

## Scintillator design for CDMS

By: Jack Bluebaugh

Using an RTC XP 2262 B photomultiplier tube (PMT), we analyzed the effectiveness of 2,5-diphenyloxazole (PPO), 9,10-diphenylanthracene (DPA), and trimethyl borate (TMB) as possible constituents for the Cryogenic Dark Matter Search (CDMS) scintillation development. These materials were selected as candidates since they all have properties, which should work to increase the light yield, which is useful for identifying and separating mono energetic particles. Our tests allowed us to compare the efficiencies of these materials and maximize the effective light yield we received. We also used Monte Carlo simulations to analyze these scintillator designs to determine whether the results we received were realistically feasible or whether they were anomalies that we were observing due to errors in the data acquisition system, experimental setup, or genroot algorithms used to calculate the light yield. Results indicated that adding some of each of the PPO or POPOP, DPA, and TMB did in fact increase the light yield of our scintillators. However, the effectiveness of the scintillator to produce light did not continue to increase as the concentrations of each chemical was increased in the scintillator designs;

instead, there was a peak percentage of each chemical which resulted in maximum light yield for the scintillators.

## I. MOTIVATION

Since dark matter is still not understood and has not yet been observed, the Cryogenic Dark Matter Search (CDMS) plans to increase the light yield of its scintillators significantly in the new SuperCDMS experiment. This means that there is a need to know what sort of chemical composition would comprise a scintillator which would optimize the light yield given a certain amount of space. This greater light yield would allow more particles to be detected that have low energies, because the energy imparted to the scintillator would lead to an amount of light which could be detected by the PMTs, where the same energy imparted to other scintillators with less optimal light yields may not produce enough light for the PMT to detect an event. One technique for optimizing the light yield is to fine-tune the percentages of already well-known scintillation materials within a new scintillator that would then produce a maximized amount of light. As particles pass through the scintillator they lose energy and produce photons, which are an effect of the scintillation materials; these photons then travel to the PMT where a chain reaction of dynodes converts the photon into many photoelectrons, which identifies an event. This works well for high-energy particles, which produce a lot of photons in the scintillator naturally because of the amount of energy they are transferring. However, lower energy particles do not produce as many photons in the scintillator, and because of the inherent absorption length of the scintillator (that is the average distance a photon travels before it is absorbed and lost in the scintillator), these photons may never reach the PMT or too few may reach the PMT to create sufficient photoelectrons to register an event.. These weakly interacting massive particles (WIMPs, dark matter) we are trying to observe are predicted to have very low energy and

therefore will produce far less photons within the scintillator than other types of observable phenomena such as gamma radiation. Therefore, to detect the WIMPs we must create a scintillator, which produces the maximum amount of photons from the small amount of energy that may be deposited by the WIMPs.<sup>1</sup>

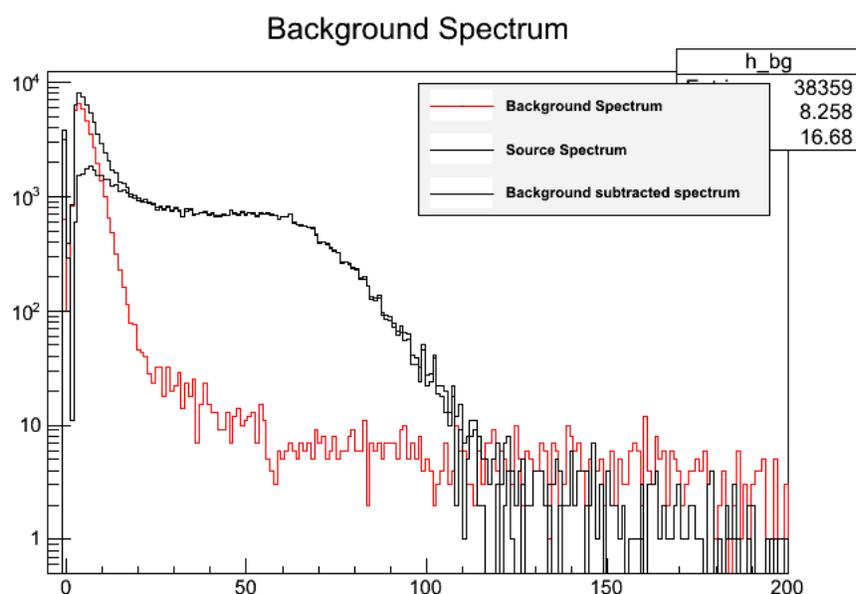
## II. SCINTILLATION MATERIALS

Scintillation is the process by which a usually transparent material absorbs radiation of some energy and then emits light of some characteristic spectrum usually of lower energy than the absorbed radiation. This process by which light is emitted is an inherent characteristic of various chemical compounds; often compounds such as conjugated and aromatic organic molecules have these properties. In these compounds certain orbitals interact and form nodal planes; these nodal planes delocalize electrons, which can then be excited by radiation. These excited electrons vibrate and then de-energize releasing photons according to the perimeter free-electron model in either singlet states which are faster or triplet states which are slower. These unique materials that have electrons that can be excited by radiation and then produce photons as the electrons return to a lower energy state are scintillation materials and are the basis of the mixtures which we were created for our scintillators.

## III. LIGHT YIELD

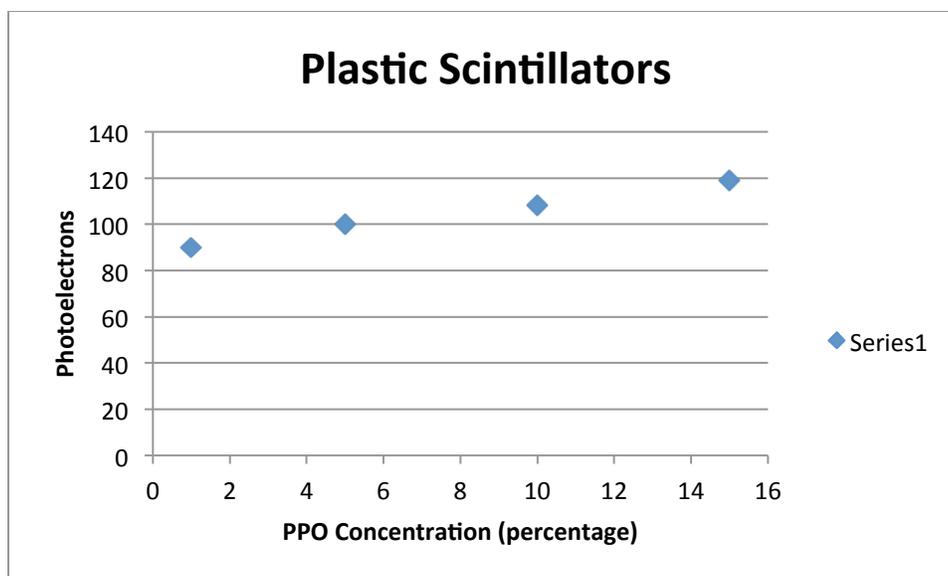
The main aspect of the project we focused on was finding what percentages of certain scintillation materials maximize the light yield in a scintillator. To do this we polymerized several different types of both plastic and liquid scintillators with varying percentages of the compounds which we were interested in. We attached the plastic samples directly to the PMT with optical grease, and the liquid scintillators were poured into vials, which were then attached to the PMT. We then took data where the scintillators were exposed to gamma radiation from

barium-133 and cesium-137, neutrons (due to spontaneous fission) from californium-252, and to background (where the scintillator was exposed to only radiation from outside sources which were beyond our control such as cosmic radiation). We then subtracted the background radiation from the gamma and neutron radiation data so that we could analyze the effective light yield of our scintillators due solely to the absorption of the gamma or neutron radiation and reemission of photons.



#### A. 2,5-diphenyloxazole (PPO)

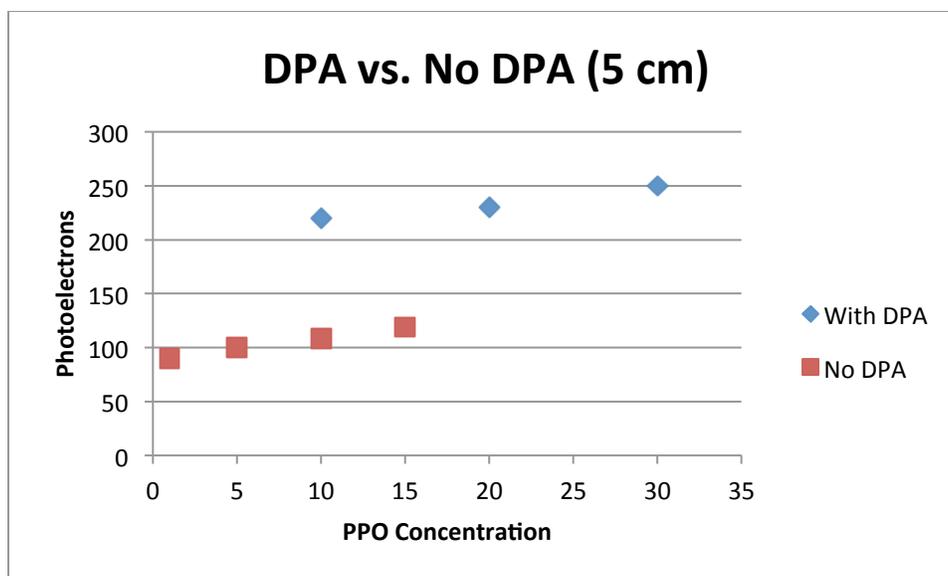
PPO is a high-temperature thermoplastic, which exhibits scintillation properties. This compound is the first we tested in our attempts to maximize the light yield of our scintillators. The PPO was mixed with polystyrene into plastic scintillators which contained varying amounts of PPO and the remaining composition was only polystyrene. 1%, 5%, 10%, 15%, 30%, and 35% PPO concentration scintillators were tested.



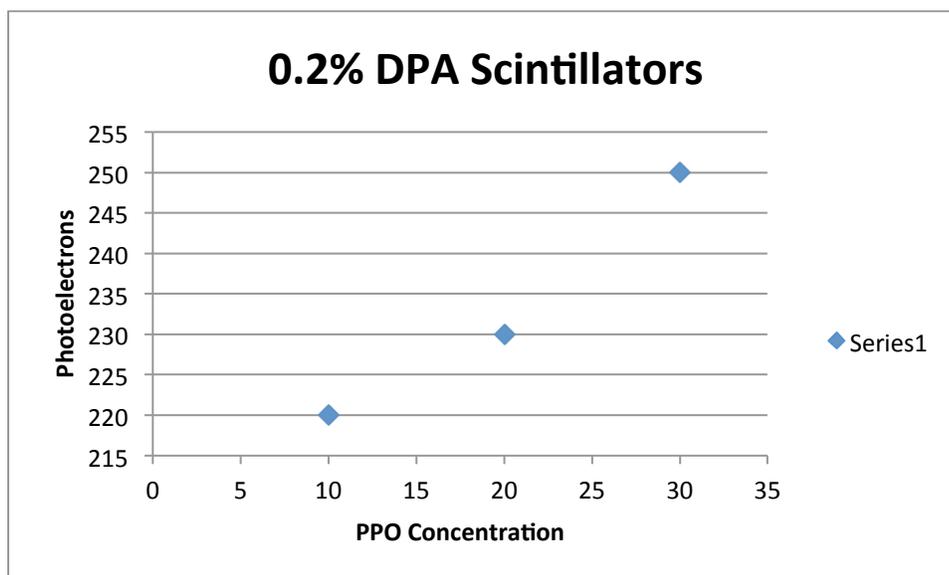
As one can see from the graph above, we found that the light yield increased as a function of PPO in what appears to be a linear fashion until the PPO concentration reaches 30%, at which time it is at its maximum and slowly begins to decrease after that.

#### B. 9,10-diphenylanthracene (DPA)

The next thing we tested was DPA. DPA is a slightly yellow polycyclic aromatic hydrocarbon which acts as a secondary wave shifter in the scintillation material; in other words, it takes the photons created by the PPO and changes their wavelength again to higher wavelengths increasing the light yield. Since DPA is a secondary wave shifter it cannot be used without including another material in the scintillator such as PPO or POPOP.<sup>4</sup> To test the effectiveness of the DPA, we created plastic scintillator samples which contained 10% PPO, varying amounts of DPA (.1%, .15%, .2%, and .3%) along with polystyrene. We found a linearly increasing trend to a maximum light yield at .2%, which then appeared to decline quickly. We then compared the scintillators with varying amounts of DPA to scintillators that did not include DPA in them and found that any amount of DPA (at least that we tested) is better than not having any at all.



Finally, we took data of a fixed amount of DPA (.2%) with varying amounts of PPO to see if there was any sort of co-dependencies between the amount of PPO and DPA. We tested plastic scintillators containing polystyrene, DPA, and concentrations of 1%, 10%, 20%, and 30% PPO and found that each seemed to increase in light yield at a similar rate as the scintillators without DPA and, therefore, concluded that there was no codependency between the two.



### C. Trimethyl borate (TMB)

Next we tested the efficiency of TMB as a constituent of our scintillators. TMB is an organic boron compound that has chemical properties which allows for captures of certain energetic particles such as alphas. Though this compound is used more for discriminating pulse shapes of different types of radiation, we did test its effectiveness at increasing light yield slightly. However, we were not able to acquire significant data to draw any conclusions about its actual effectiveness in increasing light yield.

### D. Polystyrene vs. polyvinyl toluene

Lastly, we tested the effectiveness of polyvinyl toluene against polystyrene. Polyvinyl toluene like polystyrene is a plastic which is often used as a base for scintillator plastics. We compared both plastics with concentrations of 1%, 10%, and 30% PPO .2% DPA and 1%, 5%, and 10% TMB and found that all light yields were higher for the polyvinyl toluene.

### E. Liquid vs. solid

Although not part of our main goal in this experiment we did compare the light yields of plastic scintillators; namely 10% PPO, 10% TMB, and polyvinyl toluene with a liquid sample containing .1% PPO, .0015%bisMSB (a secondary wave shifter) and linear alkylbenzene. We found that the plastic sample did appear to give more light, but this result is inconclusive as we did very few tests and could not compare samples with similar enough chemical compositions to draw any actual conclusions.

## IV. CONCLUSION

In conclusion, we found that polyvinyl toluene is the most effective base plastic to use when trying to maximize light yield in the scintillators. We found that light yield appears to increase linearly as a function of PPO until it reaches 30%, at which time it reaches its maximum

and then decreases. We also found that light yield also increases seemingly linearly as a function of DPA until it reaches a maximum of .2% (regardless of PPO concentration) at which time it reaches its maximum and then decreases. Therefore, we concluded that an optimal scintillator for producing light yield would be a polyvinyl toluene-based scintillator containing 30% PPO, .2% DPA, and some percentage of TMB (most likely 10%, which would also be used for pulse shape discrimination).

## V. FUTURE WORK

One weakness of the tests we performed was our inability to tell what sort of result had actually occurred in the experiment. Though we were easily able to determine which quantities of which scintillation materials gave us the highest light yields, it was often difficult, due to our low resolution (a possible error of the data acquisition system, the PMT, or both) to determine what peaks we were looking at; were they the photopeak or the Compton edge or were they possibly some manifestation of the algorithms which we used to subtract off background radiation and light leaks? In future experiments more precise instruments should be used to determine what exactly a spectrum should look like if the optimal scintillation materials are used and what sort of energies should be expected from certain sources.

## VI. ACKNOWLEDGEMENTS

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Visiting Faculty Program (VFP).

I would like to acknowledge Dr. Dan Bauer and Dr. Abaz Kryemadhi who allowed me the opportunity to come to Fermilab to assist in the CDMS experiment. I would also like to thank Dr. Ben Loer who explained many of the ideas that were essential to the operation and theory of

the scintillators that were used in the experiment and for guiding us and helping us troubleshoot every time we were stuck (which was often). Finally, I would like to acknowledge Joel Love who worked with me throughout the entire process.

## REFERENCES

- [1] Zaitseva, Natalia, et al. "Plastic scintillators with efficient neutron/gamma pulse shape discrimination." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 668. (2012): 88-93. Web. 7 Aug. 2013.  
<<http://www.sciencedirect.com/science/article/pii/S0168900211021395>>.
- [2] Leo, W. R. (1994), [Techniques for Nuclear and Particle Physics Experiments](#), 2nd edition, Springer, ISBN 354057280.
- [3] Berlman, I. B. (1971), *Handbook of Fluorescence Spectra of Aromatic Molecules*, Academic Press: New York.
- [4] Adams, J. M.; Ramdas, S. (1979), "The Crystal Structure of Solution-Grown 9,10-Diphenylanthracene. A Combined Computational and X-Ray Study." *Acta Crystallographica Section B* **35** (3): 679–683.
- [5] Robert J. Brotherton, C. Joseph Weber, Clarence R. Guibert, John L. Little "Boron Compounds," *Ullmann's Encyclopedia of Industrial Chemistry*, 2000, Wiley-VCH.