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Latest results from the DEAP-3600 experiment at SNOLAB

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The latest results from the DEAP-3600 experiment will be presented. Located 2 km underground at SNOLAB in Sudbury, Canada, DEAP-3600 is looking to detect dark matter using 3.3 tonnes of liquid argon contained in a large ultralow-background acrylic cryostat that is instrumented with 255 photomultiplier tubes. Key to this experiment is the excellent demonstrated performance of pulse-shape discrimination against low-energy beta decays, as well as position reconstruction and other background rejection techniques against alpha decays and neutron scatters. The broad physics programme of DEAP-3600, with measurements and searches for new physics will be discussed, as well as the status of detector upgrades in progress.

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1. Introduction

While there is clear evidence from astrophysics and cosmology that dark matter exists, representing approximately 85% of the matter in the Universe [1], if dark matter is a particle, its mass is unknown. Direct detection experiments seek to observe interactions between particles of dark matter and ordinary matter, creating observable signals in the detector's target.

The DEAP-3600 experiment [2] at SNOLAB, located 2070 m underground in Sudbury, Canada, is the largest liquid argon (LAr) dark matter detector in operation. It contains 3296 ± 24 kg of LAr [3] in a 1.7 m diameter acrylic vessel instrumented with 255 photomultiplier tubes (PMTs). When particles deposit energy in LAr, scintillation light is emitted at a wavelength of 128 nm. This ultraviolet light propagates to the inner surface of the acrylic vessel which is coated with a 3-μm thick layer of tetraphenyl butadiene (TPB), a wavelength-shifting material that re-emits visible light. These visible photons can then travel through the acrylic light guides and be detected as photoelectrons (PE) at the PMTs.

A detailed pulse-shape model for DEAP-3600, including fits to the singlet and triplet lifetimes of Ar_2^* as well as an intermediate time component of LAr scintillation, PMT response parameters, and TPB re-emission time constants, was published in Ref. [4]. DEAP-3600 has world-leading performance for pulse-shape discrimination (PSD), enabling the rejection of electronic recoil (ER) backgrounds, such as ^{39}Ar beta decays, with a leakage probability of 10^{-10} at 50% nuclear recoil (NR) acceptance at 110 PE ($\sim$ 17.5 keV$_{ee}$) [5] near the threshold of the dark matter search.

The sensitivity of DEAP-3600 spans 18 orders of magnitude in the mass of particulate dark matter, from around 20 GeV/c^2 all the way up to the Planck mass 1.2×10^{19} GeV/c^2. The latest results in the search for dark matter with LAr are summarized here, followed by a discussion of other searches and measurements carried out using DEAP-3600 data, and hardware upgrades that aim to improve the sensitivity of the detector in the next period of operation.

2. Search for WIMP dark matter

The first results from DEAP-3600 in the search for dark matter appeared in Ref. [6], an analysis of 4.4 live-days of data collected during the first LAr fill of the detector in August 2016. Backgrounds from alphas, betas, gammas, and neutrons are mitigated using event selection variables such as the number of PE detected in the event, a PSD variable, and a fiducial cut selecting the innermost region of the LAr volume. No candidate event appeared in the WIMP region of interest.

This was followed by the analysis of the first year of data collected in the second LAr fill of DEAP-3600 from November 2016 to October 2017 [7]. In addition to improvements in PSD performance and energy calibration, maximum-likelihood position reconstruction algorithms were introduced in order to define the fiducial volume, and to discriminate against a challenging background from alpha decays originating in the neck of the detector, from where the scintillation light is shadowed. This null result was reinterpreted in a more general non-relativistic effective field theory framework, also exploring how possible substructures in DM halo affect these constraints [8].

Coming up, a profile-likelihood ratio (PLR) Bayesian analysis framework has been developed for the WIMP dark matter search on the full second LAr fill data collected until the end of March 2020. The main benefits of the PLR strategy are to drastically increase WIMP acceptance by relaxing event selection cuts, and modelling background probability distribution functions explicitly in the PLR fit. At the time of writing, this analysis is under internal review by the collaboration.

Two additional, subtle backgrounds are considered in the updated model. First, alpha decays from trace amounts of dust particulates suspended in LAr can create low-PE events in the NR band and in the fiducial region. These alphas are attenuated in the dust particulate before entering LAr, and the small amount of scintillation light generated in LAr is then shadowed. Ex-situ measurements of metallic dust in liquid nitrogen, that was used in the detector during construction, support this hypothesis. Event rates from this background are constrained in analysis using a pure control region defined in the NR band spectrum at intermediate PE, as shown in Figure 1, and extrapolated to the WIMP region of interest.

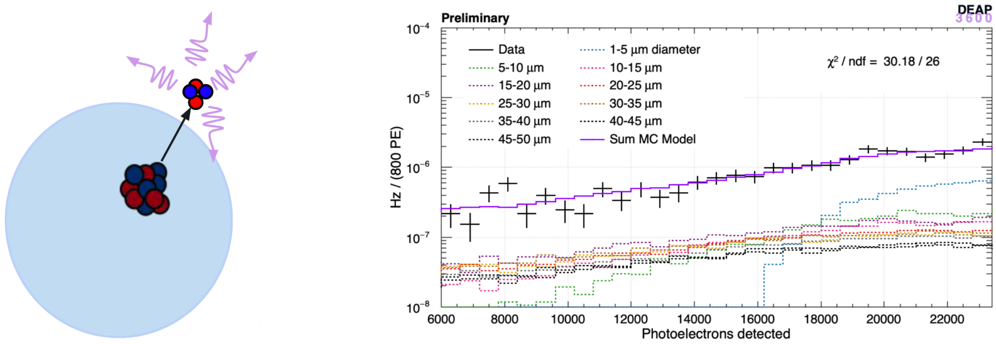

Figure 1: (Left) Cartoon of scintillation from an attenuated alpha decay originating from a dust particulate. (Right) Fit to data in the intermediate PE range using templates from Monte Carlo simulations of alpha decays in copper dust particulates of different sizes.

Second, data taken with DEAP-3600 at vacuum in 2021-2022 revealed a surprise: events passing all selection cuts of the WIMP search were found in the region of interest. The working hypothesis to explain these events is Cherenkov radiation at two sites in the acrylic vessel, from gamma rays traveling across the detector. In the dark matter search dataset, such an event could occur if a gamma crosses the gas argon phase above the LAr. A dedicated algorithm against this background has been developed based on double-cluster identification in the observed PE pattern.

This analysis will also benefit from new machine-learning algorithms trained against shadowed alphas from the neck, a neural network for position reconstruction, and a maximum-likelihood algorithm dedicated to tagging events due to alphas from the acrylic vessel surface.

3. Search for Planck-scale mass dark matter

By virtue of its size, DEAP-3600 is also sensitive to dark matter particles with low number density and high mass. Planck-scale mass dark matter particles would have enough energy to multiply scatter through the SNOLAB overburden and into the LAr target, leaving a distinct signature consistent with multiple recoils in succession. This would be observed as an event where either multiple coincident pulses are recorded, or a single very-high-PE pulse.

In this search, four regions of interest are defined with high signal acceptance and negligible expected background. In the full second LAr fill dataset of 813 live-days, no candidate signal events are observed, allowing DEAP to set world-leading limits on Planck-scale mass dark matter [9].

4. Other searches and measurements

DEAP-3600 recently achieved the most precise measurement of the specific activity of ^{39}Ar in atmospheric argon [3]. This analysis requires a careful determination of the data acquisition live time; as well, the relative uncertainty on the LAr mass in the detector is reduced to 0.7%, smaller by a factor 4 compared to the previous uncertainty. The dominant systematic uncertainty then comes from the event selection efficiency for single ^{39}Ar decays and pile-up events: a data-driven method is used in this case. Other components from ER backgrounds are also constrained in the fit. Finally a correction is applied considering the time between argon extraction from the atmosphere and data collection. The specific activity of ^{39}Ar is measured to be 0.964 ± 0.024 Bq/kg$_{\mathrm{atmAr}}$. A measurement of the ^{39}Ar half-life is also carried out, currently under internal collaboration review.

The characterization of ER backgrounds in DEAP-3600, published up to 5 MeV in Ref. [10], is extended up to 10 MeV to search for solar axion-like particles (ALPs). These particles could be produced in the Sun's core by the reaction $p + d \rightarrow {}^{3}\mathrm{He} + a$ where an ALP is produced instead of a 5.5 MeV gamma. As the background is dominated by neutron capture gammas, a fit is performed to AmBe neutron source calibration data before looking at regular data for the ALP search.

Further analyses in progress include a measurement of alpha quenching factors in LAr, a measurement of the muon flux at SNOLAB, and a search for ^{8}B solar neutrino absorption in LAr.

5. Hardware upgrades and outlook

Upgrades to the DEAP-3600 detector are scheduled to be completed in 2024, when a new data taking campaign will start with a third LAr fill in the detector. The main objective of the hardware upgrades is to mitigate the limiting sources of background to the dark matter search. New neck flow guides are installed, coated with pyrene, a slow wavelength shifter to identify and remove the shadowed alpha background with PSD. An alternate cooling system is in place to enable filtering out dust particulates from LAr. The neck seal is replaced, allowing an eventual complete LAr fill, although operations will start in the partial-fill configuration that is well understood from the second LAr fill data. In addition to having improved expected sensitivity to dark matter, the new data will inform the design of next-generation dark matter experiments with LAr as the detection material.

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