PROCEEDINGS OF SCIENCE

Dark matter search in DEAP-3600: status and prospects

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DEAP-3600, with its 3.3 tonnes liquid argon target, is a dark matter direct detection experiment set at SNOLAB in Sudbury, Canada. Since 2019, the experiment has held the most stringent exclusion limit in argon for Weakly Interacting Massive Particles (WIMPs) above 20 GeV/c^2. Detector upgrades have been ongoing since the end of the second fill run in 2020 to reduce the backgrounds from shadowed alphas and dust dissolved in it in the upcoming third fill run.

In parallel with that, the physics reach of the experiment has been widened, with unique contributions to the WIMP search within the Non-Relativistic Effective Field Theory, also including the impact of the galactic substructures to the dark matter halo, while setting world-leading exclusion limits at Planck-scale dark matter candidates. More recently, the collaboration has investigated the ^{39}Ar activity and the α-particles quenching in argon while developing a detailed Profile Likelihood Ratio WIMP search on the entire second-fill dataset, which will push the experiment down to unprecedented sensitivity.

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1. Introduction

DEAP-3600, welcoming more than 100 members in about 20 institutions, is devoted to the search for dark matter candidates using noble liquid-filled detectors. The DEAP-3600 experiment is set at SNOLAB (Ontario, Canada), under 2 km of rock, in one of the most-radiopure underground laboratories. The target, consisting of (3269 ± 24) kg of liquid argon, is hosted by an 85 cm radius spherical vessel, filling it up to 550 mm from the equator [1]. When an incident particle scatters on the argon, it induces an excited argon dimer state, whose de-excitation results in scintillation light, which is detected by the 255 photomultipliers tubes (PMTs) coupled to the inner vessel through light guides. The space within the light guides is filled with high-density polyethylene and polystyrene filler blocks, serving as passive neutron shields. A 3-μm-thick layer of 1,1,4,4-tetraphenyl 1,3-butadiene (TPB, $C_{28}H_{22}$) is evaporated on all the inner surfaces to shift the argon scintillation light, peaking at 128 nm, to 420 nm, where the PMTs detection efficiency is higher. The top neck, breaking the spherical symmetry, hosts the cooling coil and allows for operations inside the inner vessel. The neck and the inner vessel are contained in a 2.5 m radius stainless steel shell, which is placed in a 7.8 m diameter cylindrical tank filled with ultra-pure water and instrumented with 48 PMTs, serving as active muon veto.

2. The WIMP search

The experiment is designed to perform the direct detection of Weakly Interacting Massive Particles (WIMPs), dark matter candidates thermally decoupled from baryonic matter during the expansion of the primordial Universe. Considering the extremely low interaction cross-section expected from WIMPs, a large exposure and an extremely low background level are the driving needs behind the design of any direct detection experiment such as DEAP-3600. The set in underground labs allows for strongly reducing cosmic rays-induced backgrounds from the atmosphere, with muon fluxes as low as $(3.31 \pm 0.1) \times 10^{-10}$ cm^2/s at SNOLAB [2]. Specifically, neutrons produced by muon spallation on the rock can mimic the signal of a WIMP scattering on the argon nucleus. Both these backgrounds are rejected by removing any event in the argon happening in coincidence with the muon veto.

The argon scintillation process allows for a unique rejection power against γ-rays and the β-particles released by the the detector material. Indeed, both β-particles and γ-rays induce electronic recoils in argon, while WIMPs and neutrons create nuclear recoils. Nuclear recoils excite the singlet excited state (with a livetime τ_s = 8.2 ns) more frequently than the triplet (τ_t = 1.445 μs) [3]. Consequently, the photoelectron time distribution, i.e., the pulse shape, dramatically depends on the specific particle inducing the argon recoil. The high statistics from ^{39}Ar β-particles allowed for full modeling of the detector response, including the scintillation light, the PMT dark and correlated noise, as well as the late scintillation from TPB [3]. Thanks to the three orders of magnitude between the two excited states' livetimes, it was shown that the pulse-shape discrimination (PSD), parametrized by the fraction of the prompt scintillation light F_{prompt}, holds a rejection power of about 10^{-10} at 18 keV$_{ee}$ (electron-equivalent) for 50 % nuclear recoil acceptance [4].

While α-induced argon recoils give MeV-scale energy deposits, argon recoils induced by degraded α-particles, which lose a fraction of their energy before reaching the argon (in the acrylic, for instance), can fall in the WIMP deposited energy range, below about 100 keV. Most of them are rejected by a radial and z-fiducial cut. Still, α-particles can be released by the ^{210}Po in the acrylic flowguides in the neck, giving scintillation light which gets shadowed by the neck geometry, reflected at the liquid-gas interface and finally collected by the PMTs. These events are efficiently rejected according to their pulse shape and the light distribution in the top PMT rings. Thanks to the experiment exposure and the low background level achieved in the detector, the WIMP search over 231 days could exclude them down to 3.9×10^{-45} cm^2 at 100 GeV/c^2 within 90 % C.L. for the spin-independent interaction [5].

In this search, the interaction is described by the spin-independent, parity-even interaction $O_1 = 1_\chi \cdot 1_N$. The same exclusion limits have also been reinterpreted within the Non-Relativistic Effective Field Theory (NREFT), as well as non-standard kinematics of the dark matter halo due to the galactic substructures such as past galactic mergers or in-falling clumps, as for instance shown in Figure 1 for Enceladus substructure. Additionally, each interaction was evaluated for both isospin-conserving and isospin-violating scenarios. Within this context, DEAP-3600 could set the world-leading exclusion limits for xenon-phobic dark matter heavier than 100 GeV/c^2 [6].

Besides WIMPs, DEAP-3600 has demonstrated world-leading sensitivity to multi-scattering,

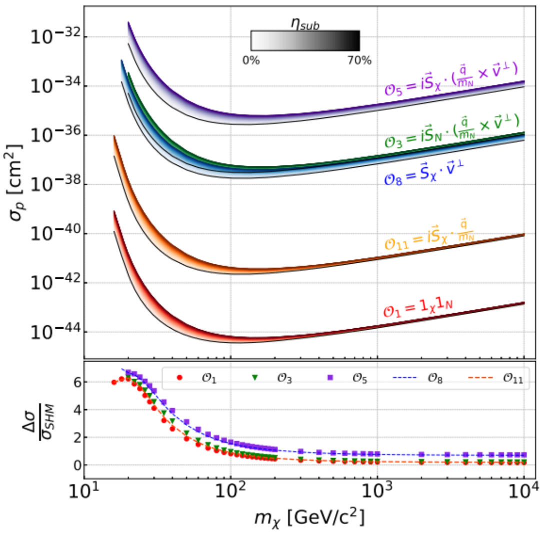

Figure 1: WIMP exclusion limits in terms of the NREFT operators relevant in argon, assuming that a fraction η_{sub} of the total dark matter is in the Enceladus or "Gaia Sausage" galactic substructure, as it is usually referred to [6].

Planck-scale mass dark matter candidates. These are expected in Grand Unification Theories and can be produced in out-of-equilibrium mechanisms in the early Universe. The extremely low background and high exposure allowed for setting world-leading exclusion limits for dark matter candidates at Planck-scale masses, shown in Figure 2 [7].

The next fill of the detector is scheduled to start in early 2025, with two major upgrades expected to strongly improve the sensitivity and inform background expectations in future argon-filled experiments, such as DarkSide-20k and ARGO. To improve the rejection of α-decays in the

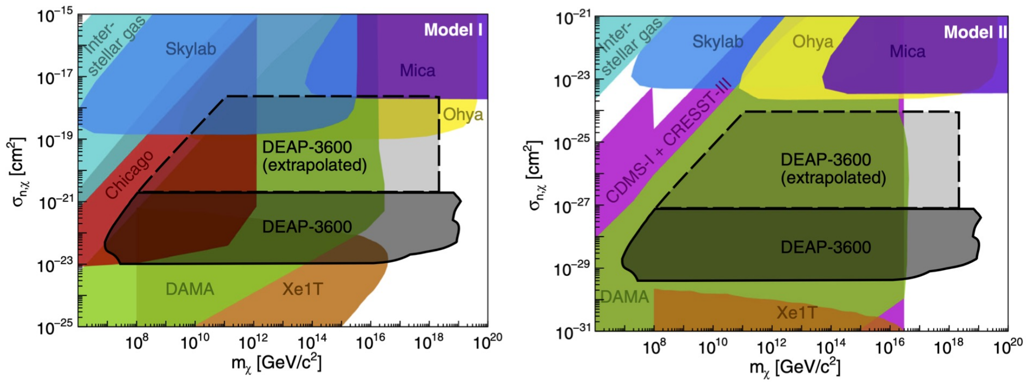

Figure 2: Exclusion limits set on two composite dark matter models after the unblinding of three years of data with a livetime of (813 ± 8) live-days. With a background level of (0.05 ± 0.03) events, no event was found after the unblinding, allowing for excluding Planck-scale dark matter candidates [7].

neck of the detector, pyrene-coated flowguides have been installed in place of the original ones. Pyrene is, in fact, a wavelength shifter with an average re-emission time of about 300 ns. This strongly slows the photoelectrons from the α-decays in the neck of the detector, allowing for their efficient pulse-shape discrimination [8].

The other significant background found during the second fill, which limited the WIMP search so far, has been α-decays embedded in dust mixed into the liquid argon. According to the most recent models, dust with a diameter between 5 μs to 45 μs can release degraded α-particles, which then scintillates on the argon condensed on the dust floating in the argon target. More studies are ongoing to better model and reject this background, which is expected to be significantly suppressed in the third fill dataset thanks to the argon extraction and filtration system installed in 2023.

3. Deep into the argon physics

The high statistics available in 3.3 tonnes of argon allow for a deeper understanding of the expected background and the argon response, which will inform future detectors filled with argon. The first effort on this track has been the precise evaluation of the ^{39}Ar specific activity. This is defined as

$$S_{Ar-39} = \frac{N}{T_{live} \cdot m_{LAr}} \tag{1}$$

where N is the number of ^{39}Ar β-decays observed within a liquid argon mass m_{LAr} along a dataset with a livetime T_{live}. The mass is evaluated from the fill level and the acrylic vessel's inner radius. The latter was found to be (845.6 ± 0.9) mm according to the measurements performed during the construction and after correcting for the acrylic thermal contraction at about 87 K. The fill level is evaluated by comparing the photon distribution along each PMT ring with Monte Carlo simulations for different fill levels. The best fit is found for a fill level of (550 ± 10) mm above the equator.

The number of events N is given by single β-induced recoils happening within the acquisition window (N_{single}) togethter with pile-ups, events having two or more recoils ($N_{pile-up}$), as evaluated from the fit on the electromagnetic spectrum, performed run-by-run, as shown in Figure 3. For a resulting livetime T_{live} = 167 days, the specific activity is found to be $(0.964 \pm 0.001_{stat} \pm 0.024_{sys})$ Bq/kg$_{LAr}$, resulting in the most precise measurement ever performed [9].

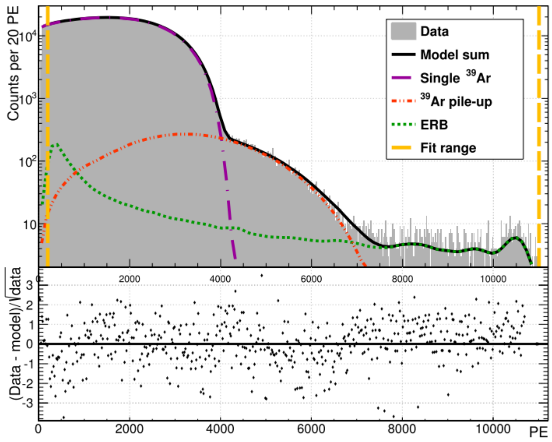

Figure 3: Example fit for a 28.5 h long run, including single ^{39}Ar events, the residual electromagnetic background (ERB) after the selection cuts and the ^{39}Ar pile-ups, including events with two and three β-particles, one β particle together with any γ-ray released by the inner detector radioactivity, or a β-particle together with a high-F_{prompt} event due to Cerenkov light shining in the TPB or a nuclear recoil [9].

The argon response due to α-particles has been recently under investigation, being α-decays in the neck and α-decays embedded in the dust the main backgrounds affecting the experiment sensitivity during the second fill. The quenching factor is defined as

$$Q = \frac{PE}{Y \cdot E_{dep}} \tag{2}$$

where PE is the number of recorded photoelectrons, and Y is the scintillation yield for a deposited energy E_{dep}. Three points are used to frame the α-particles quenching in argon. One comes from the experimental measurement for ^{210}Po from Doke et al [10], giving (0.710 ± 0.028) at 5.305 MeV. Two more points are added using DEAP-3600 data of ^{218}Po, giving (0.712 ± 0.001) at 6.002 MeV, and ^{214}Po, giving (0.716 ± 0.003) at 7.686 MeV; both have been measured relatively to ^{222}Rn, to suppress any impact due to non-linearities in the light detection efficiency observed at a few MeV of deposited energy. The extrapolation down to keV-scale energy, where the degraded α deposits are observed in the experiment, is evaluated as the product of the nuclear and electronic components. The nuclear quenching factor is modeled with the TRansport of Ions in Matter (TRIM) simulation [11], reproducing the loss in ionization, phonon generation and radiation damage for α-particles in the range (10 keV-10 MeV). By fitting Birks's law with the three mentioned data points, the electronic quenching is extrapolated down to 10 keV. The resulting quenching factor is reported in [12]. More measurements are foreseen in local institutions to constrain further the uncertainties at the keV-scale for future argon-filled detectors.

4. Next steps

The experiment is currently finalizing the next WIMP search, performing a Profile-Likelihood Ratio search on the full second-fill dataset, considering all the mentioned backgrounds. Additional MeV-scale searches are now underway after the cutting-edge search for heavy, multi-scattering dark matter. While the 5.5 MeV solar axions search is under review, the first search for electron neutrino absorption in argon addresses the unblinding process. The impact of such a search goes beyond our experiment, as this process is at the very base of the supernova neutrino detection in DUNE, and it eventually increases the sensitivity of DarkSide-20k outer veto, promising a broader physics program within the Global Argon Dark Matter Collaboration.

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References

[1] P.A. Amaudruz *et al* (DEAP Collaboration), *Astroparticle Physics*,108, 1-23(2019).

[2] B. Aharmim *et al* (SNO Collaboration) *Phys. Rev. D 80, 012001* (2009)

[3] P. Adhikari *et al* (DEAP collaboration), *Eur. Phys. J. C*, 80 303 (2020).

[4] P. Adhikari *et al* (DEAP collaboration), *Eur. Phys. J. C*, 81 823 (2021).

[5] R. Ajaj *et al* (DEAP collaboration), *Physical Review D, 100, 022004* (2019).

[6] R. Ajaj *et al* (DEAP collaboration), *Phys. Rev. D 102, 082001* (2020) *Erratum Phys. Rev. D 105, 029901* (2022).

[7] P. Adhikari *et al* (DEAP collaboration), *Physical Review Letters, 128, 011801* (2022).

[8] D. Gallacher A. Leonhardt, H. Benmansour, E. Ellingwood,Q. Hars *et al Nucl. Instrum. Meth.A 1034* (2022)

[9] P. Adhikari *et al* (DEAP collaboration), *Eur. Phys. J. C* (2023)

[10] T. Doke *et al Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 269(1), 291* (1988).

[11] J.F. Ziegler, J.P. Biersack, *Springer US, Boston, MA, 1985*

[12] P. Adhikari *et al* (DEAP collaboration), *arXiv:2406.18597*(2024).