XENON100 Detector Upgrade: Gamma Backgrounds

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Research and development of the XENON100 Detector Upgrade is motivated by the search for Weakly Interacting Massive Particles (WIMPs). The purpose of this upgrade is to lower the overall background significantly and to double the fiducial volume while increasing the fiducial to total volume ratio in order to increase the efficiency of the detector. Monte Carlo simulations using Geant4 were used to simulate gamma ray radiation in detector construction materials. Various fiducial volume cuts were applied in order to minimize overall background levels.

I. INTRODUCTION

Evidence of non-baryonic dark matter which constitutes the majority of our universe calls for physics beyond the standard model [1]. One possible form of dark matter are Weakly Interacting Massive Particles (WIMPs), which can be detected through elastic collisions with ordinary matter. The XENON collaboration has been at the forefront of the search for WIMPs starting with the XENON10 detector with 15kg of xenon at Gran Sasso National Laboratory. This detector demonstrated that nuclear recoil events (from WIMPs and neutrons) can be distinguished from electronic recoil (ER) events (from gamma and beta backgrounds) by the ratio of the direct scintillation signal (S1) to the ionization signal (S2). If dark matter exists in the form of WIMPs, detectors must have extremely low background as WIMP collisions are so rare. The detector was scaled up with a factor of 100 less background and ten times the target mass to create the current XENON100 detector, with a fiducial mass of 50kg. The ultimate goal is to have a one ton detector, currently under development as XENON1T, but more work needs to be done to face the challenges of scaling up the detector such as handling high voltage and long drift lengths while fine tuning the design for ultra low intrinsic background. The XENON100 upgrade will be the next step towards XENON1T with 100kg of fiducial mass and double the drift length. It will also become the testing ground for the low radioactivity Quartz Photon Intensifying Detector (QUPID) currently being developed by Hamamatsu Photonics and Professor Arisaka of UCLA specifically for this application.

II. XENON100 Detector

The XENON100 detector is a position sensitive liquid xenon time projection chamber (TPC). The top array of photomultiplier tubes (PMTs) located in the gaseous xenon reconstruct the X and Y position of the events. The Z position is reconstructed from the drift time and known drift velocity. The bottom array of PMTs in the liquid xenon is essential in collecting the primary scintillation signal (S1). At the top of the TPC, the gas/liquid interface has a high reflectivity thanks to the high refractive index of LXe. Along the sides of the TPC, a PTFE cylinder reflects scintillation signals on the inside and separates the active target volume from the active veto xenon used as shielding. A anode and cathode cap off the TPC at the top and bottom, respectively, and are biased to create the drift field of 1kV/cm with a 30 cm drift length of LXe. Two meshes sandwich the anode at the top and the liquid level is maintained between. A stainless steel bell, which works similarly to a diving bell, keeps the liquid level constant by allowing the flow of gaseous xenon in and out of the enclosed volume under the bell. It also allows the PMTs located inside to be surrounded by veto liquid xenon. The TPC encloses 65kg of xenon, but the volume can be “fiducialized” to include only events in the inner core—where there is less background due to the self-shielding property of xenon.

III. XENON100 UPGRADE PROPOSAL

The upgrade for XENON100 has two main components: scaling up the detector from 50kg fiducial volume to 100kg and reducing the background by two orders of magnitude. The major contributors to the ER background in XENON100 are the PMTs (Figure 1) despite that they are the lowest radioactivity models on the market at this time. The newly developed QUPIDs designed with ultra pure synthetic fused silica (quartz) for low radioactivity will replace some of the PMTs [2]. A hexagonal pattern of 19 QUPIDs covers approximately the same area. Although it is possible to add another ring of QUPIDs, bringing the total to 37, this would nearly double the cost. The high cost of each QUPID limits how many can be used for the detector. It was proposed that only the bottom PMTs be replaced by 19 QUPIDs and that the top PMT array remain unchanged since the 1” PMTs have a better XY position resolution compared to the larger QUPIDs.

The next largest background comes from the stainless steel which makes up the cryostat inner and outer vessel and bell (Figure 1). The radioactivity of the cryostat can be lowered if the steel were replaced by low background oxygen free copper. The thickness of the copper can be increased in order to compensate for its softness and for better mechanical stability. The overall rate should decrease despite a larger cryostat mass because of the lower radioactivity of copper. Although the original proposal described a copper cryostat, copper's high thermal conductivity can make maintaining the liquid xenon at 170K difficult. It is better to keep a steel inner vessel and to only make the outer vessel copper. Also, the thickness of the stainless steel can be lowered to reduce the background rate, but further testing is needed to determine if it is actually possible to reduce the thickness from 1.5mm to 0.1mm.

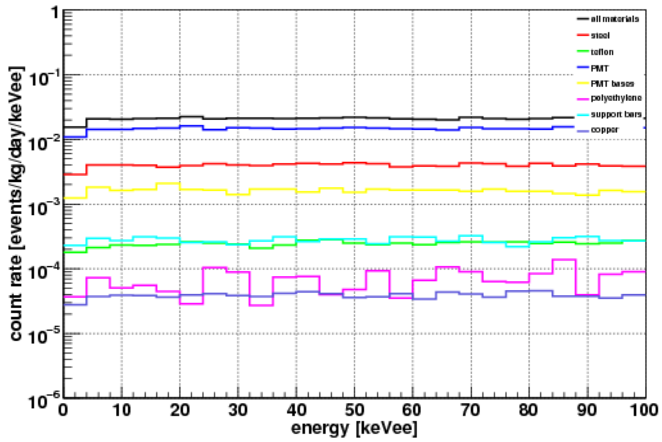

Figure 1. Energy spectrum of simulated gamma background in XENON100 (Alexander Kish), with a 50kg fiducial volume cut.

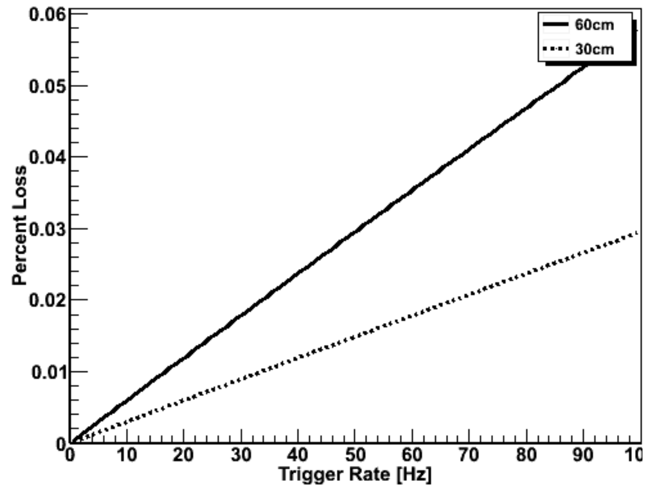

Figure 2. Dead time loss as a function of the true interaction rate for a drift length of 60 cm (Upgrade) and 30 cm (XENON100).

IV. RESULTS AND DISCUSSION

A. Long Drift Lengths and Dead Time Loss

Due to the long experimental run time, events are recorded by triggers instead of being taken continuously. Knoll describes two common models of dead time behavior of counting systems: paralyzable and nonparalyzable response [3]. In the paralyzable case, after each interaction, the detector records for a fixed time, τ. If another interaction occurs, the recording time is extended by another period, τ. The record length is chosen to be twice the time for an electron to drift from the bottom of the detector to the anode. This ensures that both the triggering signal and the second signal are recorded together as a single event. If two or more events occur in one record (which is known as pileup), then one event cannot be distinguished from the other and so this particular record cannot be used for analysis. When designing the new detector, the longer drift length may make the dead time loss unacceptably high. Knoll derives the following relationship between the true interaction rate, n, and the recorded count rate, m:

$$m = ne^{-n\tau}$$

Thus the percent of interactions lost due to dead time is:

$$\text{Loss} = 1 - e^{-n\tau}$$

To estimate the dead time loss due to pileup, the true interaction rate must be known. The interactions with the xenon detector will be the ER and NR backgrounds and WIMP events. The background event rate can be estimated from Monte Carlo simulations (See Section C.) For XENON100, the trigger rate was less than 1 Hz. The trigger rate for the upgrade has been estimated from simulations (only for the ER background from steel, copper, teflon, and top PMTs) to be 0.03 Hz. Even if the trigger rate increases by a few orders of magnitude, the dead time loss remains below 6% (Figure 2).

B. Geant4 and Detector Geometry

The Monte Carlo simulations for ER backgrounds were simulated using GEANT4. The code used for the XENON100 detector was edited for the upgraded detector by changing the geometry parameters. Currently, only the most basic parts of the detector have been included in the construction of the detector geometry code (Figure 12).

1) Cryostat vessel (steel and copper)
2) Bell (steel)
3) Hexagonal panel to enclose the TPC (Teflon)
4) Top PMTs

These are the major contributors to the ER background but eventually all the parts, such as the grid meshes, anode, and cathode, have yet to be added to the simulation. The QUPIDs have not yet been included in the Geant4 code, but the rest of the detector design is highly dependent on them. The radial dimensions are fixed by the 19 QUPID hexagonal arrangement such that the Teflon reflective panel tightly encloses them. If otherwise, too much space between the QUPIDs would lower the light collection efficiency. In order to double the fiducial volume, the height of TPC would have to be doubled, thus creating a 60cm drift length. As mentioned previously, the outer shell of the cryostat was changed from steel to low radioactivity copper and the steel thickness was thinned from 1.5mm to 0.1mm to lower the mass. Since copper is a softer metal than steel, the thickness of the outer cryostat shell—now copper instead of steel—was quadrupled to make up for mechanical stability.

C. ER Backgrounds

The gamma rays from radioactive decay chains of ^{238}U, ^{232}Th, ^{40}K, and ^{60}Co in the detector materials and shield make up most of the ER background. The radioactivity of these materials used in XENON100 were measured with a dedicated Ge detector in LNGS [2]. and construction materials were selected to minimize radioactivity. These results were used in the Geant4 simulations to predict the radioactivity of the detector upgrade. Each material and decay chain was simulated separately. The four decay chains were summed up as the total radioactivity of the material. Since the design of the new detector is based on the XENON100 detector's geometry, we expect the rates to scale proportionally with the mass of the materials. As a simulation check, the background rates were simulated with the new geometries but scaled appropriately for comparison with the results for XENON100. They agree with our prediction.

The raw simulation results have to be adjusted to account for detector resolution. Scatter events that occur less than 3mm apart would not be distinguishable in XENON100, thus it would be considered a single scatter event. WIMP events should only occur in the low energy range so it is fair to cut out multiple scatter events. Single scatter events in the TPC can be easily distinguished due to the high efficiency of the PMTs there. However, for the veto region, where the PMT efficiency is much lower and the number of PMTs is few, only events that deposit enough energy to be seen can be cut out as multiple scatter events.

After these appropriate cuts have been made, an additional 100kg fiducial volume cut must be applied to see if we can reach the target background levels in the upgrade proposal (Table 1) with our current geometry.

D. 100kg Fiducial Volume Cut

XY and XZ plots of event distributions have been made for each individual material and for the sum of all materials to determine whether a radial or a height cut will be more efficient in removing background events (Figures 3-11 and 13). These have been scaled by the level of radioactivity for that material. For stainless steel in the cryostat vessel and bell, the distribution of events was mostly uniform along the XY plane but slightly higher at the edge of the hexagon. The distribution along the Z-axis was top heavy since the majority of the mass (16kg out of the 20kg) came from the flange located at the top of the cryostat. Similarly for the PMTs, most of the background was located at the top of the TPC as that is the region closest to the PMTs located right above Z=0 (Figure 6). For the Teflon panel, the background was uniform along Z but strongly decreased with distance from the panel (Figure 8). Several types of hexagonal prism fiducial volume cuts were applied to observe the differences in background rates with cuts from the top and cuts from the radius. For all cuts, the bottom of the fiducial volume cut was at z = -550mm, the location of the bottom of the Teflon and thus the bottom limit of the TPC. The results in Table 1 follow the patterns observed in the event distribution plots. As the fiducial volume cut becomes less tall and more wide, the PMT and steel background generally decreased. The Teflon slowly increased at first but then the background levels exponentially increased as the cuts include volume very close to the Teflon walls. The copper background rates remained mostly unchanged with various cuts.

The results are fairly promising, as one cut yielded background levels below those for the proposal for each individual material. However, the relatively high and top-heavy background rate from steel prompted a change in the detector construction to reduce this background source. In the first simulation, the amount of xenon was oversimplified (Figure 12). The liquid level below the bell was at the same level as the veto liquid outside the bell. This was not the case for XENON100, where the liquid level inside the bell was further below to take advantage of a top active veto. The Geant4 code was edited again to include this top xenon veto above the bell so that liquid xenon fills the entirety of the inner cryostat vessel (Figure 14). The background that originates from above the bell should be reduced due to the veto shielding. The steel contribution should be noticeably lowered as it is already top heavy due to the flange. Copper, for the same reason, should be lowered but to a lesser extent since it is not top heavy.

The fiducial volume cuts were repeated again with this second simulation and the results are summarized in Table 2. As predicted, the steel contribution was lowered from before. The copper background levels were also lowered slightly. Two veto energy cuts (50 and 100 keVee) were applied and there was not a significant change in background levels between the two. The individual material background levels remain mostly the same for the two veto energy cuts except for steel. This may be because the majority of the veto energy originated from the radioactivity of the steel flange. The same analysis should be done with the simulation without the top LXe veto to confirm this explanation but time was limited and there was not opportunity to do so.

ER Background in low energy region [1e-3 dru]											
	Xenon100	Proposal	Different Fiducial Volume Cuts with ns=1 and etotv<100								
PMTs and bases	4.910	0.098	0.149	0.137	0.092	0.065	0.056	0.056	0.056	0.056	0.044
Stainless steel	<2.01	<0.052	0.099	0.090	0.090	0.074	0.074	0.049	0.049	0.057	0.073
PTFE	<0.18	<0.017	0.007	0.009	0.010	0.010	0.010	0.013	0.029	0.076	9.986
Copper cryostat	-	<0.033	0.011	0.011	0.011	0.011	0.011	0.012	0.012	0.012	0.016
Sum	6.94	0.200	0.266	0.247	0.203	0.161	0.152	0.130	0.146	0.202	10.120
		ztop [mm]	100	120	140	150	160	170	180	190	20.6
		t. radius [mm]	148.5	152	156	157.5	159.5	161.7	164	166	170

Table 1. Simulated (with no top LXe veto) background rates for XENON100 upgrade construction materials with various fiducial volume cuts with a single scatter cut and veto energy cut of less than 100 keVee. These are taken to be the maximum rates in events/day/kg/keVee in the low energy WIMP search (1-100keVee) region. *ztop* is the height cut taken off the top of the liquid level. *t. radius* is the tangential radius of the hexagon.

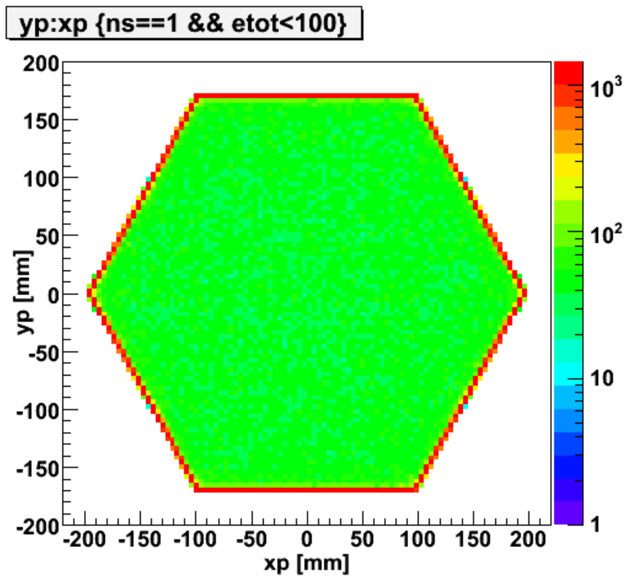

Figure 3. Monte Carlo simulation of events distribution for all materials in the current design of XENON100 upgrade of y position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

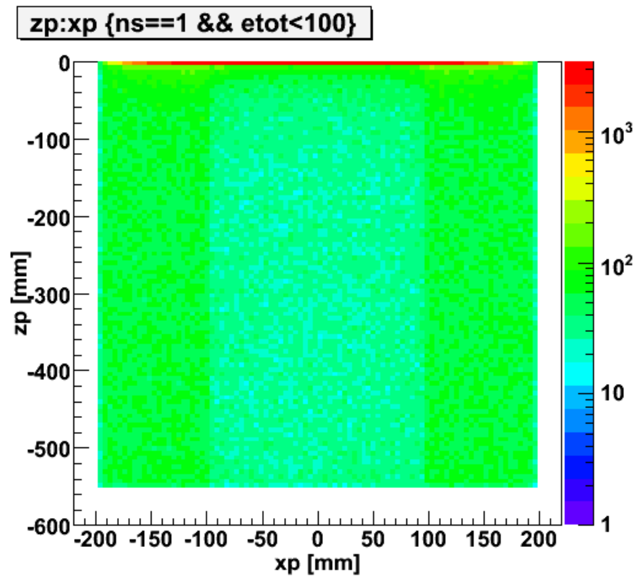

Figure 5. Monte Carlo simulation of events distribution for all materials in the current design of XENON100 upgrade of z position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

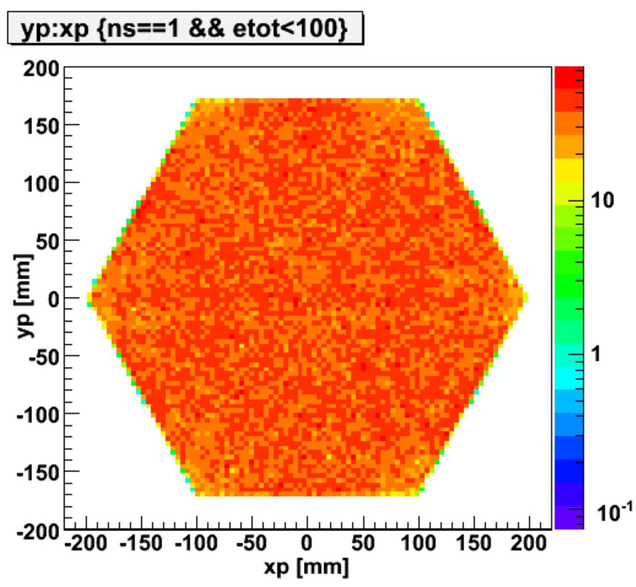

Figure 4. Monte Carlo simulation of events distribution for top PMTs in the current design of XENON100 upgrade of y position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

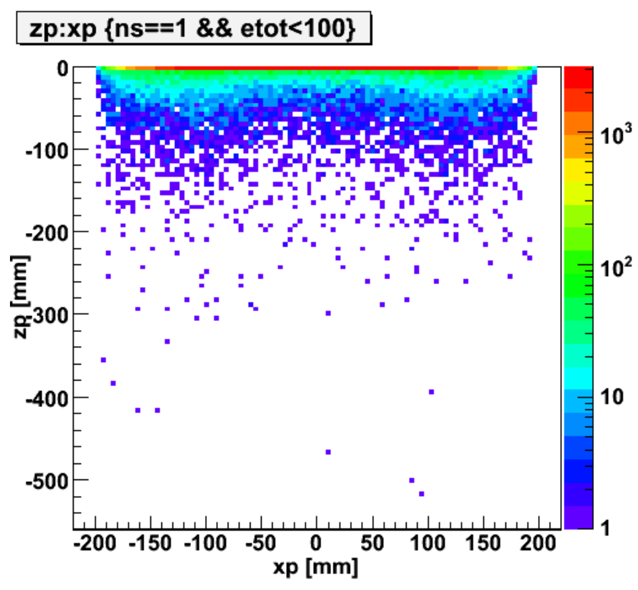

Figure 6. Monte Carlo simulation of events distribution for top PMTs in the current design of XENON100 upgrade of z position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

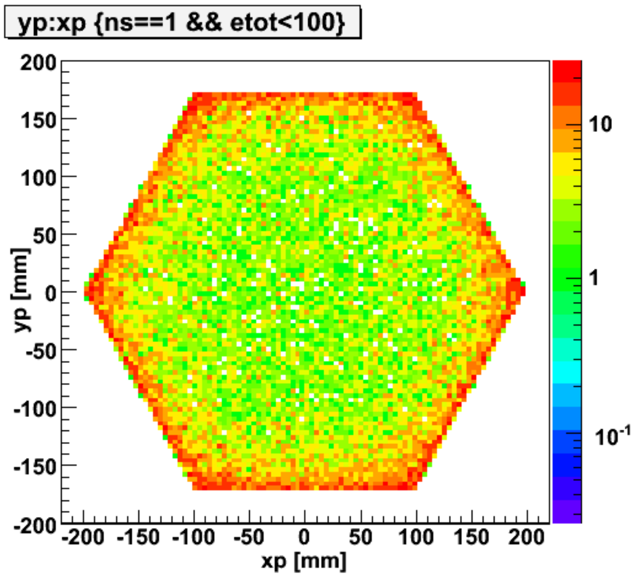

Figure 7. Monte Carlo simulation of events distribution for steel in the current design of XENON100 upgrade of y position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

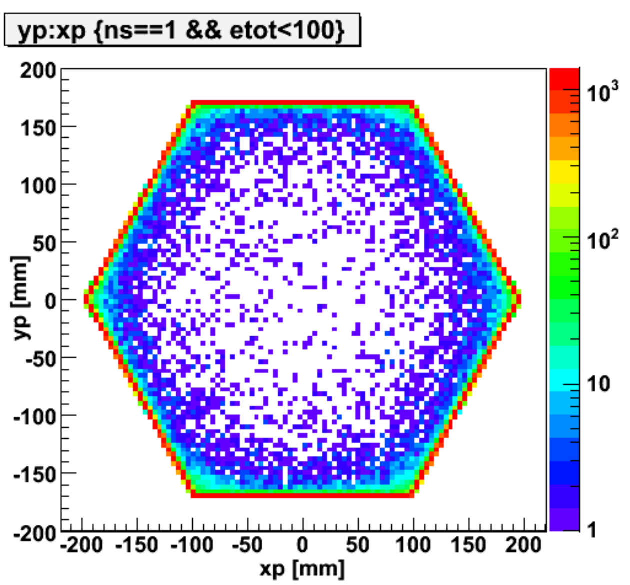

Figure 8. Monte Carlo simulation of events distribution for Teflon in the current design of XENON100 upgrade of y position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

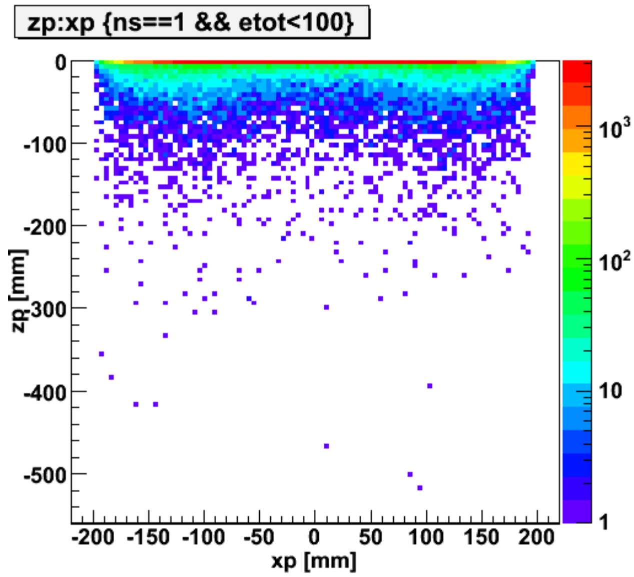

Figure 9. Monte Carlo simulation of events distribution for steel in the current design of XENON100 upgrade of z position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

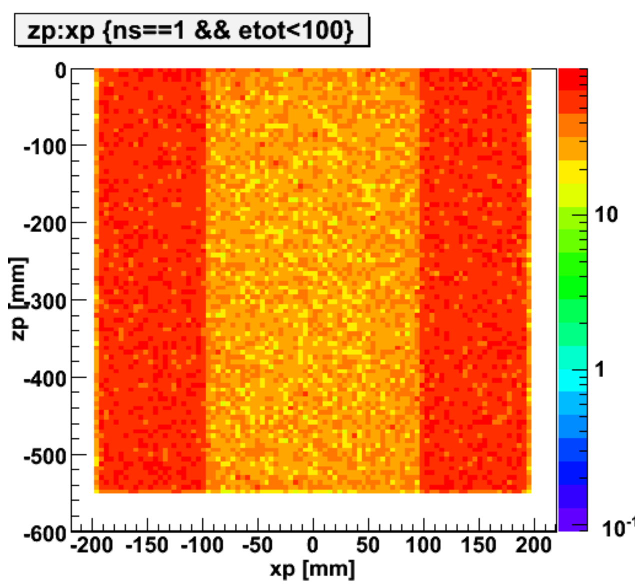

Figure 10. Monte Carlo simulation of events distribution for Teflon in the current design of XENON100 upgrade of z position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

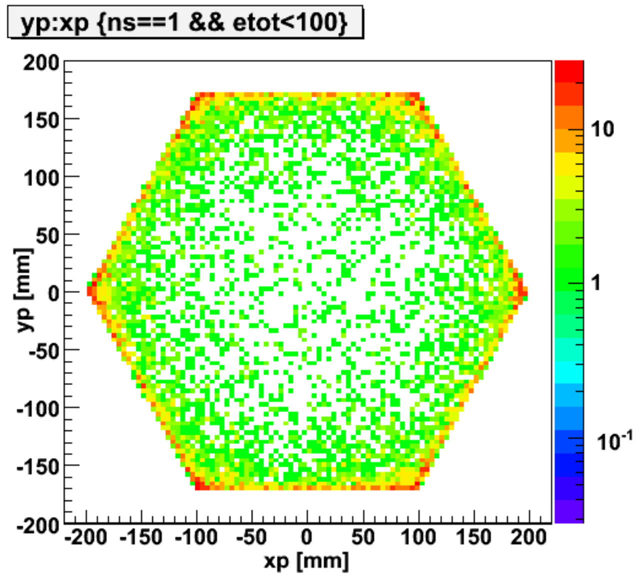

Figure 11. Monte Carlo simulation of events distribution for copper in the current design of XENON100 upgrade of y position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

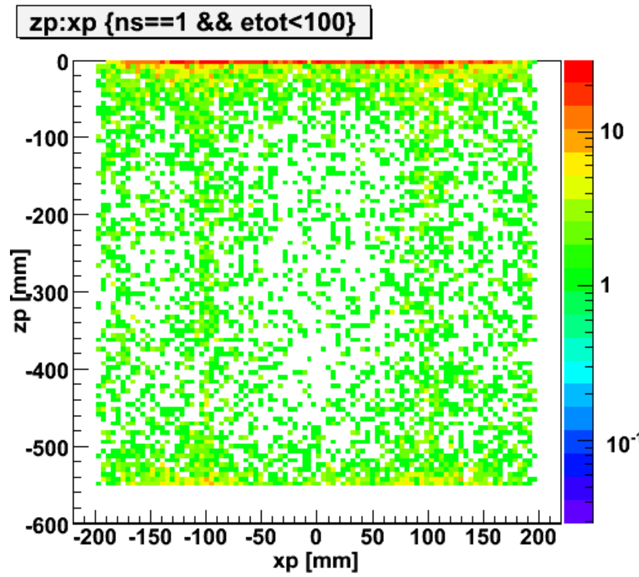

Figure 13. Monte Carlo simulation of events distribution for copper in the current design of XENON100 upgrade of z position vs x position with a target volume cut, single scatter cut, and veto energy less than 100keVee cut.

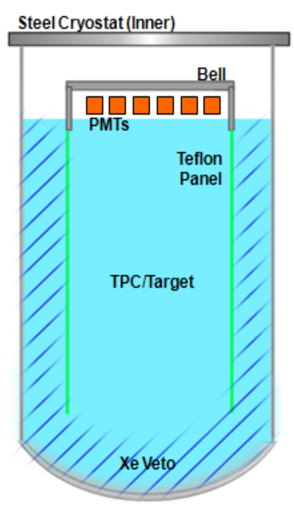

Figure 12. Original detector setup (conceptually) in Monte Carlo simulation, not to scale. Copper outer vessel of the cryostat is not shown, but was included in the simulation.

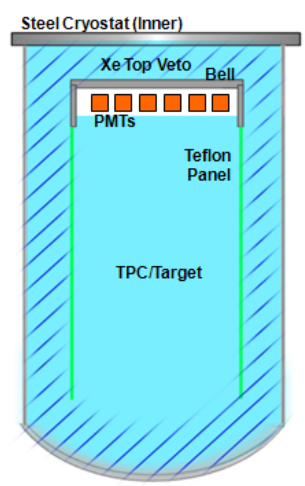

Figure 14. Second detector setup (conceptually) in Monte Carlo simulation, not to scale. Copper outer vessel of the cryostat is not shown, but was included in the simulation. The liquid xenon active veto and xenon gas inside the bell are now included.

ER Background in low energy region [1e-3 dru]

ztop [mm]	100	140	150	170	185	190	206
t. radius [mm]	148.5	156	157.5	161.7	165	166	170
Various 100kg FV Cuts with ns=1, etotv<50							
PMTs and bases	0.173	0.118	0.119	0.118	0.054	0.054	-
Stainless steel	0.033	0.025	0.025	0.033	0.020	0.020	-
PTFE	0.008	0.011	0.011	0.013	0.031	0.072	-
Copper cryostat	0.010	0.010	0.011	0.011	0.007	0.007	-
Sum	0.223	0.164	0.165	0.175	0.112	0.154	-
Various 100kg FV Cuts with ns=1, etotv<100							
PMTs and bases	0.173	0.118	0.119	0.118	0.054	0.054	0.054
Stainless steel	0.041	0.033	0.033	0.033	0.029	0.029	0.037
PTFE	0.008	0.011	0.011	0.013	0.039	0.075	10.097
Copper cryostat	0.010	0.011	0.011	0.011	0.007	0.007	0.013
Sum	0.231	0.172	0.173	0.175	0.128	0.164	10.201

Table 2. Simulated (with no top LXe veto) background rates for XENON100 upgrade construction materials with various fiducial volume cuts with a single scatter cut and veto energy cut of less than 100 keVee. These are taken to be the maximum rates in events/day/kg/keVee in the low energy WIMP search (1-100keVee) region. *ztop* is the height cut taken off the top of the liquid level. *t. radius* is the tangential radius of the hexagon.

V. Conclusion

The goal for this summer was to find a detector geometry for the XENON100 upgrade that would have background levels below those in the NSF proposal in a 100kg fiducial volume. Preliminary Monte Carlo simulations have shown that this can be achieved with the current geometry with a total background for the currently simulated detector parts that can be as low as 0.123e-3 dru which is below the 0.148e-3 dru design level. In the original proposal, the cryostat was to be constructed entirely of copper with a background rate of less than 0.033e-3 dru. These simulations have shown that we can afford to make the cryostat out of steel and copper and still be below the overall background levels in the proposal. However, more research is needed to determine if these low background levels can be reached with an even more efficient fiducial to total volume ratio. Currently the ratio is 100/327 or 0.31. For comparison, the same ratio for XENON100 is 0.34.

VI. Acknowledgments

I'd like to thank Professor Elena Aprile and the entire XENON group at Nevis labs for giving me the honor of working with them this summer as a Columbia REU student. I'd like to especially thank Rafael Lang, Guillaume Plante, and Bin Choi for their enormous help and patience. I'd also like to thank Kyungeun Elizabeth Lim and Luke Goetzke for keeping me in the loop with other XENON R&D projects. This summer could not have been as exciting and enjoyable without my fellow REU students and the graduate students at Nevis. I'd also like to thank Professor Michael Graf from Boston College for the continued support and encouragement. Last but not least, I'd like to thank Mike Shaevitz and John Parsons for organizing and making this research experience more fulfilling than I could have wished for.

References

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[2] XENON Collaboration, NSF Proposal No. 6838551, “Continuation of the XENON Dark Matter Project: Construction and Underground Operation of an upgraded XENON100 detector” (2008).

[3] Knoll, G. F., *Radiation Detection and Measurement*., Wiley, 1987.