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The DarkSide-20k veto detector

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Summary. — The DarkSide experiment aims to directly detect weakly interacting massive particles using a dual-phase liquid argon Time Projection Chamber (TPC). The next generation experiment —DarkSide-20k— will be based on a 20 tonne fiducial mass TPC filled with radio-pure underground argon. DarkSide-20k will be housed at the Gran Sasso underground laboratory (LNGS), and it is expected to obtain a sensitivity to WIMP-nucleon cross section of 6.3×10^{-48} cm^2 for the 90% C.L. exclusion considering 1 TeV/c^2 WIMPs, over a 200 t yr exposure. DarkSide-20k is designed to operate maintaining an instrumental background level in the WIMP search region ∼0.1 nuclear recoil events for the total exposure. To achieve this goal, a dedicated neutron veto detector is mechanically integrated with the TPC itself and immersed in liquid argon. The veto is made of gadolinium loaded acrylic to enhance the neutron capture probability and produce high-energy deposit in liquid argon. The scintillation signals will be read with custom made cryogenic silicon photomultipliers. To obtain gadolinium-loaded ultra-pure acrylic sheets, specific procedures to treat gadolinium nano-grains avoiding clusterization and consequent sedimentation in the polymerization process of the acrylic have been developed.

1. – Introduction

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, but are so weakly interacting that they have yet to be observed in a terrestrial experiment. Given the discovery potential of an argon-based detector [1, 2], scientists from all of the major experiments currently using LAr to search for dark matter, including ArDM, DarkSide-50, DEAP-3600, and MiniCLEAN, have joined to form the Global Argon Dark Matter Collaboration (GADMC) with the goal of building a series of future experiments that maximally exploit the advantages of LAr as a detector target.

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DarkSide-20k (fig. 1), which is the first objective of the GADMC, is designed to observe dark matter particles scattering in a liquid argon target. The visible signal from WIMPs scattering is a nuclear recoil, depositing tens to hundreds of keV of energy in the argon. In particular, the detector will be based on a dual-phase Time Projection Chamber (TPC), filled with 50 t of radio-pure argon extracted from underground sources [3], which will operate in Hall-C of the INFN Gran Sasso National Laboratory (LNGS). The DarkSide-20k experiment will have ultra-low backgrounds and the ability to measure its backgrounds in situ, resulting in an expected sensitivity of $6.3 \times 10^{-48}\,\mathrm{cm}^2$ for the 90% C.L. exclusion for a WIMP mass of 1 TeV/c^2 with an exposure of 200 t·yr run. To achieve this objective, DarkSide-20k is designed to operate almost background free, meaning that all sources of instrumental background are reduced to <0.1 events over a 200 t·yr exposure.

The detector has a nested structure and it will be housed within a ProtoDUNE-style membrane cryostat filled with atmospheric argon [4]. The innermost part has a novel design in which the neutron veto and the TPC are integrated into a single mechanical unit that sits in a common bath of low-radioactivity argon, separated from the atmospheric argon in the main cryostat by a sealed titanium vessel. The central active volume of the TPC is defined by eight vertical reflector panels and the top and bottom windows made with pure transparent PMMA (poly(methylmethacrylate)). 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 to a wavelength detectable at high efficiency by silicon photomultipliers (SiPMs). 8448 SiPM-based Photodetector Modules will view the argon volume through the top and bottom windows. Each module is a $5 \times 5\,\mathrm{cm}^2$ board equipped with a cryogenic preamplifier and 24 SiPMs 7.9×11.7 mm^2 each. The height of the TPC is 350 cm and the total mass of LAr in the active volume is 49.7 t. The eight lateral walls of the TPC will be made of PMMA, loaded with gadolinium, in order to moderate and capture neutrons. These walls are in fact both an integral part of the TPC and of the neutron veto detector, which are united in a single mechanical structure. The veto consists also of two Gd-loaded PMMA planes, located outside the SiPMs plates. The details of the neutron veto detector are discussed in the following sections.

2. – The DarkSide-20k neutron veto

2·1. *Why is a neutron veto detector needed and how does it work.* – One of the biggest advantages of using liquid argon as the target is its excellent pulse shape discrimination (PSD) capability [5]. The liquid argon scintillation light is emitted from two different states, a long-lived ($\sim$1.5 μs) triplet state, and a short-lived (6 ns) singlet state. Electronic recoils, induced by electrons or gammas, have more of the slow scintillation component than nuclear recoils, which produce a faster signal because of a larger singlet state fraction. Since the first category of events is the primary source of background for the experiment, while the second is the type of signal expected from WIMP-nucleus scattering, this feature makes electron backgrounds easily distinguishable. The PSD and the strong reduction of the ^{39}Ar in the ultra-pure argon extracted from underground sources, together with a careful choice of the construction materials and their handling, make the background induced by β and γ events negligible within a time scale of 10 years. Neutrons undergoing an elastic scattering in the fiducial volume are the most dangerous remaining instrumental background, as a single induced nuclear recoil can fully mimic a WIMP event. For this reason, an active neutron veto detector is needed.

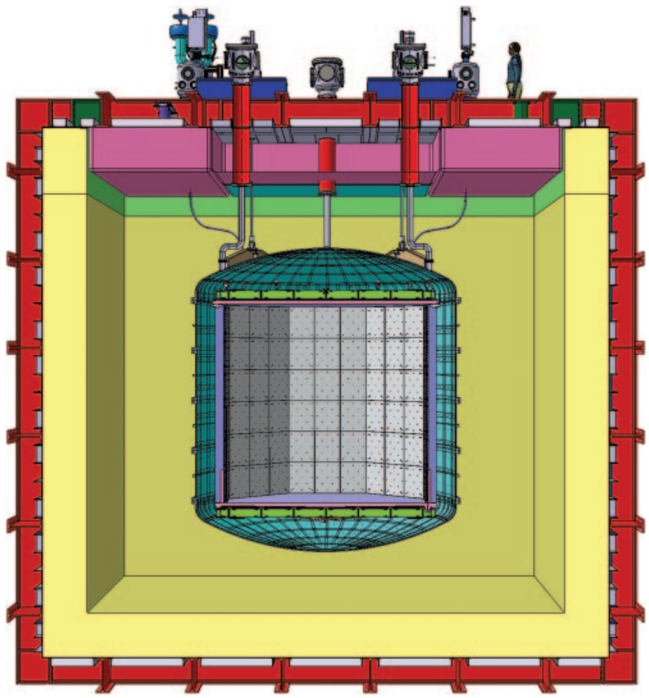

Fig. 1. – Front view of the DarkSide-20k detector. The membrane cryostat, that contains atmospheric argon, is depicted in red and yellow. The titanium vessel is shown in light blue. It contains the structure of the TPC and the veto and is filled with ultra pure argon. The core of the detector is the central octagon, fully made of PMMA: the violet parts, that are the TPC walls, and the green blocks are all made of Gd-loaded PMMA, all together these form the veto bulk. The magenta parts, that are made in pure transparent PMMA, are the TPC windows, from which the signal is seen by the photosensors.

The key point of the veto is the material that constitutes the bulk, which is gadolinium-loaded PMMA. This hybrid material has very high efficiency in moderating, thanks to the high quantity of hydrogen, and then capturing neutrons, capture resulting in the emission of several γ's, with total energy 7.9 MeV. These γ-rays interact in the ultra-pure liquid argon contained in the titanium vessel and cause the emission of scintillation light. The scintillation light is then shifted from 128 nm to 420 nm with wavelength shifter foils and detected by SiPM-based photosensors.

2˙2. *The veto structure and the Gd-loaded PMMA.* – The Gd-loaded PMMA is arranged in an octagon of eight vertical panels and two end caps of thickness 15 cm. The eight vertical panels also serve as the lateral walls of the TPC, while the end caps externally surround the TPC photosensors plates. The thickness of the loaded sheets and the gadolinium concentration —which needs to be between 0.5% and 1% in mass— are set to achieve a neutron capture inefficiency of <1%. The Gd-loaded PMMA is surrounded by 40 cm of ultra-pure argon: this thickness ensures the production of enough light from the interaction of the gammas. Both the outer surface of the Gd-loaded PMMA and the inner surface of the titanium vessel are covered with PolyEthylene Naphthalate (PEN) foils, used as wavelength shifter, and reflective foils needed to maximize the light collection.

Arrays of SiPMs are distributed over the surface of the Gd-PMMA facing the argon volume.

A special R&D project was developed to obtain Gd-loaded PMMA plates. First, a market research was made to find a sufficiently radio-pure and widely available gadolinium compound. A particular gadolinium oxide (Gd_2O_3) has been selected, which exhibits contamination levels of the order of a few tens of mBq/kg. Since gadolinium oxide is not soluble in the liquid monomer (methylmethacrylate, MMA) used to produce PMMA, a procedure has been developed to obtain a homogeneous dispersion of the compound; for this reason, it was chosen to use the oxide in the form of nano-grains. To maximize the uniformity of the dispersion and avoid the sedimentation of the Gd_2O_3, a molecular functionalization of the surface of the nano-grains is done, aimed at creating repulsive electrostatic forces and steric hindrance factors. Also, the polymerization procedure has been optimized to obtain samples up to 20 cm thick.

2·3. *The photosensors.* – The basic optical detector element is a $5 \times 5\,\mathrm{cm}^2$ tile made with custom cryogenic SiPMs developed in collaboration with Fondazione Bruno Kessler (FBK), in Italy. The same SiPMs are also used for the TPC readout. Each tile is read as a single channel using a custom-made ASIC, developed by the INFN Torino group, used as an amplifier. Tiles have been tested in liquid nitrogen, illuminating them with a 403 nm laser diode and operating SiPMs at 7 V and 9 V of over voltage. The measured mean peak amplitude of the single photoelectron is 9.7 mV (at 9 VoV), with a shape in agreement with the simulated one. The signal-to-noise ratio obtained in these conditions, defined as the ratio between the gain and the width of the baseline noise peak, is 17. The performance of the photodetector module at cryogenic temperature meets the requirements and allows passing to the mass production phase.

3. – Conclusions

The neutron veto detector is a crucial part of the DarkSide-20k experiment, that allows keeping the nuclear recoil backgrounds expected during the full exposure of 200 t·yr around 0.1 nuclear recoil events. Its structure completely integrated with that of the TPC allows having two detectors with a single mechanical structure. The hybrid material consisting of an acrylic matrix loaded with gadolinium oxide has been successfully developed on a laboratory scale; the next step will be to do tests on an industrial scale. Regarding the photosensors, the R&D phase is completed and the production phase is starting. In conclusion, it can be said that the various components of the veto are almost ready for production and installation, which will take place in the next two years.

REFERENCES

[1] DarkSide Collaboration (Agnes P. *et al.*), *Phys. Rev. D*, **98** (2018) 102006.
[2] DEAP-3600 Collaboration (Ajaj R. *et al.*), *Phys. Rev. D*, **100** (2019) 022004.
[3] DarkSide Collaboration (Agnes P. *et al.*), *Phys. Rev. D*, **93** (2016) 081101.
[4] Abi B. *et al.*, arXiv preprint, arXiv:1706.07081 (2017).
[5] DEAP-3600 Collaboration (Adhikari P. *et al*)., *Eur. Phys. J. C*, **81** (2021) 823.