Estimation of PMT exposure in the phase II system test

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1 Cosmic Rays

The significant contribution from cosmic rays should result from the incident muon flux. The flux is $70\,\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{str}^{-1}$ (PDG) incident directly downward with a $cos^2\theta$ profile. Integrating over all angles gives an incident flux of $345.4\,\mathrm{m}^{-2}\mathrm{s}^{-1}$. The portion of our vessel inside the reflector wall has a cross-sectional area of $2.09\,\mathrm{m}^2$, so we then have a flux of $721.9\,\mathrm{s}^{-1}$.

Assuming all of these muons are minimum ionizing, they should deposit, on average, $\approx (2\,\mathrm{MeV}\frac{\mathrm{cm}^2}{\mathrm{g}})\rho$ per centimeter traveled in the detector (Tavernier). ρ here is the mass density. The distance between the reflector plate and the PMTs (during a grid test) is 28.4 cm and xenon at room temperature (at 3 bar) has a density of $0.016\,\frac{\mathrm{g}}{\mathrm{cm}^3}$. Assuming -for simplicity- that all of our muons go straight down (despite us knowing otherwise) each will deposit
$\approx 2\,\mathrm{MeV}\frac{\mathrm{cm}^2}{\mathrm{g}} \cdot 28.4\,\mathrm{cm} \cdot 0.016\,\frac{\mathrm{g}}{\mathrm{cm}^3} = 909\,\mathrm{keV}$.

If we don't have any electric field applied, all of this energy should end in the form of scintillation photons. The work function of xenon is 13.7 eV, so each muon should result in the creation of $\frac{909 \times 10^3}{13.7} = 66 \times 10^3$ photons. This would result in 4.76×10^7 photons/s from muons.

We have a detection efficiency of ≈ 0.015 (granted this is for light emitted in the S2 region), so our PMTs should be exposed to 7.1×10^5 photons/s as a collective, or 2.2×10^4 photons/s each (we have 32). Note that these should come in pulses, this is not our detection rate, but only the photon rate.

If we bias our grids, 2.3 cm of our previous 28.4 cm will create S2 light (maybe more will). If we assume a 50% chance for electron vs photon emission, then $\approx 0.5 * \frac{2.3}{28.4} = 0.04$ of the events will emit ≈ 500 photons instead of 1. So we would have $0.04 \cdot 2.2 \times 10^4\ \frac{\mathrm{electrons}}{\mathrm{s}} \cdot 500\,\frac{\mathrm{photons}}{\mathrm{electron}} + 0.96 \cdot 2.2 \times 10^4\ \frac{\mathrm{photons}}{\mathrm{s}} = 4.6 \times 10^5$ photons/s.

If we run for 50 days with the grid biased, this amounts to $\approx 2 \times 10^{12}$ photons per PMT. The ring only tests do not have an active region, but have a larger visible volume (34 cm). So they should yield light equal to $\frac{34}{28.4} = 1.20$ times the previously mentioned unbiased case. That is, $\approx 2.6 \times 10^4\ \frac{\mathrm{photons}}{\mathrm{s}} = 1.1 \times 10^{11}$ photons in a 50 day run.

2 Ground Radiation

We'll use the typical estimate of $\approx 100\,\frac{\text{Bq}}{\text{kg}}$ and a conservative value for average energy deposited of $\overline{E} \approx 400\,\text{keV}$. The volume of the detector visible to the PMTs is the area below the PMTs and above the reflector plate, $\approx \pi(81\,\text{cm})^2 \cdot 28.4\,\text{cm} = 5.85 \times 10^5\ \text{cm}^3$. The density of our xenon will be $0.016\,\frac{\text{g}}{\text{cm}^3}$ so our target mass will be $0.016\,\frac{\text{g}}{\text{cm}^3} \cdot 5.85 \times 10^5\ \text{cm}^3 = 9.4\,\text{kg}$. We will therefore have a radiation-induced background rate of $\approx 940\,\text{Hz}$.

Each interaction will create on average $\approx \frac{E}{w} = \frac{400\,\text{keV}}{13.7\,\text{eV}} = 2.92 \times 10^4$ photons. So in total we will have $\approx 940\,\text{s}^{-1} \cdot 2.9 \times 10^4 = 2.7 \times 10^7\ \frac{\text{photons}}{\text{s}}$. Factoring in detection efficiency, we get $1.3 \times 10^4\ \frac{\text{photons}}{\text{PMT}\cdot\text{s}}$.

Following our previous reasoning about the number of interactions in the interaction region, we get ≈ 0.04 of the events giving 500 photons instead of 1. Therefore, we expect $1.3 \times 10^4\ \frac{\text{quanta}}{\text{s}}(0.04 \cdot 500\,\frac{\text{photons}}{\text{quantum}} + 0.96 \cdot 1\,\frac{\text{photons}}{\text{quantum}}) = 2.7 \times 10^5\ \frac{\text{photons}}{\text{s}}$ in each PMT.

Making the same assumptions about run time, we expect 1.2×10^{12} photons per PMT over the course of a run. As in the cosmic radiation case, the ring-only runs should be much lower at $\approx 1.2 * 1.3 \times 10^4\ \frac{\text{photons}}{\text{s}} = 1.6 \times 10^4\ \frac{\text{photons}}{\text{s}}$, which gives 6.7×10^{10} photons in a 50 day run.

3 Grid Contribution

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4 Sparking

Using the most pessimistic assumption possible, we assume the spark releases all of the stored potential energy as light. The stored energy is $E = \frac{1}{2}cv^2$. Since we assume that all of this energy goes to light in the detector, we have $n_{\text{photons}} = \frac{E}{W}$. With a light collection efficiency of 0.015 and 32 PMTs we have an average of $\frac{0.015}{32}n_{\text{photons}}$ photons per PMT per spark.

Approximating the grid-plate system as two parallel plates, we get $c \approx \frac{\epsilon_0 A}{d} = \frac{\epsilon_0 \pi 1.5^2\text{m}^2}{d}$. Using this, we get the following:

Test	Voltage	Capacitance	Energy	Photons	Photons/PMT
Cathode	20 kV	2.7 nF	0.54 J	2.5×10^{17}	1.2×10^{14}
Bottom	15 kV	2.7 nF	0.30 J	1.4×10^{17}	6.6×10^{13}
Extraction	13.5 kV	1.5 nF	0.13 J	5.9×10^{16}	2.8×10^{13}

5 Comparison

According to the note "Photocathode Degradation Analysis" written by CH Faham, these PMTs have been shown to experience no degradation when exposed to light resulting in $\approx 200\,\text{C}$ of charge loss over a long period of time.

Dividing this by the gain of 1×10^6, this means that a $200\,\mu\text{C}$ (1.25×10^{15} photoelectron) charge loss on the photocathode over an extended period results in no PMT degradation.

There will be three tests of grids with full wires, one bottom grid, one cathode grid, and the extraction region. The numbers in the above cosmic ray and ground radiation sections are valid for the cathode and bottom grid tests, while the extraction region test has a smaller visible volume and smaller S2 generation volume and so will contribute less than the other two. If we sum the totals from these three tests (assuming, conservatively, 50 day biased tests) we get $< 6 \times 10^{12}$ photons in each PMT from cosmic rays, and $< 3.6 \times 10^{12}$ photons from ground radiation.

There will also be two tests of grid rings only, one of the cathode, and one of the extraction region. Summing the contributions from these will be $< 2.2 \times 10^{11}$ photons from cosmic rays and $< 1.3 \times 10^{11}$ photons from ground radiation.

In total we expect $< 1.0 \times 10^{13}$ photons. A total 1250 less than that which yielded no degradation in the aforementioned test over a longer time period than that of the test.

Comparisons of these estimates with data taken from a gas-only run of the Phase 1 system test indicate that these conservative estimates are as much as 100 times higher than the actual rates.

No similar test of light bombardment in a short amount of time has been done, however these PMTs have been exposed to sparks before and come out fine. In addition, if we are simply comparing to the same light total as before, we expect degradation to occur either at the photocathode or at or beyond the last dynode. The photocathode is exposed to the full 1×10^{14} photons, but the amount of charge that could leave the last dynode is limited by the charge on the parallel $10\,\text{nF}$ capacitor. The voltage drop here is $90\,\text{V}$ when the PMT is fully biased to $1.5\,\text{kV}$ ($\frac{7.5\,\text{M}\Omega}{125.2\,\text{M}\Omega}$). This results in a total available charge of $q = cv = 0.9\,\mu\text{C}$ for any given pulse, including one from a spark. This is very far from the $200\,\mu\text{C}$ total which is known to cause no degradation.