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Abstract. Directional sensitivity to nuclear recoils would provide a smoking gun for a possible discovery of dark matter in the form of WIMPs (Weakly Interacting Massive Particles). A hint of directional dependence of the response of a dual-phase argon Time Projection Chamber (TPC) was found in the SCENE experiment. Given the potential importance of such a capability in the framework of dark matter searches, a new dedicated experiment, ReD (Recoil Directionality), was designed by the Global Argon Dark Matter Collaboration, in order to scrutinize this hint. Prior to the irradiation with a neutron beam, the ReD TPC underwent a long campaign of characterization and optimization: some selected results are presented in this contribution.

1. Introduction

The existence of dark matter (DM) in the Universe is nowadays commonly accepted as the explanation of many astrophysical and cosmological phenomena, ranging from internal motions of galaxies to the large scale inhomogeneities in the cosmic microwave background radiation and the dynamics of colliding galaxy clusters.

In the framework of particle astrophysics, experiments searching for weakly interacting massive particles (WIMPs) play a central role in the studies on the nature and properties of dark matter in the Universe. Among the others, in the direct search of DM, liquid argon (LAr) is particularly well suited since its powerful background rejection properties through the pulse shape discrimination method [1] and the use of low-radioactivity argon from underground sources [2, 3]. In this respect, the Global Argon Dark Matter Collaboration (GADMC) is following a multi-staged program to construct a sequence of argon-based detectors with the final goal to improve the sensitivity to WIMPs by several orders of magnitude. The DarkSide-20k experiment [4], a double-phase argon Time Projection Chamber (TPC) currently under construction at the INFN - Laboratori Nazionali del Gran Sasso (LNGS), will be in this respect one of the first steps of the GADMC.

2. The ReD Experiment

WIMP directional information is potentially available in a dual-phase LAr TPC by exploiting the electron recombination effect [5]. Hints of such directional phenomena have already been observed by the SCENE experiment [6]. To further investigate this process, the ReD detector was irradiated with a neutron beam of known energy and direction, produced via the p(^{7}Li,^{7}Be)n reaction by the TANDEM accelerator at the INFN - Laboratori Nazionali del Sud (LNS) in Catania.

The ReD TPC has several key characteristics in common with the future DarkSide-20k experiment, including some mechanical aspects although on a smaller scale and the innovative readout system entirely based on cryogenic silicon photomultipliers (SiPMs). It consists of a volume of liquid argon, above which lies a thin layer of the same element in the gaseous phase in thermal equilibrium with the liquid phase. The active volume of the detector is 5 cm (l) $\times$ 5 cm (w) $\times$ 6 cm (h) and it is viewed by two tiles of SiPMs, of size 5 cm $\times$ 5 cm, each containing 24 devices. The two tiles are placed at the top and at the bottom of the TPC, and are coupled

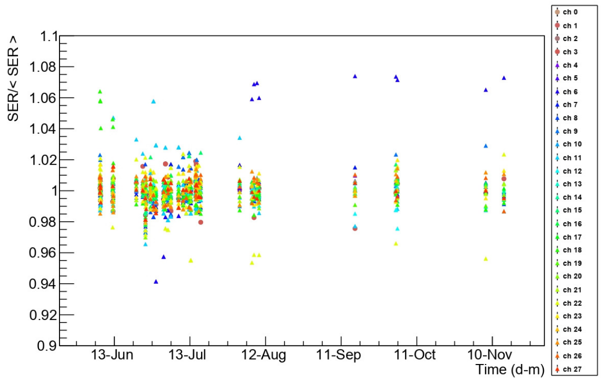

Figure 1. Single Electron Response (SER) relative variations vs. time from the 28 individual channels of ReD SiPMs, calculated from all available laser calibrations. Different colors identify different channels (the first four refer to the bottom channels). Details in the text.

with a Front-End Board (FEB) electronics. The two FEBs for the top and bottom tiles are distinct, as the top tile features an individual readout for all 24 SiPM, while the SiPM of the bottom tile are grouped into a 4-channel readout. This readout system, based on a total of 28 channels SiPMs, guarantees a higher photon detection efficiency relative to typical cryogenic photomultipliers [4, 8]. A detailed description of the detector, its signals, the calibration and the Monte Carlo simulation can be found in [7].

The ReD TPC data reported here were taken at the INFN "Cryolaboratory for the Dark Matter Research" at the Università degli Studi di Napoli Federico II, continuously operating between 7 June 2019 and 18 November 2019 for a total of about 165 days.

3. SiPM response to single photons

The Single Electron Response (SER) of the ReD TPC is studied using a Hamamatsu PLP-10 pulsed diode laser with a wavelength of 403 nm, externally triggered at 100 Hz. Pulse emissions of 50 ps are delivered to the inner volume of the TPC via a bundle of optical fibers; signal responses from each of the 28 SiPM readout channels are digitized inside an acquisition window of 20 µs. Laser calibrations were regularly performed during the 165 days of continuous operation of the system and the SER of SiPMs evaluated.

In Fig. 1, the relative fluctuation of the SER values, calculated from all 42 available laser calibrations, is displayed. It is 0.7% (1.0%) rms for bottom (top) channels. This is consistent with the level of temporal variation in the output voltage of the power supply. Variations of the SER between consecutive laser calibrations are well below 2% for all channels, except for two SiPMs of the top tile, which occasionally exhibited variations up to 6–7%.

4. TPC performance

Measurements of the TPC response were conducted by using an external ^{241}Am source, which emitted monoenergetic γs of 59.54 keV energy. The scintillation response (S1) of the detector is then studied by operating it in the so-called single-phase mode, i.e. filled with liquid argon only, and without the application of any electric field. The light yield (LY) is calculated using the energy peak of ^{241}Am in the S1 spectrum. The distribution is then fitted to a template taken as the convolution of the ^{241}Am spectrum from Monte Carlo (MC), with a Gaussian smearing function to account for the detector resolution. Data (black points) and the best fit to the MC template (red line), are shown in Fig. 2. The final value of the LY, that accounts also for the contribution from after pulsing and cross talk of SiPMs, is $LY = (9.80 \pm 0.13)$ PE/keV at null

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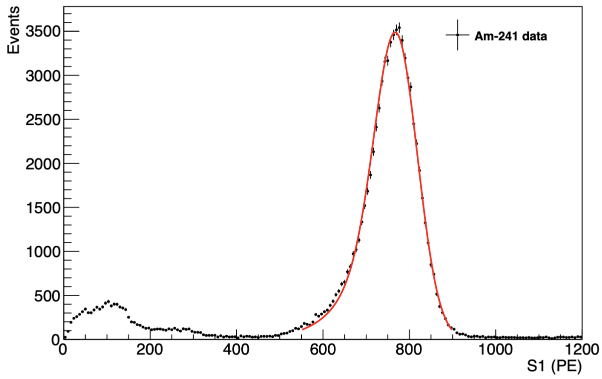

Figure 2. S1 distribution for a ^{241}Am source run taken in single-phase mode at null field. The distribution is fitted with a MC template (red line) as discussed in the text.

field. The LY is found to be reproducible within 2%, from repeated calibrations taken with ^{241}Am throughout the entire operational period.

The detection of the ionization signal (S2), on the other hand, requires drifting the free electrons from the interaction point to the liquid-gas interface, extracting and accelerating them in the gas to produce electroluminescent light. The TPC must therefore be operated in the so-called double-phase mode, a thin layer of Ar gas is created above the liquid argon, and appropriate electric fields are applied in the detector [7]. In this case, the S2/S1 ratio is a fundamental key ingredient for the characterization of the performance of a LAr TPC, since it provides a powerful tool for discriminating between nuclear (NR) and electronic recoils (ER). Moreover, the need to achieve an excellent detector resolution on S2/S1 is essential for precise studies of recombination. It was found that the measured S2/S1 dispersion is 12% and 18% for NRs and ERs, respectively, improving the previous results by the SCENE collaboration [6]; this it is sufficiently low to ensure that a potential directional effect should not be hidden by instrumental resolution.

5. Conclusions

The ReD experiment aims to investigate the directional sensitivity of argon-based TPC to nuclear recoils in the energy range of interest for WIMP dark matter searches. A compact double-phase argon TPC, equipped with innovative readouts by cryogenic SiPMs, was constructed for ReD and fully characterized using laser, γ and neutron sources. In this respect, the performance of the TPC reported here were found to fully meet the requirements needed to reach the main goals of the ReD experiment in the search for a possible directional effect due to columnar recombination in NRs.

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