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Program and Term
Mathematical Physics 2B

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Brian McNamara, Department Chair
Physics and Astronomy,
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200 University Ave West
Waterloo, ON, N2L 3G1

Dear Professor McNamara,

This report, titled "Shielding Design for Ar2D2: An Argon-39 Detector", was prepared after my 2B term in Mathematical Physics, and was my first work term report for SNOLAB. The purpose of this report is to attempt to verify the shielding design for an Argon-39 detector using GEANT4 simulations.

SNOLAB is an organization that is located 2 km underground, and has the main goal of detecting subatomic particles such as neutrinos, and also searches for other dark matter candidates. My job at this organization was to add functionality to their simulation of an Argon-39 detector. I am in the DEAP/Liquid Argon group, and my supervisor is Szymon Manecki.

I would like to thank my supervisor, Szymon Manecki, for providing inspiration, encouragement, and direction to write this report, and constantly answering any questions I had. I would also like to thank the liquid argon group for their support. I have read over and formatted this report. This report was written entirely by me and has not received any previous academic credit at this or any other institution.

Sincerely,
Ruhi Shah
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1 Summary

Liquid argon is largely used in dark matter experiments. A significant impurity that exists in this liquid argon is Argon-39. This substance undergoes beta decay and releases an electron that is within the energy range of interest of dark matter particles. Ar2D2 will be a detector that detects the amount of Argon-39 in liquid argon. In this report, a proposed shielding design required for such a detector is evaluated. All impurities within and outside the shielding are simulated. The goal is to obtain only 1 event/day in the range of interest from backgrounds related to shielding. The results show that this particular design gives 300 events/day. The geometry is then adjusted to bring the number down to 150 events/day. Finally, the activities of the materials are adjusted such that this number can be further reduced to 1 event/day. However, since materials with such low activities do not exist, it may not be possible to create a detector with this particular shielding design.

2 Introduction

Liquid argon is used in detectors such as DEAP-3600 (P.-A. Amaudruz et al, 2019) to detect dark matter particles. It is expected that these dark matter particles will be found in the $0-100$ keV window. The greatest impurity, and hence the biggest issue for dark matter detection, is the Argon-39 that exists inside the liquid argon. This is because the Argon-39 will undergo beta decay often, and a significant amount of this decay will fall into the $0-100$ keV region (J. Xu et al, 2012).

However, some underground sources of Argon allow for a really small percentage of Argon-39 to be present in the Argon (J. Xu et al, 2012). The goal of Ar2D2 is to detect this small percentage of Argon-39, and hence needs to be very sensitive in low energy regions. This means the detector needs to be shielded intensely from all background events. These events can come from both the environment, and the shielding that makes up the detector.

In order to shield from the gammas in the environment, we place a large block of lead. However, this lead has impurities of its own emanating from its volume, so we place a smaller layer of lower background lead. However, this lead still has impurities in it, so we finally add a layer of clean copper. Hence, there are four sources of impurities that can reach the detector: the environment, the lead, the lower background lead, and the copper.

2.1 Geometry

A proposed geometry for the detector is shown in Figure 1. Lead is used because of its high z-number and ability to shield from gammas. Copper is used because of its relatively high z-number and because sources of incredibly clean copper can be found.

The dimensions and density of each layer are described in Table 1.

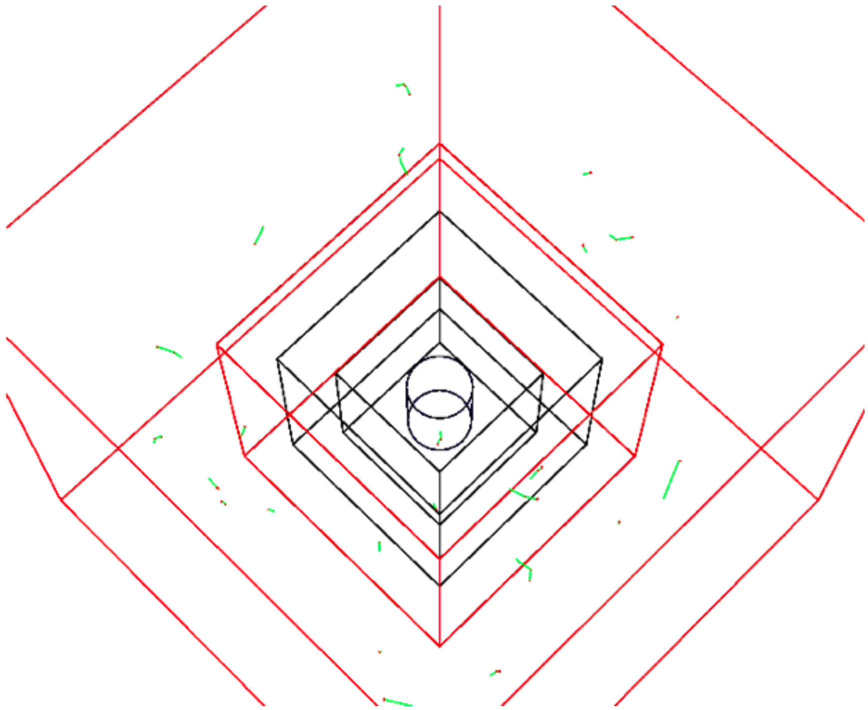


Figure 1: A diagram showing the geometry of the detector. The red outlines the outer lead, the layer inside is the low background lead, followed by a layer of copper, a layer of vacuum, and finally a cylinder filled with liquid argon.

2.2 Calculating the Target Event Rate

In order to calculate exactly how many events we are allowed to have from the impurities, we use the fact that the activity of the Argon-39 is on the order of 10^{-5} Bq/kg (J. Xu et al, 2012). In order to calculate the number of events emanating from a source, we require the activity, the mass, and the time.

$$e = a * m * t \tag{1}$$

In the equation (1), e is the number of events we wish to calculate for a particular mass and time; a is the activity in Bq/kg, m is the mass in kg, and t is the time in seconds.

For one day, there are $60 * 60 * 24 = 86400$ seconds. We can assume that we have 1 kg of argon. Therefore, the number of events from the Argon-39 beta decay will be $10^{-5} * 86400 * 1 = 0.864$. Hence, there will be approximately 1 event/day in the detector from Argon-39 beta decay. This

Source	Material	Shape	Width/Depth (cm)	Height (cm)	Density (g/cm^3)
-	Liquid Argon	Cylinder	8.5	12.6	1.39
-	Vacuum	Box	18.5	22.6	0
1	Copper	Box	28.5	32.6	8.96
2	Low-background Lead	Box	38.5	42.6	11.34
3	Lead	Box	79.14	83.24	11.34
4	Surroundings	Spherical surface	83.24	83.24	-

Table 1: A table showing the dimensions of the detector

decay will happen somewhere in the region from 0-600 keV.

In order to be able to differentiate the background events from the Argon-39 events, we need to ensure that they exist in at least a one-to-one ratio. That is, the number of events from Argon-39 beta decay should equal to the number of events from the shielding. Therefore, the ultimate goal for this detector is to achieve a rate of 1 count/day in the 0 – 600 keV region from the external gammas, the lead, the low background lead, and the copper.

3 Implementing the Simulation

The main code for the simulation exists in the Ar2D2 GitHub repository (T. Sonely, 2020). This simulation was written using GEANT4, a Monte-Carlo simulation software. Processing, running, and storage for the simulation was given by the Nearline computing cluster for SNOLAB. Analysis of the resulting data was done using ROOT.

The GEANT4 simulation is able to create a finite number of mono-energetic events evenly (spherically) distributed within the source material. It is also capable of simulating a spectrum of beta decay evenly (spherically) within the source material.

3.1 Simulating Impurities in Materials

In order to simulate each material appropriately, the impurities in each material need to be found. Equation 1 is used again in order to calculate the number of events for a given activity. The type of impurities and their corresponding activities for any given material were taken from the gamma assays done at SNOLAB (SNOLAB, 2020). The material used for the outer lead was the SNOLAB 51 Lead Shield, the inner lead was the SNO+ 1 Lead, and the copper was SNOLAB 68 Copper. Table 2 shows an example of the impurities present inside copper.

Impurity	Activity (mBq/kg)
238U from 226Ra	< 0.0043
238U from 234Th	< 0.47
235U	< 0.015
232Th	< 0.0068
40K	< 0.160
137Cs	< 0.0113
60Co	< 0.0039

Table 2: A table showing the impurities in copper. Taken from the SNOLAB gamma assays website.

Now, given an activity we can obtain the total number of events that we need to simulate for a source over some period of time. However, each of these sources decays into multiple energies. Since the simulation is capable of simulating only one energy at a time (mono-energetic), we need to figure out how many events correspond to each energy in the spectrum of the given impurity.

For example, from Table 2, copper has a significant amount of U-238 from Th-234 within it. The presence of U-238 results in a long sequence of gamma decays. Each of these decays will have individual energies of gammas that are released from them. The branching percentages of each of these decays and their corresponding energies can also be found using gamma assays done at SNOLAB (T. Sonely, 2018). Once we have all the energies released from each impurity, and their corresponding percentage of abundance, we can multiply the total number of events from the activity obtained using equation one by the percentage to get the number of events resulting from each energy. After this, the simulation is able to simulate the specified number of events for each energy, and ultimately return the number of events that made it to the sensitive liquid argon volume.

A special note should be made regarding impurities from external gammas. These are simulated from a surface, and hence Equation 1 needs to be modified slightly.

$$e = f * A * t \quad (2)$$

Here, e is the number of events simulated for a given time, area, and flux; the flux f is the number of events that occur through a surface per cm^2 per second, the area A is the area of the surface that we are simulating, and the time t is the duration of the simulation.

Activity and branching percentage data for all sources can be found in the appendix.

4 Results

4.1 Gammas from the Environment

The events from the gammas were simulated both with and without shielding to see the effect of the shielding. Figure 2 shows the number of gammas deposited in the liquid argon with and without shielding. Without the shielding, when run for five minutes, there are 14392 events that end up in the liquid argon. With the shielding, when run for 6 hours, none of the events make it through. Hence, the externals are effectively shielded, and do not pose a major concern.

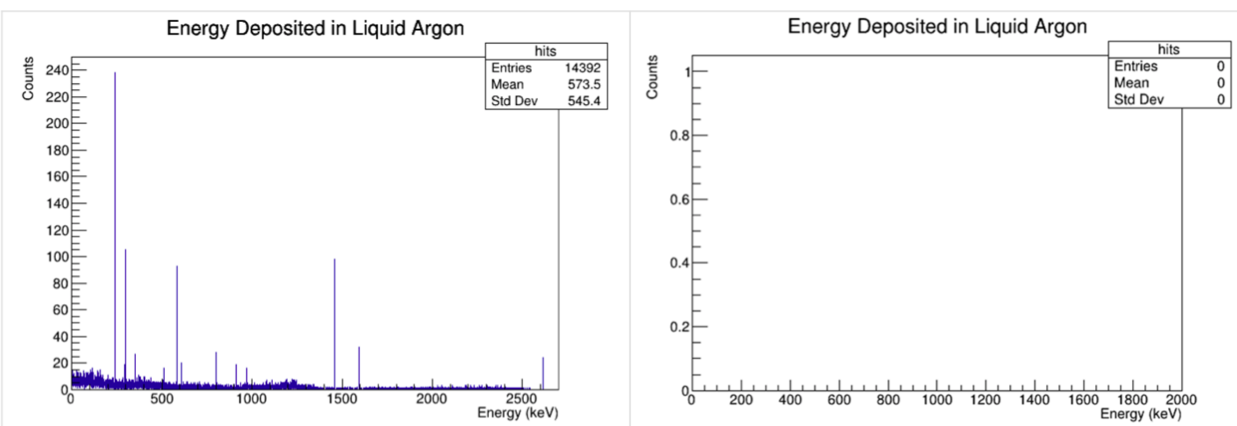


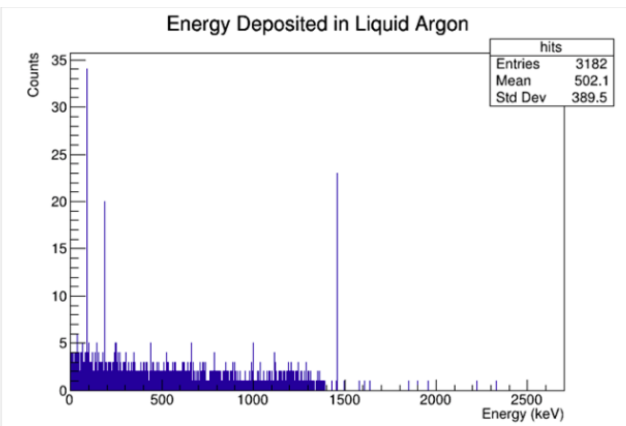
Figure 2: Histograms showing the number of events from the external gamma backgrounds that are deposited in the liquid argon without any shielding for five minutes (left), and with shielding implemented for 6 hours (right).

4.2 Gammas from the Shielding

The events from the shielding materials were also simulated both with and without the inner layers of shielding.

4.2.1 Lead

Figure 3 shows the number of gammas deposited in the liquid argon with the low-background lead and copper, and without the low-background lead and copper. Without the inner shielding, for 1 day, there are 3182 events that end up in the liquid argon. With the shielding, for 1 day, 27 events make it through. Since our ideal budget is 1 event / day, we have a significant number of events from the gammas in the lead that make it to the sensitive volume.



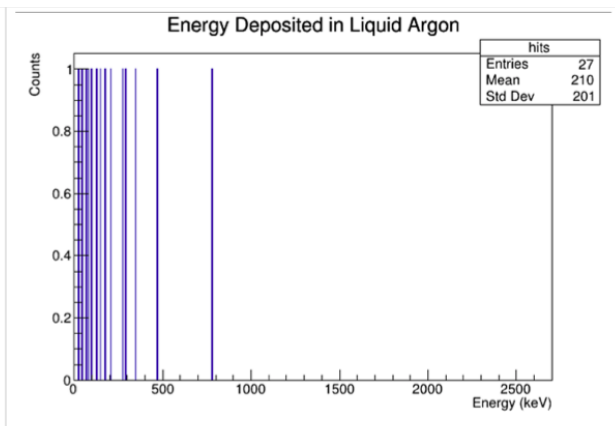


Figure 3: Histograms showing the number of events from gamma backgrounds in the outer lead that are deposited in the liquid argon without any inner lead and copper shielding for 1 day (left), and with all shielding for 1 day (right).

4.2.2 Low-background Lead

Figure 4 shows the number of gammas deposited in the liquid argon with and without the copper. Without the copper, for 1 day, there are 845 events that end up in the liquid argon. With the copper, for 1 day, 227 events make it through. Hence, we have an incredibly significant number of events from the gammas in the low-background lead that make it to the sensitive volume. The copper is not able to reduce the number of gammas as well as expected.

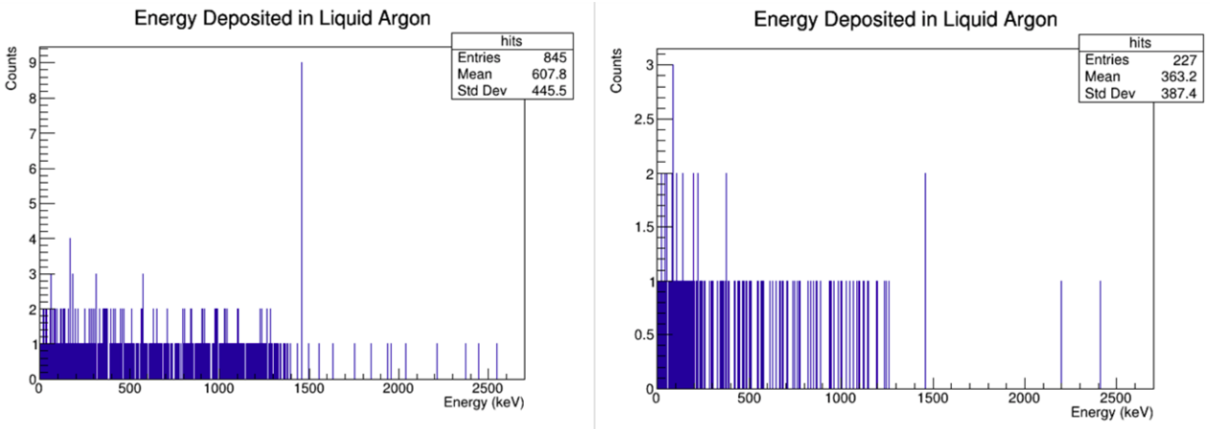


Figure 4: Histograms showing the number of events from gamma backgrounds in the inner lead that are deposited in the liquid argon without any copper shielding for 1 day (left), and with all shielding for 1 day (right).

4.2.3 Copper

Figure 5 shows the number of gammas deposited in the liquid argon originating from the copper. 65 events make it through. Hence, we have an incredibly significant number of events from the gammas in the copper as well that make it to the sensitive volume. The copper is not as clean as expected.

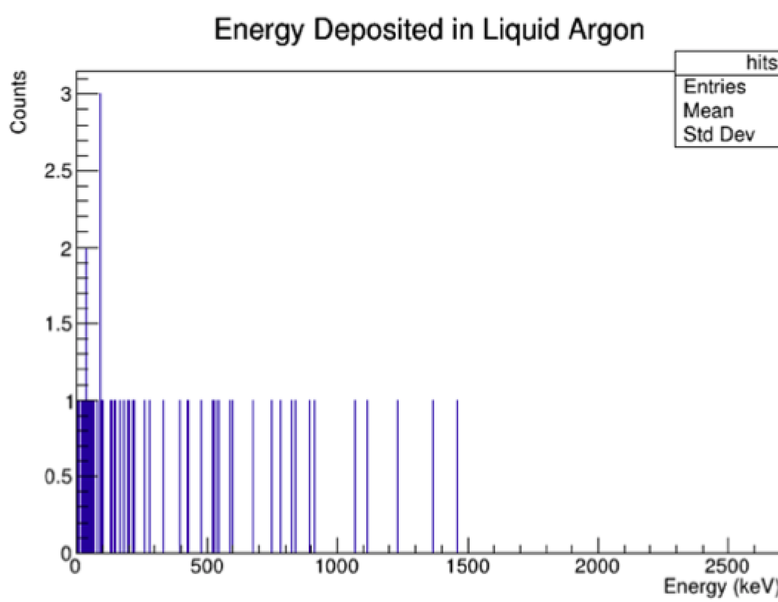


Figure 5: Histograms showing the number of events from gamma backgrounds in the copper that are deposited in the liquid argon with all shielding for 1 day.

4.3 Pb-210 Beta Decay

The lead is also made impure by Pb-210 beta decay that occurs in the larger volume. Although none of the Pb-210 beta decay events from the outer layer of lead make it through, Pb-210 beta decay does affect the inner layer of lead significantly. We assume there is 3 Bq/kg of Pb-210 in the inner lead. Figures 6 and 7 show the number of events that make it through over 156 hours. The number of events per day are then 49. Hence, the beta decay also adds a significant number of events to our budget.

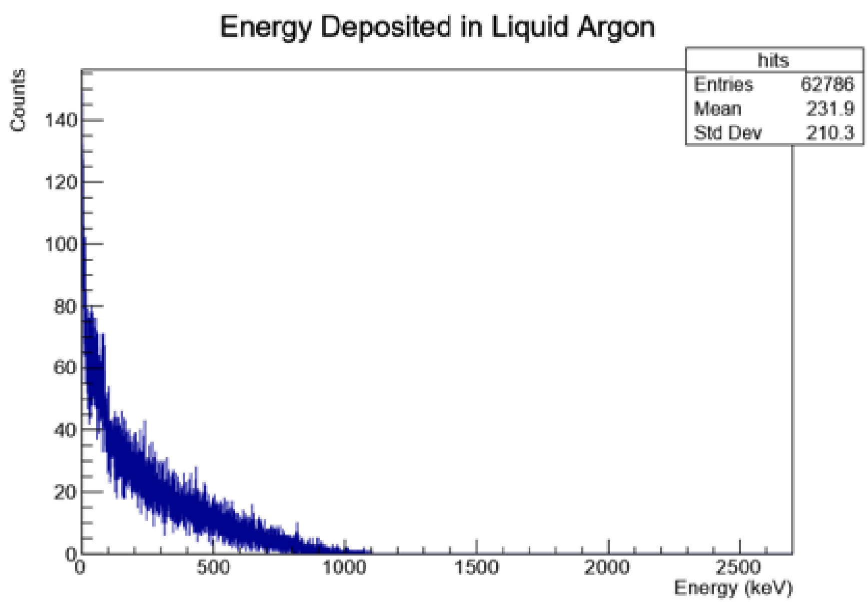


Figure 6: A histogram showing the number of Bremsstrahlunged gammas in the low-background lead that are deposited in the liquid argon with no copper shielding for 156 hours.

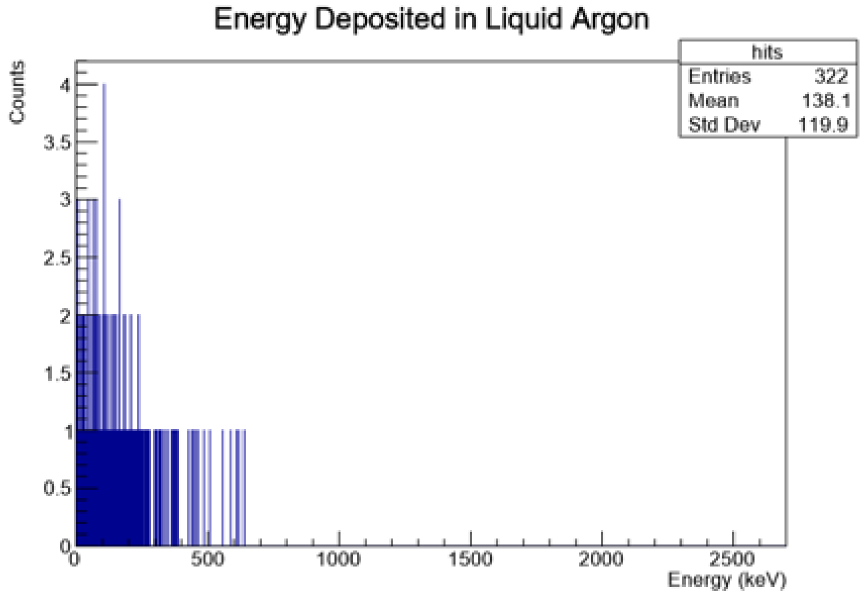


Figure 7: A histogram showing the number of Bremsstrahlunged gammas in the low-background lead that are deposited in the liquid argon with copper shielding for 156 hours.

4.4 Adjusting Thickness of Copper

Since the low-background lead is the largest contribution towards the events deposited in the shielding, the thickness of copper is adjusted to see the effect. Increasing the thickness of the copper by 5 cm reduces the gammas from the low-background lead from 185 to 78. This is still significant, but not nearly enough. Table 3 shows the number of events deposited before and after the thickness of the copper is increased.

Source	Events/day in ROI	Events/day in ROI with 15 cm of copper
External Gammas	0	0
Outer Lead Gammas	22	0
Inner Lead Gammas	185	78
Inner Lead Betas	49	4
Copper Gammas	55	64

Table 3: A table showing the effect of increasing the thickness of the copper by 5 cm.

4.5 Adjusting Activities

After increasing the thickness of the copper, we still have not reached our goal of 1 event / day outlined in Section 2.2. Hence, we now reduce the activities of the materials until we reach the desired 1 event / day.

In order to do this, we figure out the ratio of events simulated in source to deposited in the crystal for each particular energy. From Equation 1, when changing the activity of a source, we are essentially only changing the number of events simulated. Hence, we work backwards. We can now adjust the activity, figure out the new number of events simulated, and then find the number of events deposited using the ratio by multiplying.

The activities were then adjusted in order to obtain the desired 1 event / day. Table blah blah shows the ratio between the original detected activity, and the desired activity, and the resulting total number of events from each material. It can be seen that some of the activities need to be adjusted up to an order of magnitude of 3. However, since it may not be possible to obtain materials this clean, the design of Ar2D2 may need to be redone.

Source	Decay Chain	Initial Activity / Required Activity	Total Events/day in ROI
Copper	238U from 226Ra	100	0.533
	235U from 234Th	100	
	232Th	100	
	40K	1000	
	137 Cs	100	
	60 Co	10	
Inner Lead	238U from 226Ra	100	0.249
	232Th	100	
	40K	1000	
	Pb210	100	
Lead	238U from 234Th	10	0.18
	40K	100	
Total Events per Day			0.962

Table 4: A table showing the magnitude of activities decreased and the results of doing so.

5 Conclusion and Discussion

The proposed design for Ar2D2 still needs improvement. With the current design, gammas in the copper and low-background lead easily make it through to the sensitive volume. This report showcased that the cleanest available materials still need to be further cleaned by a nearly impossible amount in order to reduce the events caused by the shielding. In the future the design of Ar2D2 needs to be reconsidered.

Furthermore, the only investigations done in this report was of the shielding around the sensitive liquid argon volume. However, there will be multiple sources of gamma, beta, and alpha radiation coming from the inner detector, which is all the instrumentation that actually holds the liquid argon. All of this will make it directly into the liquid argon, since there is no shielding to stop it. The events from the inner detector will make up a significant amount of the budget as well.

Therefore, in the future, both the shielding design for Ar2D2, and the inner detector components need to be implemented for an accurate and complete picture of what we will be able to detect.

6 References

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