Status of the DEAP-3600 Experiment

Susnata Seth*, on behalf of the DEAP Collaboration

Department of Physics, Carleton University, Ottawa, ON K1S 5B6, Canada

Arthur B. McDonald Canadian Astroparticle Physics Research Institute, Queen's University, Kingston, ON K7L 3N6, Canada

Abstract

DEAP-3600 is a direct detection of dark matter experiment that utilizes about 3.3 tonnes of liquid argon contained in a spherical acrylic vessel. The scintillation light from the target medium is viewed by 255 photomultiplier tubes. It is located at SNOLAB underground facility to reduce the cosmic-ray muon induced neutron backgrounds. The analysis technique demonstrated excellent performance for pulseshape discrimination between nuclear recoils and electronic recoils induced by β and γ-rays. It has achieved the most sensitive limit for the spin-independent Weakly Interacting Massive Particle (WIMP)-nucleon cross-section above 30 GeV/c^2 WIMP mass among argon-based experiments and leading sensitivity among all experiments for various dark matter scenarios. The data have been taken from November, 2016 to March, 2020 and currently the detector is undergoing hardware upgrades.

1 Introduction

The existence of dark matter (DM), a non-luminous form of matter is well established by a plethora of astrophysical observations [1, 2]. By contrast, the particle nature of the DM is under investigation to date. The Dark matter Experiment using Argon Pulseshape discrimination (DEAP) utilizes a single-phase liquid argon (LAr) detector aiming to acquire the scintillation light produced by DM candidate via spin-independent interaction with target nuclei. The following sections describe the detector design and background model in view of Weakly Interacting Massive Particles (WIMPs) candidate of DM search. The latest limits for various DM scenarios are summarized. Furthermore, the ongoing activities on analysis techniques along with a hardware upgrade plan to mitigate dominant backgrounds are detailed here.

2 The DEAP-3600 Detector

The DEAP-3600 detector [3] consists of (3279 ± 96) kg LAr contained in a spherical acrylic vessel (AV) with an inner radius of 85 cm. The inner surface of the AV is coated with tetraphenylbutadiene (TPB, $C_{28}H_{22}$) wavelength shifter (WLS) which absorbs the 128 nm LAr scintillation light and re-emits it in the visible wavelength region, peaked at approximately 420 nm. The wavelength shifted scintillation light travels through the AV and acrylic light guides (LGs) and is detected by 255 inward-facing high quantum efficiency photomultiplier tubes (PMTs).

The volume between LGs is filled with high density polyethylene and Styrofoam, which work as a thermal insulator and provide passive shielding of neutrons. This entire assembly is housed in a spherical stainless steel vessel with 48 outward-looking PMTs on its outer surface and is submerged within a water tank. Together, the water tank and these PMTs serve as a Cherenkov muon veto. In addition, the water suppresses neutron and gamma backgrounds from the cavern which is located 2 km below the Earth surface at SNOLAB facility in Sudbury, Canada to mitigate the cosmic-ray muon flux to (3-4) $\times 10^{-10}$ muons/cm^2/s [4].

---

[*] Email: susnataseth@cunet.carleton.ca

Presented at the 30th International Symposium on Lepton Photon Interactions at High Energies, hosted by the University of Manchester, 10-14 January 2022.

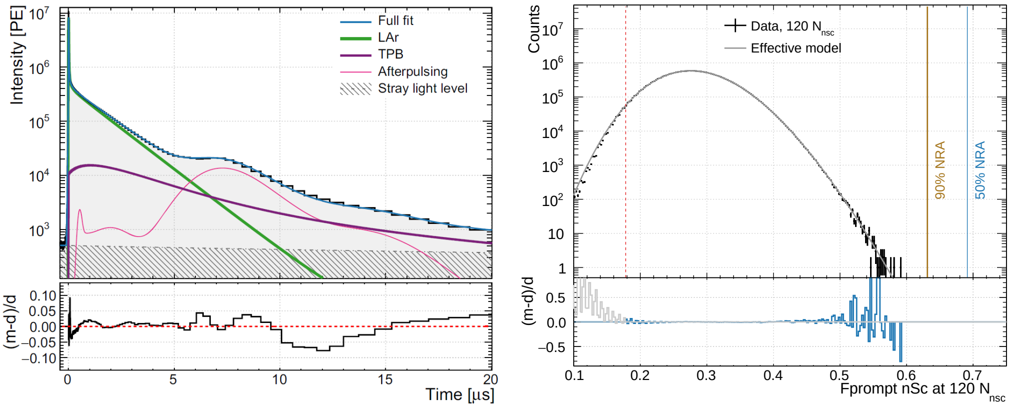

Figure 1: (Left) LAr scintillation pulseshape measured using ^{39}Ar β-decays in the DEAP-3600 detector shows a good agreement with the pulseshape model [5]. (Right) $\mathrm{F_{prompt}}$ distribution for ^{39}Ar β-decay events at 120 $\mathrm{N_{nsc}}$ (approximately 19.65 $\mathrm{keV_{ee}}$ - 19.82 $\mathrm{keV_{ee}}$) together with model fit [6] where $\mathrm{N_{nsc}}$ stands for total number of PE in the event window.

3 Pulseshape Discrimination

Ionizing particles can excite or ionize the argon atom and eventually forms an excited molecule, Ar_2^* (known as 'excimer') either in a short-lived singlet or a long-lived triplet state. The LAr scintillation pulseshape has been studied in detail in [5] using ^{39}Ar β-decays naturally present in the DEAP-3600 detector. A complete pulseshape model has been developed which accounts for LAr scintillation physics, time response of TPB WLS and PMT response. Figure 1 (left) shows the event peak region (up to approximately 5 µs) is dominated by LAr singlet and intermediate decay followed by triplet decay. Features at the region from (5 - 10) µs are mostly due to PMT afterpulsing whereas starting at approximately 13 µs, TPB delayed emission becomes noticeable. The deviation between the model and data is less than 11% between (0 - 160) µs time window.

Electron recoil events originating from betas, gammas, or muon interactions mostly give rise to the argon excimer's triplet state having lifetime (1.4 - 1.6) µs. By contrast, nuclear recoil events produced by neutrons or WIMPs predominantly excite the argon atom in the short-lived ($\approx$ 6 ns) singlet state resulting in light emission over a span of ns. This characteristic of LAr leads to the definition of the pulseshape discrimination (PSD) parameter, $\mathrm{F_{prompt}}$, as the fraction of photoelectron (PE) detected in a prompt window spanning [-28, 60] ns around the event peak:

$$\mathrm{F_{prompt}} = \frac{\sum_{-28\ \mathrm{ns}}^{60\ \mathrm{ns}} \mathrm{PE(t)}}{\sum_{-28\ \mathrm{ns}}^{10\ \mu\mathrm{s}} \mathrm{PE(t)}}. \tag{1}$$

Different PSD algorithms have been employed using prompt-fraction (Eq. 1) and log-likelihood ratio and discussed in detail in [6]. The existing PSD parameter model describes the data well and is shown in Fig. 1 (right). The excellent PSD performance of LAr allows to suppress the dominant electron-recoil background arises due to the β-decay of ^{39}Ar isotope.

4 Background Model

The full energy spectra of β and γ-rays from radioactive isotopes existing in the detector materials including LAr have been explored. In addition to the PSD technique mentioned in the above section, the electromagnetic background model demonstrated agreement with the observed data over nine orders of magnitude and for an energy range up to about 5 MeV [7].

The neutron background is dominated by (α, n) reactions induced by α-decays in the detector materials. The neutron rate is estimated in-situ by counting nuclear recoils followed by neutron capture high energy γ-rays from ^{1}H and ^{40}Ar within 1 ms coincidence time window. The background model predicted $0.10^{+0.10}_{-0.09}$ events in 231 live-days in the WIMP region of interest (ROI) [4].

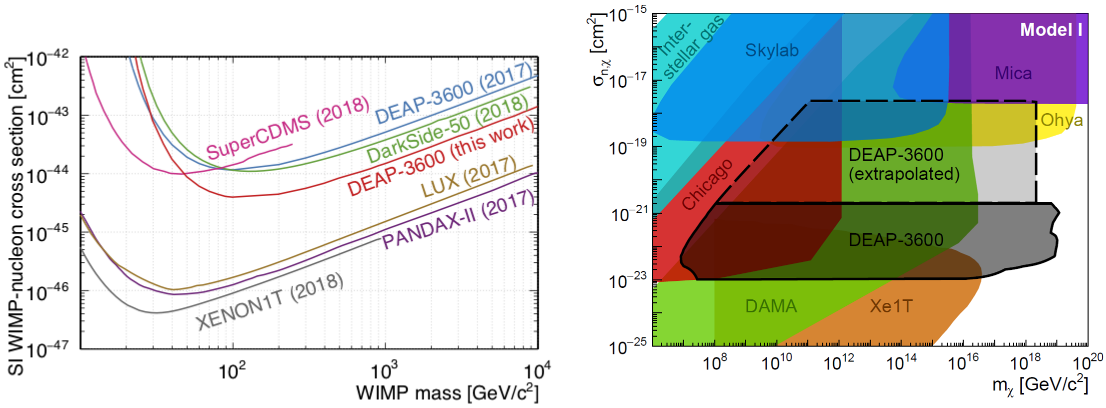

Figure 2: (Left) 90% C.L. upper limits (red curve) on the spin-independent WIMP-nucleon cross-section as a function of WIMP mass [4]. (Right) Planck scale DM masses m_χ and nucleon scattering cross sections $\sigma_{n\chi}$ excluded by DEAP-3600 [8].

The alpha background in the DEAP-3600 detector originates from several locations within the detector: (a) in the LAr bulk, (b) on the inner surface of AV and (c) on the surfaces of the acrylic neck flow-guides (FGs) at the top of AV. In the case of α-decays in the LAr bulk, the full energy is deposited in LAr and results in more scintillation light compared to that expected to be produced in interactions with WIMPs. In contrast, α-decays on the inner AV surface are efficiently removed by position reconstruction and by selecting a fiducial volume in the centre of the detector.

A challenging background arises from α-decays from the neck region of the detector. The neck contains FGs located in the gaseous argon (GAr) region and there is a possibility that the surfaces of FGs are coated with a thin layer of LAr and/or mist due to current cooling set-up. The α-decays on the surfaces of FGs can pass through this LAr layer or mist producing scintillation light which is shadowed by the geometry of the FGs. Therefore only a small fraction of the photons from such events are detected by the PMTs. Consequently, the reconstructed energy of such an event can enter the energy region of interest expected for WIMP-induced nuclear recoils (NRs). The events can also mis-reconstruct within the fiducial volume. The PSD technique can be used to distinguish these α-particle induced events because of the comparatively higher F_{prompt} than that of WIMP-induced NR events, but with a much-reduced separation than for ER events in LAr. Appearance of early pulses in PMTs in GAr region of the detector and different pattern of reconstructed position can also be used to further reduce this background.

Another dominant background comes from α-activity on or embedded within the dust particulates observed in the LAr volume. When an α-decay occurs within a dust particulate, some of the energy can be lost within the dust before the alpha enters the LAr. There is a possibility that the scintillation light produced within LAr is shadowed by the dust itself. This shadowing and energy loss within the dust can result in these alpha-induced events with a similar reconstructed energy to WIMP NR events. A Monte Carlo model has been developed for such events where the number density of dust particles having a given particle size range is described by power law. This model describes the data well at energies above the WIMP search energy region.

5 Detector Sensitivity

The latest WIMP result is based on data collected between November, 2016 - October, 2017 having total 758 tonne-day exposure [4]. The null result observed within the ROI provides the most sensitive constraint on spin-independent WIMP-nucleon scattering among argon-based DM experiments by excluding the cross-section above 3.9×10^{-45} cm^2 for WIMPs with a mass of 100 GeV/c^2 at 90% C.L. [shown in Fig. 2 (left)]. This limit assumes the standard halo DM model, and assumes that WIMPs couple equally to neutrons and protons. This result has been re-interpreted using Non-Relativistic Effective Field Theory (NREFT) and considering the deviation of Maxwell-Boltzmann DM velocity distribution arising due to DM halo substructures [9]. Figure 8 in Ref. [9]

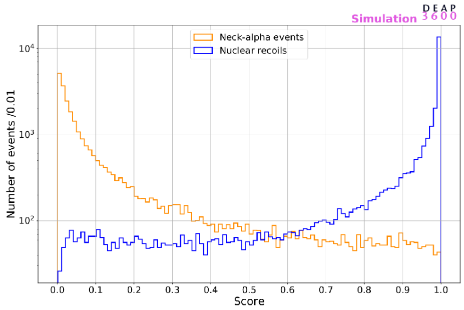

Figure 3: ‘Score” values of simulated alpha backgrounds events from neck region of the detector and nuclear recoil events predicted by multilayer perceptron (MLP) implementation.

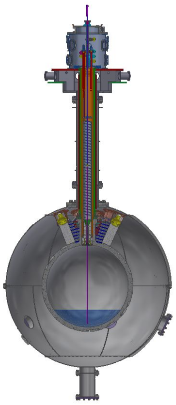

Figure 4: A schematic diagram of the dust filtration system planned for the upgraded DEAP-3600 experiment.

shows world leading sensitivity at high WIMP mass (above 100 GeV/c^2) for the “xenonphobic (XP)” coupling scenario which assumes WIMPs couple differently to the proton and the neutron.

DM with Planck-scale mass is predicted by several theories. Unlike WIMPs, such candidates have a large scattering cross-section. Therefore, they can scatter multiple times while passing through the detector material producing “multi-scatter” signatures which are usually rejected as background events in WIMP search. The low number density of such heavy DM candidate results in comparatively low interaction rate. As a consequence, the maximum DM mass can be probed depends on the area of the detector as well as the data collection time period. The full dataset of 813 live-days are employed for studying Planck-scale mass DM [8]. No candidate signal is observed in the ROI. This results in first direct detection constraints on DM mass between 8.3×10^6 and 1.2×10^{19} GeV/c^2 and ^{40}Ar-scattering cross-section between 1.0×10^{-23} and 2.8×10^{-18} cm^2, shown in Fig. 2 (right). This limit is obtained by assuming that the DM candidate is unable to distinguish the target nucleons and discussed in detail in Ref. [8].

6 Multivariate Analysis and Hardware Upgrade

Multivariate analysis (MVA) techniques are being studied to discriminate the alpha backgrounds from nuclear recoil induced events. Figure 3 indicates that the alpha background originating from the neck region of the detector can be distinguished by multilayer perceptron (MLP) of the artificial neural network (ANN) technique – it is possible to reject 99.9% of neck alpha background events with 44.4% acceptance of the nuclear recoil events.

The main objectives of the hardware upgrade are to mitigate the α-backgrounds originating from the surfaces of FGs and the dust particulates. In addition, necessary maintenance has been planned to be executed including repair of a neck seal of the AV which will allow the filling of the detector with LAr to its original design capacity, filtration of the liquid argon during operation, and replacement of inoperative muon veto PMTs.

In order to reduce the alpha backgrounds from the surfaces of FGs, two independent approaches are being implemented. Firstly, a new set of acrylic FGs has been fabricated and coated with a pyrene-doped polystyrene (15% pyrene + 85% polystyrene by weight) WLS [10]. The coating of WLS makes the α-induced ultraviolet scintillation light detectable by PMTs which prevents the leakage of such events into WIMP energy ROI. Furthermore, this WLS has a re-emission time much longer than the lifetime of the LAr singlet state which enables efficient PSD. The Monte Carlo simulation indicates that with a proper choice of PSD parameter the reduction of such alpha background events by a factor of about 1.2×10^{-5} within WIMP ROI can be achieved.

In addition, an alternate cooling system has been designed and fabricated which will bring liquid argon directly into the detector. During previous data taking, the lab-temperature argon gas was injected into the detector and cooled down within the neck region of the detector using LN_2-filled stainless steel cooling coil. This cooling configuration allows the development of a liquid argon film on the FGs and leakage of alpha-backgrounds into the WIMP ROI as discussed earlier. In the new system the cooling can be performed externally which will keep the neck region warm and reduce such backgrounds.

This new system will also allow the installation of a LAr extraction tube close to the bottom of the acrylic vessel (see Fig. 4). This extraction tube will be used to take LAr out and filter out the dust particles through the external system to reduce the background events from dust. This filtration process will be carried out before filling the detector with purified LAr.

7 Summary and Outlook

The DEAP-3600 experiment collected data from November 2016 to March 2020. Our physics data has been 80% blinded since January 2018. The analyses of the three years dataset are in progress using the complete background model described here and deploying the MVA techniques. The hardware upgrade is aiming to mitigate the intrinsic alpha backgrounds in WIMP ROI and expected to be completed by late 2022 followed by filling of the detector and starting a new data collection run. Furthermore, the DEAP collaboration is performing other physics analyses, including the precision measurement of specific activity of ^{39}Ar in atmospheric argon and the first measurement of the ^{8}B solar neutrino absorption in argon.

8 Acknowledgments

We thank the Natural Sciences and Engineering Research Council of Canada, the Canadian Foundation for Innovation (CFI), the Ontario Ministry of Research and Innovation (MRI), and Alberta Advanced Education and Technology (ASRIP), Queen's University, the University of Alberta, Carleton University, the Canada First Research Excellence Fund, the Arthur B. McDonald Canadian Astroparticle Research Institute, DGAPA-UNAM (PAPIIT No. IN108020) and Consejo Nacional de Ciencia y Tecnología (CONACyT, Mexico, Grant A1-S-8960), the European Research Council Project (ERC StG 279980), the UK Science and Technology Facilities Council (STFC) (ST/K002570/1 and ST/R002908/1), the Leverhulme Trust (ECF-20130496), the Russian Science Foundation (Grant No. 21-72-10065), the Spanish Ministry of Science and Innovation (PID2019-109374GB-I00), and the International Research Agenda Programme AstroCeNT (MAB/2018/7) funded by the Foundation for Polish Science (FNP) from the European Regional Development Fund. Studentship support from the Rutherford Appleton Laboratory Particle Physics Division, STFC and SEPNet PhD is acknowledged. We thank SNOLAB and its staff for support through underground space, logistical, and technical services. SNOLAB operations are supported by the CFI and Province of Ontario MRI, with underground access provided by Vale at the Creighton mine site. We thank Vale for their continuing support, including the work of shipping the acrylic vessel underground. We gratefully acknowledge the support of Compute Canada, Calcul Québec, the Centre for Advanced Computing at Queen's University, and the Computation Centre for Particle and Astrophysics (C2PAP) at the Leibniz Supercomputer Centre (LRZ) for providing the computing resources required to undertake this work.

References

[1] Planck Collaboration et al. Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics*, 641:A6, September 2020.

[2] Douglas Clowe, Anthony Gonzalez, and Maxim Markevitch. Weak-lensing mass reconstruction of the interacting cluster 1e 0657-558: Direct evidence for the existence of dark matter. *The Astrophysical Journal*, 604(2):596–603, apr 2004.

[3] P.-A. Amaudruz et al. Design and construction of the DEAP-3600 dark matter detector. *Astroparticle Physics*, 108:1–23, 2019.

[4] R. Ajaj et al. Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at snolab. *Phys. Rev. D*, 100:022004, Jul 2019.

[5] P. Adhikari et al. The liquid-argon scintillation pulseshape in DEAP-3600. *Eur. Phys. J. C*, 80(4):303, 2020.

[6] P. Adhikari et al. Pulse-shape discrimination against low-energy Ar-39 beta decays in liquid argon with 4.5 tonne-years of DEAP-3600 data. *Eur. Phys. J. C*, 81(9):823, 2021.

[7] R. Ajaj et al. Electromagnetic backgrounds and potassium-42 activity in the DEAP-3600 dark matter detector. *Phys. Rev. D*, 100:072009, Oct 2019.

[8] P. Adhikari et al. First direct detection constraints on planck-scale mass dark matter with multiple-scatter signatures using the DEAP-3600 detector. *Phys. Rev. Lett.*, 128:011801, Jan 2022.

[9] P. Adhikari et al. Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector. *Phys. Rev. D*, 102:082001, Oct 2020.

[10] D. Gallacher et al. Development and characterization of a slow wavelength shifting coating for background rejection in liquid argon detectors. *(submitted to Nucl. Instrum. Meth. A), ArXiv e-print: 2109.06819*, September 2021.