Early commissioning calibration data sets for DEAP-3600

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Abstract. The DEAP-3600 experiment is a single phase dark matter detector using 1000 kg fiducial mass of liquid argon as scintillating target. An array of 255 high quantum efficiency PMTs detect the argon scintillation light. The experiment is located at SNOLAB, 2 km underground in Ontario, Canada. In February 2015 the PMTs were switched on and data were taken with vacuum and N₂ in the detector. Optical and gamma calibration data have been collected to commission the data acquisition hardware and software and characterize the optical properties of the detector.

1. The DEAP-3600 dark matter project

The DEAP-3600 experiment (Fig. 1) is a single phase dark matter search experiment using 3600 kg of liquid argon as the target. The argon is contained by a two inches thick acrylic vessel (AV) sphere with inner radius of 85 cm. Argon scintillation light is 128 nm in wavelength and therefore a coating of 1,1,4,4-tetraphenyl-1,3-butadiene (TPB) wavelength shifter had to be applied onto the inside surface of the AV to make it transparent by shifting the UV light into the visible spectrum.

The AV is faced by 255 high quantum efficiency 8-inch diameter photomultiplier tubes (PMTs) that provide 71% optical coverage for the scintillation light produced inside the vessel. The PMTs are set back from the spherical volume by 18-inch long light guides that act as neutron and thermal shields for the PMTs. Between the light guides there are custom fit polyethylene filler blocks which also complete the thermal and neutron shield between the AV and the PMTs.

At the top of the AV there is a long neck opening that contains a stainless steel cooling coil filled with liquid nitrogen. The liquid argon remains cold due to a convective flow that pushes the warm argon up to the cooling coil volume where it cools down becoming heavier and therefore flows down back into the vessel.

A stainless steel shell with inner radius of 133 inches houses the AV, LG, filler blocks and PMTs. 48 veto PMTs are anchored in the outside of this pressure vessel. The whole setup is immersed in a 8-meter diameter ultrapure water tank.

DEAP-3600 has been designed to be sensitive to dark matter in the form of WIMPs. The target sensitivity to the spin-independent WIMP-nucleon cross section is $10^{-46}$ cm$^2$ at 100 GeV. In order to archive this improvement of two orders of magnitude in sensitivity over current searches, DEAP-3600 has been designed with a background target of $< 0.6$ events in 3 years in the fiducial region of interest.
The water tank reduces external neutron and gamma radiation from the rock while the outward facing PMTs act as a muon veto by detecting their Cherenkov light in the water tank. The light guides and filler blocks have been designed to shield the neutrons produced in the \((\alpha, n)\) reaction in the PMTs photocathode.

Alphas from \(^{238}\text{U}\) and \(^{232}\text{Th}\) decays in the surface of the acrylic have been mitigated by keeping a very stringent quality control during the production of the acrylic so that its \(^{238}\text{U}\) content is less than \(3 \times 10^{-13}\) g/g and the \(^{232}\text{Th}\) content is less than \(1.3 \times 10^{-12}\) g/g. To remove the \(^{210}\text{Pb}\) concentration that has accumulated on the surface due to \(^{222}\text{Rn}\) exposure a custom resurferacer [1] was built to sand the AV inner surface prior to filling it with Ar gas.

Backgrounds from beta decay of \(^{39}\text{Ar}\) are reduced by using pulse shape discrimination (PSD) [2], which exploits the fact that argon scintillation has two very distinct time constants that get populated differently for electronic and nuclear recoils.

2. Optical calibration data
By February 2015 all the PMTs were installed and cabled. The inside of the acrylic vessel is hermetically sealed and kept in an overpressure N\(_2\) atmosphere to prevent radon from mine air from depositing in the sanded inner walls. During 2015 calibration and background data have been collected while the process systems needed to store and flow argon into the vessel were installed.
2.1. LED-Optical fiber calibrations
Optical fibers have been installed onto 20 of the LGs directed towards the PMT (Fig. 2). The fiber shines onto an acrylic and aluminum reflector piece glued to the LG in an angle such that the light points at the face of the PMT, where $\approx 20\%$ will reflect into the vessel. Two of these optical fiber calibration sources are attached at the acrylic neck of the vessel. Most of the data collected uses a 445 nm wavelength LED connected to the optical fibers, although some special data has been collected with 375 and 405 nm laser heads. These data are being used to monitor detector stability, to study the PMT response to single photoelectrons and to calculate the optical parameters of the detector used in DEAP-3600 Monte Carlo (MC) model.

Figure 3 shows the distribution of the light in the detector for one of these optical fiber runs. The PMT with the optical fiber and the neighbouring PMTs see the highest number of photons, while for the rest of the detector the occupancy distribution is uniform. By trying to reproduce this behaviour with the MC package we can find the range of optical parameters that describe the detector accurately and their systematic errors.

Figure 4 shows an example fit to the charge spectrum of a PMT in order to calculate the mean single photoelectron charge. Fits like this are batch performed for all the PMTs in every optical fiber run and stored in a CouchDB database to later be used during analysis to calculate the total charge deposited in a PMT.

![Figure 3. Occupancy (hit probability) in each PMT for an optical fiber calibration run. The x and y axes show the $\phi$ and $\theta$ coordinates of the PMTs in the detector, where the neck is at $\text{Cos}(\theta)=1$. The z axis ranges from 0 to 1. The PMT with the optical fiber and the neighbouring ones see the highest number of photons, while for the rest of the detector the occupancy distribution is very uniform.](image)

![Figure 4. Charge spectra for one PMT during an optical fiber run. The single photoelectron charge can be derived by fitting this spectrum with a series of Polya functions (a special case of the negative binomial distribution) plus a pedestal.](image)

2.2. Laser ball calibration
A laser ball calibration source was deployed inside the detector during July 2015 after the TPB coating was applied to the inner surface of the AV. The main purpose of this calibration is to determine the relative time offsets between PMTs, contribute towards a measurement of the absolute PMT efficiency, and provide an optical calibration method by comparing the data to simulation. A laser head is coupled with an optical fiber that runs down to the laser ball PFFA...
flask head. The head (Fig. 5) is filled with a gel thus ensuring that the light will be diffused while exiting the laser ball head. Lasers with 445, 405 and 375 nm wavelength have been used, which allow for wavelength dependent calibration of the optical parameters of the vessel.

Extensive ex-situ calibration of the inhomogeneity of the source have been done before and after it has been deployed in the vessel. Both the optical fiber data and the laser ball runs are being used to calculate the PMTs relative efficiency in-situ.

2.3. Gamma calibration
Gamma rays from $^{232}\text{U}$ in the rock surrounding the experiment produce Cherenkov light from electron Compton scattering in the acrylic. The water tank shields DEAP-3600 from these potential backgrounds. Since April 2015, with the water tank still empty, we have measured and characterized these gamma events by triggering on Cherenkov in the light guides. Furthermore, these event rates have been enhanced and studied by placing a $^{232}\text{U}$ gamma source at different $\theta$ positions of the steel shell. Figure 6 shows how the rate of Cherenkov events decreases as the water tank shielding is filled with ultrapure water as expected.

3. Conclusion
The DEAP-3600 construction and assembly at SNOLAB is completed. During 2015 gamma and optical calibration data has been collected and are being analyzed. These data allow us to commission the data acquisition hardware and software and characterize the optical properties of the detector.
References
[1] See Pietro Giampa’s article “In-situ Surface Contamination Removal and Cool-down Process of the DEAP-3600 Experiment” in this proceedings volume for more detail on the resurfacer apparatus.
[2] Boulay M and A. Hime A 2006 Astropart. Phys. 25 179