EPJ Web of Conferences **280**, 06003 (2023) https://doi.org/10.1051/epjconf/202328006003
RICAP-22

Direct Detection of Dark Matter with DarkSide-20k

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Abstract. DarkSide run since mid 2015 a 50-kg-active-mass dual phase Liquid Argon Time Projection Chamber (TPC), filled with low radioactivity argon from an underground source and produced world class results for both the low mass (< 20 GeV/c^2) and high mass (> 100 GeV/c^2) direct detection search for dark matter. The next stage of the DarkSide program will be a new generation experiment involving a global collaboration from all the current Argon based experiments. DarkSide-20k, is designed as a 20-tonne fiducial mass dual phase Liquid Argon TPC with SiPM based cryogenic photosensors, and is expected to be free of any instrumental background for an exposure of >100 tonne year. Like its predecessor, DarkSide-20k will be housed at the INFN Gran Sasso (LNGS) underground laboratory, and it is expected to attain a WIMP-nucleon cross section exclusion sensitivity of 7.4×10^{-48} cm^2 for a WIMP mass of 1 TeV/c^2 in a 200 t yr run. DarkSide-20k will be installed inside a membrane cryostat containing more than 700 t of liquid Argon and be surrounded by an active neutron veto based on a Gd-loaded acrylic shell. The talk will give the latest updates of the ongoing R&D and prototype tests validating the initial design. A subsequent objective, towards the end of the next decade, will be the construction of the ultimate detector, ARGO, with a 300 t fiducial mass to push the sensitivity to the neutrino floor region for high mass WIMPs.

1 Direct Dark Matter Search with Liquid Argon

There is strong evidence from astronomical and cosmological observations for the existence of dark matter in our Universe. Weakly Interacting Massive Particles (WIMPs) are a well-motivated dark matter candidate that may have been produced in the early Universe and would show the correct relic abundance observed today. They are however so weakly interacting that they have yet to be observed in a terrestrial experiment. Earth-based direct detection experiments aim at detect galactic dark matter particles via their interaction with ordinary matter in an instrumented target. Noble liquid detectors, in the dual phase Time Projection Chamber (TPC) layout, are particularly suitable for these searches, thanks to scalability, intrinsic radio-purity and good ionization and scintillation properties of the target. The TPC consists of an active volume filled with liquid, which is immersed in a uniform electric field, to drift ionization electrons towards a gaseous region on top of the detector, where charges are accelerated to stimulate light production by electro-luminescence. Photo-detectors collect both the prompt scintillation light produced in liquid (S1), and the delayed electro-luminescence light (S2) generated in gas, allowing for energy measurement and 3D vertex reconstruction.

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 https://doi.org/10.1051/epjconf/202328006003

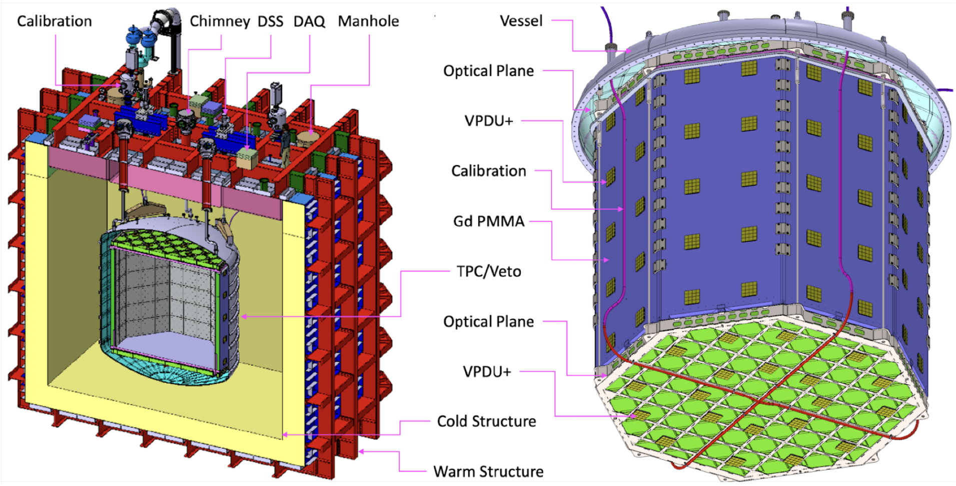

Figure 1. Schematics of the whole DarkSide-20k experimental setup to be installed in Hall C at LNGS (left). A closeup of the inner detector is shown on the right.

In addition to this, liquid argon (LAr) has excellent event discrimination capabilities: scintillation light initiated by particles recoiling from atomic electrons, that is the primary source of background in a WIMP direct detection experiment, has a time constant of approximately 1 μs. This is in stark contrast to the nanosecond time constant of scintillation light emitted during an expected WIMP-nuclear recoil event. The DEAP-3600 experiment has exploited this effect via pulse shape discrimination (PSD) to achieve electron recoil background rejection of 2.4×10^8 [1]. DarkSide-50, whose experimental layout is described in [2], has presented results from a 532,4 live-days exposure, and observed no background events over a run period in excess of two years [3]. In addition to sensitivity to WIMPs with masses above 100 GeV/c^2, the two-phase DarkSide-50 detector has extended its reach to WIMP masses below 10 GeV/c^2 by detecting single ionizaton electrons extracted from the liquid argon volume [4–6]. These results were possible as argon extracted from deep underground sources (UAr) was used as the active medium, to avoid the $\sim$ 1 Bq/kg ^{39}Ar activity in atmospheric argon produced by cosmic-ray activation. DarkSide-50 has demonstrated that using underground argon the rate of ^{39}Ar events could be reduced by a factor of 1400 ± 200 [7].

2 The DarkSide-20k detector

The DarkSide-20k detector consists of three nested detectors housed within a ProtoDUNE-style membrane cryostat [8] as shown in the sketch in Figure 1. The inner detector is a dual-phase argon TPC, filled with 49.of UAr. The TPC is inserted in a stainless steel vessel, filled with an additional 36 t of UAr, acting as radiogenic neutron veto. The AAr filling the cryostat (700 t) is instrumented to detect scintillation light from cosmic muons crossing the volume.

2.1 The procurement of Underground Argon

The journey of the DarkSide-20k UAr starts in Cortez, CO. It is extracted from underground as a byproduct of CO_2 in an industrial extraction plant at a rate of 250-330 kg/day, in the

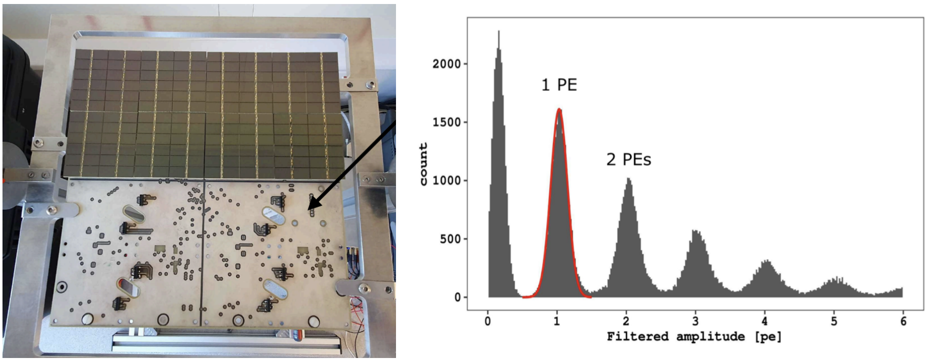

Figure 2. Left: an assembly of 4 PDMs being populated. Right: a typical charge spectrum from a single PDMs, showing the excellent singe photoelectron resolution.

URANIA facility. The expected purity at the output is 99.99%. Once extracted, the UAr will travel to Europe, mainly at the surface level to minimize the s activation during transport. The UAr will reach the Carbosulcis mine, in Sardinia, where the 350 m tall ARIA distillation column will be operated. ARIA will be able to further chemically purify the UAr and removing rare stable isotopes at a rate of 1 t/day [9]. Beyond DarkSide-20k, ARIA has the potential to further reduce the ^{39}Ar content in the target by a factor of 10 by cryogenic distillation at the slower rate of 10 kg/day. A sample of the UAr production will be shipped to the Canfranc Underground Laboratory, where the DArT detector, installed inside ArDM, will be used to characterize the residual ^{39}Ar with target uncertainty of 10 % in few weeks of data taking [10].

2.2 The DarkSide-20k TPC

The active volume of the TPC is defined by eight vertical reflector panels (1.5 m wide, 3.5 tall) and the top and bottom windows of the acrylic vessel. The top and bottom caps of the vessel are made of ultra-pure acrylic (PMMA), while the lateral walls are made of Gd-loaded acrylic. All the TPC surfaces in contact with the active argon volume will be coated with a tetraphenyl-butadiene wavelength shifter (TPB) to convert LAr scintillation light (at 128 nm) to a wavelength detectable at high efficiency by the light detection planes, made of silicon photomultipliers (SiPMs). The lateral walls are coated, behind the reflector panels, with clevios electrodes, to maintain a uniform 200 V/cm drift field in the bulk. A transparent clevios coating is present also on the inner surfaces of top and bottom windows, to make anode and cathode of the drift cage. A steel mesh is positioned 1 cm below the top window, to generate the strong electric field required for the extraction of ionization electrons in the gaseous phase (7 mm thick).

2.3 The photo-detector systems

The light detection system is made of 2112 SiPM-based Photodetector Modules (PDMs), viewing the argon volume through the top and bottom windows of the acrylic vessel. The the light detection system must satisfy stringent performance requirements in order to meet the physics goals of the experiment. The choice of SiPMs is motivated by the numerous advantages of SiPMs compared to traditional photo-multipliers: the higher photo-detection efficiency (typically exceeding 50% at 420 nm), the superior single electron resolution, the lower operation bias voltage (< 100 V) and the smaller amount of required material, making them potentially extremely radio-pure. Several years of R&D within the Collaboration allowed to overcome the challenges related to this technology. These are: the coverage of large areas with small devices (individual SiPMs usually don't exceed the ~cm scale, due to the large capacitance per unit area responsible for slowing down the signal); and the high dark noise rate, solved by adopting the NUV-LF technology developed at FBK [11].

Each TPC PDM consists of 4 tiles of grouped SiPMs, covering a total area of 100×100 mm^2 operated as a single detector. Besides the tile, each module will also contain a cryogenic preamplifier board that will amplify and shape the signal in the immediate proximity of the sensor. In order to maximize the amplification factor while preserving a stable signal bandwidth and SNR, the Collaboration has developed and optimized a transimpedance amplifier with excellent performance at 87K. Figure 2 (left) shows one prototype assembly of 4 PDMs partially populated.

The proposed configuration matches all the performance requirements and the Collaboration is currently entering the mass production phase of these devices, foreseen at the NOA facility (Nuova Officina Assergi) at LNGS.

2.4 The radiogenic neutron veto

Neutrons are one of the most dangerous background to WIMP searches, as their signature can mimic that of the expected signal. Detailed simulations show that the combined use of Gd-loaded acrylic and an instrumented UAr volume surrounding the TPC, can reduce the radiogenic neutron background by a factor of ~ 10. Gadolinium is widely used for neutron tagging due to the high neutron capture cross section and the large amount of energy released after a neutron capture event (~ 9 MeV). The typical capture time of neutrons in the Gd-loaded acrylic is $\tau_c < 50\mu$s. The neutron background is efficiently suppressed if coincident energy deposits are observed in both the TPC and the surrounding UAr. The UAr volume surrounding the TPC is instrumented with 480 SiPM-based light detectors, distributed uniformly on the surfaces. The inner surfaces are covered with PEN sheets (acting as wavelength shifter) and Tyvek reflectors. This will enable to efficiently collect the scintillation lights from energy deposits in the UAr, with a light yield of about 2 PE/keV.

The Collaboration pioneered the development of Gd-loaded acrylic and identified, in combination with industrial partners, a strategy to produce 17 cm thick acrylic panels, with satisfactory Gd-loading uniformity (at 1% concentration) and meeting the required specifications in terms of radio-purity. These panels will be used to build the TPC barrel and the top and bottom cap of the neutron shield, to guarantee 4π shielding of the active volume.

3 Projected sensitivity

The sensitivity projections for DarkSide-20k, planned to start taking data in 2026, are show in Fig. 3. These are obtained with a Profile-Likelihood Ratio approach, where signal form spin-independent DM-nucleus interactions is compared to the expected backgrounds from radiogenic neutrons and coherent elastic neutrino-nucleus scattering (domainated by the contribution from atmospheric neutrinos). The electron recoil backgrounds (induced by β-decays and γ-ray interactions) are efficiently removed by the powerful PSD, which sets the acceptance to nuclear recoil backgrounds and signal. The projections are shown for two scenarios: one which only uses the events occurring in the innermost 20.2 t fiducial volume; and one which uses nearly the whole active volumes. The sum of NR backgrounds is expected to be

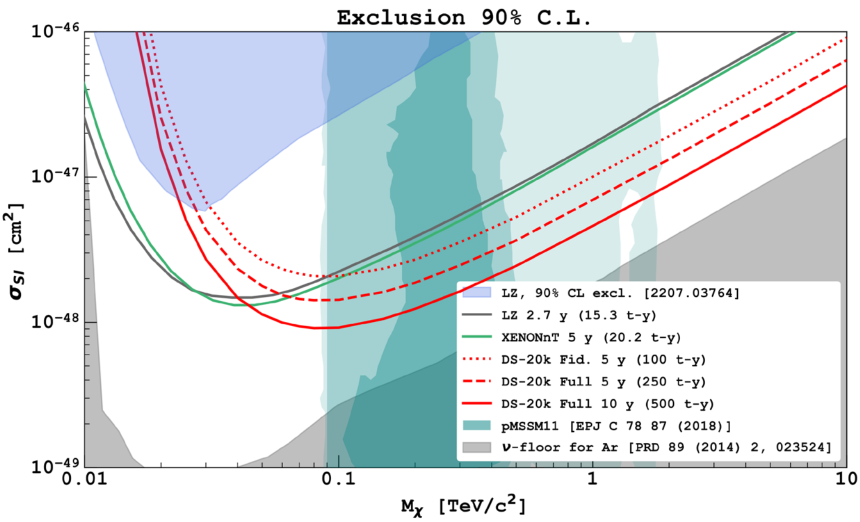

Figure 3. Projected 90% CL exclusion sensitivity for the Darkside-20k experiment for the spin-independent WIMP-nucleon cross section σ_{SI} as function of the WIMP mass M_χ, compared to existing constraints from LZ [12] and the projected sensitivities for XENON-nT [13] and LZ [14]. The shaded grey area represents the neutrino floor, while the teal shaded area show the parameter space favored by the pMSSM11 model [15].

< 0.1 events in a 5 yr exposure in the FV, while neutrinos will contribute to 1.7 ± 0.3 events. The full volume analysis accounts for higher backgrounds according to the weaker fiducialization, and it is shown for a 5 and a 10 yr lifetime run.

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