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First direct detection constraints on Planck-scale mass dark matter in DEAP-3600

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Several astrophysical observations suggest that about 27 % of all the energy in the Universe is due to a non-luminous, non-relativistic kind of matter, the "dark matter". Among all the possible models that can fulfill the observed abundance, one of the most promising are Weakly Interacting Particles (WIMPs), thermal relics with masses below 100 TeV. Despite the high number of attempts during the last two decades to directly detect WIMPs, no confirmed discovery has been made. Hence, the interest in other dark matter candidates has recently increased, even motivating the search for super-massive dark matter candidates. These dark matter candidates might have been produced non-thermally, as radiation from primordial black holes, decay products of the inflaton, or as products of a dark sector with an extended thermal production mechanism. DEAP-3600, with a target of 3.3 tonnes of liquid argon, is the largest running direct detection experiment in terms of size. Though it is designed for the WIMP search, it is also sensitive to candidates with masses from 10^7 GeV to 10^{19} GeV. Due to the high cross-section and the large area of the detector, the expected signal is a track of collinear nuclear recoils, different from both WIMPs and most of the backgrounds. This motivated the development of a custom analysis, looking for a multi-scattering dark matter signature. Thanks to the quality of the selection cuts, four different Regions of Interest have been defined, each with a background level of much less than one event in three years of data taking. After the unblinding, no events were found; consequently, world-leading constraints on two composite dark matter models, up to Planck-scale masses.

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1. Introduction

DEAP-3600 experiment, set 2 km underground at SNOLAB, is designed for the direct detection of Weakly Interacting Massive Particles (WIMPs), one of the most promising cold dark matter candidates. The target consists of (3279 ± 96) kg of liquid argon, which fills the inner vessel detector up to 551 mm from the equator [1]. When an incident particle scatters on the argon, it goes into an excited dimer state, which can be either a singlet or triplet state, having 8 ns and 1.4 μs time decays, respectively [2]. The scintillation light is collected by the 255 photomultipliers tubes (PMTs) coupled to the inner vessel through light guides. The PMTs are set in the inner surface of a stainless-steel shell, which is submersed in a cylindrical tank filled with ultrapure water.

2. Entering the multi-scatter game

The usual assumption standing on the very base of the WIMP search is that the signal can at most perform one scatter in the target volume due to the low expected WIMP-nucleon elastic scattering cross-section, which was excluded down to 3.9×10^{45} cm^2 at 100 GeV/c^2 within 90 % C.L. in DEAP-3600, for the spin-independent interaction [3]. WIMP candidates are modeled as thermal relics from the early universe; such low cross-sections also imply WIMPs masses below about 10^5 GeV so as not to incur in dark matter overabundance today. Still, Grand Unified Theories allow for much heavier dark matter to be produced in out-of-equilibrium mechanisms, like from the decay of the inflaton, or as thermal production in a secluded sector, via gravitational production, or even as a relic from a weakly-haired primordial black hole [4]. Such candidates can be as heavy as Planck-scale masses; consequently, their direct detection is mainly limited by the low dark matter flux. To compensate for that, ultra-heavy dark matter candidates can be searched in DEAP-3600 at a much higher nucleon cross-section, at about 10^{-25} cm^2. A Monte Carlo simulation was performed to evaluate the kinetic energy loss of the candidates due to the scatterings with the atoms in the atmosphere and the Earth before reaching the underground detector. If the particle enters the inner vessel, it performs a collinear track of nuclear recoils, each giving O(40) keV of deposited energy, of which only about 25 % is detected, whereas the remnant is lost as heat. Such a multi-scatter signal gives a unique signature in the detector, opposite to the one in the WIMP search, and indeed eventually rejected in past dark matter searches in the experiment, looking for a single-scatter event. The photoelectron time distribution for two simulated events is given in Fig. 1, together with the values of the key features for multi-scatter signals in DEAP-3600, for two representative cross-sections, both for a candidate mass of $m_\chi = 10^{18}$ GeV. The number of reconstructed photoelectrons (PE) increases with the cross-section, which is indeed proportional to the number of scatterings along the argon target. F_{prompt} is the pulse shape discrimination parameter in DEAP-3600, optimized to reject background events from WIMP events by looking at the fraction of the prompt scintillation light [5]. N_{peaks} is the number of dominant peaks along the photoelectron time distribution, which is determined according to the local time derivative.

This variable was designed to reject WIMP single-scatter events from "pile-up" background events, where two or more recoils happen in the same acquisition window. As detailed in [6], F_{prompt} decreases as the dark matter-nucleus cross-section and the number of photoelectrons increases. Indeed, as the number of pulses in the same event rises, the fraction of photoelectrons inside the time prompt window goes down. In parallel with this, N_{peaks} decreases as the pulses start merging, making it more and more unlikely to record outstanding peaks with respect to the others. These events can still be identified as the signal due to the high number of PE.

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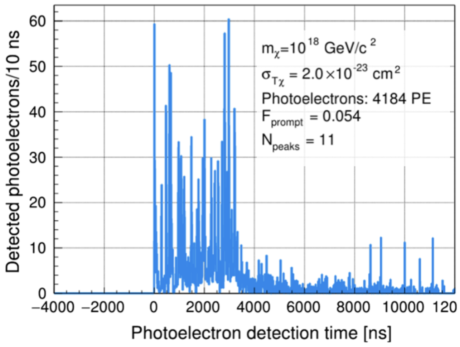

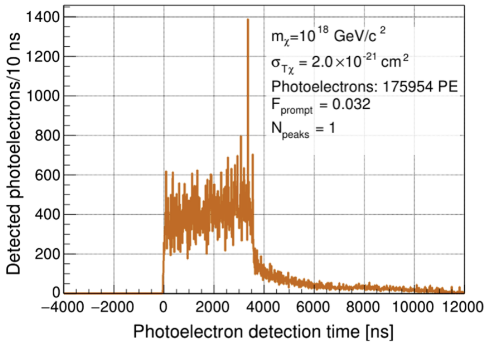

Figure 1: Simulated photoelectron time distribution for two ultra-heavy dark matter candidates at 2.0×10^{-23} cm^2 (Left) and 2.0×10^{-21} cm^2 (Right), both for a candidate mass of 1.0×10^{18} GeV/c^2.

3. Backgrounds and selection cuts

The present analysis was performed as a blind search on the data acquired from November 4, 2016, until March 8, 2020. Four regions of interest (ROIs) are determined according to their energy range and the consequent PE range, together with the custom-developed selection cuts in N_{peaks} and F_{prompt}. In DEAP-3600, the most present backgrounds are the argon recoils due to the βs released by ^{39}Ar, in the argon bulk, usually rejected in the WIMP search thanks to the pulse shape discrimination. Any single scatter events can, in principle, be rejected from the multi-scattering dark matter by requiring $N_{peaks} > 1$. Still, βs, as well as γs released by the inner detector materials, can pile-up in the same acquisition window, overlapping with the multi-scatter dark matter signal. Thanks to the knowledge on the βs and γs background in DEAP-3600 [7], and by assuming that the number of pulses in one pile-up event follows a Poisson statistics, the threshold on N_{peaks} is set according to the specific energy range. Thanks to the pile-up events from an Americium-Beryllium calibration run, the validation of such an approach was performed up to 10 MeV of observable energy; below this energy range, the selection cut in N_{peaks} determined three ROIs [6]. The ROI 4 extends above 10 MeV up to the maximum energy scale at which the DAQ could be calibrated with a light injection system, about 60 GeV of observable energy. At such high energies, the pile-up events are negligible in three years of data due to the decisive decrease of the neutron capture γs. The left background events are muon events entering the liquid argon vessel. These are successfully rejected as events in coincidence with a trigger in the water tank surrounding the detector. This had no impact on the signal acceptance, as the candidates are not relativistic. To further reduce the background level, an upper selection cut on F_{prompt} is applied. The left background level after the selection cuts is found to be much less than one event for each ROI, allowing for the blind analysis with a data lifetime of (813 ± 8) days.

4. Reaching the Planck scale dark matter mass

After the unblinding procedure, no event was found in all the ROIs. Fig. 2 shows the exclusion limits within 90 % C.L. set for two dark matter composite models. Specifically, Model 1 assumes a composite candidate opaque to the argon nucleus; the reported exclusion limits can also be reinterpreted for strongly interacting dark matter candidates. Model 2 is instead referred to as "dark nuggets", where the scattering on the argon is sensitive to the structure of the dark nucleus with its dark nucleons. More details on the specific models can be found in [6]. The left edge on the exclusion limits in Fig. 2 corresponds to the mass at which 90 % of the signal would release 1 MeV

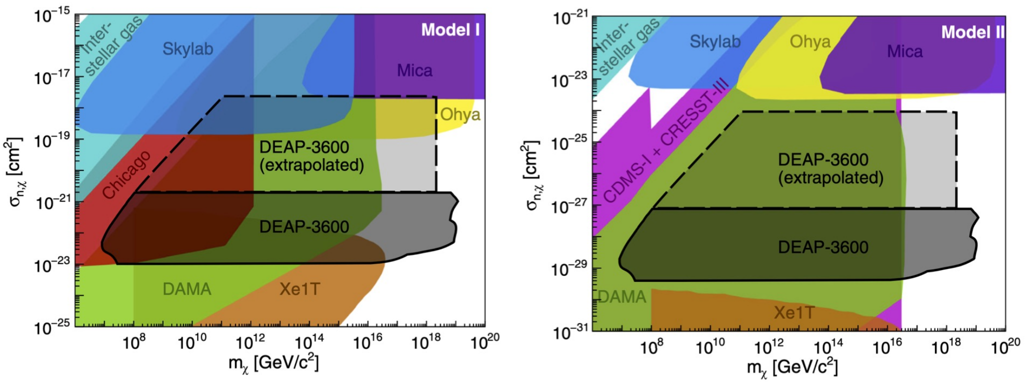

Figure 2: Exclusion regions within 90 % C.L. for two different composite dark matter candidates.

of observable energy, so when the overburden is starting sensibly affecting the kinetic energy of the incident dark matter particles. The bold straight line represents the highest cross-section that could be simulated, $\sigma_{n-\chi}^{max}$. At higher cross-sections, both the lack of calibrations and computational limits impeded the evaluation of the signal acceptance from the simulations, which was extrapolated at 35 %, determining the light grey excluded area in Fig. 2. Thanks to the detector exposure and the custom-developed analysis here briefly resumed, DEAP-3600 is the first experiment that could exclude dark matter candidates up to the Planck scale masses [6].

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