Passive shielding and neutron veto design for CDMS

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Using Geant4 to run Monte Carlo simulations, we analyzed water and polyethylene as possible materials for the Cryogenic Dark Matter Search (CDMS) passive shielding since they both contain large amounts of hydrogen, which is useful for blocking out charged particles. Our analysis allowed us to compare the efficiencies of these two materials and maximize the shielding effects while minimizing the cost and remaining within the size constraints of the SNOLAB facility. We also analyzed various scintillator/detector configurations using blank scintillator and available PMTs, SiPMs and APDs found online, also with a Monte Carlo simulation. Results indicated that using wave-shifting fibers to gather photons and feed them to PMTs, SiPMs or APDs is reasonably efficient and extremely cost-effective.

I. MOTIVATION

Since dark matter has still not been observed, the Cryogenic Dark Matter Search (CDMS) plans to boost the sensitivity of its detectors significantly in the new SuperCDMS

experiment. This creates a need for better methods of filtering out background events from the dark matter events; in other words, the greater sensitivity would create more false positives unless preventative measures are implemented. One method for blocking out background events involves surrounding the detector with passive shielding. As charged particles pass through the material in the shielding, they lose energy and eventually stop, never making it to the detector and thereby eliminating them from the data. This works well for charged particles and removes them from the CDMS background, but it has no effect on neutrons in particular. Neutrons have no charge, and unfortunately behave very similarly to the weakly interacting massive particles (WIMPs, dark matter) we are trying to observe. Neutrons require a special kind of protection — a neutron veto — that will detect their presence before they enter the detector, and "veto" the data collected by the detector when the neutron reaches it. This neutron veto will surround the detectors, but be surrounded by the passive shielding, so it will not see many charged particles. In this way, we can remove neutrons from the CDMS background and have greater confidence in the WIMPs detected.

II. PASSIVE SHIELDING

The passive shielding, as previously mentioned, will be used to block out neutrons and other background particles from ever reaching the germanium detectors. We specifically analyzed the interaction between neutrons and two different types of shielding material: water and polyethylene, to determine which is better. Water is composed of two hydrogen atoms and one oxygen atom, while polyethylene contains four hydrogen atoms and two carbon atoms. We used the National Nuclear Data Center website to find sigma values for carbon, hydrogen, and oxygen at different energy levels and used them to calculate the displacement of particles in the shield (how far a particle of a given energy level would

travel into the shield). Since hydrogen is the best element at ionizing particles, we wanted to maximize the hydrogen atoms in the passive shielding. Polyethylene contains more hydrogen atoms per gram than water, so we naturally expected polyethylene to be the better shield material. But when we factor in cost, it might be more economical to use larger quantities of water instead of polyethylene to achieve the same shielding effect.

For the actual analysis, we also calculated the flux of neutrons through the shield using the approximate number of neutrons produced by the cave walls in the SNOLAB mine (4000 neutrons per square centimeter) and the displacements previously calculated. This allowed us to compare the effectiveness of the two materials. After performing the analysis, we found that polyethylene was indeed more effective; it would take approximately 72 cm of water to shield 10 MeV neutrons as effectively as 60 cm of polyethylene. (The graphs are attached for reference in Figures 1 and 2.) However, water is much cheaper than polyethylene, and this difference of 12 cm is quite small, so it seems in CDMS' best interest to adopt water for the passive shielding.

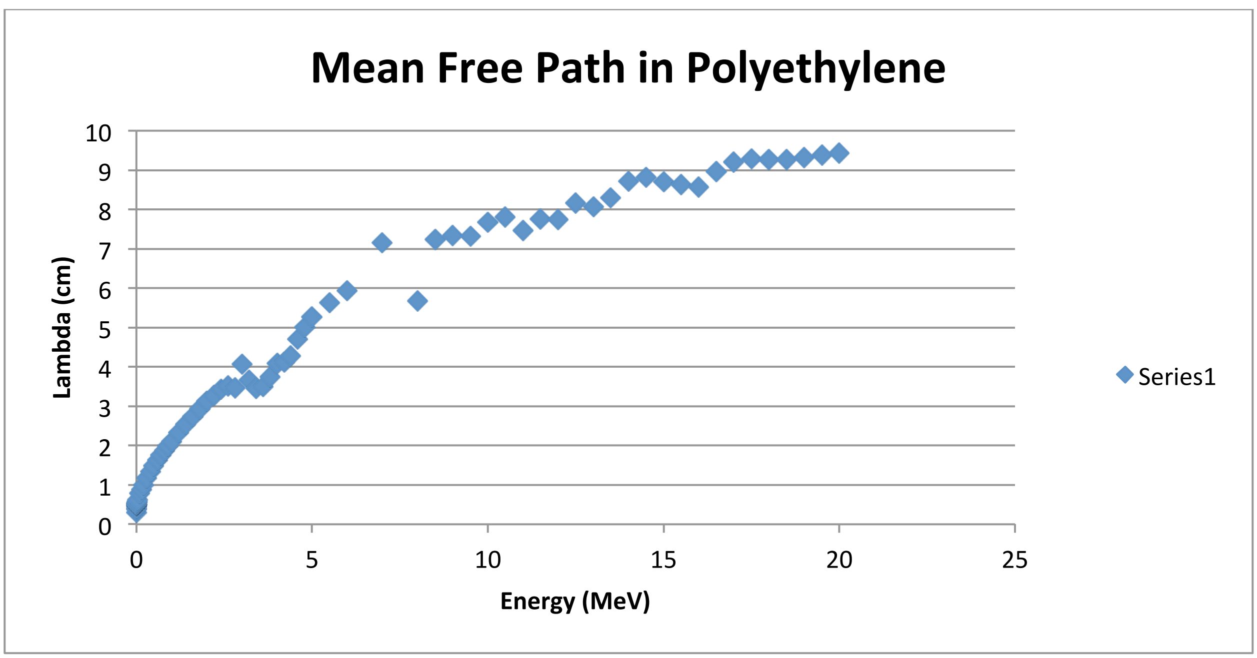

FIG. 1. This charts the displacement of particles in 60 cm of polyethylene at varying energy levels. The higher the energy of a particle, the further it will travel into the polyethylene shielding.

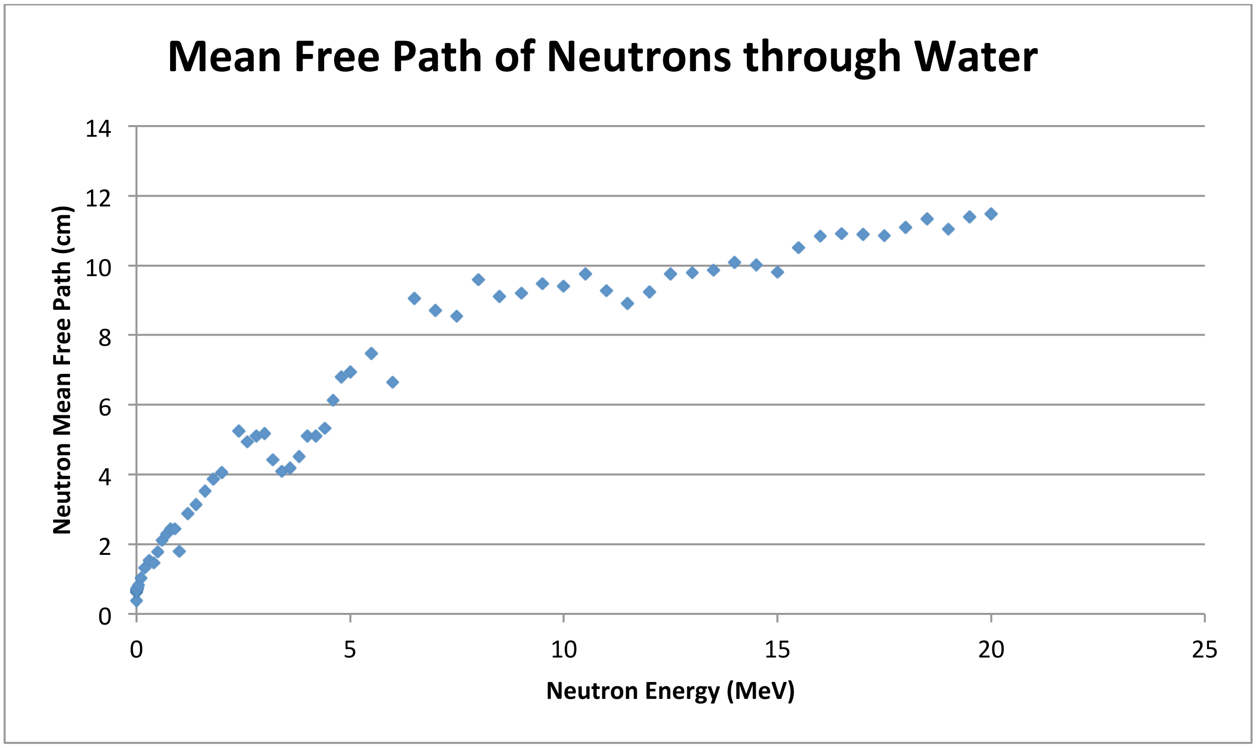

FIG. 2. This charts the displacement of neutrons in 72 cm of water at different energy levels. At higher energy levels, particles travel further into the shielding.

III. NEUTRON VETO

The second aspect of the project we researched was the neutron veto. Since some neutrons will inevitably get through our passive shielding, we need some way of detecting them so they are not misidentified as WIMPs. We can detect them by using scintillator and some kind of light detector. When neutrons pass through the scintillator, they give off photons (small particles of light) before they move on to the germanium crystals. If we can “see” that light, then we know a neutron has passed through our passive shielding and made it to the detector. This allows us to then remove the subsequent interaction in the germanium crystal, since we know it is our neutron. The type of scintillator had already been chosen by the CDMS team to be boron-loaded. We, then, began researching techniques to capture the photons produced in the scintillator and thereby detect the neutron. We explored three

mainstream tools: PMTs, SiPMs, and APDs before simulating the wave-shifting fibers we eventually settled on.

A. 8-Inch Photomultiplier Tubes (PMTs)

First, PMTs, or photomultiplier tubes, are a very common tool for light detection, and once we observed them being used in many other Fermilab experiments, they were our first choice. Looking at available PMTs, we found there were two sizes available — 8-inch PMTs, and 3-inch PMTs. The 8-inch PMTs, though, had a radioactivity of 2.2 Becquerels; this is not very much on its own, but since we would need 12–18 PMTs per scintillator module, the cumulative radioactivity became quite high. The PMTs would be producing more particles than we would expect to catch in our scintillator. Additionally, 8 inches was just too tall for our experiment. These PMTs would require a larger shell of passive shielding and lead, which would drive up costs for CDMS. The 8-inch PMTs, though, did have great coverage of the scintillator blocks and excellent light detection efficiency and cost only $3300 per PMT. We wanted to preserve the excellent coverage and light detection, as well as the minimal cost per PMT the 8-inch PMTs had, but eliminate the size and radioactivity problems in another choice.

B. 3-Inch Photomultiplier Tubes (PMTs)

The 3-inch PMTs were far less radioactive, with a rating of only 3 millibecquerels per PMT; however, they also covered a much smaller area. We analyzed various configurations of the 3-inch PMTs, but to achieve the desired coverage, we would need 72–96 PMTs for a single scintillator block. These PMTs were also more expensive than the larger 8-inch models, costing $7500 per PMT. These two facts simply put the 3-inch PMTs outside the CDMS price range and we were forced to abandon them.

C. Silicon Photomultipliers (SiPMs)

Next, we analyzed SiPMs — another common light detection tool. The SiPMs had a higher quantum efficiency than the PMTs, which means they could detect small amounts of light even better, thus increasing our veto's sensitivity, but they were even smaller than the 3-inch PMTs. Our analysis showed that we would need between 1800 and 3600 SiPMs per scintillator module to achieve the desired coverage. The SiPMs only cost $500 each, but since we needed so many, they were too expensive as well.

D. Avalanche Photodiode (APD)

Finally, we examined a little known and fairly new technology — the avalanche photodetector (APD). The APD is a solid-state electronic device that detects light like the PMT and generates an electrical data signal. Since it is a solid-state electronic, the APD is not radioactive at all, and is incredibly small, being only a printed circuit. This is both good and bad; its thinness means less shielding is needed to surround it, but its small surface area means huge numbers would be needed to cover each scintillator block. Our analysis showed that APDs had very good quantum efficiency, and they are fairly inexpensive, costing around $500 each. However, again, since we needed so many APDs to get the required coverage, the cost became astronomical to use them.

E. Geometry

At this point, we had exhausted all available options using our current geometric configuration. Our initial configuration placed photodetectors on either side of the scintillator block as shown below.

FIG 3. The first ge
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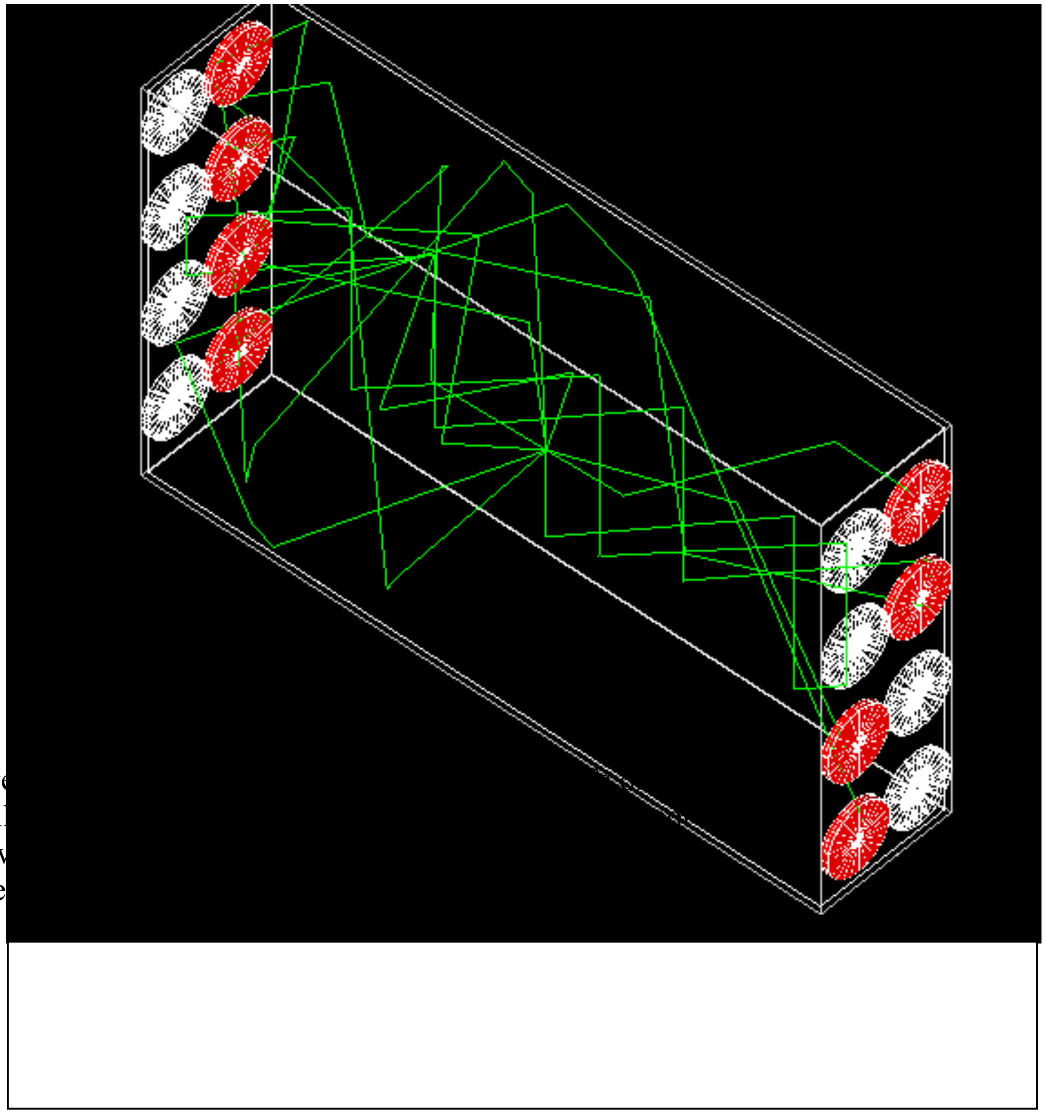

This geometry works excellently for just detecting photons, but it requires so much coverage, that all our options were too expensive. As an alternative, we analyzed a "split" geometry that removed all photodetectors from one side and replaced them with a reflective surface. We hoped that the photons would bounce off of the reflective surface and eventually to the detectors on the other side of the scintillator block. The new geometry is shown below.

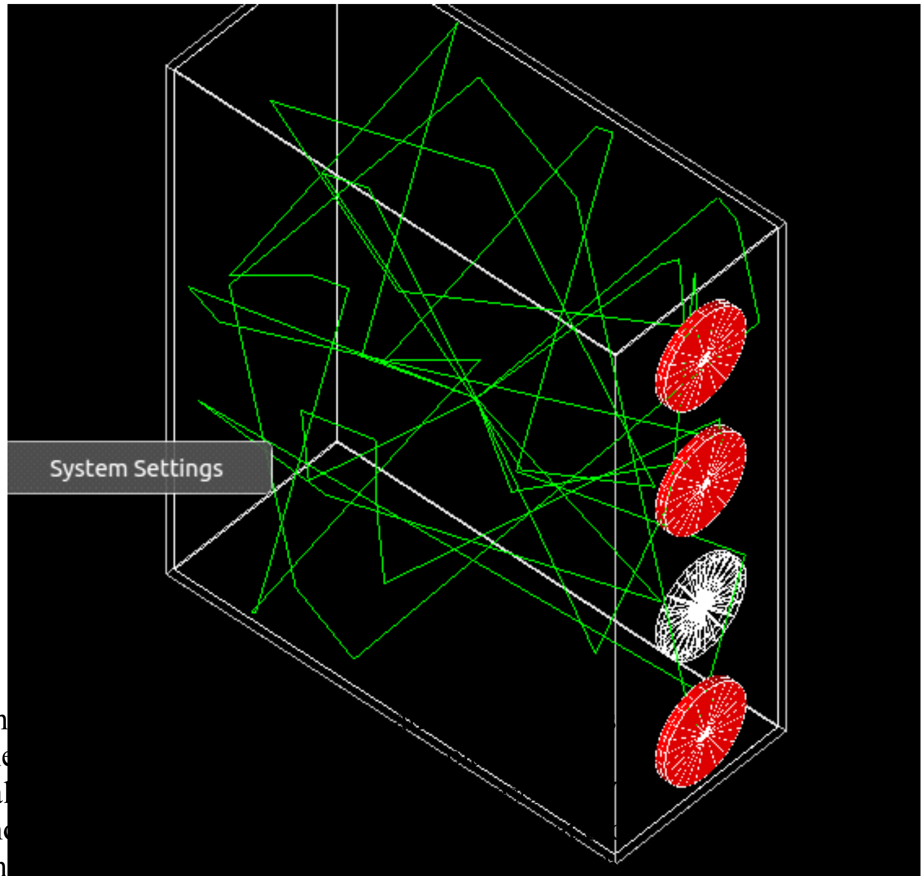

FIG. 4. The secon
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reflective material
that detected a ph
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photons.

Analysis of the new geometry revealed that it was nearly as effective as the old model. Not surprisingly, we lost some sensitivity, but not enough to be of undue concern. This new geometry cut the veto costs significantly, but was still beyond the CDMS budget. Running out of ideas, we visited the retired DØ experiment, and noticed that they had embedded wavelength shifting fibers into their plastic scintillator to collect the photons generated in the scintillator and feed them to a single PMT. In this way, they were able to greatly expand the coverage of each individual PMT at a minimal cost. (Wavelength shifting fibers are very cheap.) We decided to explore this idea for CDMS.

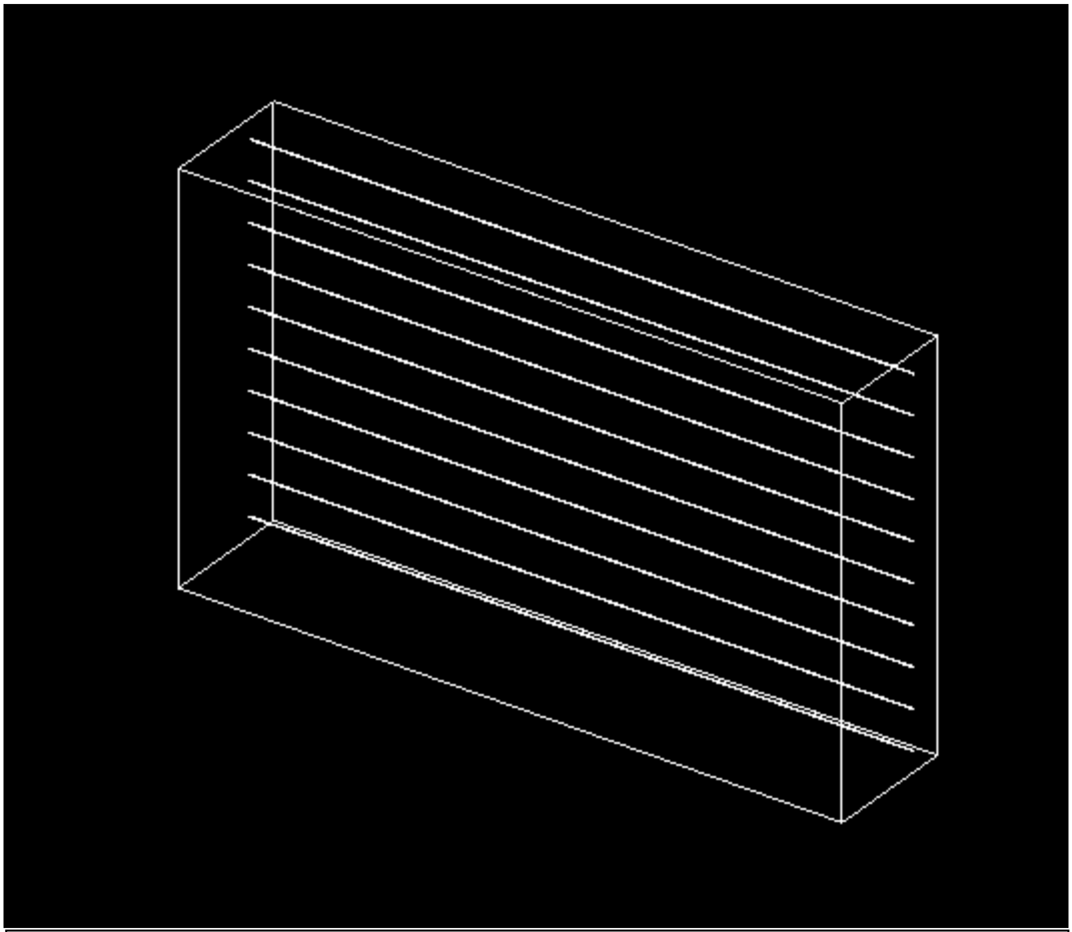
F. Wavelength Shifting Fibers

Our first concern was the difference in scintillators between the two experiments. In DØ they used a plastic scintillator, which is quite harmless, but our boron-loaded scintillator is in liquid form and could ruin the sensitive fibers when they were immersed in it. After some research, we found that the fibers would indeed be ruined by the scintillator should they come in contact, but the fibers' sides were protected by an acrylic coating, making only the ends vulnerable. So, if we were careful and secured the ends of the fibers before adding the scintillator, the fibers would be fine.

Next, we analyzed the sensitivity and efficiency of the fibers; if they could not capture enough light, they would be useless. We set up a Geant4 simulation with the scintillator block and fibers, and shot neutrons through it. We then measured the number of photons generated in the scintillator and compared it to the number of photons captured in the fibers to measure their efficiency as a percentage. In our initial test, we used only 10 fibers, and found the efficiency to be quite low — only about 8%; this was much too small to be useful on its own, but by increasing the number of fibers in the scintillator, we hoped to increase the efficiency as well.

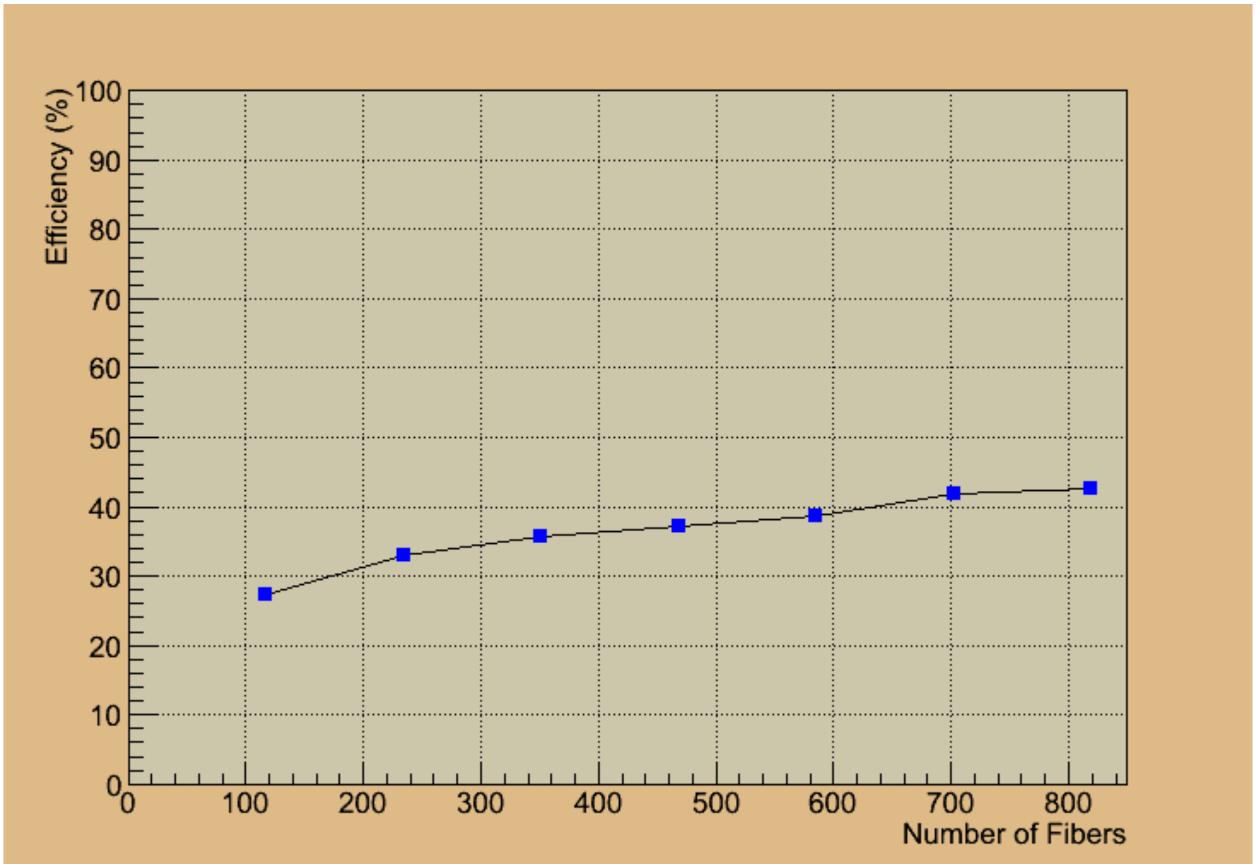
Each fiber had a diameter of 1 mm while the block had a width of 117 cm; so 10 fibers barely took up any volume in the block. In our next simulation, we used 117 fibers, which would cover 1/10 of the width of the block. We placed the fibers in the center of the scintillator block along a line that bisected the block into two halves. The configuration is shown below.

FIG. 5. The geometric configuration of the wavelength shifting fibers in the scintillator block: as we increased the number of fibers, we placed them symmetrically spaced along the same line depicted here.



So, even when using 117 fibers, only a small portion of the block's volume would be filled with fibers. Comparing the number of photons generated by the scintillator to the number captured by the fibers, we found that the efficiency increased to 27.4%. This efficiency was still too small, but it gave us hope that greater numbers of fibers might be viable. We continued increasing the number of fibers up to 6/10 of the width of the scintillator block. The corresponding efficiencies are plotted below.

6. This graph charts the light capturing efficiency of increasing numbers of wavelength
ng fibers. As one can see, the greater the number of fibers, the higher the photon capture



As one can see, the efficiency increases steadily up to 43% with 819 fibers. Finally, using these efficiencies, we calculated the number of photons that the APD would see if a 40 keV neutron crashed into our experiment. A very conservative estimate predicted that 1–3 photons would reach the APD using 300 fibers. This number is still somewhat small, but naturally, increasing the number of fibers would increase the number of photons that reach the APD.

IV. CONCLUSION

In conclusion, we found that water is an effective and inexpensive alternative to polyethylene in the passive shielding. Blocks of water, then, will probably be used in the

SuperCDMS experiment in place of polyethylene. We also found that a neutron veto can be installed in SuperCDMS while remaining within the budget if we use large numbers of wavelength shifting fibers, and small numbers of APDs. These two techniques will allow SuperCDMS to eliminate much of its neutron background, thus giving us much better data.

V. FUTURE WORK

One particular weakness of the work we performed was that it was all simulations. We were unable to perform any physical experiments to confirm our simulation results. In the future, a physical test of the efficiency of the wavelength shifting fibers would be of great benefit, especially since various figures must be approximated or left out when running a simulation.

VI. ACKNOWLEDGEMENTS

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