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The CYGNO experiment(*)

R. ANTONIETTI(1)(2), E. BARACCHINI(3)(4), L. BENUSSI(5), S. BIANCO(5), R. CAMPAGNOLA(5), C. CAPOCCIA(5), M. CAPONERO(5)(6), L. G. CARVALHO(7), G. CAVOTO(8)(9), I. A. COSTA(5), A. CROCE(5), M. D'ASTOLFO(3)(4), G. D'IMPERIO(9), E. DANÈ(5), G. DHO(5), F. DI GIAMBATTISTA(3)(4), E. DI MARCO(9), J. M. F. DOS SANTOS(10), D. FIORINA(3)(4), F. IACOANGELI(9), Z. U. ISLAM(3)(4), E. KEMP(11), H. P. LIMA JR.(3)(4), G. MACCARRONE(5), R. D. P. MANO(10), R. R. MARCELO GREGORIO(12), D. J. G. MARQUES(3)(4), G. MAZZITELLI(5), A. G. MCLEAN(12), P. MELONI(1)(2), A. MESSINA(8)(9), C. M. B. MONTEIRO(10), R. A. NOBREGA(7), I. F. PAINS(7), E. PAOLETTI(5), L. PASSAMONTI(5), F. PETRUCCI(1)(2), S. PIACENTINI(3)(4), D. PICCOLO(5), D. PIERLUIGI(5), D. PINCI(9), A. PRAJAPATI(3)(4), F. RENGA(9), R. J. D. C. ROQUE(10), F. ROSATELLI(5), A. RUSSO(5), G. SAVIANO(5)(13), P. A. O. C. SILVA(10), N. J. SPOONER(12), R. TESAURO(5), S. TOMASSINI(5), S. TORELLI(3)(4) and D. TOZZI(8)(9)

(1) *Dipartimento di Matematica e Fisica, Università Roma Tre - 00146, Roma, Italy*
(2) *Istituto Nazionale di Fisica Nucleare, Sezione di Roma Tre - 00146, Rome, Italy*
(3) *Gran Sasso Science Institute - 67100, L'Aquila, Italy*
(4) *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso 67100, Assergi, Italy*
(5) *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati 00044, Frascati, Italy*
(6) *ENEA Centro Ricerche Frascati - 00044, Frascati, Italy*
(7) *Universidade Federal de Juiz de Fora, Faculdade de Engenharia - 36036-900, Juiz de Fora, MG, Brasil*
(8) *Dipartimento di Fisica, Università di Roma Sapienza - 00185, Roma, Italy*
(9) *Istituto Nazionale di Fisica Nucleare, Sezione di Roma - 00185, Roma, Italy*
(10) *LIBPhys, Department of Physics, University of Coimbra - 3004-516 Coimbra, Portugal*
(11) *Universidade Estadual de Campinas, UNICAMP - 13083-859, Campinas (SP), Brazil*
(12) *Department of Physics and Astronomy, University of Sheffield - Sheffield, S3 7RH, UK*
(13) *Dipartimento di Ingegneria Chimica, Materiali e Ambiente, Sapienza Università di Roma 00185, Roma, Italy*

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Summary. — The existence of non-luminous matter in the Universe, known as Dark Matter, is a fundamental ingredient of modern cosmological theories. Its nature and characteristics are currently unknown. The CYGNO project, using a directional detector, aims to study events such as Dark Matter interactions in the low mass region O(GeV/c^2). The proposed detector is a Time Projection Chamber (TPC), filled with a gas mixture of He:CF_4 (60:40) at room temperature and atmospheric pressure. The signal is produced by primary ionization from a few keV nuclear or electron recoil, which is amplified using a triple Gas Electron Multiplier (GEM) stack. During this process, light proportional to the primary electrons is generated. By combining the use of a sCMOS camera and photomultiplier, the signal is acquired allowing for the reconstruction of the energy and direction of the recoils. The R&D phase is concluding with the Long Imaging ModulE (LIME) prototype, a 50 liters TPC. It is currently taking data underground at the Laboratori Nazionali del Gran Sasso (LNGS) to study the performance of the prototype in a low background environment. The latest results on LIME operations in different configurations are shown.

1. – Introduction

The presence in the Universe of a large amount of matter with a very low interaction with ordinary matter, known as Dark Matter (DM), is nowadays well established. One of the leading candidates for Dark Matter are the Weakly Interacting Massive Particles (WIMPs). The CYGNO project will investigate in the low mass range of O(GeV/c^2).

Due to their non-relativistic speed, the evidence of DM interaction may be observed through elastic scattering with ordinary matter. While DM particles have a random direction in the Galactic reference frame, on the Earth, a DM particle would appear to move along the direction of the motion of the Earth in the Galaxy, which is given by the motion of the Sun, apparently toward the Cygnus constellation.

The possibility to infer the direction of the incoming DM particles is crucial for discriminating DM signals from other background sources. The main background sources are given by two contributions: the cosmic rays or external radioactivity and the internal radioactivity of the detector materials. To mitigate the first source, the detector is placed underground and shielded, while radio-pure materials have to be used for the second one.

The CYGNO project [1] aims to deploy a high resolution Time Projection Chamber (TPC) underground at the Laboratori Nazionali del Gran Sasso (LNGS). The TPC is filled with a gas mixture based on light atoms as target with optical readout for studying rare events such as the low mass DM particles interactions. A triple Gas Electron Multiplier (GEM) stack is used to amplify the signal, emitting light during the GEM amplification phase.

As shown in fig. 1, we are currently concluding PHASE_0 which finalizes the R&D phase with the LIME prototype, and transitioning to PHASE_1, involving the construction of the 0.4 m^3 demonstrator: CYGNO-04.

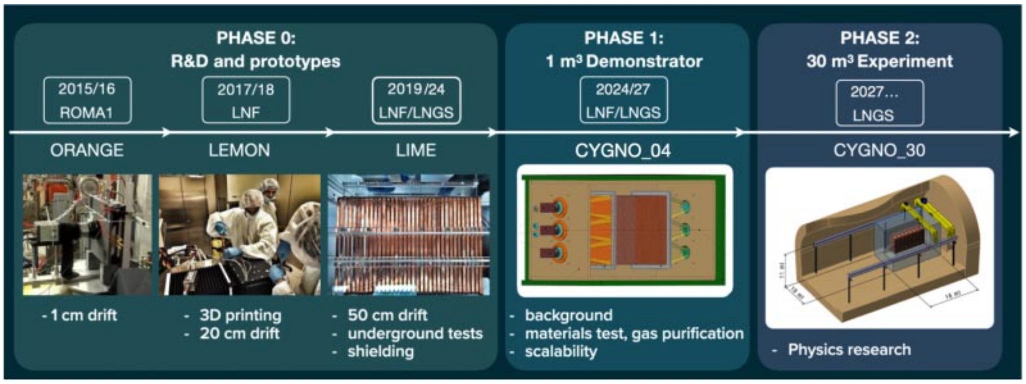

Fig. 1. – Timeline of the CYGNO project.

2. – The optical readout

Charged particles traversing the gas ionize atoms and molecules, and excite them as well. Ionization electrons are drifted along the electric field towards the anodic plane, where a triple GEMs stack is located. This stack amplifies the signal, and notably photons are generated during the amplification process.

The combined use of PhotoMultiplier Tubes (PMTs) to measure the tilt in the direction along the drift field and of a sCMOS camera for the x-y plane, enables the reconstruction of 3D tracks [2].

The optical readout allows also to measure the energy and help to discriminate electron recoil and nuclear recoil.

3. – The Lime prototype

The Long Imaging ModulE (LIME) is the last prototype developed to conclude the R&D phase. It features a 50 cm long drift volume. A uniform electric field, directed orthogonally to the cathode plane, is generated by a series of copper rings, electrodes, designed in a rounded shape to prevent discharges. The scheme of the prototype is shown in fig. 2. The detector is enclosed within a 3 mm thick aluminium metal box, which acts as a Faraday cage and ensures the light tightness of the detector.

Each GEM installed to amplify the signal has a 33×33 cm^2 surface. The light is detected by a scientific CMOS camera, the Hamamatsu Orca Fusion [3], along with four Hamamatsu R7378 PMTs [4] placed symmetrically around the camera for the 3D reconstruction.

The detector operates with a $He:CF_4$ (60:40) gas mixture, kept a few millibars above the atmospheric pressure. As shown in fig. 3, the electro-luminiscence spectra [5] of the gas mixture used show two main peaks: one around a wavelength of 300 nm and another around 620 nm. This second peak matches the range where the Fusion camera sensor achieves an 80% quantum efficiency (QE), while the first peak aligns with the maximum efficiency of the PMTs.

The reconstruction algorithm for the tracks is based on DBSCAN (Density-Based Spatial Clustering of Applications with Noise) [6], a clustering method that identifies dense regions of data points, allowing for the effective separation of track signals from noise.

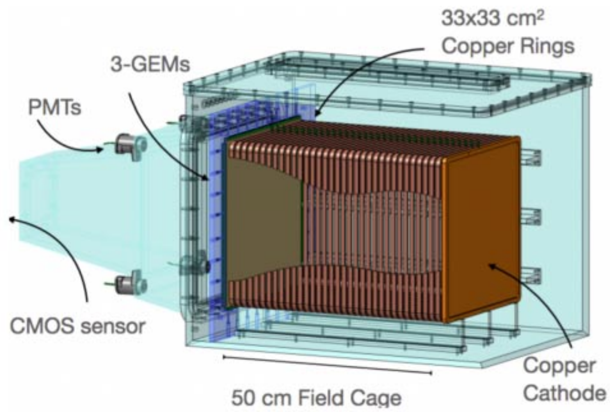

Fig. 2. – The scheme of LIME protoype: it features a 50 cm long drift volume. A series of copper rings generates a uniform electric field. The signal is amplified by a triple GEMs stack. The generated photons are read out by the combined use of four PMTs and a sCMOS camera.

The LIME prototype operated for several months overground at LNF [7] to study its operational capability. A multi-source system was installed on the upper surface of the prototype to evaluate the detector response linearity. The promising results obtained are shown in fig.4.

At the beginning of 2022, the LIME prototype was installed underground at LNGS to test the detector performance in a low radioactivity and low pile-up environment.

To mitigate and study external radioactivity, runs with various configurations were taken. These included Run1 with no shielding, Run2 with 4 cm of copper shielding, Run3 with 10 cm of copper shielding and Run4 with an additional 40 cm water shield. Table I provides a summary of the data collection plan and the corresponding background rate for each configuration.

To test the detector's stability, a ^{55}Fe source was placed 25 cm from the GEMs in order to acquire calibration runs. Starting from Run3, a humidity sensor was installed

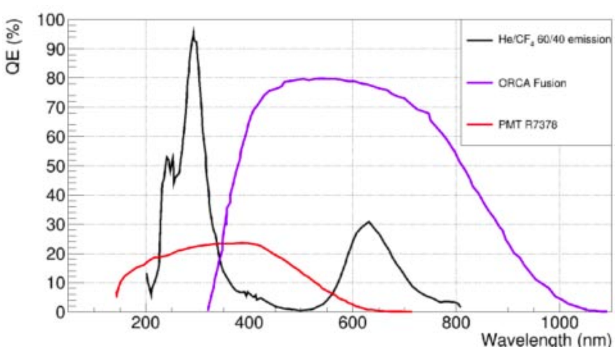

Fig. 3. – The superimposition of the electro-luminiscence spectra of the He:CF_4 gas mixture in black, the quantum efficiency of the Hamamatsu Orca Fusion camera in violet and the Hamamatsu PMT in red.

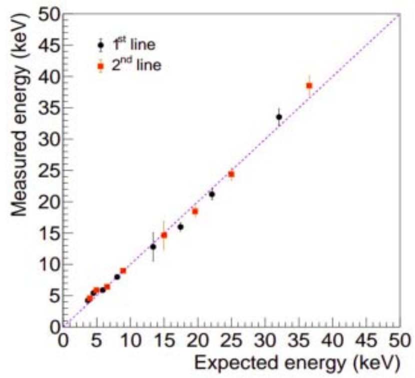

Fig. 4. – The linearity response of the LIME prototype.

TABLE I. – *Timetable of the Run acquired underground at LNGS.*

Time	Autumn 2022	Winter 2023	Spring/Summer 2023	Winter 2024
Name	Run1	Run2	Run3	Run4
Description	No shielding	4 cm Cu shield	10 cm Cu shield	10 cm Cu shield 40 cm water
Background rate	$\sim$ 35 Hz	$\sim$ 3.5 Hz	$\sim$ 1.5 Hz	1 Hz

and the spot intensity induced by the ^{55}Fe source was normalized to the spot intensity of the first acquired run. As shown in fig. 5, the spot intensity produced by the ^{55}Fe source decreases exponentially as humidity increasing.

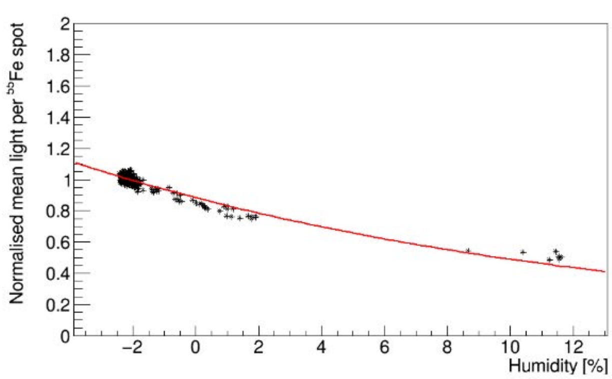

Fig. 5. – The ^{55}Fe normalised *versus* the humidity; the spot intensity decreases exponentially with increasing humidity.

4. – Conclusions

The CYGNO collaboration is developing a high-precision gaseous TPC with optical readout for the direct search of WIMPs-like Dark Matter particles.

The LIME prototype is currently collecting data at the underground LNGS facility. Analysis of data is still ongoing. The insights gained from the LIME prototype's performance will significantly contribute to the refinement and success of the CYGNO_04 demonstrator.

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