Nuclear Inst. and Methods in Physics Research, A 1051 (2023) 168207

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

LIME — A gas TPC prototype for directional Dark Matter search for the CYGNO experiment

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ARTICLE INFO

Keywords:
Dark matter
Time projection chamber
Optical readout

ABSTRACT

The CYGNO experiment aims at the development of a large gaseous TPC with GEM-based amplification and an optical readout by means of PMTs and scientific CMOS cameras for 3D tracking down to O(keV) energies, for the directional detection of rare events such as low mass Dark Matter and solar neutrino interactions. The largest prototype built so far towards the realization of the CYGNO experiment demonstrator is the 50 L active volume LIME, with 4 PMTs and a single sCMOS imaging a 33 × 33 cm^2 area for 50 cm drift, that has been installed in underground Laboratori Nazionali del Gran Sasso in February 2022. We will illustrate LIME performances as evaluated overground in Laboratori Nazionali di Frascati by means of radioactive X-ray sources, and in particular the detector stability, energy response and energy resolution. We will discuss the MC simulation developed to reproduce the detector response and show the comparison with actual data. We will furthermore examine the background simulation worked out for LIME underground data taking and illustrate the foreseen expected measurement and results in terms of natural and materials intrinsic radioactivity characterization and measurement of the LNGS underground natural neutron flux. The results that will be obtained by underground LIME installation will be paramount in the optimization of the CYGNO

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https://doi.org/10.1016/j.nima.2023.168207
Received 4 July 2022; Received in revised form 6 February 2023; Accepted 7 March 2023

demonstrator, since this is foreseen to be composed by multiple modules with the same LIME dimensions and characteristics.

Contents

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1. The CYGNO experiment

The identification of the nature of Dark Matter (DM) is one of the most compelling tasks for fundamental physics today. A well motivated DM candidate are weakly interacting massive particles (WIMPs), which could interact with the ordinary matter of a target on Earth producing a nuclear recoil (NR). A promising approach is to look for the directional signature of low energy (less than 100 keV) NRs, whose angular distribution should point to the direction of the Cygnus constellation [1]. The goal of the CYGNO experiment is the direct detection of DM, with the use of a gaseous time projection chamber (TPC) with an optical readout equipped with a triple-GEM (Gas Electron Multiplier) amplification stage, operated at atmospheric pressure [2]. The ionization electrons produced by the interaction of charged particles within the gas volume are drifted by an electric field towards the triple GEM stack, where they are amplified. The secondary scintillation light produced in the electron avalanche is detected by scientific CMOS-based cameras (sCMOS), which capture the light emission projected on the GEM plane, and by Photo Multiplier Tubes (PMTs) to determine the component along the drift direction, allowing the 3D reconstruction of the tracks. The He:CF_4 gas mixture in 60/40 proportion provides a low energy threshold and a high scintillation yield. Several prototypes were built and are being used for R&D studies towards the final goal of a O(1 m^3) CYGNO demonstrator with a modular design, which will be installed underground at Laboratori Nazionali del Gran Sasso (LNGS) of INFN to prove the feasibility of the approach.

2. The LIME prototype

The 50 L LIME detector is the largest prototype we built so far, and it matches the dimension of one basic module of the future CYGNO demonstrator. Triple thin GEMs with an area of 33 × 33 cm^2 amplify the charge produced in the 50 cm long drift region. The high granularity Hamamatsu ORCA Fusion sCMOS and 4 PMTs located at the readout area's corners detect the secondary scintillation light. The camera has 2304 × 2304 pixels, each imaging an area of about 155 × 155 μm^2, with a low noise of about 1 photon per pixel, and a large quantum efficiency of 80% at 600 nm, which nicely matches the spectral emission of our mixture. The employment of the camera and PMTs together for 3D track reconstruction not only makes the detector sensitive to the direction of the events, but also allows for the fiducialization of the sensitive volume, lowering the impact of the background on the detector's sensitivity reach even further. LIME was tested using multiple radioactive X-ray sources at the INFN Laboratori Nazionali di Frascati (LNF). The detector'stability was tested for a whole month, confirming the possibility of underground continuous operation. The energy resolution was measured to be around 15% across the 50 cm drift length using a ^{55}Fe source generating 5.9 keV X-rays positioned on top of the sensitive volume at varying distances from the GEM plane. An energy threshold of 0.5 keV can be achieved while keeping less than 10 electronic noise events per year. A multivariate regression analysis taking the position of the track and various shape parameters as inputs is under development, and preliminary results show an improvement in the energy resolution. To evaluate the detector's response, multiple radioactive X-ray sources with energies ranging from 3.7 keV to 47 keV were employed, and a linear behavior was observed across the whole energy range.

3. Monte Carlo simulation of the tracks

To reproduce the electronic recoil (ER) and NR tracks seen by the sCMOS, a Monte Carlo (MC) simulation of the detector's response is being performed. First, a MC simulation of the ionization energy deposition as a function of 3D position is done using GEANT4 [3] for the ERs and SRIM [4] for the NRs. Various processes (such as ionization e^- yield, diffusion along the drift region and inside the GEMs, charge amplification, photon yield and collection efficiency, absorption in the gas, gain saturation) are considered, and an image is produced, which is then analyzed using an intensity-based DBSCAN clustering algorithm [5], which we also use for the analysis of the real images. The light integral and the track dimension of the simulated 5.9 keV ERs was compared to ^{55}Fe data, showing a good agreement across different GEM gain values. In the linearity study, a preliminary comparison of X-ray data and the MC simulation reveals an agreement within 10%. The ER background rejection capabilities of our approach are also under study in order to improve the results obtained with a smaller prototype [6].

4. Outlook

In February 2022, LIME was installed underground at LNGS to be tested under the conditions of the future CYGNO experiment. These measurements will allow us to characterize the performance of the detector in low radioactivity and low pile-up configurations, measure the actual background, and validate the MC simulation, as well as test the gas system and all the data analysis tools developed for 3D track reconstruction and background rejection. The expected background was simulated, taking into account both the intrinsic radioactivity of the detector materials and the natural ambient gamma and neutron flux. The application of fiducial cuts to our sensitive volume showed that the radioactivity induced background events can be reduced by 96%. The shielding design was optimized through dedicated MC simulations for different phases of the upcoming data collection underground, and it comprises the use of copper to shield the detector from gammas and water tanks to shield it from neutrons. Before the installation of the water shielding, a spectral measurement of the fast neutron flux underground will be done, which will provide valuable information for all rare events search experiments running underground at LNGS. The neutron spectrum will be retrieved by deconvolving the NRs spectrum measured with LIME with the response of the detector. LIME is a critical step towards the development of the CYGNO demonstrator, which will demonstrate the scalability of this approach to large volumes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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). 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.

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