Metal-Doped Plastic Scintillator for Neutron Detection

David-Michael T. Poehlmann

University of Minnesota – Twin Cities, School of Physics and Astronomy, UROP Spring 2018

INTRODUCTION

The Super Cryogenic Dark Matter Search (SuperCDMS) is an experiment that looks for dark matter, specifically weakly-interacting massive particles (WIMPs) via nuclear recoils with germanium and silicon atoms. Currently, the SuperCDMS SNOLAB dark matter detector, the successor to SuperCDMS Soudan, is being developed for placement at the SNOLAB research facility in Canada.[1] As the sensitivity of this detector is increased, the suppression of neutron backgrounds through the traditional methods of using highly radiopure materials and passive shielding becomes much more difficult.[2] Single-scatter neutron events can produce nuclear recoils that are indistinguishable from WIMP interactions.[1] These events can be detected by replacing some of the passive neutron shielding with an active neutron veto composed of a metal-loaded plastic scintillator.

EXPERIMENTAL OBJECTIVES

1. To load metal dopants with high neutron cross-sections in plastic scintillator, namely Gd(i-Pr)_3 and Gd(TMHD)_3.
2. To characterize properties relevant to optical photon propagation in scintillator samples.
3. To determine a neutron capture efficiency for the fabricated samples.

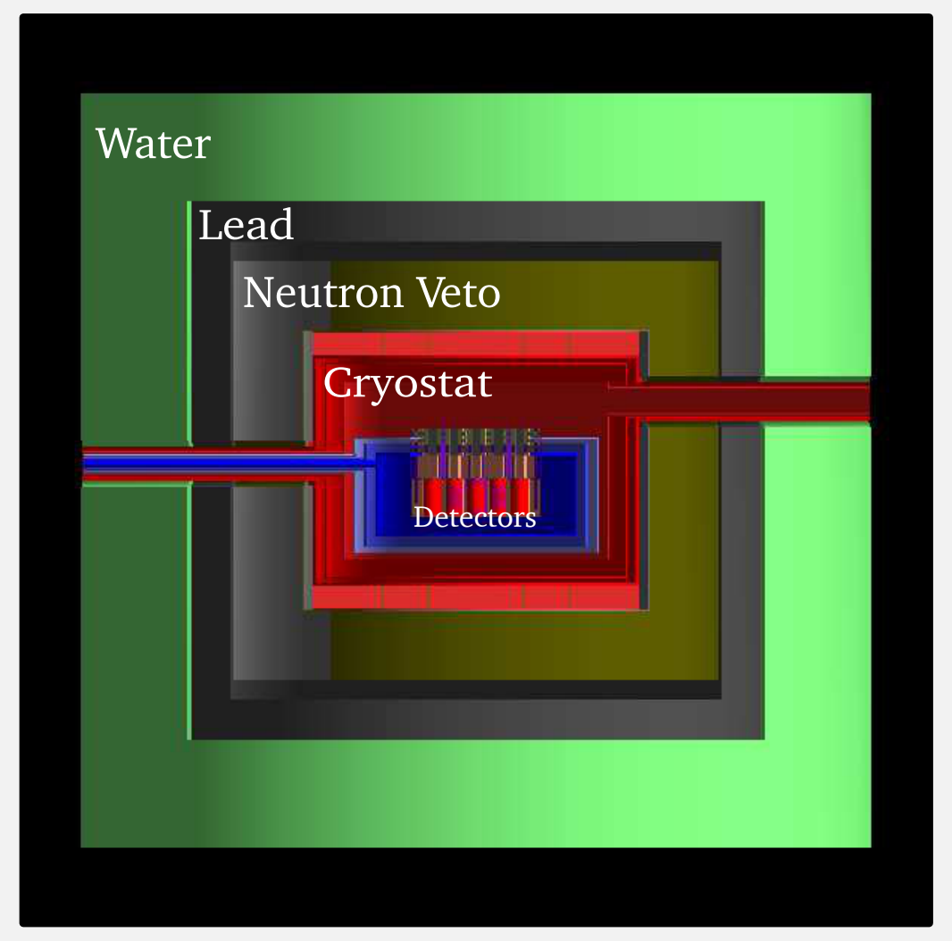


Figure 1: The shielding components for SuperCDMS SNOLAB are depicted.[1]

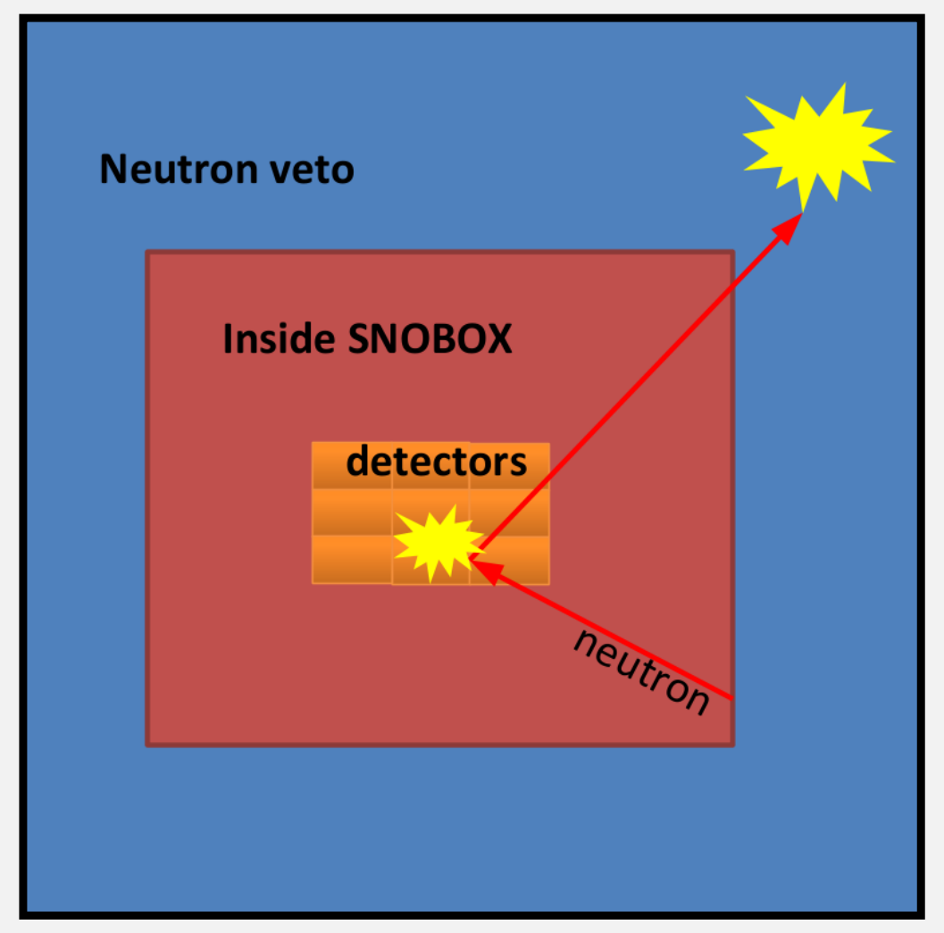


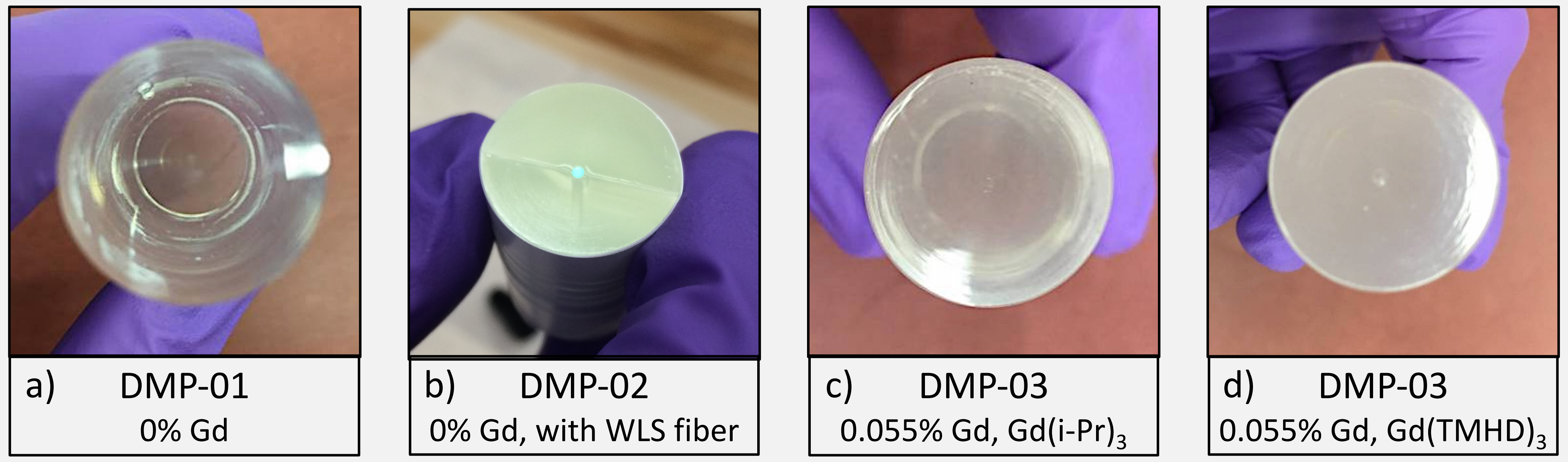
Figure 2: The desired mechanism to discriminate between WIMP detections and neutron scatters is shown above.[1]

PROPOSED VETO DESIGN

While a lot of background can be removed by placing the SuperCDMS SNOLAB experiment underground, additional shielding as shown in Figure 1 is required. Irremovable radioactive contaminants within the detector shielding materials will produce neutrons. These neutrons can singly scatter off of nuclei in the detectors, creating signals similar to that of the proposed WIMP signal.[1] However, an active neutron veto can be used to differentiate between such events. As shown in Figure 2, Gd atoms in an active veto surrounding the detectors would capture these neutrons, producing gammas detected by the plastic scintillator. Thus, an active veto would allow for WIMP-neutron discrimination on an event-by-event basis, as opposed to the existing statistical, background rate-based method. Simulations show a uniform doping of 1% wt. Gd in polystyrene will give 87% veto efficiency while a Gd resin applied to the surface of each segment of scintillator at 10% wt. will only give a 77% veto efficiency.[3] Thus, to minimize cost and maximize efficiency, the plastic scintillator should be uniformly doped with gadolinium.

MATERIALS AND METHODS

To fabricate scintillators, about 60g of styrene was combined with the desired dopant concentration.[4] Then, the fluors, PPO and POPOP, were added to at 1% wt. and 0.1% wt. respectively. Benzoyl peroxide was added at 0.8% wt. to act as an initiator for the polymerization of styrene. The mixture was sonicated for up to 30 minutes and then de-gassed via the bubbling of nitrogen gas for 60 minutes. The vial was placed in a 60°C water bath for 5 days and then cooled slowly to room temperature over the course of an additional 24 hours. Polymerized samples were then machined and polished, as shown in Figure 3. Wavelength-shifting (WLS) fibers, shown in Figure 3d, were embedded in some samples to examine properties relevant to the construction of an active veto. Maximum loadings of 0.15% wt. Gd(i-Pr)_3 and 0.25% wt. Gd(TMHD)_3 were achieved, significantly less than expected from previous publications.[5,6] Additional heating and sonication prior to and throughout the polymerization process did not improve the solubility of either compound, but instead decreased the quality of the resulting scintillator.



a) DMP-01 0% Gd

b) DMP-02 0% Gd, with WLS fiber

c) DMP-03 0.055% Gd, Gd(i-Pr)_3

d) DMP-03 0.055% Gd, Gd(TMHD)_3

Figure 3: Three different Gd loadings are shown above in Figures 3a-3c. These samples were machined to be (2.50 ± 0.02) cm in diameter with lengths of (11.1 ± 0.1) cm. In Figure 3d, a WLS fiber was embedded by cutting the sample in half and machining a groove down the center. The Kuraray (300)M WLS fiber was cemented in the grove, and the two sample halves were cemented together

RESULTS

Scintillator emission spectra:

Emission spectra for the samples shown in Figures 3a-3c are displayed in Figure 4. The peak emission wavelength for all samples was located at (431.0±0.5)nm, a value consistent with typical spectra of plastics in which POPOP is used as the secondary fluor.[6] Additionally, both doped samples had a local maximum at (441.0±0.5)nm. The sample loaded with Gd(TMHD)_3, DMP-04, also emitted more power over all wavelengths than either of the other two samples. As DMP-04 is slightly cloudier than DMP-01 and DMP-04, it was thought that increased scattering off of undissolved particles allowed more light to reach the monochromator.

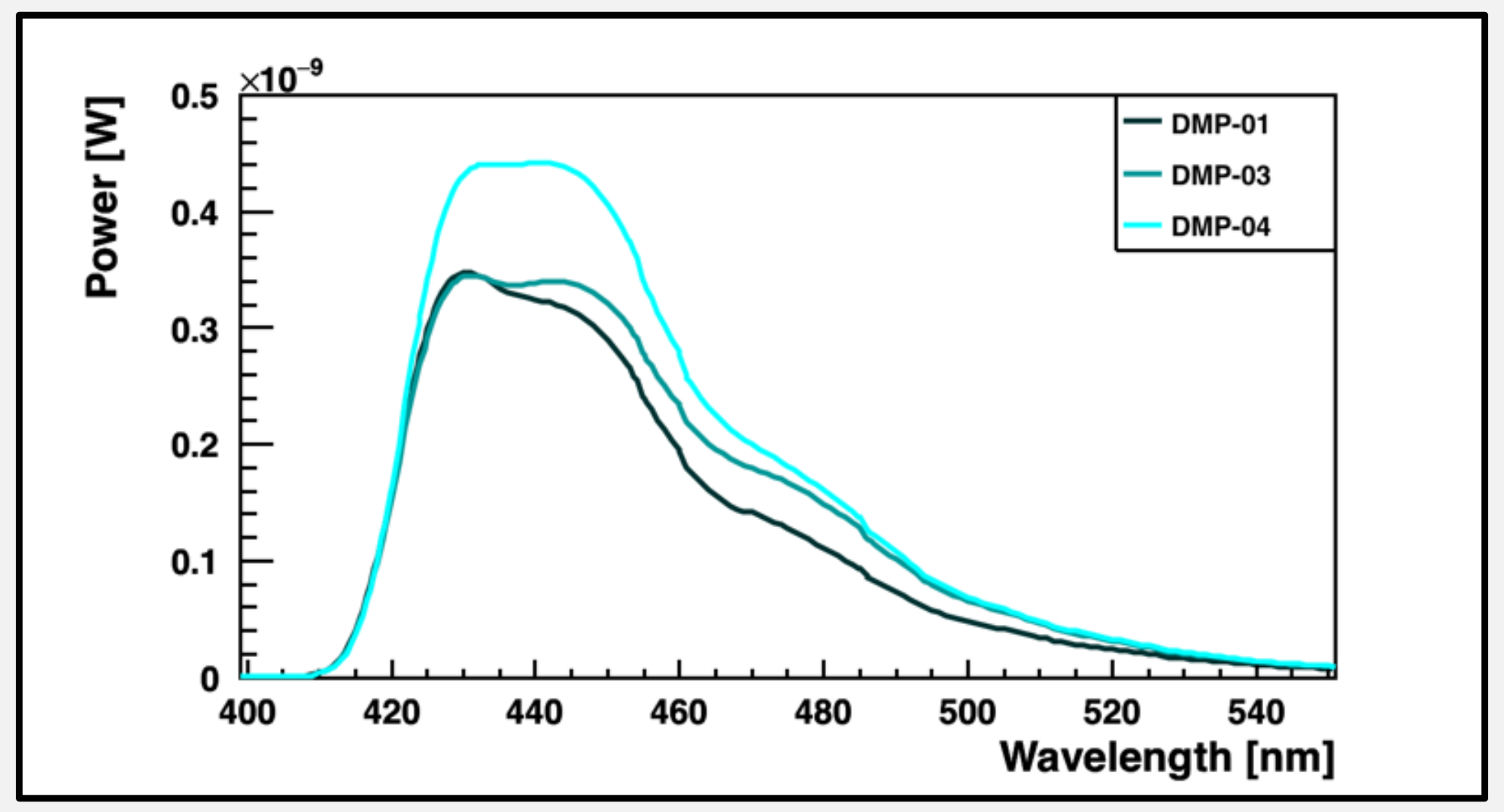


Figure 4: The samples corresponding to the three Gd loadings above are shown in Figures 3a-3c. Error bars are shown when larger than the line width.

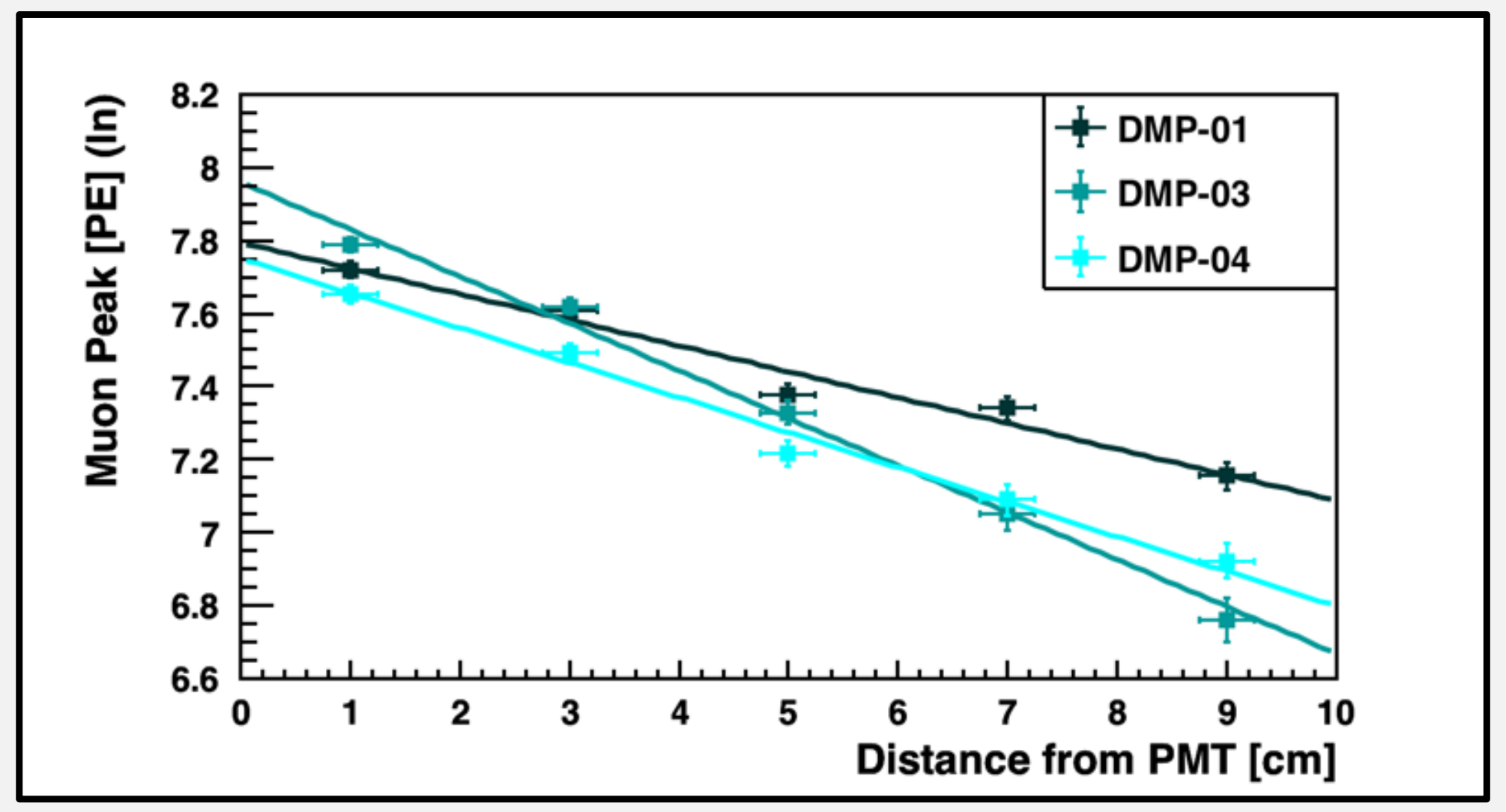


Figure 5: Attenuation lengths of (14.1±1.0)cm for DMP-01, (7.73±0.49)cm for DMP-03, and (10.49±0.75)cm for DMP-04 were determined. Reduced chi-squared values of the linear fits were close to 1.

Attenuation length measurement:

The attenuation length of the scintillator samples was determined using a muon telescope. The number of photoelectrons deposited as a function of the distance of the muon coincidence cross-section from the face of the PMT was plotted and fit using the chi-squared method. The attenuation lengths are shown in Figure 5. Initial light output at 1 cm from the PMT face was increased for DMP-03 as compared to the other samples. However, the attenuation lengths for both loaded samples were notably smaller than the unloaded sample. It should also be noted that even the unloaded attenuation length, (14.1 ± 1.0)cm, was not close to that of commercially available plastic scintillators, which typically have attenuation lengths close to 150cm.[7]

CONCLUSIONS

Two gadolinium compounds were loaded into plastic scintillator with minimal success, not achieving concentrations reported in prior literature.[5,6] Nonetheless, properties relevant to the construction of an active neutron veto were measured. Light output at 441nm was increased in both loaded samples as compared to the unloaded sample. The attenuation lengths of both loaded samples were notably smaller than that unloaded sample. Consequently, a greater density of WLS fibers would need to be used in the construction of an active veto. Additional characterization measurements are currently being conducted to determine the plastic's response to gammas, as well as a measurement of the trapping efficiency of WLS fibers. Neutron capture efficiency measurements are also being performed. This work is being done in parallel with a computational analogue using Geant4.

A metal-doped plastic scintillator has the potential to be used with other particle detectors whose measurements are affected by background neutron levels, most notably neutrino experiments. The ability to measure background levels will allow SuperCDMS SNOLAB to make credible claims of dark matter detection to a higher degree of precision as well as reduce the expected run time.

ACKNOWLEDGEMENTS

First, I would like to thank Tanmay Agarwal for his assistance with data collection and analysis. Notable contributions were also provided by Ryan Schmitz. I would like to thank the graduate students of the SuperCDMS group, specifically Hannah Rogers and D'Ann Barker, with whom I worked closely throughout the course of the project. I would also like to thank the Undergraduate Research Opportunity Program at the University of Minnesota – Twin Cities for funding my research. Finally, I would like to thank Priscilla Cushman for mentoring me during this project and providing me with the assistance and resources I needed to complete it.

REFERENCES

1. SuperCDMS Collaboration, “The SuperCDMS SNOLAB Experiment,” DOE Proposal (2013).
2. R. Calkins and B. Loer. "Prototyping an active neutron veto for SuperCDMS." *Cornell Digital Library* (2015).
3. D. Barker *et al.* SuperCDMS internal document.
4. Z. Bell, G. Brown, C. Ho, and F. S. Jr., Proceedings of SPIE 4784, 150 (2002).
5. L. Ovechkina *et al*., Phys. Procelia 2, 161 (2009).
6. Bertrand et al., Journal of Materials Chemistry C 3, 6006 (2015).
7. Lakowicz, *Principles of Fluorescence Spectroscopy*, 2nd ed. (Plenum Press, New York, NY, 1999) p. 883.
8. W. Leo, *Techniques for Nuclear and Particle Physics Experiments* (Springer Berlin Heidelberg, 1994).
9. K. A. Olive *et al*. (Particle Data Group), Chin. Phys. C38, 090001 (2014).
10. R. Breukers, C. Bartle, and A. Edgar, Nucl. Instr. Meth. A 701, 58 (2013).
11. K. Abe *et al*., Phys. Rev. D 83, 052010 (2011), arXiv:1010.0118.
12. G. Knoll, Radiation Detection and Measurement, 4th ed. (Wiley, Danvers, MA, 2010) pp. 223 – 320.