valid. However, when justifying the ideal photomultiplier tube suitable for the next generation dark matter detectors, the QUPID holds characteristics to being the best bidder. The only problem faced with the QUPID at this moment is determining the cause of its discrepancies regarding its uniformity. When the ratio of the uniformity of the photocathode and avalanche photo diode is compiled together (as soon in figure 11 and 12), one is able to see multiple spots along the surface of the QUPID where it is not ideally uniform.

By looking at the Cathode Uniformity plots, one more conclusion is able to be made. The Cathode Uniformity plots are a measurement of the uniformity of the photocathode material. These plots shows fluctuations throughout the surface of the photocathode. This indicates that throughout the hemiphere of the QUPID there are different amounts of photocathode material layered upon the PMT. This is due to the spraying of the photocathode upon the QUPID. In some spot more photocathode material was sprayed than in others.

Furthermore,there are two characteristics of the QUPID that effect the Anode Uniformity. The first is the actual photocathode uniformity of the QUPID, while the second is the electron collection of the APD. By comparing both Figures 7 and 10, a number of conclusions are able to be justified. For example, the symmetry of both plots seem to differ. At the edge of Figure 7 there seems to be a increase in voltage except for at 8 and 9 volts on the LED where there is an indication of saturation due to the resistivity of the photocathode. However, at the edge of figure 10 which are measurements of Anode Uniformity there seems to be a dramatic decrease. This is not expected because an increase in voltage upon in the Cathode Uniformity plot of Figure 7 should result in more electrons to be ejected out of the photocathode material. As a result, there should be a higher percentage of electron collection. Thus, the two plots should be practically the same. However, this is indeed not the case, and one must conclude that it is due to the actual symmetry of the QUPID.

Furthermore, with the further development of the QUPID, dark matter detection and research will be able to expand even more. The reduction in background will allow for the rare occurrences of dark matter to become evident and will set the stage for its detection. However, the uniformity of the QUPID due to photocathode non-uniformity and the symmetery of the Quipd must be adjusted.

7. ACKNOWLEDGEMENTS

I would like to first thank Katsushi Arisaka for giving me an opportunity to work with his research group this summer and giving me a better insight and equipping me with the tools to becoming a researcher. I also appreciate Artin Teymourian, Kevin Lung, and Ethan Brown for assisting me through my research and teaching me how to operate the hardware used in our laboratory investigations. Furthermore, I would like to show gratitude towards the National Science Foundation and the UCLA Physics and Astronomy department for their support of the program. Lastly, I want to give a special thanks to Francoise Queval for allowing me to participate in the 2010 UCLA REU program and surrounding me with the resources to make the best out of the program.

[1] X. . Collaboration, First Dark Matter Results from the XENON100 Experiment **1**, 1 (2010).
[2] J. A. Sellwood, What is the Evidence for Dark Matter? **2**, 1 (2004).
[3] G. H. B. Griswold, *What is the universe made of?* (16,April,2010).
[4] G. H. B. Griswold, *Wilkinson microwave anisotropy probe* (16,April,2010).
[5] Hamamatsu, *Photomultiplier tubes* (2010), URL `http://sales.hamamatsu.com`.
[6] Hamamatsu, *Concepts in digital imaging technology photomultiplier tubes*, URL `http://learn.hamamatsu.com`.
[7] H. W. K. Arisaka and M. Suyama, QUPID, a single photon sensor for extremely low radioactivity **1**, 1 (2010).
[8] K. Arisaka et al., XAX: A multi-ton, multi-target detection system for dark matter, double beta decay and pp solar neutrinos **31**, 63 (2009).