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The veto apparatus of DarkSide-20k: Dark Matter search in a background-free experiment

M. Rossi(1)(2) on behalf of the DarkSide Collaboration

(1) *INFN, Sezione di Genova - Genova, Italy*
(2) *Dipartimento di Fisica, Università di Genova - Genova, Italy*

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Summary. — DarkSide-20k is a background-free experiment under construction at INFN, Laboratori Nazionali del Gran Sasso. Its purpose is to directly detect Dark Matter particles exploiting WIMP-nucleon scattering in liquid argon. The detector incorporates an innovative gadolinium-doped veto to identify neutron interactions, which takes advantage of liquid argon scintillation. The optimal placement of the photodetectors in the veto made possible to obtain a non-uniformity of the light collection of 3% at 1σ.

1. – Description

The most surprising discovery of the 20th century was that ordinary matter, thus protons, neutrons and electrons, constitutes an incredibly small amount of the total mass of the Universe. The rest appears to be made of Dark Energy (70%) and about 25% is a kind of invisible matter, called Dark Matter [1]. Several evidences of its presence were found, but its particle nature is still unknown. In order to explain the current abundance of Dark Matter, a particle candidate has to satisfy specific properties: it has to be stable on cosmological timescales, since nowadays we can observe its effects that would not be present if it would have already decayed; it cannot be charged under neither electromagnetic or strong interactions; it has to be at most weakly and gravitationally coupled to ordinary particles [2]. Weakly Interacting Massive Particles (WIMP) are particles that can assume all these features, and they represent one of the different Standard Model extensions that can explain Dark Matter.

DarkSide-20k [3] aims to detect the WIMP-nucleon scattering in liquid argon exploiting ionization and scintillation processes and by the use of photodetectors. It is a Dark Matter direct detection experiment: this means that, based on its predecessor DarkSide-50 experience [4], its purpose is to detect Dark Matter scattering with ordinary matter nuclei; consequently, the nuclei recoil with energy of some tens of keV which is released to atoms and molecules, giving origin to an observable signal. DarkSide-20k is composed of three main volumes: from the inside out, a dual-phase (liquid and gaseous argon) Time Projection Chamber (TPC), whose fiducial(1) volume measures 20 tons and represents where the detector is expected to be sensitive to WIMP-nucleon interaction, a neutron veto and a cryostat [2]. Both the TPC and the neutron veto shapes are octagonal-based prisms. The TPC height and inscribed radius are respectively 350 cm and 175 cm, while the neutron veto thickness is 90 cm both radially and vertically.

The DarkSide-20k experiment aims to be background-free for its entire planned exposure of 200 ton years; this means that the detector is designed to operate while maintaining the background coming from construction materials in the WIMP search region less than 0.1 events for the total exposure. Its purpose is to investigate WIMP-nucleon spin-independent interaction cross-sections up to $10^{-47}\,\mathrm{cm}^2$ for a WIMP with a mass of 1 TeV in a 10 years run. For that reason, it is necessary to minimise all radioactive backgrounds that can induce false signals: this means that distinguishing WIPMs from β and γ radioactivity (which are rejected directly in the TPC with efficiency higher than 10^9) and from neutron-induced nuclear recoils is of paramount importance [1].

Therefore, it is essential to identify neutron interactions: elastic scattering on argon nuclei would produce a nuclear recoil that can mimic a WIMP interaction. For this purpose, DarkSide employs an active veto, built with gadolinium-doped acrylic, which slows down and captures neutrons with a consequent energy release in the form of a gamma-ray cascade, whose energy totals 8 MeV [1]. These gadolinium gamma photons generate argon scintillation that can be detected using cryogenic Silicon PhotoMultipliers (SiPMs), as in the TPC.

The emission of gamma photons in the gadolinium-doped plastic is isotropic; to maximise the efficiency of detecting them, the material, whose thickness is 10 cm, is placed at the center of the neutron veto liquid argon volume, dividing it in two distinct and optically isolated regions, the Inner Argon Buffer (IAB) and the Outer Argon Buffer (OAB), as sketched in fig. 1. The readout electronics for the SiPMs is mounted on the back of the SiPMs tiles themselves and these photodetection modules are mounted on both sides of the gadolinium-doped plastic, exploiting a frame made of Titanium, in order to detect events in both the buffers [2].

Each one of the two regions is in turn divided in eight optically-isolated sectors (see fig. 2) by reflector sheets held up by a plastic support, to reduce pile-up events on veto SiPMs [2]. This choice is done since the veto is filled with atmospheric argon, which contains the long-lived β-emitter ^{39}Ar with a specific activity of 1 Bq/kg. The high rate in the veto due to ^{39}Ar can cause a significant dead time for the experiment [2].

In addition, in order to enhance the quantum efficiency of SiPMs for argon scintillation light (128 nm), a wavelength-shifter is deposited on all internal surfaces. This material changes that wavelength up to 420 nm, corresponding to a SiPM photodetection efficiency of about 40% [1].

A uniform light collection in the active volumes is one of the veto requirements, since all the parts of the veto volume have to behave the same way in order to identify neutron events as accurately as possible [2]. Moreover, a uniform light collection allows to easily infer the energy deposited in the veto from the number of collected photons, regardless of the position of the neutron capture. If the placement of the SiPMs is

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(1) The total volume of the TPC is 50 tons but the detection strategy includes fiducial volume cuts which exclude events occurring at a distance from the TPC walls less than 30 cm in the radial direction and less than 70 cm from the top and bottom.

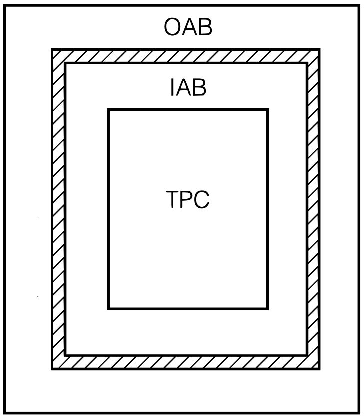

Fig. 1. – Sketch of the layout of the DarkSide-20k experiment: the TPC is placed at the center and is surrounded by the liquid argon buffers (IAB and OAB) and the gadolinium-doped acrylic, dashed Both the TPC and the neutron veto shapes are octagonal-based prisms. The TPC height and inscribed radius are respectively 350 cm and 175 cm, while the neutron veto thickness is 90 cm both radially and vertically [2].

optimal and this requirement is satisfied, the generation of uniform events in a buffer should result in a uniform light collection in the buffer itself. The placement of the SiPMs has been optimised using the G4DS [5] Monte Carlo (MC) simulation based on the Geant-4 toolkit [6, 7], by generating scattering events uniformly in a buffer and optimising the placement of the veto SiPMs to ensure a uniform light collection in the buffer itself. As a consequence, a non-uniform SiPMs distribution was chosen for all surfaces, which provides for an accumulation of photosensors in correspondence of the upper and lower surface edges, as one can observe in fig. 3.

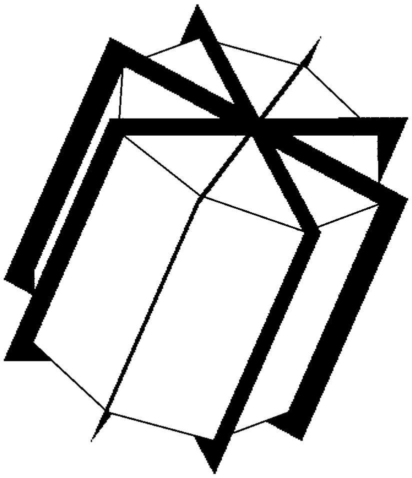

Fig. 2. – Detail of the eight optically-isolated sectors of the veto from the DarkSide-20k Geant-4 simulation. The black volumes are the reflector sheets which divide the neutron veto in separated regions avoiding pile-up events on veto SiPMs [2].

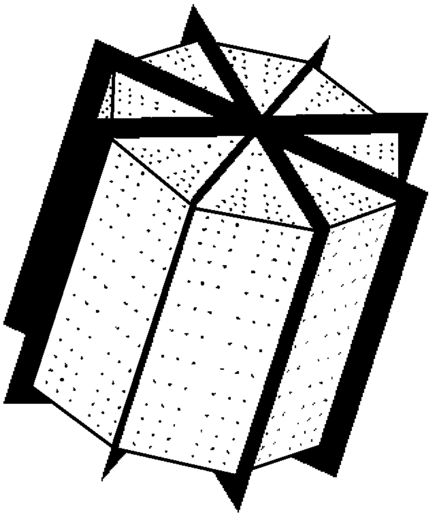

Fig. 3. – Placement of the SiPMs resulting from the MC-based optimisation: the dots represent the SiPMs on the gadolinium-doped acrylic surface, and their accumulation in correspondence of the upper and lower surface edges is shown [2].

Light generation in the veto system was done exploiting 1 MeV electrons, uniformly distributed within the veto volume, giving rise to excitation and ionization of argon atoms. The studies on the optimal placement of SiPMs allowed to obtain a light collection non-uniformity of 3.1% at 1σ in the OAB and 3.7% at 1σ in the IAB [1]; fig. 4 shows the result for the OAB case.

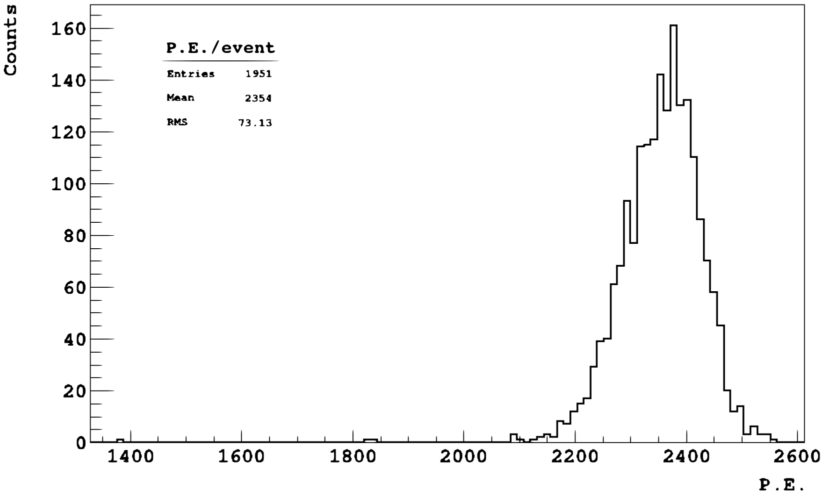

Fig. 4. – Distribution of the number of photons collected per event from the MC simulation of the Outer argon Buffer of the DarkSide-20k neutron veto. The events correspond to 1 MeV electrons uniformly generated within the OAB volume [2].

2. – Conclusions

DarkSide-20k aims to directly detect elastic scattering of WIMPs Dark Matter particles on liquid argon nuclei exploiting a dual-phase Time Projection Chamber; the scattering event, searched in the region of recoil energy ($\sim$ 1–100 keV), is expected to generate photons, that can be collected using photosensors: in the specific case of DarkSide-20k these are cryogenic Silicon PhotoMultipliers. The experiment is expected to be free of any instrumental background for an exposure of 200 tons × year, thus making possible to attain a WIMP-nucleon cross section exclusion sensitivity of $10^{-47}\,\mathrm{cm}^2$ for a WIMP mass of $1\,\mathrm{TeV}/c^2$ in a 10 years run. In order to reach such extreme performances, it is needed to reduce the background of the measurement, exploiting an optimal choice for the materials the whole detector is made with and a liquid argon active veto made of acrylic loaded with gadolinium, which wraps the TPC and can detect particles that may mimic a WIMP interaction signal. The acrylic acts as passive material to moderate neutrons, that are the main source of background, while the gadolinium captures them because of its high capture cross-section, resulting in the emission of multiple photons that will be collected in the argon veto. The fundamental feature of the veto system is therefore the light collection, in order to identify at best a neutron interaction. By using this innovative veto system and optimising the placement of the photosensors, it is possible to reach optimal performances in both the buffers the neutron veto is composed of: in the Inner argon Buffer and in the Outer argon Buffer the light collected by the SiPMs has a non-uniformity of 3.1% at 1σ in the OAB and 3.7% at 1σ in the IAB [1].

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