Dark Matter Detection: Photomultiplier Tube Potting and Gamma Ray Energy Calibration

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Discussed is a method to cost-efficiently and effectively pot photomultiplier tubes, for use in the Large Underground Xenon detector, by housing them in a polypropylene encasement and achieving a water-seal via a structural plastic adhesive (3M's Structural Plastic Adhesive DP-8005). It is found that the bond holds strong even while tested for two week under water at 80°C. Also discussed are procedures utilized to calibrate the detected gamma ray energies from the Converted Air Cherenkov Telescope Using Solar-2.

I. INTRODUCTION

The case for the existence of dark matter is well documented[1] and has bred various experiments searching for the mysterious particle and its properties[2,3,4]. Considering that the dark matter particle has never been detected, and its properties (cross-section, mass, etc.) have yet to be rigorously defined, detector experiments of this kind require a careful and deliberate methodology in order to ensure accurate data and confidence in the experimental results. Here, we investigate two specific procedures designed to ensure a successful execution of the experiment: a method to effectively pot photomultiplier tubes (PMTs), to be used in the Large Underground Xenon detector (LUX), and an energy calibration scheme for the Converted Air Cherenkov Telescope (CACTUS).

LUX and PMT potting

The LUX detector is the newest member to the WIMP detector family. Designed to increase the sensitivity of WIMP detection, LUX houses a 300 kg active mass, two-phase xenon core, with a 100 kg fiducial volume capable of obtaining sensitivities orders of magnitude better than its predecessors CDMSII or XENON10[5]. Noble gases, being inert, of relatively high atomic mass and easily purified, have recently been heavily involved in dark matter detection experiments. Of particular interest to this research, however, is the water tank that surrounds the xenon core.

The LUX xenon core is surrounded by a 6-meter diameter water tank that serves as both an active and passive barrier to background radiation and noise. The hydrogen-rich water actively shields and thermalizes fast neutrons (which can then be absorbed by trace amounts of Gd within the water). The water barrier also signals muon entry via a Cherenkov veto system: following the entry of a relativistic muon, coherent Cherenkov radiation emission in the water tank marks muon passage and tags the data acquisition timeframe. Since muons can produce neutrons via spallation events, and neutrons are theorized to mimic the WIMP signal due to similar properties (neutral, massive), the water tank plays a critical role in reducing background noise and allowing for a detectable WIMP signal. Detection of the Cherenkov radiation, however, requires PMTs within the water tank and thus also

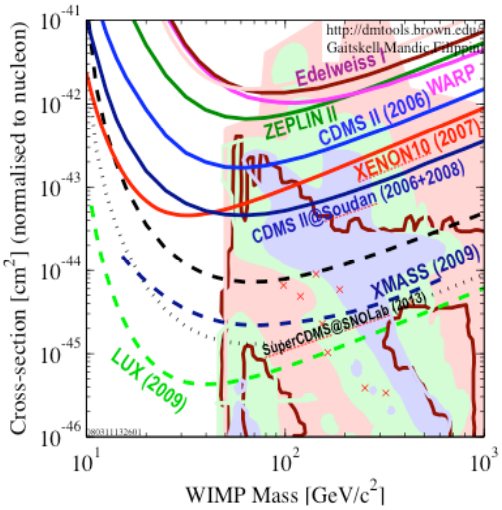

Figure 1: LUX dark matter sensitivity[5]

a method to reliably water-seal, encase, and protect (i.e. 'pot') the valuable electronic components.

Our PMT provider, Hamamatsu, has already developed techniques that allow it to sell potted PMT assemblies. It costs around 30% more (~$900) per PMT assembly, however. When ordering tens or hundreds of PMTs, this price difference proves to be very relevant. Thus, we aim to develop our own cost-effective PMT-potting technique. Here we discuss the advantages and disadvantages of various materials (PVC, polypropylene, acrylic) that could be used for this purpose.

PVC

In discussions with Dr. Robert Svoboda, it became clear that PVC was an unlikely option for the potting procedure: although there are strong adhesives that bond the material, black PVC is a known emitter of radon gas. This emission is unacceptable in the context of a sensitive dark matter detector, particularly when the PVC would lie within the water tank.

Polyolefins

Specifically polypropylene and polyethylene, these polymers appeared to be a good candidate: flexible, durable, and leak-proof. In respect to LUX, the main disadvantage became that a strong plastic adhesive proved difficult to find. A more delicate plastic-welding technique then became an option. Following the discovery of 3M's Structural Plastic Adhesive DP-8005, usage of polypropylene became much more attractive.

Acrylic

Acrylics, like PVC, are easily sealed and come in a wider variety of diameters and sizes. This allows for a sealable and customizable PMT housing. Acrylics, however, tend to be more rigid. After insertion of a potting gel into the housing, the acrylic may crack or apply unwanted pressure on the electronics.

CACTUS Energy Calibration

In the same vein of dark matter detection, the CACTUS mirror array[6], last operated in 2005, was utilized to detect the Cherenkov radiation and particle shower created by the interaction of a cosmic gamma ray with the Earth's atmosphere. Excess gamma rays from galaxies such as Draco are now explained as the products of dark matter annihilations reaching the Earth's atmosphere. This fact makes defining the energy of the gamma rays critically important to the field of dark matter detection, since doing so would provide concrete information on the properties of dark matter and its interactions.

A B

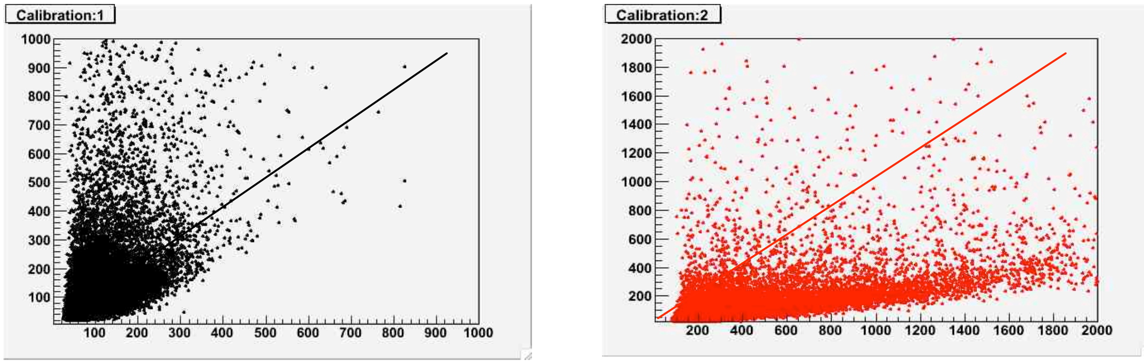

Figure 2: (A) Broad, non-linear energy calibration fit using sum of photoelectrons in each event; (B) Semi-linear fit but off desired 1:1 correspondence that includes a correction based on the positioning of the field hit.

As of now, however, the complexities of the field array coupled with the fact that the telescope only *samples* the shower's total energy forces a heavy reliance on simulation to reconstruct the gamma ray's energy. In order to properly calibrate this theoretical energy with the detectable, measurable results collected from the CACTUS mirror array, an ~1:1 linear correlation between a tangible experimental variable (arrival time of shower, arrival positioning, etc.) and the simulated gamma ray energy is required. Unfortunately, previous analyses have proven to be difficult and inadequate.

Previous calibrations were either too broad, non-linear, or off the desired 1:1 correlation line (Figures 2A, 2B-which plot the simulated gamma ray energy against previous fits). A proper, consistent calibration technique will allow for a more detailed energy/flux determination from the distant galaxies that CACTUS has monitored and therefore provide more detailed information on the properties of dark matter.

II. METHODS

PMT Potting

The potting procedure needs to water-seal and protect the electrical components while allowing for cables to feed into and out of the PMT. For the reasons outlined above, we chose to test polypropylene as the potting material. Figure 3 below depicts the basic potting scheme: a polypropylene bottle encases the base of the PMT and is heat shrink-wrapped to the PMT. Here we investigated the way to create and seal a pathway for the power/signal cable.

The basic set up is to drill a hole in the PP bottle, reinforce this hole by bonding some semi-rigid PP tubing to the bottle, and heat shrink-wrap the rigid tubing to the electrical cable (with the potting assembly further water-sealed by an RTV gel). As an added security measure, we also wanted to block any water that might leak into the signal/power cable from directly traveling to the PMT's components. Here we discuss these two methods.

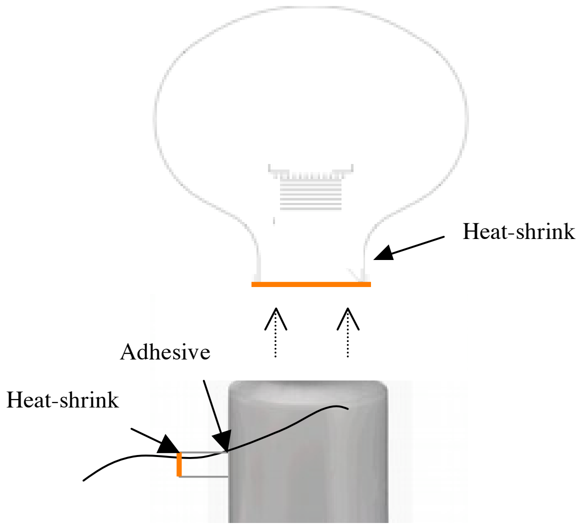

Figure 3: PMT potting assembly; PP bottle potted with RTV gel

The difficulty with reinforcing the PP bottle with PP tubing is that there appeared to be no easy method of bonding the PP tubing to the bottle. I investigated plastic welding and other techniques until I discovered a 3M adhesive that is advertised to replace plastic welding of polyolefins such as PP (3M Structural Plastic Adhesive DP-8005). To test bond strength (prior to attempting the procedure on a PMT), we bonded two PP centrifuge tubes using 3M's product. We decided a rudimentary visual inspection would suffice to determine its water sealing capability: we stuffed the tubes with brown paper towels and sealed using the adhesive. The cured product was then placed in a water bath initially at 50°C, but then upgraded to 80°C (for a 2 week period) and 90°C (for a 4 day period). (Note: 3M had already performed bond strength tests under water which were all successful as the bond held up to near 1000 psi, but they were all performed for two weeks at room temperature. In order to simulate years of water exposure, we deemed the high temperatures necessary). Once this test was complete, we could begin assembly of the actual version shown in Figure 3, to be tested on a spare PMT.

With respect to safeguarding against direct water flow up the signal cable, this is generally done by stripping the jacket off the cable conductor (for a 1 cm length or so) within the potting region so that the RTV gel within the housing and tubing sticks to the cable metal.

CACTUS Energy Calibration

The goal of the energy calibration is simply to obtain a 1:1 correspondence between any (or a combination) of CACTUS' field array variables (a subset of which is printed at the end of this paper) and the simulated energy[6]. Any method of doing so is acceptable. The three methods utilized are here discussed.

The first was simply plotting the simulated energy against each variable to determine if there was already some linear correspondence. In figure 4-A,B below, the simulated energy is plotted against numEntries and sumPE. These two examples are of particular interest because they appear to have a linear correspondence with the simulated energy, even before applying any correction. The second technique involved analyzing σ (given explicitly below), the standardized difference between the energy fits in Figure 2 (FitEnergy) and the simulated energy.

$$\sigma \equiv \frac{FitEnergy - SimulatedEnergy}{SimulatedEnergy}$$

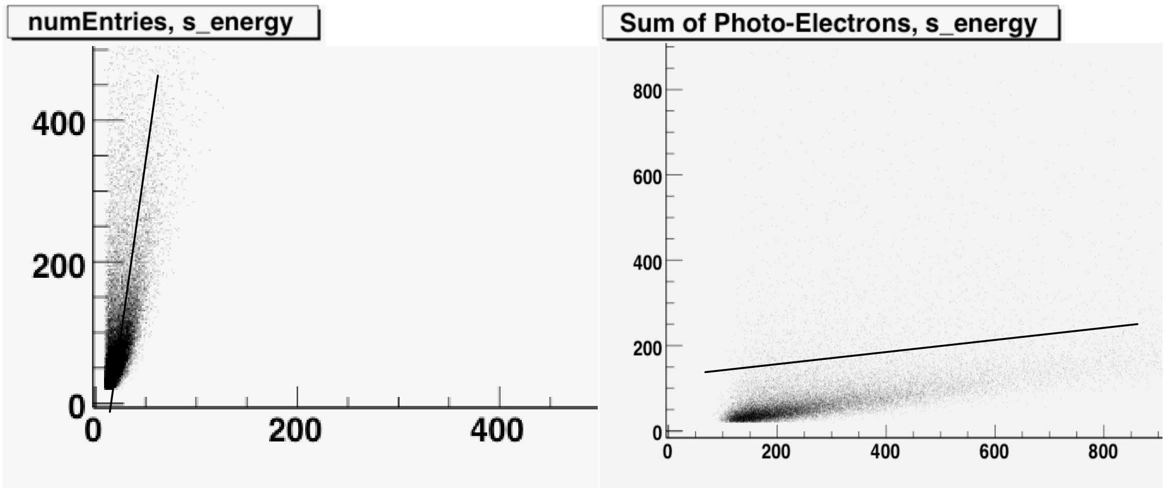

Figure 4: Simulated energy plotted against CACTUS array variables. A) Simulated energy vs. numEntries; B) Simulated energy vs. sumPE

Ideally, a plot of σ against the CACTUS variables would converge at 0. If this was not the case, I attempted to find a 'correcting function' (dependent upon the CACTUS independent variable) that could establish this convergence. As a final step in this method, this 'correcting function' was then applied to FitEnergy in an attempt to correct the calibration.

The final method utilized to obtain a better calibration fit involved characterizing and excluding problematic points within the calibration plots. That is, if subsets of points that lay off of the 1:1 correspondence line all traced back to a given range/value of a specific variable, these points were labeled and excluded when reconstructing the calibration fit. Here, Figure 2A-since it is closest to the 1:1 correspondence-was analyzed in this fashion.

III. RESULTS

PMT potting

The main goal here was to determine whether 3M's product could stand up to 2-3 weeks of high degree water treatment. 3M has already performed bond strength tests under water (with a reported bond strength of over 900 psi after water exposure for 2 weeks), but we decided our own test was required, using the heat bath to simulate the years that LUX will be operational.

The polypropylene tubing set-up remained waterproof for two weeks at 80°C. It was not until the temperature was raised to 90°C that there appeared to be water within the tube (in the form of condensation lining the inside of the tube).

We believe this to be a result of temperature effects, and not a poor sealing job, for three reasons: i) 3M's engineers advised that near 200°F (~93°C) the bond becomes soft; ii) the 90°C is well above water's boiling point, allowing for the possibility that water trapped within the PP tubing was boiled out into the bottle; iii) the condensation was not evident until the temperature was raised to 90°C. With this in mind, we are confident in the adhesive's ability to water-seal a PP potting assembly.

CACTUS Energy Calibration

The method used to analyze Figure 4-that of simply plotting the simulated energy against CACTUS array variables, and then adjusting the curve to obtain the correct calibration- has proven unsuccessful. Assuming a near linear correspondence of the plots in Figure 4, and simply altering the slope, results in a spread of the points that destroys most or all of the initial linearity (data not shown). A more sophisticated method was then employed.

So, I then moved onto analyzing the plots of σ vs. the CACTUS variables. Figure 5 on this page shows an example. The plot of σ vs. sumPE is here analyzed because the previous calibration attempts utilized sumPE in their analysis. Furthermore it is conceivable to assume a linear fit to correct Figure 5 and center it around 0. As when utilizing the previous method, however, assuming a linear fit proved not to be sufficiently accurate: when correcting the plot assuming linearity of the plot, it is manageable to center it around 0, but the spread becomes undesirably large. Applying this correcting function to the previous calibrations proved to be fruitless.

Finally, I attempted to characterize the points (as discussed earlier). Here explore how the calibration points of Figure 2-A correspond to the values of zeroTime.

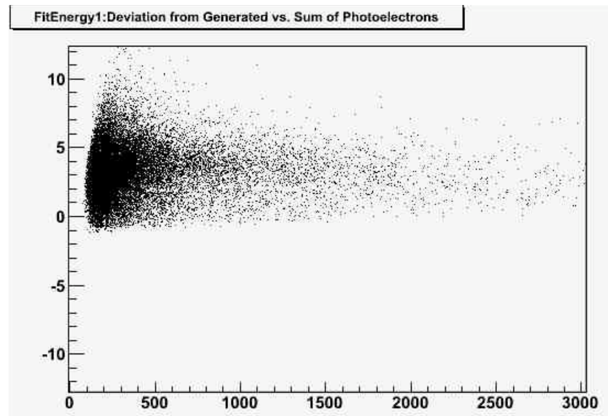

Figure 5: σ plotted against the sum of photoelectrons detected using Figure 2A's values as Fit Energy. Note that the plot seems to converge at 2 or 3, and that the high-density region is well above the desired mark of 0. A function (that depends on the sum of photoelectrons and corrects these problems) could be used in this case to correct Figure 2A.

zeroTime is explored because, as depicted in Figure 6-A, it has distinct regions of existence. I thought it would be interesting to see how these regions map into the previous calibration plots. I performed this in sections of 50 units of the zeroTime variable. The results for three of these sections are plotted in Figures -7A,B,C. One can see that distinct zeroTime domains appear to lie in distinct regions within the calibration fit. Interestingly, one notices that Figures 7-B and 7-C show a large density of points, which are very near linear, while the points in Figure 7-A are not nearly linearly correlated. This provides hope that with this method, analyzing all the various CACTUS variables in this fashion affords an easy, yet effective, technique that bests the previous calibration attempts.

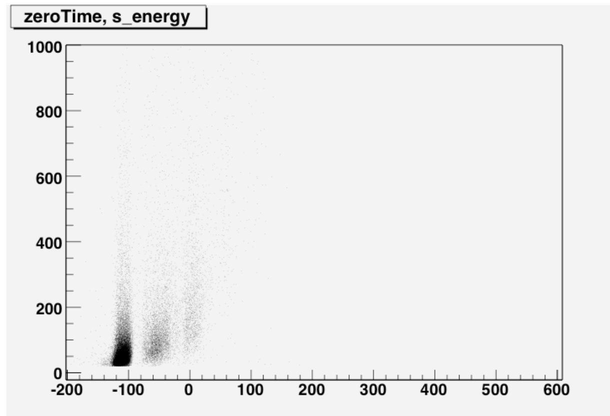

Figure 6: Simulated energy vs. zeroTime. Note the three distinct regions of interest.

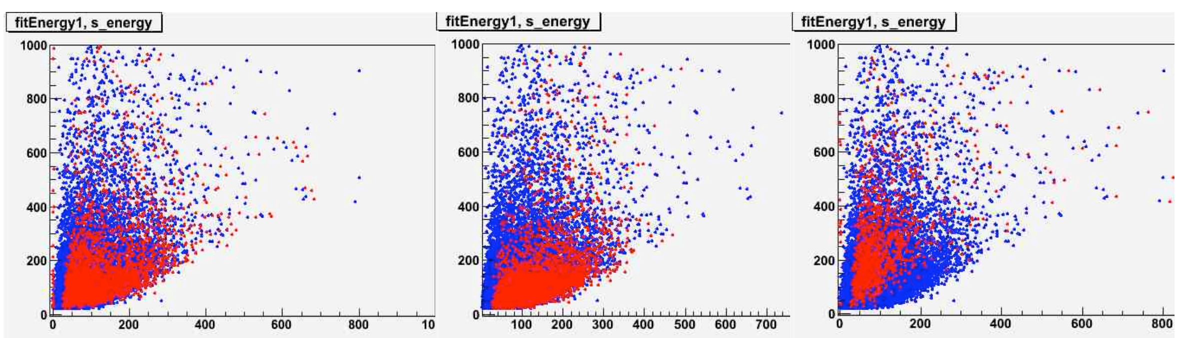

Figure 7: The calibration fit of Figure 2-A is shown in blue with various regions of zeroTime highlighted in red: A) -150 < zeroTime < -100; B) -100 < zeroTime < -50; C) 0 < zeroTime < 50.

IV. DISCUSSION

We remain confident in the 3M structural plastic adhesive's ability to water-seal and bond polypropylene substrates. Currently, we are testing the potting assembly of Figure 3 on a spare PMT. Since LUX will not be operational until at least next year, we are offered more time for further testing of the bonding capability.

Promising results from the energy calibration suggest that one can obtain a better fit if outlying or troublesome points are excluded from the analysis. Considerable amounts of analysis had already been done prior to my work with the aim of obtaining better fits. To the best of my knowledge, however, all previous attempts/fits included all points. Thus, I feel that the method of characterizing and excluding problematic points from the calibration is the most promising approach (in combination with the previously described correcting functions, perhaps)

Finally, I mention that three weeks of the program were initially devoted to documenting radioactive decay chains (U-235, U-238, Th232) to be used as part of simulating the background/noise expected in the LUX detector. Although this work was important, it limited the amount of time that was allotted to the potting testing and energy calibration (a project I received late into the summer). For this reason, I have spoken with Dr. Tripathi and look forward to continuing my analysis throughout the coming semester.

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References

[1]. Bertone, G., Hooper, D., Silk, J. *Particle Dark Matter: Evidence, Candidates and Constraints*. Phys. Rept. (2005).

[2]. Aprile, E. et al. *XENON: a 1 tonne Liquid Xenon Experiment for a Sensitive Dark Matter Search*. Submitted to World Scientific on Feb. 1, 2008.

[3]. Stiegler, T., Camp, C., Marquez, Z., Rodinov, A., White, J. *The LUX Two-Phase Xenon Dark Matter Search Experiment*, Amer. Phys. Soc. (2007).

[4]. Profumo, S., Kamionkowski, M. *Dark matter and the CACTUS Gamma-Ray Excess from Draco*. JCAP. (2006)

[5]. LUX website: lux.brown.edu.

[6]. UCDavis CACTUS website: http://ucdcms.ucdavis.edu/solar2/detector/simulations.php

Subset of CACTUS simulation variables:

S_energy: Simulation generated energy
numEntries: Number of hits in a shower
zeroTime: Arrival time of shower
FitEnergy: Attempted energy reconstruction
sumPE; Sum of estimated photoelectrons in shower