PROCEEDINGS OF SCIENCE

LIME: a gaseous TPC with optical readout

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The Cygno project aims at the construction of a gaseous Time Projection Chamber (TPC) with optical readout for the high precision three-dimensional tracking of low energy nuclear and electronic recoils down to few keVs. The efficient discrimination between these two processes represents the main challenge of the modern dark matter direct detection experiments. In this context, the gaseous TPCs with optical readout are a promising and innovative technique that can reach very good energy and 3D position reconstruction capabilities thanks to the high performance of the latest generation of scientific CMOS (sCMOS) light sensors. The Cygno experimental setup is characterized by a TPC filled with a He:CF_4 gas mixture at atmospheric pressure and equipped with a triple Gas Electron Multipliers (GEM) amplification stage. The visible light produced at the GEMs is collected by a scientific CMOS camera and by a set of fast photosensors. In this contribution we will present the 50 L prototype, called Long Imaging ModulE (LIME), foreseen to conclude the R&D phase of the Cygno project. LIME has been recently installed underground at the Laboratori Nazionali del Gran Sasso (LNGS), with the aim of studying the performance of the Cygno experimental approach in a low background environment and developing a refined trigger and DAQ system for the future upgrades. This is a crucial step towards the development of a larger $O(1\text{m}^3)$ demonstrator, which will be an evolution of the LIME detector.

41st International Conference of High Energy Physics - ICHEP 2022
Bologna, Italy
6 - 13 July, 2022

1. Introduction

Cosmological and astronomical observations at very different scales strongly support the existence of dark matter (DM) [1]. However, its nature is unknown and huge experimental efforts are being deployed to detect it on Earth. In this context, the goal of so-called "direct detection" experiments is to reveal the interactions between the DM particles traveling through Earth and the ordinary matter particles, mainly with nuclei. Under reasonable assumptions [2], these interactions are non-relativistic, and typically induce nuclear recoils (NRs) at the $O(1\text{ keV})$ scale. The discrimination between the NR events possibly induced by the DM particles and the electronic recoil (ER) events induced by other background particles at such low energy, which is close to the typical experimental low energy threshold, is one of the main challenges of the modern direct detection experiments.

In this respect, good candidates are the gaseous Time Projection Chambers (TPCs) with an optical readout. This is the experimental approach pursued by the Cygno collaboration, whose goal is to contribute to the direct search for dark matter candidates by means of a large detector with directional capabilities. The experimental strategy is to acquire high resolution pictures of NRs produced inside a TPC filled with a 1 atm He:CF_4 gas mixture [3]. A triple layer of Gas Electron Multipliers (GEMs) [4] amplifies the ionization induced in the TPC during an event, and scintillation light is emitted by the CF_4 and captured by a scientific CMOS (sCMOS) camera and by a set of PhotoMultiplier Tubes (PMTs).

The Cygno project is currently in the R&D phase, and in particular in the so-called “PHASE-0”. In this contribution we will present the PHASE-0 detector: it is called “Long Imaging ModulE” (LIME) and it is a 50 L TPC equipped with a triple GEM layer, an sCMOS camera and four

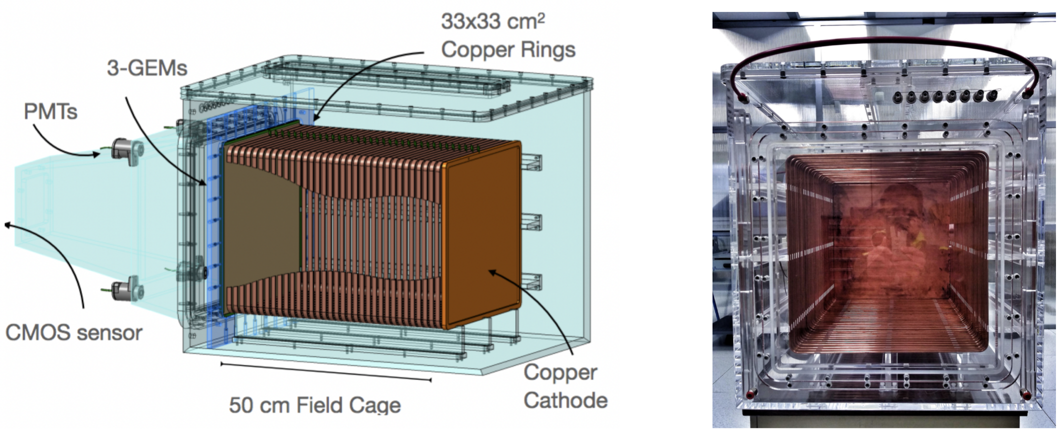

Figure 1: Left: a schematic drawing of the LIME experimental setup. **Right:** a front view of the TPC, where also the copper rings for the field cage are visible (figure from [3]).

PMTs, see Fig. 1. The prototype has been designed, developed and tested overground at Laboratori Nazionali di Frascati (LNF), and it is installed underground at Laboratori Nazionali del Gran Sasso (LNGS) since the beginning of 2022. This experimental setup, the largest prototype built so far by the Cygno collaboration, has been originally conceived to be the fundamental unit of a modular and scalable final Cygno detector, and thus it will be a crucial step towards the realization of a large detector for physics searches.

This work is structured as follows. In Sec. 2 we give a detailed description of the LIME detector, while Sec. 3 shows the preliminary ER energy calibration obtained using overground data collected at LNF. In Sec. 4 we will describe the plans for the forthcoming experimental activities, and, finally, we will draw our conclusions.

2. The LIME detector

The LIME detector is shown in Fig. 1. The TPC has the shape of a parallelepiped with a $33 \times 33\,\mathrm{cm}^2$ squared transverse area and a 50 cm drift length, corresponding to a total active volume of 50 L. The gas, an atmospheric pressure mixture of He (40%) and CF_4 (60%), is enclosed in a 10 mm thick Plexiglas box providing gas tightness. The gas chamber is limited by a stack of three GEMs on one of the transverse sides, and by a copper cathode on the other one. Laterally, the field cage for the electric drift field is made of a set of copper rings at a 16 mm pitch. The copper rings have a square shape, with rounded vertices to avoid discharges.

On the GEMs side, the optical readout is realized with a water-cooled Hamamatsu Orca-Fusion scientific CMOS (sCMOS) camera and 4 symmetrically-arranged Hamamatsu R7378 PMTs. While the camera gives direct access to the transverse xy position of the track, the 4 PMTs are needed to have a better reconstructing ability for the track inclination. The Orca-Fusion camera sensor is a matrix 2304×2304 pixels, with a dark noise of 0.7 electrons per pixel, and a quantum efficiency of 80% at 600 nm. With this properties, it is possible to operate with a lower energy threshold of 0.7 keV [3]. The sensor is able to acquire the whole GEM surface thanks to a Schneider Xenon

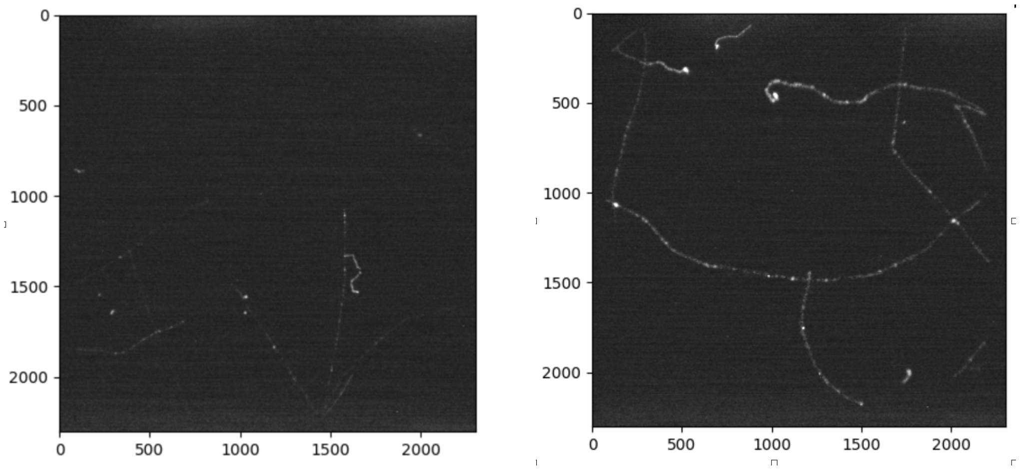

Figure 2: Two pictures collected by the sCMOS camera during the LIME underground campaign at LNGS. The two photos, collected without the shielding, show long tracks induced by natural radioactivity of the cave.

0.95/25-0037 lens, characterized by a 25.6 mm focal length and a 0.95 aperture. In order to image the 33 × 33 cm^2 area, the lens is placed at at distance of 62.3 cm from the GEMs.

The data acquisition is realized by means of a Linux server. More precisely, the camera is acquired via USB 3.0 connection, while the acquisition of the signals from the PMTs and the GEMs is done with NIM modules (for splitting and discrimination) and VME digitizers (fast discrimination for the PMTs and slow digitization for the GEMs). From the software point of view, the whole DAQ system and the slow control system are implemented with MIDAS [5], the data are stored using the INFN Cloud service, and a so-called “Middle Ware” has been implemented to check the data quality and preform a quick pre-analysis and reconstruction [6].

The detector has been designed, built and commissioned overground at LNF, and it has been recently moved underground at LNGS at the beginning of 2022. It is currently collecting data without a shielding, but the final configuration involves a shielding with 10 cm of copper and, externally, another layer of 40 cm of water. The alternation of different shielding configurations will be crucial to validate the Monte Carlo (MC) simulation of the LIME setup. Figure 2 exhibits, as an example, two pictures recently collected during the underground campaign, showing tracks induced by natural radioactivity.

3. The ER energy calibration

A preliminary calibration of the ER response has been performed by exposing the detector to different X-ray sources during the overground campaign, and analyzing the images collected by the sCMOS sensor. For this data taking campaign, the pictures has been acquired in free-running mode with an exposure of 200 ms. A clustering and reconstruction algorithm has been used to select the energy deposits induced by the X-ray sources [7]. This algorithm proceeds in steps: the first one is the noise suppression, which includes hot-pixels removal, pedestal subtraction, and filtering operations to enhance the efficiency of reconstruction for the next steps; after that, the image is analyzed by a Directional DBSCAN algorithm that is able to identify the ionization

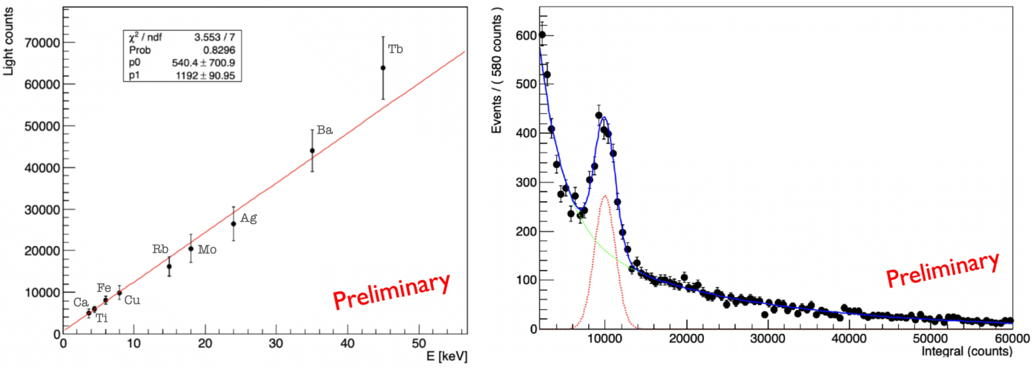

Figure 3: **Left**: LIME preliminary ER energy calibration curve. The fit has been performed on 200 ms exposed images collected overground at LNF using different X-ray sources. **Right**: gaussian-plus-exponential fit to the Cu 8 keV X-ray line.

clusters corresponding to the different tracks; finally each cluster is analyzed to extract information such us the total amount of photons of the cluster, the photon density, the *xy* cluster position, etc.

Figure 3 shows, on the left, the preliminary ER calibration curve: the data points are obtained as result of a gaussian-plus-exponential fit to the observed spectrum (expressed as function of the total number of pixels in the cluster). The right part of the figure shows, as an example, the spectrum, and the fit results, for the copper 8 keV X-ray line. The response curve shows a good linearity, and an energy resolution of 13% across the whole 50 cm drift length has been measured at 5.9 keV.

4. Forthcoming activities and conclusions

The Cygno collaboration is currently involved in the accomplishment of the experimental underground activities for the LIME detector. In particular, new measurements in presence of X-ray sources to calibrate the detector response in a low background environment are foreseen to be performed in the next months. Measurements with different shielding options will be also performed to measure the background spectrum and validate the background models and MC simulations.

During the material screening campaign, we measured at LNGS the activities of the radioactive isotopes contained in all the detector components. The results suggest that main ER internal background contributions are related to the copper rings, the resistors used in the field cage, the GEMs, the cathode, and the sCMOS sensor. In order to reduce those backgrounds, the collaboration is therefore involved in other R&D activities: selection of low radioactivity copper and resistors; development of low radioactivity GEMs; collaboration with the producers to develop radio-pure lenses and a less radioactive sCMOS sensor.

The LIME detector is the latest of a series of prototypes that characterized the evolution of the Cygno project since 2015 [8–10]. The R&D activities for the LIME detector are foreseen to be concluded by the end of 2023, when we will enter our “PHASE_1” [3]. During this phase the collaboration will commission a larger $O(0.4\ \mathrm{m}^3)$ detector based on modules built using the same technology of the LIME prototype. The construction of a $O(0.4\ \mathrm{m}^3)$ detector is a crucial step towards the possible construction of a bigger $O(30-100\text{ m}^3)$ apparatus, our “PHASE_2” able to provide significant results for directional DM and neutrino searches.

Acknowledgments

We want to thank General Services and Mechanical Workshops of Laboratori Nazionali di Frascati (LNF) and Laboratori Nazionali del Gran Sasso (LNGS) for their precious work and L. Leonzi (LNGS) for technical support. This project has received fundings under the European Union’s Horizon 2020 research and innovation programme from the European Research Council (ERC) grant agreement No 818744. This project is supported by the Italian Ministry of Education, University and Research through the project PRIN: Progetti di Ricerca di Rilevante Interesse Nazionale “Zero Radioactivity in Future experiment” (Prot. 2017T54J9J).

References

[1] N. Aghanim et al., *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* 641 (2020) A6, [arXiv:1807.06209].

[2] E. Del Nobile, *The Theory of Direct Dark Matter Detection: A Guide to Computations*, *Lect.Notes Phys.* 996 (2022), [arXiv:2104.12785]

[3] F.D. Amaro et al., *The CYGNO Experiment*, *Instruments*, **6**, (Jan. 2022), [arXiv:2202.05480]

[4] M. Marafini, V. Patera, D. Pinci, A. Sarti, A. Sciubba, and N. M. Torchia, *Study of the Performance of an Optically Readout Triple-GEM*, *IEEE Transactions on Nuclear Science*, **65** (Jan., 2018), 604-608.

[5] PSI and TRIUMF, “MIDAS modern data acquisition page”, [https://daq00.triumf.ca/MidasWiki/index.php/Main_Page]

[6] F.D. Amaro et al., *Exploiting INFN-Cloud to implement a Cloud solution to support the CYGNO computing model*, *PoS* ISGC2022 (2022) 021

[7] E. Baracchini et al, *A density-based clustering algorithm for the CYGNO data analysis*, *JINST*, **15** (2020), no. 12 T12003, [arXiv:2007.01763]

[8] M. Marafini, V. Patera, D. Pinci, A. Sarti, A. Sciubba, and E. Spiriti, *ORANGE: A high sensitivity particle tracker based on optically read out GEM*, *Nucl. Instrum. Meth. A*, **865**, (2017), 285-288

[9] E. Baracchini et al., *Stability and detection of a GEM-based Optical Readout TPC with He/CF$_4$ gas mixtures*, *JINST*, **15** (2020), no. 10 P10001, [arXiv:2007.00608]

[10] E. Baracchini et al, *Identification of low energy nuclear recoils in a gas TPC with optical readout*, *Meas. Sci. and Tech.*, **32** (2020) 025902, [arXiv:2007.12508]