The CYGNO/INITIUM experiment

F. D. Amaro[1], E. Baracchini[2,3], L. Benussi[4], S. Bianco[4], C. Capoccia[4], M. Caponero[4,5], D. Santos Cardoso[6], G. Cavoto[7], A. Cortez[2,3], I. A. Costa[9,12], E. Dané[4], G. Dho[2,3⋆], F. Di Giambattista[2,3], E. Di Marco[8], G. D'Imperio[8], F. Iacoangeli[8], H. P. L. Jùnior[6], G. S. P. Lopes[1], G. Maccarrone[4], R. D. P. Mano[1], R. R. M. Gregorio[11], D. J. G. Marques[2,3], G. Mazzitelli[4], A. G. McLean[11], A. Messina[7,8], C. M. B. Monteiro[1], R. A. Nobrega[10], I. Fonseca Pains[10], E. Paoletti[4], L. Passamonti[4], S. Pelosi[8], F. Petrucci[9,12], S. Piacentini[7,8], D. Piccolo[4], D. Pierluigi[4], D. Pinci[8], A. Prajapati[2,3], F. Renga[8], R. J. C. Roque[1], F. Rosatelli[4], A. Russo[4], J. M. F. dos Santos[1], G. Saviano[4,13], N. J. C. Spooner[11], R. Tesauro[4], S. Tommasini[4] and S. Torelli[2,3],

1 LIBPhys; Department of Physics; University of Coimbra; 3004-516 Coimbra; Portugal
2 Gran Sasso Science Institute; 67100; L'Aquila; Italy
3 Istituto Nazionale di Fisica Nucleare; Laboratori Nazionali del Gran Sasso; 67100; Assergi; Italy
4 Istituto Nazionale di Fisica Nucleare; Laboratori Nazionali di Frascati; 00044; Frascati; Italy
5 ENEA Centro Ricerche Frascati; 00044; Frascati; Italy
6 Centro Brasileiro de Pesquisas Físicas; Rio de Janeiro 22290-180; RJ; Brazil
7 Dipartimento di Fisica; Università La Sapienza di Roma; 00185; Roma; Italy
8 Istituto Nazionale di Fisica Nucleare; Sezione di Roma; 00185; Rome; Italy
9 Dipartimento di Matematica e Fisica; Università Roma TRE; 00146; Roma; Italy
10 Universidade Federal de Juiz de Fora; Faculdade de Engenharia; 36036-900; Juiz de Fora; MG; Brasil
11 Department of Physics and Astronomy; University of Sheffield; Sheffield; S3 7RH; UK
12 Istituto Nazionale di Fisica Nucleare; Sezione di Roma Tre; 00146; Rome; Italy
13 Dipartimento di Ingegneria Chimica; Materiali e Ambiente; Sapienza Università di Roma; 00185; Roma; Italy
⋆ giorgio.dho@gssi.it

September 12, 2022

14th International Conference on Identification of Dark Matter
Vienna, Austria, 18-22 July 2022
doi:10.21468/SciPostPhysProc.?

Abstract

The CYGNO project for the development of a high precision optical readout gaseous TPC for directional Dark Matter search and solar neutrino spectroscopy will be presented. It is to be hosted at Laboratori Nazionali del Gran Sasso. CYGNO peculiar features are the use of sCMOS cameras and PMTs coupled to GEMs amplification of a helium-based gas mixture at atmospheric pressure, in order to achieve 3D tracking with head tail capability and background rejection down to O(keV) energy, to boost sensitivity to low WIMP masses. The latest R&D results within the CYGNO project will be discussed along with the underground installation and operation of a 50 l prototype, soon to be followed by a O(1) m3 experiment demonstrator in 2024-2026. The latest results on the negative ion drift operation at atmospheric pressure within CYGNO optical readout approach will be illustrated, which is the aim of the ERC Consolidator Grant project INITIUM.

1 Directional Dark Matter Search

In the last decades, the existence of Dark Matter (DM) has become well established, even though its nature is still elusive and unknown. One of the supported candidates predicts the existence of at least one new particle not included in the Standard Model of particle physics. The Weakly Interactive Massive Particles (WIMPs) stand out among various possibilities as they were foreseen by models of both Cosmology and Particle physics. It is believed that a DM halo made of these hypothetical neutral massive particles which would interact only weakly with standard matter is enveloping our Galaxy [1]. The motion of the Sun around the centre of the Galaxy along with the rotation of the Earth around its own axis produces an apparent wind of DM particles coming from the Cygnus constellation. This wind causes an excess of interactions with standard matter whose recoils with nuclei of the order of few keV can be detected by experiments on Earth. Moreover, the wind of particles introduces a directional dependence on the recoils that can be exploited to further inspect DM. Indeed, the angular distribution will be highly dipolar, a key element for positive identification of DM, DM astronomy [2] and will fundamentally help to survey the parameter space within the well known neutrino fog [3,4].

2 The CYGNO detector concept

The CYGNO experiment aims at building a large volume gaseous Time Projection Chamber (TPC) in a back-to-back configuration with 50 cm drift, filled with a He:CF_4 60:40 gas mixture operated at atmospheric pressure and room temperature in the Laboratori Nazionali del Gran Sasso (LNGS) [5]. The passage of an ionizing radiation frees charge in the gas inside the sensitive volume and an electric field will drift this primary charge towards the amplification stage which consists in a triple Gas Electron Multiplier (GEM) structure. Here, there will be multiplication of the charge and, thanks to the properties of the gas mixture chosen, also light will be produced. The readout will be optical by means of two cooperating light detectors: PMTs and sCMOS cameras by Hamamatsu. The PMT will exploit its fast response to obtain information on the impinging radiation such as the energy, through the amount of photons collected, and the length of the track along the drift direction (z), thanks to the time spread and topology of the signal. On the other hand, a sCMOS camera has a high granularity with single photon sensitivity which will allow to take 2D pictures of the track of the original radiation projected on the GEM plane, other than counting the photons for the energy evaluation. Linking the information coming from the two detectors it will be possible to reach a fully three dimensional reconstruction of the tracks together with a precise measurement of the energy.

3 Phase-0: LIME

Different prototypes were built in the past to test the characteristics of the amplification stage and the optical readout [5]. With the years the dimension of the readout and especially the drift distance increased reaching the current largest built prototype LIME. This is a 50 l detector with 50 cm drift and 33x33 cm^2 readout plane area which operates with a gas mixture of He:CF_4 at 60:40 ratio. It works at atmospheric pressure and room temperature in order to avoid the necessity of extra infrastructure usually needed for low pressure or cryogenic detectors. The optical readout comprises a Hamamatsu ORCA Fusion sCMOS camera and 4 PMTs (Hamamatsu R7378), with a dedicated DAQ system that allows to collect data from these diverse detectors keeping them synchronous. A dedicated gas system provided by the

AirLiquide company takes care of the flux of gas along with the re-circulation and recovery of the used gas. Several tests were performed overground, when the detector was at the Laboratori Nazionali di Frascati, with the help of a radioactive source which was irradiating targets of different materials, inducing K_α emission from the targets that were directed toward the sensitive volume of the detector. Thanks to these measurements, the linearity of the response was measured to be quite good between 3 keV up to 45 keV, and the results were found in very good agreement with the simulation of the signal production. Since February 2022, LIME is located underground in the Laboratori Nazionali del Gran Sasso (LNGS), between Hall A and B to furnish the first data taken in an environment suitable for the actual DM search. It is taking data at a steady pace remotely controlled by an automated system. Pictures and waveforms from the sCMOS camera and PMTs are being saved while parameters such as pressure, temperature and some others to check the quality of the data are checked routinely. The impact of the background radiation was estimated by means of Geant4 simulations in order to optimize the shielding materials and to evaluate the main contributors of the internal radioactivity. The foreseen shielding is made of 10 cm of copper surrounded by 40 cm of water. The internal components radioactivity was measured at the facilities of LNGS and is expected to be dominant mainly due to field rings of the field cage along with the GEMs, cathode and resistors. However, it was found that simple geometrical cuts can lower drastically the number of nuclear recoils to less than 20 per year. The electron recoils number can be decreased to $O(10^5)$, but the topology of the tracks measurable by the optical readout will help distinguish them. Good results were obtained with a very simplistic cut on the measured dE/dx, but more complicated machine learning based techniques are under study.
The data taking foreseen for LIME will start with a couple of months without any shielding in order to perform some calibration tests with ^{55}Fe and AmBe sources and to measure the external background, not only to quantify it but also to crosscheck the simulations performed. Then, a first layer of 6 cm of copper shielding will be added, with the same goals as before. Later, the copper shielding will reach the 10 cm width and LIME will measure the neutron flux of the underground laboratories, possibly also their angular distribution. After four months, the water shielding will be finally added and the final validation of the MC simulation of the internal background will be carried out. The operation of this prototype in the underground environment will provide precious information for the future of the project.

4 Future of CYGNO

The next step for the CYGNO project is to build, from 2023 to 2026, Phase-1 CYGNO_04 which will be installed underground at LNGS. The detector is fully funded and the Technical Design Report was submitted to the LNGS committee for it to be installed in Hall F. The design of the detector and of the shielding has already started as well as detailed simulations of this larger detector. It will consist in a 0.4 m^3 detector with 1 m drift length, but in a back-to-back configuration, making the operative drift lengths as long as LIME. The readout area will be of 50x80 cm^2 and readout by two cameras and six PMTs. Relevant improvements include lower radioactive materials, as PMMA, cathode and other internal components, and a new camera from Hamamatsu, the ORCA Quest (https://www.hamamatsu.com/jp/en/product/cameras/qcmos-cameras/C15550-20UP.html), which possesses a much lower electronic noise. The main goal of Phase-1 is to prove the scalability of the technology to larger volumes while keeping the performances as good as before , if not better. A purification system to fully recover the used gas will also tested with CYGNO_04.
Further into the future, the CYGNO_30 will be proposed for the actual physics search exploiting an O(30) m^3 volume. The first conceptual drawings have already being started. Using the

current parameters of possible background rates, energy threshold and other detector parameters, the expected limits were evaluated through Bayesian techniques both for Spin dependent and independent interaction. In the SI region a directional detector will be competitive with other low WIMP mass experiments, while for the SD it will be competing for the best limits in the O(GeV) WIMP mass.

5 R&D for future developments

For the future detectors many R&Ds are ongoing to improve performances in a wide range of parameters. The possibility to reduce the internal radioactivity further more lead to the design of a fused silica lens for the sCMOS camera. It is under study the possibility to exploit a strong electric field below the last GEM of the amplification stage to enhance the light production signal in order to improve the energy threshold [7]. The addition of a material even lighter than helium in gas mixture like hydrogen could move the low mass detection threshold down to around 500 MeV, probing another part of the parameter space for DM for both SD and SI. It is under test the possibility of adding a hydrogen rich component to the gas mixture that would not affect the optical performances of the gas.
In synergy with the CYGNO experiment, the INITIUM project, funded by the ERC of Elisabetta Baracchini, aims at the use of Negative Ion Drift (NID) operation in the context of gaseous TPC for DM searches. The addition of an electronegative gas, such as SF_6, would make the primary charge to be captured by these molecules, effectively drifting ions in place of electrons. This would strongly reduce diffusion as the ions would more towards the thermal limit of diffusion [8]. With a small prototype available, it was possible to measure for the first time NID operation at high pressure with optical readout. These results have been presented to conferences such as iWorid and are going to be published soon. The preliminary measurement of the reduced mobility is consistent with the ones in literature for the same gas mixture of $He:CF_4:SF_6$ at 59:39.4:1.6. It was found a configuration in which the light yield of the standard mixture and the electronegative one matched and already at a drift distance of 12 cm the transverse diffusion was strongly diminished. Despite being preliminary results, the operation of this gas looks promising for future improvements.

Acknowledgements

Part of this project is funded by the European Union's Horizon 2020 research and innovation programme under the ERC Consolidator Grant Agreement No 818744.

References

[1] R. W. SCHNEE, *INTRODUCTION TO DARK MATTER EXPERI- MENTS*, Physics of the Large and the Small, WORLD SCIENTIFIC (2011), doi:10.1142/9789814327183_0014.

[2] F. Mayet et al., *A review of the discovery reach of directional dark matter detection*, Physics Reports **627**, 1-49 (2016) doi:10.1016/j.physrep.2016.02.007

[3] C. Bœhm et al., *How high is the neutrino floor?*, Journal of Cosmology and Astroparticle Physics 2019 **01**, 43-43 (2019), doi:10.1088/1475-7516/2019/01/043

[4] C. O'Hare, *New Definition of the Neutrino Floor for Direct Dark Matter Searches*, Phys. Rev. Lett. **127** 25, 251802 (2021), doi:10.1103/PhysRevLett.127.251802

[5] F. Amaro et al., *The cygno experiment*, Instruments **6**, (2022) doi:10.3390/instruments6010006

[6] E. Baracchini et al., *Identification of low energy nuclear recoils in a gas time projection chamber with optical readout*, Measurement Science and Technology **32**, (2021) doi:10.1088/1361-6501/abbd12

[7] Baracchini et al., *First evidence of luminescence in a He/CF_4 gas mixture induced by non-ionizing electrons*, JINST **15** (2020) pg 08018 doi:10.1088/1748-0221/15/08/P08018

[8] C.J. Martoff et al., *Suppressing drift chamber diffusion without magnetic field*, NIM **440** 2 (2000) pg 355-359 doi:doi.org/10.1016/S0168-9002(99)00955-9