8th CYGNUS Workshop on Directional Recoil Detection

Monday 11 December 2023 - Friday 15 December 2023

School of Physics

Book of Abstracts

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Mechanical quantum sensing and 3d momentum detection

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Optical and microwave readout of mechanical objects can be used to continuously detect the full 3d momentum vector of the object's center-of-mass. This can be done with target masses ranging from single ions to kilogram-scale objects. Increasingly, the limiting noise in these systems is determined by the quantum mechanical noise in the readout itself (the "standard quantum limit"). Nanomechanical sensors in this regime are particularly suited to directional detection in particle collisions. In this talk we will discuss a number of proposals and experimental realizations of this basic idea, targeting dark matter masses from keV to TeV, as well as sterile neutrinos produced in nuclear decays inside of the mechanical target masses.

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Anomaly aware machine learning for dark matter direct detection at DARWIN

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This talk presents a novel approach to dark matter direct detection using anomaly-aware machine learning techniques in the DARWIN next-generation dark matter direct detection experiment. I will introduce a semi-unsupervised deep learning pipeline that falls under the umbrella of generalized Simulation-Based Inference (SBI), an approach that allows one to effectively learn likelihoods straight from simulated data, without the need for complex functional dependence on systematics or nuisance parameters. I also present an inference procedure to detect non-background physics utilizing an anomaly function derived from the loss functions of the semi-unsupervised architecture. The pipeline's performance is evaluated using pseudo-data sets in a sensitivity forecasting task, and the results suggest that it offers improved sensitivity over traditional methods.

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Progress Towards Directional Detection of Dark Matter using Spectroscopy of Quantum Defects in Diamond

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Nitrogen vacancy (NV) centers in diamond have been identified as a promising future platform for directional detection of weakly interacting massive particle (WIMP) dark matter. A WIMP particle induces nuclear recoil in the diamond, resulting in a direction-dependent sub-micron damage track. This damage track induces crystal stress variations which shift the energy levels of NV centers, enabling localization of the track through spectroscopic interrogation. Subsequently, further nanoscale characterizations to determine the length and direction of the track can be performed. Thus, this method is capable of distinguishing WIMP-induced tracks from tracks produced by known sources, providing a strategy to overcome the background solar neutrino problem. In this talk, I will present an overview of the proposed detection method as well as recent experimental progress in our group towards demonstrating the required imaging techniques, such as high precision strain mapping using quantum interferometry and x-ray diffraction microscopy.

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Molecular sieve vacuum swing adsorption purification and radon reduction system for gaseous dark matter and rare-event detectors

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SF6 has become of interest as a negative ion drift gas for use in directional dark matter searches. However, as for other gas targets in such searches, it is important that contamination gases can be removed. This includes radon gas contamination that can decay, producing unwanted background events able to mimic genuine signals, but also outgassing and leaking introduce contaminants such as water, oxygen and nitrogen, which can capture interaction-produced electrons, thus suppressing signals. We present here a novel molecular sieve (MS) based gas recycling system that offers a solution for the simultaneous removal of both radon and common impurities from SF6. The apparatus has the additional benefit of minimising the total amount of gas required in experiments and utilises a Vacuum Swing Adsorption (VSA) technique for continuous, long-term operation. The gas system' s capabilities were tested with a 100 L low-pressure SF6 Time Projection Chamber (TPC) detector. For the first time, we present a newly developed low-radioactive MS type 5A, specifically engineered for this study. This material was found to emanate up to 98% less radon per radon captured compared to commercial counterparts, representing the lowest known emanation at the time of writing. Coupled with this new MS, the gas system reduced the intrinsic radon activity in the detector to 0.8 +/- 6.4 mBq, within error of the radon measurement apparatus background. MS types 3A and 4A further mitigated gain deterioration, sustaining signal for 340 hours until detector operation was terminated, compared to 50 hours without the system. These results demonstrate that a VSA gas recycling system coupled with suitable MSs can reduce intrinsic radon activity and extend detector operation in an SF6 gas-based directional dark matter detector.

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The COHERENT Experiment

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The COHERENT collaboration was the first to observe coherent elastic neutrino-nucleus scattering (CEvNS) at the Spallation Neutron Source at Oak Ridge National Laboratory (TN, USA) in 2017. The SNS is a pulsed pion decay-at-rest neutrino source with a well-known spectrum of low-energy neutrinos.

Today, the collaboration operates several detectors measuring CEVNS and neutrino-charged-current interactions across various target nuclei. This point source of low-energy neutrinos, and the proposed second target station at the SNS, provide exciting opportunities for potential new detectors that could employ directional detection techniques.

This talk will focus on the past, present, and future of COHERENT.

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NEWAGE

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Latest results, R&D status and futures of NEWAGE will be presented.

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Development of directional dark matter detector with anisotropic ZnWO4 scintillator

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The ZnWO4 crystal has been noted for its directional dependence in scintillation light output based on crystal orientation. Consequently, we are actively developing a direction-sensitive dark matter detector that utilizes this anisotropic response of ZnWO4 crystals.

In this presentation, we will share our findings from the measurement of the quenching factor and the anisotropic response of ZnWO4 crystals using a mono-energetic neutron source provided by the National Institute of Advanced Industrial Science and Technology in Japan. Our discussion will encompass the relationship between scintillation decay time constants and scintillation anisotropy. Additionally, we will present the results of our assessment of radiation impurities in a 2” crystal and estimate the sensitivity of the (currently directionally insensitive) dark matter search.

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Towards CYGNO04

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We will present the progress of the CYGNO04 project, the technical choices made based on budget constraints, and the selected site for installing the detector. The current detector layout will be illustrated along with descriptions of the chosen cathode, field cage, gas vessel, charge amplification device, and light sensors. Additionally, we will provide an update on the development of essential services and infrastructures, including the DAQ, Online Analysis, gas system, and computing infrastructure. These components are crucial for the operation of CYGNO04 and are currently undergoing testing with LIME at LNGS.

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Directional dark matter searches using levitated optomechanics

Authors: Robert James[1]; Fiona Alder[2]; Peter Barker[2]; Chamkaur Ghag[None]; Louis Hamaide[None]

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Levitated optomechanics provides a novel platform to test fundamental physics. One such application provides a unique directional dark matter direct detection technique to explore alternative parameter space to that being investigated by large scale experiments deployed underground. We present progress towards an experiment built at University College London, capable of resolving collisions in all three dimensions, utilising nanoparticles (10^{-18} kg) for composite dark matter searches in the 10 MeV –10 GeV mass range. We detail the theoretical calculations, experimental apparatus, data analysis framework and statistical inference that we aim to use to obtain results competitive with world-leading dark matter constraints. In addition, we present first results from impulse calibrations of the setup, directly demonstrating its directional force sensing capability.

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Development of a versatile TPC for neutron-induced reactions studies at the SARAF TOF facility.

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We present the research plans on the development an Optical Time Projection Chamber (O-TPC) - a multi-purpose gaseous radiation-detector system, as part of the SARAF infrastructure. SARAF Phase II accelerator will provide unique capabilities for neutron-induced reactions, offering intense primary beams for high neutron flux, and tunable neutron energy.

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Extracting Dark-Matter Mass from Directional Observables

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We propose a novel method to determine the mass scale of ambient dark matter that can be generally applied to the (at least effectively) two-dimensional direct detection experiments allowing for directional observables. Due to the motions of the solar system and the Earth relative to the galactic center and the Sun, the dark-matter flux carries a directional preference. We first formulate that dark-matter event rates have a non-trivial dependence on the angle between the associated detection plane and the overall dark-matter flow and that the curvature of this angular spectrum encrypts the mass information. For proof of principle, we take the recently-proposed Graphene-Josephson-Junction-based superlight dark-matter detector (named as GLIMPSE) as a concrete example and demonstrate these theoretical expectations through numerical analyses.

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Status of the NEWSdm experiment

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The recent progress of the NEWSdm experiment will be reported.

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NEWAGE / CYGNUS-KM

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Overview, recent results, R&D activities, and futre plans of NEWAGE and CYGNUS-KM will be presented.

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MIGDAL

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Update on the MIGDAL experiment

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Directional DM detection and Neutron Spectrometry in the keV range with MIMAC

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The talk will include Ionization Quenching Factor measurements with COMIMAC, electron-nuclear recoil discrimination and many other items related with.

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Overview of directional recoil detection

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Overview of directional recoil detection

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Overview of dark matter

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Overview of dark matter

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Direct detection experiments

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Direct detection experiments

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Neutrinos

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Neutrinos

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The Migdal effect

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The Migdal effect

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Introduction

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NR Tracking in Argon/Noble gases

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Ion transport in liquid argon

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Optical negative ion drift operation at atmospheric pressure

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Negative ion drift R&D

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CYGNUS Hawaii: Recent Detector R&D and machine learning results

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Nuclear emulsions

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Discussion on the future plans of the directional detection community

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Environmental neutron measurement at the Gran Sasso laboratory in the NEWSdm experiment

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The NEWSdm experiment is designed to search for dark matter with directional sensitivity at the Gran Sasso laboratory. Nano Imaging Tracker (NIT) used in the NEWSdm experiment is a super-high resolution nuclear emulsion detector. This extremely high spatial resolution makes NIT the unique solid tracking detector capable of determining the direction of nuclei with a track length of 100 nm, equivalent to several tens of keV in energy.
In parallel with the dark matter search, we are progressing neutron measurements targeting hydrogen in NIT itself. An automatic readout system has been well established that is capable of acquiring 3-dimensional vector for recoil protons above 100 keV. Neutron spectra measurements including sub-MeV region have been performed at the Gran Sasso laboratory, and we will report on the status of these measurements.

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Gas Gains Over 10^4 in Low Pressure SF_6 with a Novel Multi-Mesh ThGEM for Directional Dark Matter Searches

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The Negative Ion Drift (NID) gas SF_6 has favourable properties for track reconstruction in directional Dark Matter (DM) searches utilising low pressure gaseous Time Projection Chambers (TPCs). However, the electronegative nature of the gas means that it is more difficult to achieve significant gas gains with regular Thick Gaseous Electron Multipliers (ThGEMs). Typically, the maximum attainable gas gain in SF_6 and other Negative Ion (NI) gas mixtures is on the order of 10^3; whereas electron drift gases like CF_4 and similar mixtures are readily capable of reaching gas gains on the order of 10^4 or greater. In this talk, a novel two stage Multi-Mesh ThGEM (MMThGEM) structure is presented. The MMThGEM was used to amplify charge liberated by an ^{55}Fe X-ray source in 40 Torr of SF_6. By expanding on previously demonstrated results, the device was pushed to its sparking

limit and stable gas gains up to ~50000 were observed. The device was further optimised by varying the field strengths of both the collection and transfer regions in isolation. Following this optimisation procedure, the device was able to produce a maximum stable gas gain of ~90000. These results demonstrate an order of magnitude improvement in gain with the NID gas over previously reported values and ultimately benefits the sensitivity of a NITPC to low energy recoils in the context of a directional DM search.

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Detector R&D with Negative Ion Mixtures

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Negative ion (NI) gas mixtures offer many benefits for directional detection, including low (near-thermal) diffusion and the possibility of adding spin-dependent targets for dark matter (DM) searches. However, the unforeseen benefit of multiple NI species allowing for fiducialization of the drift coordinate in time projection chambers (TPCs) might allow for uses beyond directional detection. We will present some gaseous detector R&D results from an argon-SF6 mixture, and discuss plans to identify NI species suitable for use in liquid-media TPCs.

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Characterization of low-energy Argon recoils with the ReD experiment

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The Recoil Directionality project (ReD) within the Global Argon Dark Matter Collaboration aims to characterize the response of an argon dual-phase Time Projection Chamber (TPC) to neutron-induced nuclear recoils (NRs) and to measure the charge yield for low-energy recoils. This measurement is crucial to improve the sensitivity of future low-mass studies. The charge yield is a critical parameter for the experiments searching for dark matter in the form of low-mass WIMPs and measurements in Ar below 10 keV are scarce in the literature. ReD was designed to cover this gap, by irradiating a miniaturized TPC with neutrons produced by an intense Cf252 fission source, to generate Ar recoils in the energy range of interest. Data were collected during the Winter of 2023 at the INFN Sezione di Catania. The energy of the nuclear recoils produced within the TPC by (n,n') scattering was determined by detecting the outgoing neutrons by a neutron spectrometer made of 18 plastic scintillators. The neutron kinetic energy was evaluated event-by-event by using a time-of-flight approach. The ionization signal was measured for Ar recoils down to 2 keV.

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A progress report on development of Multi-layer THGEM readout structures

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Charge Amplification in Sub-atmospheric CF4, SF6, Helium Mixtures

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Low pressure gaseous Time Projection Chambers (TPCs) are a viable technology for directional Dark Matter (DM) searches and have the potential for exploring the parameter space below the neutrino fog. Gases like CF4 and SF6 are advantageous because they contain Flourine which is predicted to have heightened elastic scattering rates with a possible Weakly Interacting Massive Particle (WIMP) DM candidate. The low pressure of CF4 and SF6 must be maintained, ideally lower than 100 Torr, in order to elongate potential Nuclear Recoil (NR) tracks which allows for improved directional sensitivity and NR/Electron Recoil (ER) discrimination. Recent evidence suggests that He can be added to heavier molecular gases, like CF4 and SF6, without significantly affecting the length of 12C, 19F, and 16S recoils due to its lower mass. Such addition of He has the advantage of improving sensitivity to lower mass WIMPs. Simulations can not reliably predict operational stability in these low pressure gas mixtures and thus must be demonstrated experimentally. In this paper we investigate how the addition of He to low pressure CF4 and SF6 affects the gas gain and energy resolution achieved with a single Thick Gaseous Electron Multiplier (ThGEM) and a multistage MMThGEM.

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CYGNUS Hawaii: Recent simulations and measurements of MPGD avalanche gain

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R&D for a Gaseous Argon-Based Near Detector for DUNE

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DUNE aims to measure CP violation in the leptonic sector, observe supernova burst neutrinos, and detect rare processes such as proton decay. To achieve these goals, DUNE will use a highly capable suite of near detectors. The DUNE Near Detector complex for Phase II includes ND-GAr, a magnetized high-pressure gaseous-argon TPC (HPgTPC) surrounded by a calorimeter. Due to the low detection threshold of HPgTPC, ND-GAr will be able to constrain one of the least understood sources of uncertainty in the oscillation analysis: nuclear effects in argon at the neutrino interaction vertex. Ongoing R&D efforts for HPgTPC will be discussed.

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Solar neutrinos and electron recoils

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The Stawell Underground Physics Laboratory or The Hunt for Dark Matter in a Gold Mine

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