DIRECT SEARCHES FOR COLD DARK MATTER IN DarkSide-20k*

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The DarkSide scientific program concentrated on the dark matter search using low-radioactivity argon proposes the new generation DarkSide-20k detector as a next step. For this purpose, the Global Argon Dark Matter Collaboration was formed by joining together main current argon-based experiments. The DarkSide-20k detector is designed as a 20 tons fiducial mass liquid argon Time Projection Chamber capable of identifying nuclear recoils from WIMP over the course of a very large exposure. It will be using custom-designed large area cryogenic silicon photo-multiplier's arrays as a light detection system. Additionally, a huge effort to limit the radioactivity sources in construction materials and procedures is undertaken to fulfill the 'background free' operation goal. The construction is about to start in the INFN-LNGS underground laboratory in Italy. Due to its unique light emission properties and pulse shape discrimination abilities, liquid argon can provide excellent sensitivity for WIMP collisions and strong background suppression. The proposed experiment will reach the cross section *versus* mass range in the search for dark matter of 6.3×10^{-48} cm^2 for the 90% C.L. exclusion significance for a 1 TeV/c^2 WIMP after a 200 t yr exposure. This will allow DarkSide-20k to discover, confirm, or exclude the WIMP dark matter hypothesis down the so-called neutrino floor barrier.

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1. Dark matter searches with liquid argon

The discovery of WIMPs (weakly interacting massive particles) would certainly be a milestone in the history of physics. A large number of astronomical observations indicate that the known matter accounts only for a small fraction of the observed mass-energy of the Universe. This observed excess is called "dark matter" and it is hypothesised to be made of a new

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type of elementary particles. It is thought that new kinds of weakly interacting particles which are carrying a mass in the TeV/c^2-range, therefore, visible in gravitational observations, are a good candidate for such a dark matter. They could be a thermal relic of the Big Bang and they must differ from the ordinary known matter. The significance of dark-matter search is reflected in several decades of worldwide efforts to build larger and increasingly sensitive dark-matter detectors. However, direct detection has not yet been achieved.

Noble liquid experiments lead the field for earth-based direct detection of WIMP dark matter, with XENON1T [1] being currently the most sensitive. These experiments take advantage of large targets, collecting scintillation light emitted by argon dimers excited by passing charged particles. Liquid Argon (LAr), due to its unique light emission properties, can provide excellent sensitivity for WIMP-nucleus collisions and strong background suppression. Scintillation light in LAr generated by particles recoiling from atomic electrons differs significantly in the time constant (microseconds, background events) from the scintillation light emitted during an expected WIMP-nuclear recoil event (nanoseconds, signal events). The DEAP-3600 experiment has exploited this effect via pulse shape discrimination (PSD) techniques achieving high electron recoil background suppression of 2.4×10^8 [2, 3]. Additionally, event discrimination in an argon-based detector was demonstrated by the DarkSide-50 experiment [4, 5]. It is a two-phase time projection chamber filled with underground argon in order to avoid the 1 Bq/kg activity from ^{39}Ar in atmospheric argon. The detector design allows to measure both the prompt argon scintillation light and the delayed signal from the ionized electrons by electro-luminescence in the strong electric field in the gas phase. DarkSide-50 using 532 live-days exposure results [6] demonstrated the 'background free' operation observing no background events over a run period in excess of two years.

Liquid argon is a particularly favorable target for the detection of WIMPs thanks to its excellent event discrimination capabilities. The DarkSide-20k (DS-20k) experiment is a bold idea to continue the effort in the LAr-based experiments on a much larger scale of tens of tons of active LAr volume. The design and current status of this project are described in the following sections.

2. The Global Argon Dark Matter Collaboration and DarkSide-20k

While any dark matter discovery will require confirmation by other experiments using different targets, liquid argon has several advantages as a target material already demonstrated in a series of LAr-based experiments. Therefore, scientists from all of the major groups currently using liquid argon to search for dark matter, including ArDM, DarkSide-50, DEAP-3600, and MiniCLEAN [7], have joined to form the Global Argon Dark Matter Collaboration (GADMC) with a goal of building a series of future experiments that exploit the advantages of LAr as a detector target to a maximum. The Global Argon Dark Matter Collaboration (GADMC) aims to design, construct, assemble, install, commission, and operate the DarkSide-20k experiment in Hall C of the INFN-LNGS. The DarkSide-20k detector in its current design will have ultra-low backgrounds and the ability to measure its backgrounds *in situ*, resulting in an expected 90% C.L. sensitivity to WIMP-nucleon cross sections of 6.3×10^{-48} cm^2 for a WIMP mass of 1 TeV/c^2 with an exposure of 200 t yr run, see Fig. 1.

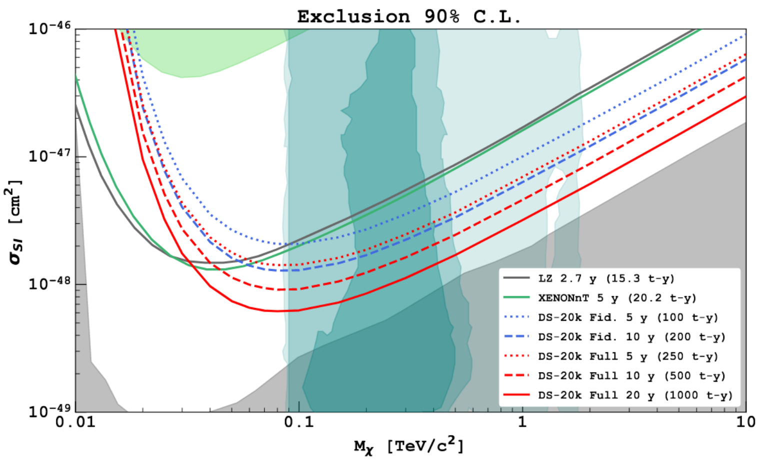

Fig. 1. (Colour on-line) The sensitivity of DS-20k to spin-independent WIMPs 90% C.L. exclusion for hypothetical different lengths of runs shown compared to the nominal sensitivity of currently funded experiments LZ (2.7 yr run, 15.3 t yr exposure) and XENONnT (5 yr run, 20.2 t yr exposure) that are expected to lead the field for high mass WIMPs searches in the next few years. The nominal run time of DS-20k is 10 yr, corresponding to a fiducial volume exposure of 200 t yr. The region excluded by XENON1T is shown in shaded green, the "neutrino floor" for argon in shaded gray, and the turquoise filled contours represent the 1-, 2-, and 3-σ favored regions from the pMSSM11 model constrained by astrophysical measurements and the 36 fbarn LHC data at 13 TeV. (Note: the XENONnT 90% C.L. exclusion curve shown in this plot uses a two-sided test statistic, leading to limits weaker by 30%, as described in [1].)

2.1. DarkSide-20k design

DS-20k is designed to observe dark matter particles scattering from argon atoms in the liquid argon target [8]. The detector is designed to operate for a minimum of 10 years while maintaining a negligible instrumental background level in the WIMP search region of interest, *i.e.* to operate almost background free, meaning that all sources of instrumental background are reduced to less than 0.1 events over a 200 t yr exposure. The background to the dark matter search is dominated by coherent neutrino–nucleus scattering interactions, thus the sensitivity approaches the 'neutrino floor'. The core of the full instrumentation is a dual-phase Time Projection Chamber (TPC) with 51.1 tons LAr mass, instrumented to detect both argon scintillation photons as well as ionization electrons. The TPC is filled and surrounded by low-radioactivity underground argon in which the level of the β radioactive isotope ^{39}Ar is lower by more than a factor of a thousand than the standard argon of atmospheric origin. The dual-phase TPC serves as both the WIMP target and the detector, with a possibility to reconstruct the interaction point in three dimensions. It uses cryogenic Silicon Photomultipliers custom designed and assembled into so-called VPDU+ large (20 cm $\times$ 20 cm) units. These photodetectors are combined in two planes covering the top and the bottom of the TPC to detect the light signals produced by the scattering of a WIMP particle on an Ar atom. Another problematic issue is the trace amount of radioactivity present in the materials used to build the detector or surrounding it as they are potential sources of background. Gammas or neutrons from spontaneous fission and (α, n) interactions can produce a background from more distant sites, while beta and alpha particles produced by a radionuclide decay can typically contribute to the background only if the nuclide is in contact with the LAr target. Therefore, the dedi-

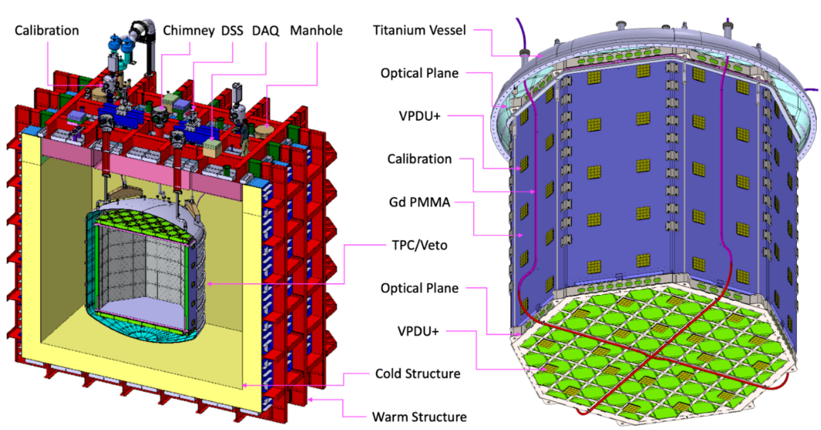

Fig. 2. (Colour on-line) Left: cross section showing the inner detector with the Gd PMMA (gadolinium-loaded polymethylmethacrylate) in green, the titanium vessel in gray. Right: external view of the TPC and Veto showing the full assembly features including VPDU+, Calibration, Optical planes and the Gd PMMA wall structure.

cated materials activity assay campaign is being carried out to assess and minimise this background source. The DS-20k detector unique design integrates the neutron Veto and TPC into one structure enclosed in a titanium vessel filled with underground, low radioactivity argon fully separated from the atmospheric argon in the main cryostat, as shown in Fig. 2.

2.2. Underground argon procurement

As the low-radioactivity argon is a key to the DS-20k scientific goals and strategy, the technology to procure argon from underground (shielded from cosmic activation) sources has been developed to achieve the production rate, *i.e.* tens of tons, necessary for DS-20k. It is also a step to lay the groundwork for future underground Ar procurement for larger argon-based detectors such as Argo. The project consists of three infrastructures: Urania — procurement of argon from underground wells in Colorado, United States; Aria — Seruci-I [9], a 350 m high cryogenic distillation column to further chemically purify argon build in Sardinia; and finally the DArTInArDM detector will measure the ^{39}Ar depletion factor in the underground argon as it is produced, therefore, the argon quality production will be monitored during the production before being shipped to LNGS and DS-20k.

2.3. Status of the project — briefly stated

The R&D phase for the DS-20k detector is completed with a goal to search the "WIMP region" down to the neutrino floor limit. Background reduction techniques both physical including veto systems and minimizing radioactivity from construction materials as well as discrimination analysis methods are tested and implemented. As the design and prototypes were successful, the production of a novel light detection system based on cryogenic SiPM tiles assembled into large VPDU+ units has already started at Nuova Officina Assergi facility at INFN-LNGS in Italy. The underground argon procurement project is ongoing including operation of large facilities such as Urania, Aria, and DArTInArDM. The detector and cryostat prototypes are under construction. The construction of the main DarkSide-20k cryostat will begin in 2022 in INFN-LNGS and the first data are expected to arrive in 2025.

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