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The Recoil Directionality (ReD) experiment

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Summary. — 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 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. Before 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 × 5 cm × 6 cm and it is viewed by two tiles of SiPMs, of size 5 cm × 5 cm, each containing 24 devices. The two tiles are placed at the top and at the bottom of the TPC, and are coupled with a Front-End Board (FEB) electronics. There are, in particular, two distinct FEBs for the top and bottom tiles, as the top one 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 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. – Single Electron Response of SiPMs

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.

The charge measured by each SiPM is calculated offline by integrating the digitized waveform, following subtraction of the average baseline, over a fixed window of 4 μs starting 600 ns before the external trigger time. The individual spectra are fitted with a sum of Gaussian distributions to model the response of single photoelectrons (PE). The SER is finally evaluated by a linear fit on the mean value of each peak *versus* the number of PE. Due to the effects of afterpulsing and crosstalk, the response of a SiPM to excitation by a single photon corresponds on average to the measurement of more than one PE in the SiPM. In this respect, the probability to detect N photoelectrons does not follow a Poisson distribution; it can instead be described by the Vinogradov model [9]. In fig. 1: data from a bottom channel are superimposed with a Poisson distribution ($\mu = 1.91$, $p = 0$) and a compound Poisson one ($\mu = 1.91$ and $p = 0.26$). Following the same argument described in [9] and defining the coefficient of duplication $K_{dup} = \frac{p}{1-p}$, the value $(1+K_{dup})$ then represents the total number of photoelectrons detected for each primary photon incident on the SiPM. Typical values of K_{dup} obtained for the individual channels range between 0.31 and 0.37, with statistical uncertainties from the fit of approximately 3%.

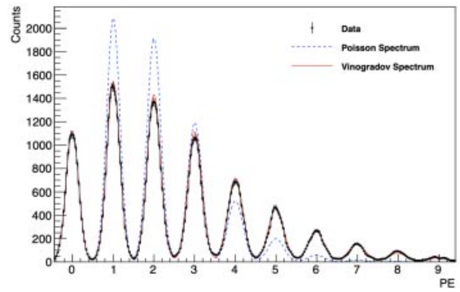

Fig. 1. – Typical charge distribution expressed in terms of photoelectrons (PE) for a bottom channel (black points) superimposed with a Poisson model (blue dashed line) with $\mu = 1.91$ and the compound model of [9] (red solid line) with $\mu = 1.91$ and $p = 0.26$.

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. 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 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. In the left panel of fig. 2 the S2/S1 ratio is shown as a function of S1 for all single-scatter events with a prompt S1 and S2 signals, as well as for events with a neutron-like-induced NR signal. The band from the latter is clearly separated from the ER one for value expressed in units of photoelectrons (PE) above ∼200 PE. The central value of the distribution and its width are calculated in intervals of S1 with varying width in the range 20 and 40 PE using a Gaussian distribution summed with a polynomial. The right panel of fig. 2, on the other hand, shows the distribution of (S2/S1)/$\mu(S1)$ in three different energy ranges: 50–80 PE ($\sim$ 20–30 keV$_{nr}$) (top panel); 150–250 PE ($\sim$70 keV$_{nr}$) (middle panel); and 400–600 PE (bottom panel), which includes the ^{241}Am peak. In the former, the

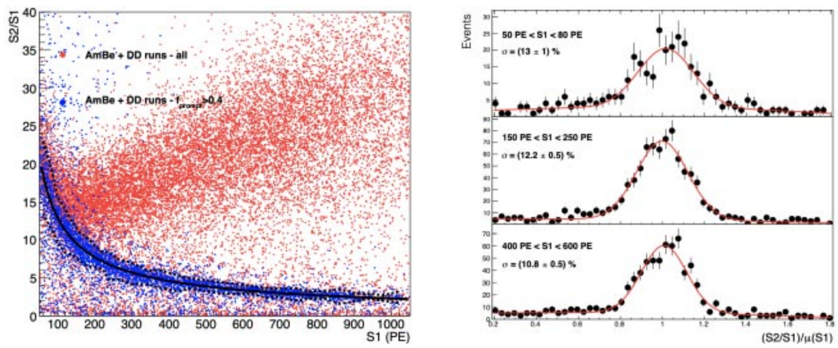

Fig. 2. – Left: Distribution of NR (blue points) events compared to the whole sample (red points) in the S2/S1 vs S1 plane. The black curve represents the most probable values as a function of energy while the black dotted lines are the 90% confidence level expectations. Right: S2/S1 distribution in the three energy range of interest for ReD as detailed in the text.

measured S2/S1 dispersion for NRs ($\sim 11\%$) is considerably smaller than the one from ERs ($\sim 18\%$) in roughly the same S1 energy range. The difference is mostly due to a smaller amount of fluctuations in recombination of NRs with respect to ERs that, in turn, bring to a better resolution in S2. Finally, the measured S2/S1 dispersion in the energy range 150–200 PE (the one most relevant for the goals of ReD) is 12%, improving the previous results by the SCENE collaboration [6], while 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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