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The CYGNO project for directional Dark Matter searches

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The CYGNO project aims to develop a high-precision optical Time Projection Chamber (TPC) for directional Dark Matter search and solar neutrino spettroscopy, to be hosted at Laboratori Nazionali del Gran Sasso (LNGS). The distinctive feature of CYGNO include the exploitation of scientific CMOS cameras and photomultiplier tubes coupled to a Gas Electron Multiplier for amplification within helium-fluorine-based gas mixture at atmospheric pressure. The primary objective of this project is to achieve three-dimentional tracking with head-tail capability and to enhance background rejection down to the keV energy range. This enhancement will significantly improve sensitivity to low Weakly Interacting Massive Particle masses for both Spin-Independent and Spin-Dependent coupling. We provide insights into the commissioning and underground operation of our 50-liter prototype, known as LIME, which represents the largest prototype developed by our collaboration to date. We showcase its capability to measure and identify low-energy nuclear and electron recoils. Additionally, we outline the design and prospects for the development of a funded $O(1\,\mathrm{m}^3)$ demonstrator, set to be housed in Hall F of LNGS. Furthermore, we present the physics potential that a future $O(30\,\mathrm{m}^3)$ experiment could bring to the field. Lastly, we discuss the results from our collaboration's research and development efforts aimed at maximizing the potential of CYGNO. This includes the recent achievement of negative ion drift operation at atmospheric pressure with optical readout, which was accomplished in synergy with the ERC Consolidator Grant project INITIUM.

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1. Introduction

Time Projection Chambers (TPCs) are a valuable detection technique to search for dark matter (DM). However, this task is challenging due to high background rates and the low energy deposited by DM interactions. When DM candidates interact with atomic nuclei, they transfer energy to the nuclei, resulting in nuclear recoils (NR) that leave detectable traces.

The CYGNO collaboration's innovative strategy involves capturing images of nuclear recoil events within a TPC filled with a He:CF4 gas mixture in a 60/40 proportion at atmospheric pressure. The ionization signal is amplified using three Gas Electron Multipliers (GEMs), with CF4 emitting visible light. A high-sensitivity CMOS camera and photomultipliers (PMT) record this light, providing high-resolution, low-noise images and three-dimensional reconstruction capabilities. This optical coupling allows sensors to be placed outside the detector volume, enabling the acquisition of large surfaces with small sensors.

The CYGNO project initiated in 2015 was gradually expanded from 0.1 liters to the current 50-liter prototype, LIME. We have evaluated LIME's performances overground at INFN Laboratori Nazionali di Frascati (NLF), and currently we are running the prototype underground at INFN Laboratori Nazionali del Gran Sasso (LNGS) to assess its performance in a low background environment, determine the radio-purity of the detector's material, and define the optimal shielding strategy. In parallel, we are building a $O(1\,\mathrm{m}^3)$ detector with multiple modules inspired to the LIME prototype, to be commissioned and operated next year at LNGS. The ultimate goal is to propose CYGNO, a larger apparatus ranging from 30 to 100 cubic meters.

2. LIME performances

The LIME prototype, a 50-liter detector, is matching the size of a detector module in the upcoming CYGNO demonstrator. It uses a triple $33 \times 33\,\mathrm{cm}^2$ GEM stack to amplify ionization charge generated in a 50 cm-long drift region. Additionally, it incorporates a high-resolution sCMOS camera and four PMTs to capture scintillation light after the amplification stage. The sCMOS camera has $160 \pm 160\,\mu\mathrm{m}^2$ pixels, a noise level of approximately one photon per pixel, and a quantum efficiency of 80% at 600 nm, which matches the spectral emission of the He:CF_4 mixture used. The combination of the camera and PMTs allows 3D track reconstruction with directional information. These are key elements to reject background and enhance DM sensitivity.

LIME was extensively tested, employing a variety of X-ray sources at the INFN Laboratori Nazionali di Frascati (LNF) [1]. Throughout a month of continuous operation, the detector maintained stable conditions, showing an acceptable rate of current spikes, thus confirming the practicality of uninterrupted underground usage. The energy resolution, as determined using a ^{55}Fe source that emitted 5.9 keV X-rays at varying distances from the GEM plane, has been measured to be around 15%, largely independent on the deposit's position in the TPC. The detector's performance was also assessed, employing a range of radioactive X-ray sources with energies spanning from 4 keV to 50 keV, revealing consistent behavior across the entire energy spectrum.

At the beginning of the 2022 the LIME prototype has been installed underground at the INFN Gran Sasso Laboratories (LNGS) to study and to characterize the detector's performance in low radioactivity and low pile-up configurations. We have concluded Run1 and Run2 with no shielding and 4 cm of copper shielding respectively. The transition from Run1 to Run2 resulted in a decrease in background rate from 33.9 ± 0.6 Hz to 4.8 ± 0.3 Hz. These runs provided us with the opportunity to enhance our event reconstruction algorithms, especially those that integrate the data from PMTs and sCMOS for improved 3D reconstruction capabilities. We are presently in Run3 which involves a 10 cm copper shielding, resulting in a background rate of approximately 1 Hz. The data acquired through different shielding setups provide us with the capability to discern various background compositions, including both internal and external components, as well as electronic (ER) and nuclear (NR) recoils. This is extremely important to develop and tune the detector simulation. Furthermore, in Run3, due to the low background yield, we had the opportunity to expose the detector to an AmBe radioactive source, which emits neutrons in the MeV kinetic energy range. This configuration provides a valuable opportunity to gain insights into how nuclear NR events manifest within the LIME detector. To distinguish NR from ER events we investigated various cluster variables. Our current algorithm relies on the cluster energy density, which strongly correlates with how particles of different natures lose energy.

3. The CYGNO demonstrator

After the commissioning of LIME underground we will move to CYGNO-phase1 with the aim of studying and minimizing the radioactivity effects on a larger scale, close to real experiments. For this purpose we have concluded at LNF the technical design of Cygno04, the $\mathcal{O}(1\ \mathrm{m}^3)$ demonstrator of the CYGNO experiment. It consists of 2 field cages on the opposite side of a common cathode closed by 2 matrices of 2×1 GEMs stages, each stage is readout by a module identical to LIME. The funding for this detector has been secured, and its installation at LNGS is scheduled for completion by 2024. Upon the conclusion of phase1, we envision progressing to phase2, where we plan to propose an apparatus comprising multiple modules, akin to CYGNO04, resulting in a sensitive volume spanning tens of cubic meters. This ambitious experiment aims to contribute significantly to the search for DM in the GeV mass range, addressing both SI and SD coupling scenarios [2]. Furthermore, in the event of signals indicating interactions inconsistent with ordinary matter, the directional capability of the detector would play a pivotal role. It could confirm the galactic origin of the detected signal as DM and provide crucial insights into its properties.

4. Conclusions

In summary, the CYGNO collaboration is developing a GEM based TPC operated with a He:CF_4 gas mixture at atmospheric pressure and readout optically by means of a sCMOS camera and photodetectors. The first detector prototypes demonstrated to have very good energy and position resolution together with a high discriminating power between electronic and nuclear recoils. Ongoing studies are dedicated to optimizing the detector's performance, with three key areas of focus: (i) deploying electronegative gas mixtures to enhance the resolution in determining the event distance from the GEMs plane, (ii) increasing the light yield induced by electrons accelerated after the last GEM plane to improve energy resolution while operating the GEMs at moderate voltages, and (iii) exploring the use of hydrogenated gas mixtures to enhance detector performance in the low DM mass region. The collaboration is actively working on commissioning the LIME prototype in an underground campaign at the Laboratori Nazionali del Gran Sasso (LNGS) in a low-background environment. Additionally, efforts are underway to construct a CYGNO demonstrator, which will be installed and operated at LNGS.

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