DEAP-3600 dark matter experiment

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Presented at: PIC 2015, Physics in Collision,
15-19 September 2015
University of Warwick

Abstract

DEAP-3600 is a single phase liquid argon (LAr) dark matter experiment, located 2 km underground at SNOLAB, in Sudbury, Canada. The detector has 1 tonne fiducial mass of LAr. The target sensitivity to spin-independent scattering of 100 GeV weakly interacting massive particles (WIMPs) is $10^{-46}$ cm$^2$. The DEAP-3600 background target is $<0.6$ background events in the WIMP region of interest in 3 tonne-years. The strategies to achieve this background include pulse shape discrimination to mitigate electron recoil and using ultra low radioactive materials for detector construction. Furthermore, to reduce neutron and alpha backgrounds, the DEAP-3600 acrylic vessel was sanded in situ to mitigate radon exposure of surfaces during construction and fabrication. The experiment is currently in the commissioning phase and will begin physics data taking later this year. This paper presents an overview of the experiment, its cross-section sensitivity to WIMPs and its current status.

1 Introduction

The Standard Model of particle physics can only describe 15.5% of the matter in the Universe. Numerous cosmological observations indicate that the remaining 84.5% does not interact electromagnetically and therefore is known as dark matter [1]. A good candidate for dark matter would be a particle that interacts gravitationally and is stable or long-lived enough to have survived since the Big Bang. It must be non-realistivistic, non-baryonic and electrically neutral. The most favourable dark matter candidates, which are predicted by models beyond the Standard Model, are the weakly interacting massive particles (WIMPs). The search for dark matter has become one of the top priorities in the particle physics community. The observable in a laboratory-based experiment which measures scattering interaction between WIMPs and target nuclei, is recoil energy and rate of interactions.

The DEAP-3600 project is one of several direct detection experiments worldwide, using a noble liquid as target and detector media. DEAP-3600 is a single phase liquid argon

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dark matter detector, measuring the scintillation signal produced from energy deposition. LAr scintillation has a powerful pulse shape discrimination (PSD) property allowing efficient identification of nuclear recoils, from WIMP interaction, in the presence of electron recoil background.

2 The DEAP-3600 detector at SNOLAB

DEAP-3600 is situated 2 km underground at SNOLAB, Sudbury, Ontario. It is composed of an 85 cm radius ultra-clean acrylic vessel (AV) which will be filled with 3600 kg LAr. The inside of the AV is coated with the wavelength shifter tetraphenyl butadiene (TPB), which shifts the ultraviolet (UV) light generated by argon scintillation to the visible blue region. Bonded to the AV are 255 acrylic light guides, each coupled to a high quantum efficiency photomultiplier tube (Hamamatsu R5912). The empty space between the light guides is filled with polyethylene filler blocks. The filler blocks and the light guides provide neutron shielding and thermal insulation. A spherical stainless steel shell encloses all the internal components and is instrumented with outward-looking muon veto photomultiplier tubes (PMTs). The entire assembly is housed in an 8 meter diameter water shield tank. The detector is cooled through a liquid nitrogen filled cooling coil, installed in the neck with acrylic flow guides attached to the bottom. A schematic view of the DEAP-3600 detector is given in Figure 1.

In order to reduce the risk of accidental contamination, radioactive calibration sources were developed to be used outside of the AV. The water tank is equipped with three vertical calibration tubes that will allow periodic deployment of an Am-Be neutron source at the equator of the steel shell. Gamma calibrations will be performed with a $^{22}$Na source moved through an additional circular tube installed around the steel shell. In addition, internal and external optical calibration systems were developed in order to characterize the detector response. The internal optical calibration system (triggered laser ball system) was deployed for a short time to the centre of the AV before filling the detector with argon. The purpose of the system is to measure the PMT relative timing response and efficiency, as well as, TPB and light guides optical properties. It consists of multi-wavelength laser pulser, an optical fibre and a Perfluoroalkoxy polymer (PFA) flask filled with light diffusing material. The external optical calibration systems consist of 20 LED driven optical fibres for light injection, attached to selected light guides.

A unique feature of DEAP-3600 is its excellent PSD against electronic recoil events. The expected electronic background reduction is more than factor of $10^{10}$. The PSD on the LAr scintillation signal is demonstrated with the DEAP-1 prototype experiment [2]. The effectiveness of PSD strongly depends on the light yield. The projected DEAP-3600 light yield is 8 pe/keV. This high light yield is due to high PMT coverage (79%) and running the detector in single phase. Unlike time projection chambers, the ionization signal is not collected in single phase dark matter detectors. This leads to no scintillation light loss from ions drifting in electric field.
3 Projected background and sensitivity

Cosmogenic backgrounds are mitigated by the depth of SNOLAB and water Čerenkov veto. Ultra-low background techniques were used in order to aim for negligible radioactive background events in the WIMP signal region. The expected number of background events in the WIMP region of interest is 0.6 in 3 tonne-years from all sources [3].

The dominant source of electron recoil background events is from $^{39}$Ar beta decay (1 Bq/kg). The PSD on the scintillation signal will be used to mitigate this background. Low background gamma assay, radon emanation measurements and alpha counting systems at SNOLAB and Queen’s University were used to select low background materials and eliminate neutron and $\gamma$ backgrounds. The targeted radon emanation from all the argon wetted process system components is less than 5 $\mu$Bq. Radon in the cryogen will be removed by a custom-made charcoal radon trap installed in the argon process system. The $^{210}$Pb level in the acrylic, which is a source of background such as ($\alpha$, n) neutrons, is measured to be $< 2.2 \times 10^{-10}$ g/g [4]. The AV surface was exposed to radon in air during construction. $^{210}$Pb builds on surfaces exposed to radon and produces $^{210}$Po, which is an $\alpha$ emitter. The $\alpha$ particle loses its energy in bulk TPB and may mimic WIMP-like events. To reduce surface $\alpha$ background, the inner surface of the AV was resurfaced in situ in
order to remove radon daughters. During and after resurfacing, the AV was sealed from the lab environment. While purged with low-radon gas, the resurfacer took away 0.4 mm of acrylic. The estimated AV event rate after resurfacing is 10 $\alpha$/m$^2$/day [5]. Neutron, $\gamma$ and $\alpha$ events are further removed by fiducialization, while keeping the targeted 1 tonne mass.

DEAP-3600’s expected spin-independent WIMP-nucleon cross section sensitivity is $10^{-46}$ cm$^2$ for a WIMP mass of 100 GeV. Figure [2] shows the projected DEAP-3600 and current WIMP-nucleon cross section experimental limits.

![Figure 2: DEAP-3600 spin-independent WIMP-nucleon scattering cross-section sensitivity. For comparison, the current experimental limits from CDMS-II [7], XENON-100 [8] and LUX [9] experiments are shown.](image)

4 Current status and summary

All the major components of the detector are in place. During 2013, the AV was fabricated [10] and the light guides were bonded to the AV (Figure 3 a). The bonding was performed underground and included multiple high temperature anneals in low-radon atmosphere. In 2014, the outside of the AV and the light guides were dressed with diffuse and specular reflectors, respectively. The space between the light guides was filled with polyethylene shielding blocks. The 255 PMTs were installed and coupled to corresponding light guides (Figure 3 b). In parallel, the process systems were commissioned. In early 2015, the steel shell was closed and the calibration tubes and veto PMTs were installed (Figure 3 c). The electronics, data acquisition system and external optical calibration system (LEDs) have been commissioned.

Since February 2015, the detector has been continuously running with the AV under vacuum or filled with ultra-clean N$_2$ gas. During this time, the data taken during LED runs has been used to perform PMT charge calibration. In summer 2015, the laser ball system was deployed in three positions inside of the AV. The laser ball was pulsed at 445 nm, 405 nm and 375 nm wavelengths. The TPB excitation starts at 410 nm and increases
at lower vacuum ultra violet wavelengths [11]. The reemission photoluminescence spectra peaks at around 425 nm. Multi-wavelength data allows for an analysis of the full optical properties in the detector. In parallel, the LED data (with LED wavelength of 435 nm) can be used as an independent cross-check of the optical model and to study the optical stability of the detector components. Studies are ongoing to extract the detector’s optical parameters using both laser ball and external LED data.

Currently, the water veto tank is sealed and is fully filled. The remaining task is commissioning the detector with Ar gas before cooling down. The Ar gas data will be used for Monte Carlo simulation tuning, electronic readout adjustments and background studies.

Figure 3: a) The DEAP-3600 acrylic vessel attached to an assembly frame after completion of light guides bonding. The full diameter with light guides is 3 m. b) The DEAP-3600 after PMTs, reflectors, shielding polyethylene blocks and copper thermal shields installation. c) The DEAP-3600 inside water veto tank after installation of the steel-shell, calibration tubes and veto PMTs.

5 Acknowledgements

This work is supported by the National Science and Engineering Research Council of Canada (NSERC), by the Canada Foundation for Innovation (CFI), by the Ontario Ministry of Research and Innovation (MRI) and by the European Research Council (ERC). We thank Compute Canada, Calcul Québec, McGill University’s centre for High Performance Computing and the High Performance Computing Virtual Laboratory (HPCVL), for computational support and data storage. We are grateful to SNOLAB and Vale Canada, Ltd. for excellent on-site support.

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