PROCEEDINGS OF SCIENCE

The Darkside-20k experiment

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DarkSide-20k is a next-generation multi-ton dark matter experiment currently being built at the INFN Gran Sasso National Laboratory (LNGS). Building on the success of the DarkSide-50 detector, which has been in operation since 2015, DarkSide-20k will feature a dual-phase Liquid Argon Time Projection Chamber (TPC) with a 20-tonne fiducial mass (50-tonne active), designed to achieve unprecedented sensitivity in direct dark matter detection. The experiment incorporates advanced technologies essential for large-scale dark matter searches, including ultra-low-radioactivity underground argon (depleted of ^{39}Ar) and large-area cryogenic Silicon Photomultipliers with custom, compact electronics for light detection. Additionally, a global radiopurity assay program is in place to ensure minimal background contamination in construction materials. The TPC will be housed inside a membrane cryostat containing over 700 tonnes of liquid argon and surrounded by an active neutron veto. DarkSide-20k aims to achieve a WIMP-nucleon cross-section exclusion sensitivity of 6.5×10^{-48} cm^2 for a 1 TeV/c² WIMP over a 200 tonne-year exposure, with no instrumental backgrounds. This work will provide updates on the ongoing construction and the current status of the DarkSide-20k project, along with a discussion of its expected sensitivity

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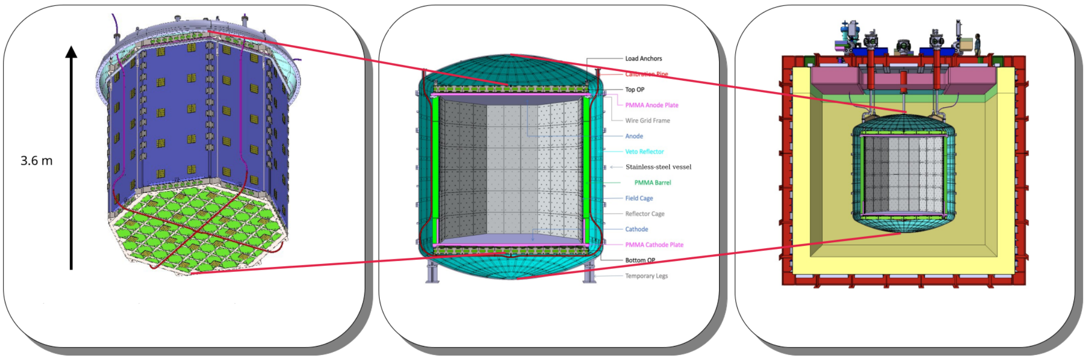

Figure 1: DS-20k design, from left to right: dual-phase TPC, neutron veto and muon (cosmic) veto

1. DarkSide-20k overview

The presence of dark matter (DM) in the universe is supported by many observations based on gravitational effects [1–3] but its real nature remains unknown. Dark matter may consist of an undiscovered elementary particle [4]. A leading candidate is a Weakly Interacting Massive Particle (WIMP), with a mass ranging from 10 GeV/c^2 to few TeV/c^2. This range is extensively searched for via elastic scattering off atomic nuclei. These searches often use an underground time projection chamber (TPC).

DarkSide-20k (DS-20k) is the next generation of dual-phase liquid argon (LAr) TPCs, currently in construction at INFN Laboratori Nazionali del Gran Sasso in Italy. It is expected to start collecting data in 2027. The detection mechanism relies on the combined observation of the scintillation light (S1) and ionization (S2) signals. It is primarily designed to perform a nearly instrumental background free search for high mass (>10 GeV/c^2) WIMPs. However, it is also expected a sensitivity improvement to light dark matter interaction cross-sections by at least one order of magnitude with respect to DarkSide-50, a first generation dual-phase LAr TPC [5].

DS-20k consists of an inner detector which is a nested integrated design of a neutron veto and the dual-phase TPC. This neutron veto will have ~32 tonnes of Underground Argon (UAr)[1] and will be equipped with ~5 m^2 of Silicon Photo-Multipliers (SiPMs) to actively tag neutron captures. The TPC has a total mass of ~50 tonnes and fiducial mass of ~20 tonnes. Two optical planes covering ~21 m^2 will view the total mass of UAr and drift time of ionized electrons is foreseen to be in the order of few ms. The outer cryostat is designed to operate as an active muon veto and will be filled with ~700 tonnes of atmospheric Argon (AAr). Figure 1 shows the design of the DS-20k detector.

2. WIMP signal and backgrounds

DS-20k is designed to detect the scattering of a WIMP with argon nuclei, looking for a single nuclear recoil with recoil energy between 30 and 200 keV$_{nr}$. The main sources of background are the products of radioactive contamination of the detector components, neutrons and gammas from the rock, cosmic rays and radioactivity of ^{39}Ar. The background arising from γ and β particles

[1] argon extracted from underground CO_2 wells

Background Source	Mitigation Strategy
^{39}Ar β decay	Use underground Ar + Pulse shape discrimination
γ from the rock and materials	PSD + Selection of materials & procedures
Radiogenic neutrons, (α, n) reaction in detector materials	Material screening & selection, MC studies, definition of fiducial volume in the TPC, Veto to reject neutron signals
Surface contamination due to Rn progeny	Surface cleaning, reduce the number of surfaces, installation of Rn abated system
Muon induced background	Cosmogenic veto
Neutrino coherent scattering	Irreducible

Table 1: Sources of background in the WIMP search in DarkSide-20k and its mitigation strategy

can be mitigated by combining the use of UAr, which is depleted in ^{39}Ar, with a pulse shape discrimination (PSD) strategy, as will be discussed in Section 2.1.

Neutrons are the most dangerous background for WIMP search as their interactions can be indistinguishable from a potential WIMP signal. Contaminants in the materials of the detector (primarily ^{238}U and ^{232}Th) generate neutrons through (α, n) reactions. Also cosmic rays can induce neutron production. All detector components have been assayed through three different techniques (ICPMS, HPGE, Po-extraction) to estimate radioactivity budget from U/Th chains and γ emitters (like ^{40}K and ^{60}Co). Protocols are being developed to take the exposure time and surface contamination under control. A key role, to achieve a WIMP search free of instrumental background, is played by the neutron veto. DarkSide developed an innovative veto system, based on an acrylic barrel equipped with a large SiPM array to achieve negligible instrumental background[2] in 200 tonne year, as will be discussed in Section 2.2. A summary of background sources and its mitigation strategy is reported in Table 1

2.1 Low radioactive argon and pulse shape discrimination

One of the sources of background in DS-20k is the decay of the isotope ^{39}Ar which is produced by cosmogenic activation of argon and has an activity of 1 Bq/kg in AAr. The isotope is a β emitter with endpoint of 565 keV and a half-life of 269 years. To reduce this source of background, the inner detector will be filled with low-radioactivity liquid argon extracted from underground wells. The use of underground argon was successfully demonstrated by DarkSide-50, which have run between 2013 and 2018, first filled with atmospheric argon and then with underground argon. DarkSide-50 showed a reduction factor of 1400 in the ^{39}Ar content of UAr with respect to AAr [6].

The underground argon for DarkSide-20k is extracted from a mine in Cortex (Colorado, USA), the plant has been installed and the extraction rate is up to 330 kg/day with a 99.9% purity. After that, the liquid argon is further purified in a cryogenic distillation column (ARIA) located in Sardinia (Italy). The first module was successfully commissioned in 2019, and reduced the isotopic fraction of ^{39}Ar by a factor of 10 per pass, with a production rate of several kg/day [7].

In a dual phase TPC is possible to distinguish between an electron recoil (ER), produced by γ or β, and nuclear recoil (NR), produced by WIMP or neutron. The S2/S1 ratio is higher for an ER

[2]Negligible with respect to the irreducible background from the neutrino coherent scattering on argon nuclei

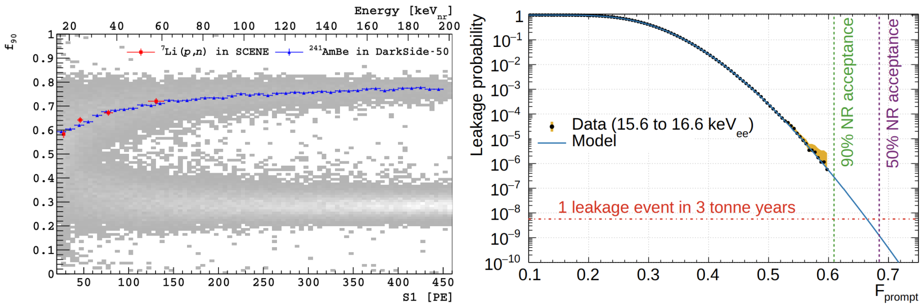

Figure 2: Left: prompt light in 90 ns vs S1 PE in DarkSide-50 [6]. Right: electron recoil leakage in DEAP [9]

than for a NR. An advantage of a LAr TPC is the rejection of ER thanks to the unique time profile of scintillation in liquid argon. When a particle hits an atom of argon, the atom may become excited (and form a dimer) or ionized. The de-excitation time of the dimer depends on its excited state and can be: ∼7 ns (fast signal) for the singlet state or ∼1500 ns (slow signal) for the triplet state. Such a significant difference offers a background discrimination possibility because electron recoils produce slow and fast components in a different proportion than neutron recoils (and WIMPs). The pulse shape discrimination parameter is defined as the fraction of the signal in a prompt window over the full signal time. The prompt window used in DarkSide-50 is 90 ns, instead DEAP used 60 ns. Both experiments, DarkSide-50 and DEAP, successfully demonstrated the capability of a liquid argon TPC to reject electron recoil events, as shown in Figure 2

2.2 Neutron Veto

The DarkSide-20k detector features an innovative design that integrates the neutron veto and the TPC into a single mechanical structure, which is immersed in a low-radioactivity liquid argon bath. The TPC is enclosed within a 15 cm thick shell of polymethylmethacrylate (PMMA), which serves as the neutron veto and is instrumented with SiPM-based light detectors. A neutron-induced WIMP-like event is characterized by a single nuclear recoil with an energy between 30 and 200 keV$_{nr}$ within a 20-tonne fiducial volume. Events depositing more than 50 keV$_{ee}$ in the TPC or 200 keV$_{ee}$ in the Veto, within an 800 μs coincidence window around a WIMP-like event are flagged as neutron-induced

The neutrons are captured on Hydrogen inside the PMMA or on Argon, producing γ's with an energy of 2 MeV or 6 MeV, respectively. Gammas can be detected in the TPC or in the veto bath, as shown in Figure 3.

3. DarkSide-20k expected sensitivity

The combined strategies for background suppression are designed to establish the sensitivity of the experiment in the search for dark matter particles. For the DarkSide-20k detector, this results in a projected sensitivity for a spin-independent WIMP-nucleon scattering cross-section of 6.5×10^{-48} cm^2 for the direct detection of WIMPs with a mass of 1 TeV/c^2 at a 90% confidence level exclusion. This sensitivity reaches the neutrino fog [14] (with expected background events from neutrinos of

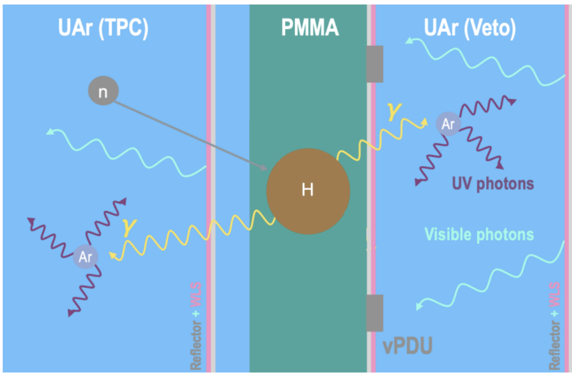

Figure 3: Scheme of neutron veto: a shell of PMMA is placed around TPC and equipped with PDUs. Neutrons captured by H or Ar can be detected in the TPC or in the neutron veto bath.

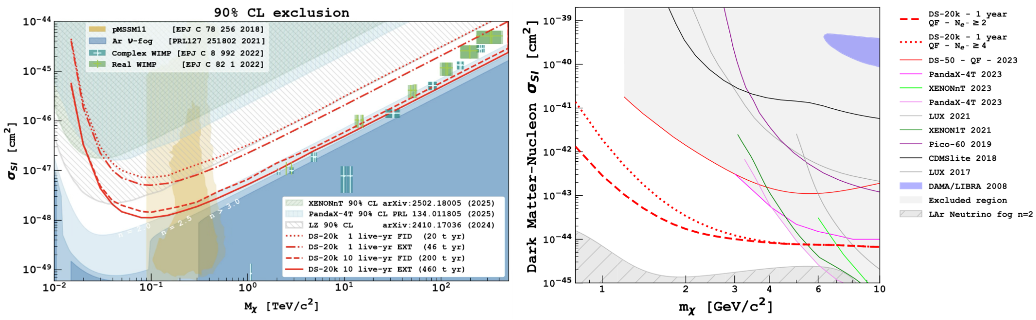

Figure 4: Left: Projected 90% CL exclusion sensitivity for the DS-20k experiment for the spin-independent WIMP-nucleon cross section as function of the WIMP mass. Right: Expected 90% CL exclusion limits for spin-independent Dark Matter-nucleon interactions in DS-20k, considering quenching fluctuations with fit from $N_{e^-} = 4$ and fit from $N_{e^-} = 2$ assuming 1 year of data

3.2 events in 200 tonne x year), as illustrated in Figure 4 (left). In addition to WIMPs, the DS-20k experiment can explore other dark matter candidates, such as light dark matter (LDM) with masses below 10 GeV/c^2, by analyzing S2-only ionization signals [5]. These candidates could interact with shell electrons via processes like absorption, elastic scattering, or inelastic scattering, all of which would lead to the ionization of argon atoms. DS-20k will be sensitive to WIMP-nucleon spin-independent interaction cross-sections below 1×10^{-42} cm^2 for WIMP masses above 800 MeV/c^2 and down to 7×10^{-45} cm^2 at 10 GeV/c^2 as shown in Figure 4 (right). With a full 10-year exposure, the sensitivity of the experiment will reach the neutrino fog around 5 GeV/c^2.

4. Light readout: Large SiPM array

Scintillation light from argon is peaked at 128 nm and a wavelength shifter (WLS) is required for its efficient detection. All the inner surfaces of both the TPC and the Veto detectors are lined with a WLS material. Since the energy threshold and the light yield are critical for the dark matter sensitivity, the TPC uses a vacuum evaporated 1,1,4,4-tetraphenyl-1,3-butadiene (TPB) coating, which has a very high wavelength-shifting efficiency. The Veto light yield requirement is less stringent than that of TPC, allowing choice of polyethylene naphthalate (PEN) material, with less

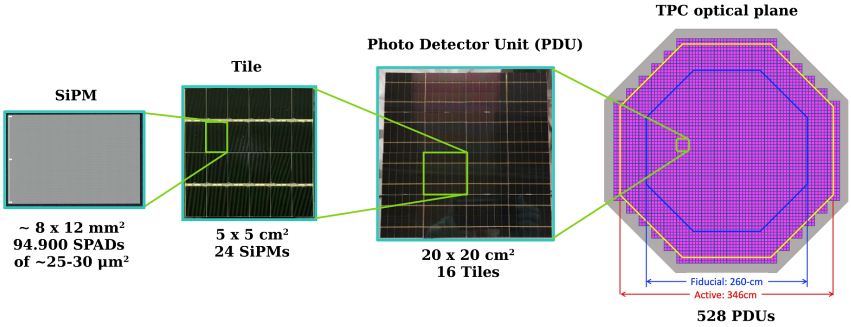

Figure 5: Stages from individual components to the fully assembled PDUs and then the complete optical plane of DS-20k

wavelength-shifting efficiency but available as a large-format polymeric film, which simplifies the production and installation in large surfaces.

The detection of photons after conversion by TPB in the DarkSide-20k experiment relies on Silicon Photomultipliers. SiPMs were chosen as the photon detection technology because of their low intrinsic radioactivity, excellent performance, and compatibility with scalable manufacturing. These photo-sensors are optimized for cryogenic operation and represent the core of the light detection system of the experiment, providing for the detector a Photon Detection Efficiency (PDE) of ~45% [10]. To meet the large-scale optical requirements of DS-20k experiment, a modular and scalable photon detection system called the Photon Detection Unit (PDU) has been designed. Each PDU is a cryogenic-compatible module with a total area of 20×20 cm^2, containing 4 analog readout channels, each of those cover 100 cm^2 of active SiPM area. The PDUs are constructed using tiles, each consisting of 24 SiPMs mounted on a custom PCB in a parallel-series configuration to reduce overall capacitance. A trans-impedance amplifier (TIA) or custom ASIC (for veto systems) processes the signal from the SiPMs into an analog voltage. DarkSide-20k will deploy 528 PDUs in the TPC, providing 2112 readout channels. An additional 150 PDUs, will be installed across the neutron and muon veto systems for light detection. The production of PDUs begins with SiPM wafers mass-produced by LFoundry and shipped to Nuova Officina Assergi (NOA), an established INFN-LNGS facility featuring a 420 m^2 ISO-6 cleanroom equipped for tile and PDU assembly and helping to minimize radio-contamination in DarkSide-20k [11]. From NOA, PDUs are sent to the Photosensor Test Facility (PTF) at INFN-Naples, where they undergo complete testing at room temperature and in liquid nitrogen [12]. Veto PDU production and testing are conducted in parallel by multiple institutions, mainly in the United Kingdom and Poland. Figure 5 depicts the process, from individual components to fully assembled PDUs, and ultimately, the complete DS-20k Optical Plane. Extensive testing of PDUs is being conducted at both ambient temperature and in liquid nitrogen to evaluate their performance against the requirements and asses variability among PDUs and their stability over time.

5. Conclusions

The DarkSide-20k experiment is driving technological progress on multiple fronts, from underground argon extraction and purification to advances in SiPM development and background control techniques, supported by an extensive assay campaign. These efforts, brought together through the worldwide expertise of the Global Argon Dark Matter Collaboration, make the achievement of ultra-low instrumental backgrounds a realistic goal, enabling a powerful exploration of dark matter parameter space well beyond the reach of heavy WIMPs. With construction already underway and data taking scheduled to begin in 2027, DarkSide-20k is set to open a new era in the search for dark matter.

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