Low Radioactivity Techniques (LRT2024)

Tuesday, 1 October 2024 - Friday, 4 October 2024

Kraków, Poland

Book of Abstracts

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Pioneering experiments in dark matter and neutrinos

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We start with the early applications of Ge detectors for fundamental physics by the group of Ettore Fiorini's search for double-beta decay of Ge-76. This was followed by the early work of the Battelle-Carolina Collaboration, IGEX, then MAJORANA. Werecognize parallel efforts by the Heidelberg group, andspecial background reduction by GERDA and LEGEND using their liquid Ar emersion technique. The main discussion will be of recently developed alternative methods of reprocessing the scrap Ge from detector fabrication.

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The BOREXINO low-background techniques

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The BOREXINO solar neutrino experiment was a pioneer in the suppression of radioactive background. The first real-time detection of sub-MeV solar neutrinos became possible only by a strict radiopurity control program.

That started with a smart detector design, in which the mass of the scintillator-containing vessel was ultimately minimized. It continued with the selection of radiopure construction materials by means of gamma-ray spectroscopy, radon emanation screening, neutron activation analysis (NAA) and inductively coupled plasma-mass spectrometry (ICP-MS) and was supplemented by thorough surface cleaning protocols. Of course, most attention was paid to the cleanliness of the scintillator itself. Distillation, water extraction and nitrogen sparging was applied to remove radioactive traces of heavy metals and noble gases from the organic liquid. Eventually, the suppression of convective movement allowed the remaining impurities to settle.

The achieved ultra-low background level is still unmatched today and many of the applied technologies became standard in the field of low radioactivity research. In the talk I will review the most important methods developed in the framework of BOREXINO and demonstrate their impact for future low-energy astroparticle physics experiments.

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Underground laboratories in Asia

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Underground laboratories in North America

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Underground laboratories in Europe

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Underground laboratories in in the southern hemisphere

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Status and future prospect of the Kamioka ultra-low BG facility

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At the Kamioka Underground Laboratory, an inter-university facility named KERNEL has been organized to search for extremely rare phenomena.
This facility is necessary for the successful construction of the ultra-low BG KamLAND2 detector.
The facility will include the super-clean facility, the clean air system, the pure water system, and the experimental space for developing low radioactivity techniques.
In this presentation, I will present a status and the future prospects of the facility.

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Inductively Coupled Plasma Mass Spectrometry: An Ultrasensitive Tool for Ultralow Background Physics

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Since its first development in the mid-1980s, inductively coupled plasma mass spectrometry (ICP-MS) quickly became the 'gold standard'for quantitative elemental analysis. Through iterative optimization in design, hardware, and software, ICP-MS continues to provide ever-impressive analytical figures of merit (e.g., sensitivity, resolution, etc.) and, thus, grow in new application arenas. It is particularly useful and now well established in the determination of naturally-occurring long-lived radioisotopes (e.g., U-238, Th-232, K-40) in ultralow background (ULB) rare-event detector materials, and is the focus of this talk. This presentation will briefly describe the basics of ICP-MS before providing some illustrative examples of the strengths and weaknesses of the technique as it relates to ULB material assays. The talk will also focus on how ICP-MS techniques are being employed to meet the stringent radiopurity requirements for current and next-generation ULB experiments.

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Low radioactivity measurements based on ICP-MS at Canfranc Underground laboratory.

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The sensitivity of rare event research experiments depends on the background signals and, therefore, a complete characterization of the radiopurity of materials is required. Due to its unique features, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) has become in a reference technique for testing materials in low background experiment research, especially for quantification of those naturally occurred long-lived radioisotopes (40K, 232Th or 238U). In this talk, an overview of the new developments on material screening carried out in LSC ICP-MS facility will be discussed. Different analytical methodologies have been developed for ultratrace quantification in different matrix types:

NaI crystals, electroformed copper and its precursor solutions, molybdate-based crystals, among others.

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Measurement of trace radioactivity with Neutron Activation Analysis

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The need to test all kinds of materials for unprecedented levels of radioactivity is a common problem for many low rate, low energy experiments. This problem can be approached by counting decays or decaying atoms. When focusing on natural radioactivity, the latter approach, in form of mass spectrometry or neutron activation analysis (NAA), often offers the best sensitivity. In my presentation I will discuss NAA work at the University of Alabama, focused on measurements supporting the development of the nEXO project. Novel ideas will be covered.

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GeMPI-Neo - A next generation material screening station

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This talk presents the next generation screening detector, GeMPI-Neo, which is currently being developed at MPIK in collaboration with LNGS. Based on a full decomposition of the background spectrum of the existing GeMPI detectors a new and improved shield design for GeMPI-Neo was developed. Additionally GeMPI-Neo will employ two HPGe detectors for greater sensitivity in order to meet the needs of current and future rare event experiments.

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Secular disequilibrium in radiopure materials

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Sourcing radiopure materials for use in ultra-low background detectors is critical to the success of rare-event searches (i.e., direct detection of dark matter, neutrinoless double beta decay, etc.). When considering material radiopurity, minimizing contributions from primordial radionuclides (i.e., 238U and 232Th) and their progeny is a matter of the utmost importance. Current inductively coupled plasma mass spectrometry assay capabilities can measure 232Th and 238U down to the nanoBq/kg level. In comparison, radiometric counting methods are typically several orders of magnitude less sensitive, even for decay chain progeny for which they are most sensitive. When direct determination of the entire decay series is not possible, due to insufficient sensitivity, many experiments assume secular equilibrium within a decay series. However, physical and chemical processes in material manufacturing can significantly fractionate the decay series, resulting in secular disequilibrium. This may lead to inaccurate background predictions and mischaracterized detector sensitivities, ultimately hampering detector performance and reducing the likelihood of successful detection.

In this work we report results from a comprehensive literature review to evaluate the current understanding of secular equilibrium in materials used for ultra-low background detectors. We use this framework to discuss current and future research geared towards understanding the processes that perturb secular equilibrium during materials production. Finally, we provide examples of how this information can be leveraged to develop/improve ultra-radiopure materials for future generation experiments.

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Performing matrix extraction and characterization of copper samples by High Resolution Inductively Coupled Plasma Mass Spectrometry

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Copper is a material that finds a wide range of use as it usually has a high purity in terms of contamination regards to Th and U, this feature makes it suitable for nuclear physics experiments where a very low degree of contaminations is required to obtain low background. Given high purity of copper, mass spectrometry analysis performed by dilution is a bad way because it would be very difficult to estimate contaminations; matrix extraction is a procedure very useful to concentrate chemical elements that need to be measured.
TRU column is a good tool to perform matrix extraction of trans-uranic elements, they're composed by chromatographic resins based on CMPO (octylphenyl-N, N-di-isobutyl carboamyle phosphine oxide) extractant diluted in TBP (tributyl phosphate). A process of conditions is necessary to reach low values (10-12g –10-15g) in terms of concentration related to Th and U, alternated rinsing with HNO3 and (NH4)2C2O4 were performed.
High Resolution Inductively Plasma Mass Spectrometry were adopted to characterize contaminations in many type of samples including copper, a procedure of mineralization is necessary to obtain an aqueous solution suitable to be measured; importance to check amount of 232Th and 238U is related to estimate natural radiation, low background in apparatus located in underground is achieved also with high purity of materials used during installation of experiments.

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Ultra-sensitive analysis with neutron activation of U, Th and K in the liquid scintillator of the JUNO experiment

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment currently under construction in southern China.
The detector consists of a 35.4 m diameter acrylic sphere filled with 20 000 t of ultra-pure liquid scintillator and makes JUNO the largest liquid scintillator-based, underground neutrino observatory. The primary goal of JUNO is to determine the neutrino mass ordering with a significance greater than 3σ after 6 years of data taking and to perform high-precision measurement of neutrino oscillation parameters by measuring the spectrum of the oscillated reactor antineutrino. The detector construction is expected to be completed in 2024.
JUNO has extremely stringent requirements for its background that can overlap with the signals of interest. One of the main background sources is the decay of radioactive nuclides in the materials of the detector and a big effort is necessary to keep the radioactive contamination under control by selecting and purifying the materials used to build the experiment. The most critical component is the liquid scintillator (LS) which is the active material of the detector: the baseline requirements for its radiopurity are less than 10-15 g/g (ppq) for 238U and 232Th and less than 10-16 g/g for 40K.
To achieve the required sensitivities, a new measurement technique has been developed to increase the typical sensitivity of the Neutron Activation Analysis (NAA). We've combined the NAA with radiochemical treatments on the sample to concentrate the nuclides of interest and remove the interfering ones. A dedicated beta-gamma coincidence detector has been developed to reduce the measurement background and a new delayed coincidence technique has been applied for the measurement of 238U by exploiting the presence of a metastable state in the Uranium activation product to further increase the sensitivity. We achieved sensitivities of <0.4 (1.6) ppq for U (Th) on 1 L samples, and <0.7 ppq for K on 0.15 L samples. The first LS samples produced during the commissioning of the JUNO purification plants are validated.

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The CAGe germanium array at the Center for Underground Physics.

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The Institute for Basic Science Center for Underground Physics continues operation of a range of instruments for measurements of radioactive decays in support of underground rare-event search experimental campaigns previously operating at the Yangyang Underground Lab, and now proceeding at the new Yemilab facility in Korea. A particularly unusual instrument, the CAGe detector array, is composed of fourteen 70% relative-efficiency high-purity germanium detectors and has been used for some of our most demanding low-radioactivity material assay jobs as well as for physics searches. This talk will report on the status, operation, and environmental background control for the CAGe detector in context of recent measurements and the upcoming move to Yemilab.

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A gaseous time projection chamber with Micromegas readout for low-radioactive material screening

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Low-radioactive material screening is becoming essential for rare event search experiments. A gaseous time projection chamber (TPC) can be used for such purposes with large active areas and high efficiency. A gaseous TPC with a Micromegas readout plane of approximately 40 × 60 cm2 is successfully constructed for surface alpha contamination measurements. We have characterized the energy resolution, gain stability, and tracking capability with calibration sources. With the unique track-related background suppression cuts of the gaseous TPC, we have established that the intrinsic alpha background rate of the TPC is (0.17 ± 0.02)×10−6 Bq/cm2. The surface-treated acrylic samples from the JUNO collaboration are currently being tested in the TPC.

Mitigation of Surface Contamination / 32

Informing dust backgrounds on low-background detector materials using ICP-MS

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Rigorous radioactive background constraints are necessary for rare-event search experiments to meet their sensitivity goals. Underground facilities provide ideal attenuation of cosmic radiation, shielding materials around the detectors are used to mitigate backgrounds from surrounding rocks and extensive radioassay campaigns are performed to source the most radiopure materials. To reduce the impact of particulate deposition on material surfaces, detectors are assembled and operated in cleanroom facilities. Even so, dust particulate fallout on rare-event detector materials remains a concerning source of radioactive backgrounds. Within the low-background community, much effort is being invested to investigate, inform, and mitigate dust backgrounds. Fallout models and assumed dust composition are typically employed. In this work, an ICP-MS based methodology for the direct determination of stable and long-lived radionuclides fallout rates from dust particulate depositing on material surfaces is presented. Applications demonstrating the ICP-MS method as a valuable tool to evaluate dust backgrounds on detector materials and validate mitigation procedures will be shown.

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Surface cleaning techniques

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The traces of radioactivity present in the materials used to construct low background detectors can contribute to the dominant background signal for rare event search experiments. The surface contamination of detector materials is part of this significant source of background, primarily due to radon diffusion and plate-out of radon daughters. Exposure to environmental Rn during fabrication, assembly, and installation of the experiment can result in the accumulation of 210Pb on surfaces. Due to its 22-year half-life, 210Pb can act as a nearly constant source of radiation, along with its daughters 210Bi and 210Po, throughout the entire duration of an experiment.

The development of novel and effective protocols of cleaning, storing, transporting and manipulation of the detector components, is necessary to mitigate the native surface contamination of materials and prevent re-contaminations. The experience of LNL Surface Treatments Team during the years is here reported, focusing the attention on materials such as copper, stainless-steel, acrylic and Teflon, commonly used in low background experiments. The approaches, ranging from chemical and electrochemical methods to atmospheric and vacuum plasma techniques adopted for this purpose are here described.

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Performance and Applications of the XIA UltraLo-1800 and ICP-MS at Boulby Underground Laboratory

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The Boulby UnderGround Screening (BUGS) facility has significantly enhanced its material screening capabilities by integrating an XIA UltraLo-1800 alpha particle detector and developing an inductively coupled plasma mass spectrometry (ICP-MS) setup. This contribution presents key findings from both techniques, highlighting their importance for minimising background interference in rare-event searches.
Our long-term operation of the XIA UltraLo-1800 demonstrates exceptional stability in energy reconstruction and a substantial reduction in background radiation levels, achieving an average activity of 0.15 ± 0.01 $\alpha/cm^2/khr$. Assay results of copper samples before and after radon exposure showcase the detector's ability to identify and quantify ^{210}Po contamination with enhanced sensitivity. We will present the effectiveness of various cleaning procedures in reducing surface alpha activity.
Furthermore, we will discuss the setup and early sensitivity measurements of the ICP-MS system at BUGS. This technique will enable the identification and quantification of trace radioactive impurities in bulk materials, complementing the surface sensitivity of the XIA UltraLo-1800.

Radiation Impact on Quantum Systems / 45

Impact of Radioactivity on Quantum Circuits: European Laboratories

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In recent years, European laboratories have provided numerous insights into the effects of radioactivity on quantum circuits. Superconducting resonators, fluxonium qubits, and transmon qubits have been operated in deep underground facilities and exposed to radioactive sources. In this contribution, I will discuss the results and future perspectives.

Radiation Impact on Quantum Systems / 53

Abatement of Ionizing Radiation for Superconducting Quantum Devices

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Ionizing radiation has been shown to reduce the performance of superconducting quantum circuits. In this report, we evaluate the expected contributions of different sources of ambient radioactivity for typical superconducting qubit experiment platforms. Our assessment of radioactivity inside a typical cryostat highlights the importance of selecting appropriate materials for the experiment components nearest to qubit devices, such as packaging and electrical interconnects. We present the Low Background Cryogenic Facility operating in PNNL's Shallow Underground Laboratory (30-meter water equivalent) to reduce the flux of cosmic rays and a lead shielded cryostat to abate the naturally occurring radiogenic gamma-ray flux in the laboratory environment. We predict that superconducting qubit devices operated in this facility could experience a reduced rate of correlated multi-qubit errors by a factor of approximately 20 relative to the rate in a typical above-ground, unshielded facility. Finally, we outline overall design improvements that would be required to further reduce the residual ionizing radiation rate, down to the limit of current generation direct detection dark matter experiments.

Noble Element Based Detectors / 77

Rare event searches with Xenon detectors

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It has been demonstrated that xenon—as a gas, liquid, and solid, and dissolved in liquid scintillator—has the potential to constitute very low radioactive background particle detectors. I will review the past success of such detectors in the the search for rare events, ongoing searches, and where these technologies may take us in the future.

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Rare event searches with argon detectors

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Liquid argon, a key player in our quest to unravel the physics beyond the standard model, is indeed one of the most sensitive targets for GeV-scale dark matter candidates, such as Weakly Interacting Massive Particles (WIMPs), as demonstrated by the DEAP-3600 experiment and DarkSide-50 experiment. The unique R&D has led to the design of the next experiment within the Global Argon Dark Matter collaboration, DarkSide-20k, currently under construction at LNGS. Its 50-tonne ultra-pure argon target will allow for investigating for the very first time in argon dark matter-nucleon cross-section as low as 7.4 x 10^{-48} cm^2 for a WIMP mass of 1 TeV/c^2 in a 200 t yr run. At the same time, the first calibrations on superheated argon are proceeding within the Scintillating Bubble Chamber demonstrator, whose setup at SNOLAB shows a projected sensitivity down to 10^{−43} cm^2 at 1 GeV/c^2. On the other hand, argon has served as an active veto for the neutrinoless double beta decay of 76-Germanium, first in GERDA and now in LEGEND-200, whose collaboration recently

showed their newest lower limit at 1.0 x 10^{27} year, confirming the substantial background rejection possible thanks to the argon bath and pushing for the extension of this technology also to the future LEGEND-1000, where the argon would be extracted in the URANIA plant, aiming for the same mBq/kg argon radioactivity level also at the very base of DarkSide-20k's success.

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Performance of radiopure large-area SiPM arrays for DarkSide-20k

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Low-background experiments are obtaining very important results about the most anticipated open problems of our universe, such as direct dark matter searches, neutrinoless double-beta decay, nucleon decay searches, neutrino astrophysics.
All these experiments have been made possible by the selection of radiopure materials to build such experimental facilities, often resulting in a challenging R\&D of the detector itself to accomplish strict radioactivity requirements.

DarkSide-20k (DS-20k) is one of the most ambitious direct dark matter search experiments of the near future. It is under construction in the Hall C of Laboratori Nazionali del Gran Sasso (LNGS), Assergi, Italy and its aim is to probe the WIMP-nucleus cross-section down to 10^{-48} cm^2.
DS-20k will use a double-phase Time Projection Chamber (TPC) filled by 50 tons of underground liquid argon whose contamination of ^{39}Ar is significantly reduced to 0.5 mBq/kg, and a radiopurity level of the same order of magnitude was established as requirement for all TPC's components.
The light emitted by the expected WIMP-nucleus scattering or background particles interacting with the TPC will be read out by two 10.5 m^2 optical surfaces located in the top and bottom planes of the TPC. The optical planes will be populated by low-noise cryogenic arrays of silicon photomultipliers (SiPM) with excellent single-photon sensitivity.
The TPC will be surrounded by an equally radiopure active veto equipped with about 5 m^2 of SiPM-based detectors.

This talk presents the radioactive assay of the photodetectors to be installed in the TPC of DS-20k and their performance in liquid nitrogen. This assay, due to the big amount of material to measure, was carried out by the underground laboratories of Boulby (UK), Gran Sasso, Canfranc (Spain) and by the Jagiellonian University (Poland).
The final SiPM arrays are assembled and characterized in Nuova Officina Assergi (NOA) at LNGS, an ISO 6 clean room built for mass production of particle physics silicon detectors and arranged to host a radon abatement system. The bagging procedures for storing and shipping of DS-20k photodetectors will be also shown.

Noble Element Based Detectors / 66

The Underground Argon program of the GADMC

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DarkSide-20k is under construction at LNGS and is designed to lead the search for heavy WIMPs in the coming years. Argon has the advantage of pulse shape discrimination compared to other noble elements, but has the drawback of the cosmogenically induced Ar-39 content with an activity of 0.96 Bq/kg. Getting rid of this background is pivotal for the success of our scientific program. Hence, the Global Argon Dark Matter Collaboration (GADMC) has put in place a program for the exploitation of underground Ar (UAr), in which the concentration of this isotope is depleted by, at least, a factor 1400.

The extraction will take place in Colorado (US) in the Urania plant, the purification in Sardinia (It) in the ARIA plant and the characterization in Canfranc (Sp) in the DArT experiment. In this talk, I will present these infrastructures and their current status.

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Measurement of the Kr-85 Activity in the GERDA Liquid Argon

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The ^{85}Kr radioactive isotope is found in significant quantities in the atmosphere largely as a result of nuclear industry. Its β-decay with a half-life of 10.8 years and a Q-value of 687 keV is a dangerous background source for low-threshold noble liquid detectors, which distill their detector medium from air. The GERDA experiment was operating high-purity germanium detectors immersed in a clean liquid argon bath deep underground to search for neutrinoless double beta decay with unprecedented sensitivity. The ^{85}Kr activity in the liquid argon at cryostat filling time has been determined through an analysis of the full GERDA Phase II data set by exploiting the excellent γ-ray spectroscopic capabilities of the experiment.

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Mitigation studies of K-42 in liquid argon for LEGEND

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The Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND) aims to detect neutrinoless double beta decay (0νββ) of Ge-76 using high-purity germanium detectors (HPGe) immersed in liquid argon (LAr). The LAr serves both as a coolant and as an active shield against background radiation. In LEGEND-200, HPGe detectors are operated in atmospheric LAr, which contains the cosmogenically activated radioactive isotope Ar-42. LEGEND-1000, however, plans to use underground LAr (UGLAr) depleted in Ar-42 to mitigate this background. In case UGLAr is unavailable, K-42, the beta-decaying progeny of Ar-42 (Qβ = 3.5 MeV), would be the dominant background at the 0νββ Q-value (2.039 MeV) due to beta-decay-induced events occurring on the surface of the HPGe detectors. These surface events must be suppressed and efficiently discriminated from 0νββ candidate events. We present K-42 suppression measurements conducted at the SCARF LAr test facility at TU-Munich using Ar-42-enriched LAr. Our study evaluates background discrimination methods, including the analysis of event topologies in HPGe detectors and the use of scintillation light readout from LAr for suppression. Additionally, we explore enhancing suppression by surrounding the detectors with optically active barriers, such as polyethylene naphthalate (PEN) enclosures and tetraphenyl butadiene (TPB) coated nylon mini-shrouds. This research is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Excellence Cluster ORIGINS EXC 2094-39078331; SFB1258-283604770.

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Self-supervised Pretraining and ^{42}K Surface Beta Events Tagging for LEGEND

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The LEGEND experiment searches for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{76}Ge using high-purity germanium detectors (HPGe). In LEGEND-200, these detectors are operated in atmospheric liquid argon (LAr), which provides active shielding against background radiation and acts as a coolant. However, atmospheric LAr contains the cosmogenically activated isotope ^{42}Ar, whose progeny, ^{42}K, undergoes beta decay (Q_β =3.5 MeV) on the HPGe surface. If the baseline mitigation strategy of using underground-sourced LAr (UGLAr), depleted in ^{42}Ar, were unavailable, this decay would become the dominant background at the $0\nu\beta\beta$ Q-value ($Q_{\beta\beta}$ =2.039 MeV) in LEGEND-1000. Pulse-shape discrimination (PSD) methods in HPGe, used for detecting and distinguishing such background events from $0\nu\beta\beta$ candidate events, rely on summary statistics that only partially exploit the information within signal traces, leaving potential for improvement if more, or all, of the raw data were utilized. However, full utilization of raw signal pulses for PSD presents technical challenges due to the high dimensionality of the data, non-linear feature relationships, noise, and energy dependence. We present an analysis of a gradient-based optimization strategy using a regularized autoencoder model to construct an invertible, lower-dimensional latent representation of the data, based on measurements of HPGe in ^{42}Ar-enriched LAr at the SCARF LAr test facility at TU-Munich. We evaluate the suppression of ^{42}K surface events via pulse-shape classification using these latent variables and compare the results to standard PSD methods used in LEGEND. This research is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Excellence Cluster ORIGINS EXC 2094-39078331; SFB1258-283604770.

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^{212}Pb and ^{214}Pb Beta Decay Branching Ratios Measurement with XENONnT

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The XENONnT experiment, primarily designed for WIMP dark matter searches, features unprecedented levels of radiopurity, allowing for precision nuclear physics studies. Among these studies, measuring the branching ratios of beta decay in lead isotopes ^{212}Pb and ^{214}Pb with XENONnT introduces a novel approach in this research field. By employing signal and background model fits, it is possible to directly determine with enhanced precision the ground state branching ratios of these beta-decaying Lead isotopes, which are currently only indirectly estimated through spectroscopy studies. This contribution discusses the measurement procedure and presents preliminary updated branching ratio values for the beta decay of ^{212}Pb and ^{214}Pb.

Liquid Scintillators and Cherenkov Detectors / 92

Liquid scintillator purification for SNO+

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SNO+ is a neutrino and double-beta decay experiment located 2km underground at SNOLAB, Canada. SNO+ developed a novel liquid scintillator based on Linear Alkylbenzene (LAB) and 2,5-diphenyloxazole (PPO). To purify all the components of the scintillator, a new process plant has been designed and constructed underground. Despite the limited space, the plant has a capacity of running several processes including the vacuum distillation, gas/steam stripping and liquid-liquid extraction. The plant also includes systems for purifying and loading additional components (PPO, bisMSB) into the scintillator. The review of the purification principles, specifications, quality control and performance of the plant will be presented.

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Te purification for SNO+

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TBA

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Purification strategy of the JUNO liquid scintillator

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JUNO (Jiangmen Underground Neutrino Observatory) [1], currently under construction in southern China, will detect neutrinos from several sources, aiming to determine the neutrino mass ordering at 3σ level in 6 years of data taking, as the primary scientific goal [2]. JUNO consists of a spherical

central detector filled with 20000 tons of liquid
scintillator (LS), which is composed of LAB as solvent, 2.5 g/l PPO as fluor and 3 mg/l bis-MSB as wavelength shifter [3]. Given the huge mass and dimensions, both the radiopurity and the optical parameters of the LS are crucial to achieving the desired energy resolution and low background. A dedicated sequence of 5 purification processes has been implemented with large-scale plants (nominal flow rate 7 m 3/h), to
purify the scintillator according to stringent optical and radiopurity requirements [4]. The purification sequence includes: LAB filtration using Al 2O3 powder, to improve its optical properties; distillation in a partial vacuum, to remove high-boiling impurities and further enhance the transparency [5]; acid washing and water rinsing of PPO and bis-MSB dissolved into LAB in a concentrated solution; water extraction of the final LS cocktail, aiming to get rid of polar radioisotopes
and ions; lastly, gas stripping with N2, for the removal of gaseous contaminants naturally dissolved into the LS. High-purity nitrogen, with low Rn content, and ultra-pure water, with low Rn and contaminants, are
produced in two separate supply systems and provided to the purification plants, aiming to achieve better purification efficiencies.

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Design, operations and reliability", NIM A, 925 (2019) 6–17

Liquid Scintillators and Cherenkov Detectors / 44

A Cherenkov muon veto detector

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At the Frascati National Laboratories, we are developing a prototype of a detector that to serve as both a muon veto and neutron shield, which utilizes water to detect Cherenkov light. This detector can be used in the Cupid experiment.
This talk will present the preliminary results from tests conducted using cosmic rays and an electron beam at the Beam Test Facility (BTF) in Frascati. The performance of the water Cherenkov detector in these tests will be discussed, showcasing its potential effectiveness in enhancing the sensitivity and capabilities of the CUPID experiment.

Crystals Scintillators / 85

Developments, features and perspectives of radiopure crystal scintillators of the Cs2MCl6 family (M = Hf or Zr) to search for rare processes

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Recently there has been considerable interest in the development of crystal scintillators of the Cs2MCl6 family of metal hexachlorides (M = Hf or Zr) due to their exceptional scintillating properties. These materials offer high light yield (up to 40000 photons/ MeV), good linearity in the energy response, excellent energy resolution (< 3.5% at 662 keV in the best configuration) and excellent ability to discriminate between pulse shapes (PSD) of gamma (beta) and alpha particles.
First low-background measurements with Cs2HfCl6 (CHC) crystal scintillator were carried out over 2848 h deep underground in the STELLA laboratory at the Gran Sasso National Laboratory (LNGS) of the INFN, Italy. Its internal radioactive contamination was studied and presented here. Additionally, recent result on the alpha decay to the ground state of 174Hf with T1/2 = 〖3.8〗_(-0.9)^(+1.7) × 〖10〗^16 yr using a new CHC crystal scintillator is discussed, together with the future perspectives of these measurements.
Hereafter, Cs2ZrCl6 (CZC) crystal scintillators were studied in a series of experiments. The first measurement using two CZC (11 g and 24 g) was done in the DAMA/CRYS low-background setup deep underground at LNGS. Its chemical and radio- purity, residual radioactive contaminants, scintillation and PSD performance are presented here. The low-background measurements over 456.5 days demonstrated the crystals'high radiopurity showing a counting rate of 0.17 (kg · keV · yr)-1 at the Q_2β= 3.35 MeV of 96Zr resulting in first limits on 0ν2β decay for 96Zr within the experimental approach "source=detector"at the level T1/2 > 1017 - 1020 yr. Another measurement was subsequently carried out using three new CZC crystals which were encapsulated using a silicone-based sealant. The crystal growth technique, raw material purification, and post-growth material treatment are discussed.

Crystals Scintillators / 69

Production of highly radio-pure NaI(Tl) crystals applied to dark matter search

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The interest in ultra-high purity, low-background NaI(Tl) crystals for dark matter direct searches has increased in recents years. This is driven by the fact that over the last two decades, the experimental effort to search for particle dark matter in underground laboratories yielded null results with the notable exception of the DAMA/LIBRA experiment at LNGS. DAMA has been observing an annual modulation of the experimental rate in its array of NaI(Tl) crystals: the outstanding radio-purity of such crystals, which drives the background level and ultimately the sensitivity of the experiment, has never been matched so far.
Radio-purity, especially at the very low level of content required by DM searches, is an extremely challenging task, only partially solved so far for NaI(Tl) crystals.
The SABRE experiment aims to deploy arrays of ultra-low-background NaI(Tl) crystals to carry out a model-independent search for dark matter through the annual modulation signature. For over 10 years, SABRE has conducted extensive R&D on ultra-radio-pure NaI(Tl) crystals. Several crystals have been grown and tested in both active and passive shields at LNGS. Recently, in order to achieve an unprecedented level of radiopurity for the crystals, SABRE is employing zone refining purification of the NaI powder prior to growth. In this talk, I will present the status and challenges from the zone refining activities, the obtained results and predictions on the ultimate radio purity achievable for the crystals. Additionally, the status of the SABRE project will be discussed.

Crystals Scintillators / 26

Ultra-purification and mass-production of NaI powder for COSINE-200

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The COSINE-200, an upgraded phase of the COSINE-100 experiment, aims to scrutinizingly verify the annual modulation signals observed by the DAMA/LIBRA experiment using 200 kg NaI(Tl) crystals with intrinsic background levels better than those of DAMA/LIBRA. To reach the projected goal, an in-house technology for the successive production of ultra-low background NaI(Tl) detectors is paramount, and it must begin with procuring ultra-pure NaI powder. A special clean facility for purifying commercial NaI powder in bulk has been constructed at the Center for Underground Physics (CUP) in Korea. The purity of CUP-produced powders is compatible with those of Astro-grade available from Sigma-Aldrich and surpasses the purity of the NaI powder used in DAMA/LIBRA crystals. The production efficiency of 35 kg per two weeks has been balanced versus the optimum product's purity, where impurities levels are < 20 ppb for natK and <10 ppt for 232Th and 238U. This report summarizes our experience, describes the mass-purification facility and the technology itself, and finally the recovery of NaI from by-products of chemical purification and the melt that residues after the crystal growing performance.

Cosmogenic Backgrounds & Material Activation / 67

Cosmogenic activation in materials used in low background experiments

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In experiments devoted to investigate rare events, demanding ultra-low background conditions, radioisotopes produced by the exposure of materials to cosmic rays mainly on the Earth's surface can become problematic to achieve the required sensitivity. The origin of this cosmogenic activation will be presented and the ways to quantify the activation yields following different approaches will be discussed, considering both measurements (either with beams or under controlled exposure to cosmic rays) and calculations. Precise quantification is important to assess the real danger of this background source and to take accordingly the necessary actions for production, transport and storage of materials. Examples of cosmogenic activation studies relevant for underground experiments will be shown, considering detector target materials (like Ar, Ge, NaI or Xe) or other ones commonly used (like Cu, Pb or stainless steel).

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Cosmogenic activation backgrounds

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Long-lived radioactive isotopes produced by cosmogenic activation are a major source of background for rare event searches such as dark matter and neutrinoless double beta decay. Understanding the production rates of these cosmogenic isotopes is extremely important for calculating accurate radioactive background models and for determining the total allowable surface residence time of detector materials during fabrication, storage, and transportation. In this talk I will review the key components needed to evaluate the expected activation rates and present recent efforts to measure and mitigate cosmogenic activation of common detector materials.

Cosmogenic Backgrounds & Material Activation / 37

Tritium Production in SuperCDMS

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The SuperCDMS experiment, which is under installation at SNOLAB, will use Ge and Si detectors to search for low-mass dark matter interactions. In the corresponding energy regime of interest, tritium produced by the cosmogenic activation of the detectors is expected to produce significant backgrounds. In this talk, I will discuss the exposure history of these detectors, as well as additional efforts by SuperCDMS to mitigate the exposure of other materials used in the construction of the experiment. In addition to the discussion of above-ground exposure, I will also present a study on the expected neutron flux and resulting tritium production at various underground sites used by SuperCDMS collaboration to mitigate cosmogenic activation on the detectors.

Cosmogenic Backgrounds & Material Activation / 34

Neutron Activation Background in the LUX-ZEPLIN Experiment

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The LUX-ZEPLIN (LZ) experiment is a dual-phase liquid-gas 10-tonne xenon time projection chamber (TPC) seeking to discover WIMP dark matter particles or set limits on their properties. The detector has been built at the SURF underground laboratory in South Dakota, USA, and first data set world leading limits on WIMP cross sections. To have the necessary sensitivity, the backgrounds in the detector have to be measured and understood. This includes background from radioactive isotopes of xenon created through neutron activation from either cosmic rays or calibration sources. The rate at which these backgrounds were produced in the LZ detector when exposed to various sources of neutrons has been measured and compared to expectations from simulations.

Cosmogenic Backgrounds & Material Activation / 38

A 14C Screening Setup for Liquid Scintillator at JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino detector under construction in China, with the main goal of determination of the Neutrino Mass Ordering (NMO). This detector will be filled with 20 kton of linear alkylbenzene (LAB) based liquid scintillator as a target, contained inside an acrylic vessel of diameter about 35 meters. For low signal event rate experiments like JUNO, control of natural radioactivity background is crucial. The ^{14}C background with 156 keV Q-value in JUNO's liquid scintillator is one of the main backgrounds in pp solar neutrino detection.
An experimental setup was built to measure ^{14}C concentration in LAB and select low ^{14}C LAB for JUNO liquid scintillator. It was designed to take small samples with volume of 1L with the purpose of fast screening. The LAB samples to be measured are prepared as liquid scintillator by adding 2.5 g/L 2,5-diphenyloxazole (PPO) and 3 mg/L p-bis(o-methylstyryl)-benzene (bis-MSB). The setup was developed at the JUNO detector cavern (~700m of rock shield) and utilizes two low-background R11410 photomultiplier tubes (PMTs) at both ends of a cylindrical acrylic container, facing the liquid scintillator to perform coincidence measurements. Lead and copper (OFHC) shielding are used to reduce external radioactivity. In this poster, the details of the design, analysis and results will be presented.

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Online Low Background Tools

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Most of us are familiar with radiopurity.org, which provides a simple, public interface to radioactivity assay results for hundreds of materials from measurements performed around the world. Background Explorer is a tool designed to simplify the common tasks in modeling backgrounds by associating assay measurements with databases of components and radiation transport simulation results through an intuitive web interface. In this talk, I will provide an overview of Background Explorer' s current and planned features, the current status of radiopurity, and briefly touch on other online tools of interest to this community.

Poster Session - Board: 9 / **71**

High sensitivity Rn emanation studies applying cryogenic detector

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A novel system for ultra-sensitive Radon emanation studies has been developed. It is based on a cryogenic
Radon detector coupled to two large-volume chambers, able to accommodate samples up to 250 L in volume. Due to the unique properties of the detector it is possible, for the first time, to study simultaneously emanation of two Radon isotopes, namely 222Rn and the short-lived 220Rn. Special

design of the system results in an extremely low internal background, making detection of even single atoms of Radon possible. The design and performance of the detector system will be discussed and results of 222Rn and 220Rn emanation for various samples will be presented.

Poster Session - Board: 11 / **28**

Mitigating radon backgrounds in dark matter searches

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Radon emanation from materials presents a major background to dark matter searches. Presenting the dual-detector radon emanation system operating at Boulby Underground Laboratory, which uses two 80L electrostatic alpha detectors. By incorporating a radon concentration line, this will enhance its sensitivity of 222Rn to below 0.1 mBq, providing more accuracy at characterising radioactive emissions from materials to build a background model.

Poster Session - Board: 1 / **11**

Acrylic and liquid scintillator radiopurity screening by ICP-MS for the JUNO experiment

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The Jiangmen Underground Neutrino Observatory is building the world's largest liquid scintillator (LS) detector, and the radiopurity in LS should reach 0.01-1 ppq (10^{-17}-10^{-15} g/g) ^{238}U/^{232}Th. The 20 kt LS is filled in the acrylic sphere with 35.4 m diameter, and both the acrylic bulk (<1 ppt ^{238}U/^{232}Th) and the surface (<5 ppt ^{238}U/^{232}Th in the first 50 μm thickness) should be clean enough. The radiopurity screening of acrylic and LS to the level near the requirement is challenging. The Inductively Coupled Plasma Mass Spectrometer (ICP-MS) is a common equipment for high-precision material composition analysis. The ICP-MS lab is built in the clean room, and the counting rate for 1 ppt (10^{-12} g/g) ^{238}U/^{232}Th solution can reach ~1000 counts/s. We have developed a practical method for screening U/Th in acrylic to sub-ppt level with ICP-MS, and the pre-treatment is mainly acrylic ashing. In addition, careful surface treatments on JUNO acrylic panel in the company were studied, and the resulted surface contamination can reach ~20 ppt in the first 5-10 μm thickness. In addition, we have developed a method for detecting U/Th in LS to sub-ppq level, and the main pre-treatment is acid extraction for LS. With meticulous cleanliness control, U/Th in approximately 2 kg of LS is concentrated by acid extraction with 0.4 (0.3) pg ^{238}U (^{232}Th) contamination. The method detection limit at a 99% confidence level of this approach can reach approximately 0.2-0.3 ppq for ^{238}U/^{232}Th with nearly 100% recovery efficiency. In this report, I will introduce the setup and method for the pretreatment and the measurement results of ^{238}U/^{232}Th in acrylic and LS, as well as the strategy of JUNO acrylic surface treatment.

Poster Session - Board: 10 / **42**

Low background Ge gamma spectrometry of thick samples

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Gamma-spectrometry has been a crucial technique for the analysis of natural and anthropogenic radionuclides in nuclear, astrophysical, and environmental investigations, although recently mass spectrometry techniques such as ICPMS (Inductively Coupled Plasma Mass Spectrometry) and AMS (Accelerator Mass Spectrometry) have reached the lowest detection limits. The great advantage of gamma-spectrometry is the possibility of analyzing samples nondestructively without any pretreatment, especially if samples are of high scientific value (e.g. meteorites), but also in the case when we have large samples of a few kg scale available (e.g. for rare nuclear decay experiments). However, there are also limitations in gamma-spectrometry applications for analysis of very low activity samples, mainly because the radionuclides of interest (e.g. K-40, Tl-208, Pb-210, Bi-214, Ra-226, etc.) are also present in the background of gamma-spectrometers.
Gamma spectrometry of construction materials used in underground experiments has been a dominant technique for their radionuclide screening at very low levels, which has been an important prerequisite for reaching desired nuclear physics results. Radiopurity investigations of construction materials usually require relatively large amounts of sample material to achieve the required precision. However, this causes complications in measurement evaluations and activity determinations. The addition of sample material changes the background of the Ge detector in two ways. The sample material itself acts as a shielding for the detector and affects its background. The addition of large volume samples also changes the internal volume of the detector shielding, and therefore changes the amount of radon and its decay products around the detector. These effects require careful consideration of the measured spectra before the activity determination. A demonstration of these effects by measuring thick copper samples using a BEGe semiconductor detector in a low background shield (also supported by Monte Carlo simulations), will be presented.

Poster Session - Board: 12 / **61**

New low-background underground facility in Poland - Książ Castle

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Książ Castle is located in the Lower Silesian Voivodeship in the south-western Poland. During the Second World War several tunnels were excavated in the castle hill. They are located 50 m below the courtyard of the castle and 350 m above sea level.

In 1968 the Geophysical Observatory of the Institute of Geophysics of the Polish Academy of Sciences was established in the tunnels. At the end of the last century, the Geodynamic Laboratory of the Space Research Center of the Polish Academy of Sciences was created in Książ as well.

This year in one of the tunnels we constructed a new facility, which will host the low-background gamma spectrometers devoted to material screening carried out in the frame of rare event searches. The new laboratory is already equipped with electricity (with 4 UPS units), internet connection, video cameras, oxygen level monitors (2 sensors, indoor/outdoor alarms), and continuous monitoring of the temperature, pressure, and humidity of the air. Portable LN2 generator will be installed soon.

So far, the laboratory background has been characterized by measuring the muon flux (~40 times lower compared to the surface), the 222Rn concentration in the building and outside (nearby tunnels), the thermal neuron flux and the gamma ray flux. The results of these measurements will be presented along with plans for the future installation of gamma spectrometers and other equipment.

Poster Session - Board: 13 / **70**

Production and characterization of ultra-pure copper for a low background HPGe spectrometer

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About two tons of ultra pure copper has been produced as a material for construction of an internal shield of a low-background gamma spectrometer. Aurubis A.G. (Germany) has prepared a dedicated casting mould, selected the best possible raw material and cast the 2-ton block. In order to minimize the cosmic exposure the block was immediately transported and stored underground, 150 m below the surface in the Wieliczka Salt Mine (Poland). It was taken out only for short time for forging cutting and fabrication of the shield components.
The purity level of the coper was determined by analyzing the long lived U/Th isotopes with an ICP mass spectrometer, Ra-226 and other gamma emitters by high-sensitivity germanium spectrometry and Pb-210 by a dedicated technique based on Po-210 separation form Cu and determination of its activity. The results showed very high purity of the material and disequilibrium between different part of the U-chain.

Poster Session - Board: 14 / **82**

Production of GEM-like structures using laser-cutting techniques

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GEM-like charge amplification structures, including FAT GEMs, can find applications in TPCs for dark matter, neutrino and generally rare event search experiments.

A new concept of GEM-like structures was recently proposed. In this concept a double-stack of GEM-like structures is used to optically decouple LAr and GAr regions from a dual-phase TPC. Its core element is a type of GEM structure machined from polyethylene naphthaline (PEN). Due to its intrinsic characteristics, such structure presents several advantages. On the one hand, it will work as self-veto regarding its own background, on the other hand it opens the possibility for doping LAr with dopants with very low ionisation energies (solving one of the main technical challenges related with optical positive feedback by having two layers of mismatched holes) while enabling at the same time the scaling up of such detectors.

In this work, we report the newest developments on the production of GEM-like structures using laser-based techniques, namely the manufacture of a first batch PEN and PMMA-based GEM-like structures. This process allows low-cost, reproducible fabrication of a high volume of such structures. In addition to being a low radioactive technique, we expect that it will allow the scaling up of the

production of these structures at a reduced cost. First tests indicate good electrical stability, while the performance assessment is still ongoing.

Poster Session - Board: 15 / **41**

Radiation screening using Germanium detectors

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One of the main challenges in rare event searches is interference from background radiation. We can travel deep underground where we experience a reduction of a factor 1 million in cosmic rays, but that still leaves background from radioactivity intrinsic to the materials we use to build these detectors. A solution to this problem, is to create a radioactive background model for these detectors: if we know the specific activity of these materials, and how much of these materials we use, we can model an expected background against which we can compare rare event search data.

To fill this demand for finding radioactive properties of materials, at the Boulby Underground Laboratory we have the Boulby Underground Screening (BUGS) Facility. One of the components within BUGS is our range of ultra-low background germanium detectors which allow us to assay gamma-ray energies from a few keV to approximately 3 MeV. This means we are sensitive to all gamma-rays associated with naturally occurring radioactive material (NORM) and a number of relevant cosmogenic and anthropogenic radioisotopes. This poster will discuss the various detectors and the steps we take to able to provide world class assay services for next generation low background rare event search experiments.

Poster Session - Board: 16 / **21**

Radioassay of lead samples using an array of HPGe detectors

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Lead is the most popular material to shield the external gamma-ray. The radioactivity of the lead shielding is important for the rare event search experiments, such as neutrinoless double beta decay and weakly interacting massive particle searches. In the rare event searches, the radioactivity of the lead shielding itself may contribute significant background signals. We cannot measure the radioactivity of the lead below mBq/kg level using the single HPGe detector due to self-absorption and reduction of the detector background by the high effective atomic number of lead. In our study, the activity levels of contaminants in lead samples were measured using an array of fourteen-channel HPGe detectors with the consideration of the screen effects.

Poster Session - Board: 17 / **22**

Radiopurity procurement for AMoRE-II

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The AMoRE-II is searching for neutrinoless double beta-decay (0νDBD) of 100Mo using cryogenic calorimeters with 360 lithium molybdate ultra-pure scintillation crystals. Experiments seeking rare nuclear processes, like 0νDBD, are propelled by pursuing ever-diminishing levels of radioactive backgrounds and the techniques that can extract a weak signal from this background. Among these techniques, the role of radioanalytical chemistry in minimizing radioactive contamination in the materials used for the experiment is paramount. This report presents the purity level of materials used for crystal synthesis and the radiopurity assessment (ICP-MS and ultra-low background HPGe gamma spectrometry) results for the crystals, detector components, and shielding materials. Special techniques were developed for material recycling and re-purification in the crystal production chain. For the detector and shielding components, surface cleaning techniques were adapted to eliminate contamination caused by the treatment of the set-up details. To confirm the effectiveness of the cleaning and recycling procedures, selective sample preparation methods using extractive chromatography were implemented for sensitive ICP-MS assay of Th and U.

Poster Session - Board: 18 / **64**

Rapid ICP-MS Analysis of Ra-226 Concentration in Ultrapure Gadolinium Sulfate Octahydrate

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Many particle physics experiments utilize gadolinium (Gd), a rare earth element with the most significant neutron capture cross-section among all elements, to detect anti-neutrinos via inverse beta decays or to remove neutron-induced background events.
For example, to load Gd into water Cherenkov detectors, Gd sulfate is dissolved and rare event search experiments are required to screen for radioactive impurities in Gd sulfate before dissolution.
This study developed a new method to rapidly measure the Ra-226 concentration in Gd sulfate octahydrate.
This method requires only 3 days to measure a batch of samples, as opposed to the usual method using high-purity germanium detectors, which takes approximately 20 days after arrival.
The detection limit for the measurement of Ra-226 concentration in Gd sulfate is 0.43 mBq/kg.
This method has already been used for Gd sulfate screening at the Super-Kamiokande Gd (SK-Gd) project, and it can be applied to future experiments.

Poster Session - Board: 19 / **39**

Status of the liquid scintillator for JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose experiment designed to elucidate fundamental neutrino properties, study neutrinos of astrophysical or terrestrial origin and search for rare processes beyond the standard model of particle physics. Its central detector is a 20 kt liquid scintillator (LS) located 650 m underground in Guangdong, China. JUNO LS needs to be highly transparent and have an exceptionally low radiation background with a very high radio purity in order to meet its physics objectives: For reactor neutrino physics, 238U, 232Th in LS <1×10–15 g/g, 40K in LS <1×10–18 g/g. Five systems were designed to purify the LS: Alumina filtration, distillation, mixing, water extraction and steam stripping. In addition, two corollary equipment, an ultra-pure water plant and a high-purity nitrogen plant, were developed to supply ultra-pure water and high-purity nitrogen for the LS purification system. Low-background stainless steel was used in the construction of key sub-systems . In accordance with JUNO requirement, the stainless steel tanks and pipes were degreased, pickled, and passivated. The leakage rate of all sub-systems is better than 1*10-6 mbarL/s. The installation of all seven plants has been thoroughly completed, and both self-commissioning and joint commissioning of the plants have been carried out.

Poster Session - Board: 2 / **48**

Background analysis of the large-surface, low-background alpha spectrometer

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To measure low surface and bulk specific activities of alpha emitters a low-background, large-surface alpha spectrometer is needed. In our studies we use the XIA UltraLo-1800 instrument, in which the low background is achieved by using radio-pure construction materials and by application of Pulse Shape Analysis (PSA). The PSA is based on inspection of amplitudes, shapes and rise times of the registered pulses in order to identify and reject unwanted events. There are different types of background sources in the spectrometer: cosmic rays, Rn-220 and Rn-222 decays in the counting gas and alpha particles emitted from the spectrometer walls and from the anode. The anode is in addition surrounded by a guard electrode which is used to reject alpha particles coming from the side walls. The sample serves as the cathode therefore, it needs to be conductive. A „zero"sample (sample with no emission of alpha particles) is needed to determine the background of the instrument, which can be later subtracted from the spectrum obtained for a given sample. Various materials like stainless steel, teflon foil, etched oxygen-free copper and electropolished oxygen-free copper were tested for this purpose. Since we are interested mainly in Po-210 the count rates in energy range 1.5 –6 MeV were analysed. The lowest signal was obtained for the electropolished oxygen-free copper: (19 ± 1) cts/d. This material was chosen for the drawer base. Monte Carlo simulation is used to deconvolute contributions the measured spectra from the bulk and surface contaminations. Taking into the background of the detector the bulk and the surface Po-210 specific activities can be determined down to 50 mBq/kg and 0.5 mBq/m2, respectively. There is also a possibility to reduce further the background by application of an additional outer veto, which should eliminate the miss-identified muons. This effort is ongoing and the expected improvement is at the level of 30%. Moreover, the count rates for the background signals coming from muons, alphas generated in the counting gas, alphas coming from the walls and from the anode were analysed. A time period of about 8 years has been checked during which various measurements were performed The analysis helps to investigate stability of the detector over many years of operations. The details will be presented and discussed in the poster.

Poster Session - Board: 20 / **9**

The Hardware Upgrades and Third Fill of DEAP-3600 at SNOLAB

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The hardware upgrades and third fill of DEAP-3600 are designed to produce a zero-background dark-matter measurement. DEAP-3600 is a single-phase liquid-argon detector containing 3300kg of liquid argon in a ultra-pure transparent acrylic sphere. TPB, on the inner surface of the acrylic, is used to wavelength shift argon scintillation light into the visible, this allowing its detection by an array of 255 Hamamatsu high quantum efficiency PMTs. Using the background model derived from the analysis of the second fill, we developed redundant techniques to remove the two leading alpha-particle backgrounds in the DEAP-3600 second-fill data set. The first class of events is degraded alphas from particulates in the bulk liquid argon and the second class is events in the neck of the detector, of which only a small fraction of light from argon scintillation enters the main volume of the detector. We have upgraded the argon process systems to allow for removal of bulk liquid from the detector, thus allowing particulate filtration. We have rebuilt the lower part of the neck in a low-radon cleanroom and have developed new techniques to paint the neck with pyrene-doped polystyrene to tag alpha neck events. This poster will present the work of the hardware upgrades and describe the run plan for the third fill.

Poster Session - Board: 3 / **35**

Background mitigation techniques with the NEWS-G dark matter detector

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NEWS-G (New Experiments With Spheres-Gas) is a project searching for sub-GeV dark matter with a Spherical Proportional Counter (SPC) filled with low-Z gases (H, He, Ne). A 140cm-diameter sphere has been commissioned at the Laboratoire Souterrain de Modane (France) and is now installed at SNOLAB (Canada). Presented here are the techniques used to reduce the backgrounds, external but more importantly internal. In particular, care has been taken to assay the purity of the sphere material and achieve a clean internal surface. As the gas purity is an important factor in the signal quality, an oxygen filter and a new zeolite-based Radon trap are being used. The goal is to reach a world-leading sensitivity for sub-GeV dark matter search.

Poster Session - Board: 4 / **20**

DarkSide-20k Veto photon-detector units: construction and characterisation

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DarkSide-20k, a direct dark matter search experiment, is located at the Gran Sasso National Laboratory (LNGS), Italy. It is designed to achieve groundbreaking 200-tonne-year exposure, nearly free from instrumental backgrounds. The core of the detector is a dual-phase Time Projection Chamber (TPC) containing 50 tonnes (20 tonnes fiducial) of underground liquid argon (UAr) with low levels of cosmogenic ^{39}Ar isotope. The TPC is equipped with large area cryogenic Silicon Photomultiplier array detectors at top and bottom planes covering ~21m^2, to acquire the faint signals emitted by the WIMP interaction with the detector. The neutron veto used to tag neutron events and veto them, is also equipped with SiPM detectors, positioned along the walls of the TPC on the outer side.

SiPMs are arranged in a compact layout to reduce the material used for the Printed Circuit Board (PCB), cables, and connectors forming the Veto PhotoDetection Units (vPDUs). Each vPDU consists of SiPMs, front-end electronics, and a motherboard, which distributes voltage and control signals and electrical signal transmission. Additionally, all SiPM materials have been carefully screened for radioactivity to minimize background interference.

This talk will focus on the production of the vPDUs, emphasizing the rigorous Quality Assurance and Quality Control (QA/QC) procedures, and the final characterization of the first completed prototypes. Extensive testing in liquid nitrogen baths has been conducted on the vPDUs, aiming to assign a "quality passport" to ensure optimal performance and reliability within the DarkSide-20k experiment."

Poster Session - Board: 5 / **10**

Data-driven background model for the CUORE experiment and measurement of the two-neutrino double beta decay of Te-130

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Neutrinoless double beta decay ($0\nu\beta\beta$) is a lepton-number-violating nuclear transition beyond the Standard Model. If detected, it would unequivocally demonstrate that neutrinos are Majorana particles. This process is expected to be extremely rare, therefore very low background tonne-scale experiments are necessary for its observation. The Cryogenic Underground Observatory for Rare Events (CUORE) is one such experiment, searching for $0\nu\beta\beta$ in ^{130}Te. The CUORE detector is composed of 988 TeO_2 crystals, operating as cryogenic calorimeters at around 15 mK in the Gran Sasso National Laboratory (Italy).

Characterizing the remaining experimental backgrounds is crucial for discovering a rare process like $0\nu\beta\beta$. This complex task is accomplished through comprehensive material screenings and assays, combined with a detailed set of Monte Carlo simulations to model the CUORE data. As a result, contaminant activities distributed in several components of the experiment can be measured with sensitivities as low as 10 nBq/kg and 0.1 nBq/cm^{-2} for bulk and surface contamination, respectively. Many studies concerning the spatial and temporal distribution of the background sources can also be performed. Additionally, the outcomes represent essential inputs for the background budget of the next-generation experiment, CUPID, which will be operated in the same cryogenic facility.

We will describe the model of the CUORE background data, presenting the results of the 1 ton·yr data reconstruction performed using a simultaneous Bayesian fit of several energy spectra. This will include a discussion about the determination of the background component activities. We will also show dedicated studies that have been conducted to achieve the most precise determination of the $2\nu\beta\beta$ decay half-life of ^{130}Te, as well as investigations into the decay's spectral shape to explore nuclear physics parameters.

Poster Session - Board: 6 / **29**

Developing a cryogenic heat pump for liquid xenon radon removal systems

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Future liquid xenon (LXe) dark matter detectors require the detector background event rate to be significantly lower non-shieldable solar neutrino background yielding the request that each radioactive background rate should be 10-times smaller than that from solar neutrinos. To achieve this ambitious goal for 222Rn, a reduction of the intrinsic 222Rn concentration to less than <0.1 µBq/kg in LXe is required —corresponding to less than one 222Rn atom in 160 mol xenon. The project "LowRad" aims to develop the technology for the next generation of radon and krypton removal systems by utilizing cryogenic distillation. Making use of the different vapour pressures of xenon and radon, radon can be removed from xenon through multiple evaporation and condensation steps in a column with partial reflux. To attain the goal of this low radon concentration, the throughput flow of the radon column must be increased from 65 kg/h, in current generation removal system of XENONnT, to O(750 kg/h), necessitating O(20) kW of heating and cooling power for the evaporation and reliquification. Therefore, a heat pump concept using liquid xenon (LXe) as the working medium is being developed. This poster will highlight the working principle of cryogenic distillation and required heat pump, as well as first results from the commissioning phase of the heat pump.

Poster Session - Board: 7 / **6**

Developing the low radon ultra-pure water for the JUNO experiment

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The Jiangmen Underground Neutrino Observatory (JUNO) is a state-of-the-art liquid-scintillator-based neutrino physics experiment under construction in South China. Thanks to 20 ktons of the ultra-pure liquid scintillator (LS), JUNO can perform innovative and groundbreaking measurements like determining neutrino mass ordering. To mitigate the impact of radioactivity emanating from the surrounding rocks and detector materials, as well as to tag cosmic muons, the central detector is immersed in a Water Cherenkov Detector (WCD) comprising 35 kton of Ultra-Pure Water (UPW) and 2400 20-inch MCP-PMTs.
A 100t/h UPW production system is equipped to supply UPW for the WCD. According to the Monte-Carlo simulation results, the radon concentration in the UPW has to be reduced to less than 10 mBq/m3. An online radon removal system based on the JUNO prototype has been developed to achieve this. By integrating micro-bubble generators to enhance degasser's radon removal efficiency, the radon concentration in water can be reduced to sub-mBq/m3 level, meeting the stringent requirements of JUNO. Additionally, a highly sensitive online radon concentration measurement system capable of detecting concentrations of ~0.25 mBq/m3 in water has been developed to monitor the radon concentrations. This talk will introduce the detail of the development of low radon UPW, the detail of the online radon concentration measurement system, and the recent progress of the JUNO 100t/h ultrapure water system.

Poster Session - Board: 8 / **33**

Development and Modeling of a Thin, Radiopure Germanium Detector Entrance Window

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Ultra-low-background (ULB) high purity germanium (HPGe) detectors are essential tools for measurements of materials with extremely low levels of radioactivity. Such detectors support research areas ranging from fundamental physics of rare events like dark matter and neutrinoless double beta decay, to nuclear safeguards and treaty verification.

A common shortcoming specific to ULB HPGe detectors is a lack of sensitivity to lower energy gamma radiation (<100 keV), due to the requirement of using highly radiopure copper for the detector shell which attenuates these low energies. At Pacific Northwest National Laboratory, we are developing a radiopure entrance window with high transmission of gammas down to 10 keV. Our team is working to create a thin window from radiopure polymers and ceramics, namely looking at polyetherimide and pyrolytic boron nitride as candidate materials. In this poster, I will present an overview of the project, along with a focus on modeling efforts used to guide the material selection, window design, and performance validation.

Rn Detection and Mitigation / 94

High sensitivity Rn studies: review

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The noble gas radon and its decay products can significantly contribute to the background in experiments searching for rare events. Consequently, many experiments implement dedicated radon mitigation strategies, which are fundamentally supported by high sensitivity radon screening techniques. This talk will review the motivation for radon screening and provide an overview of high sensitivity radon measurement techniques. Various methods of radon measurement will be discussed, including electrostatic radon monitors, cryogenic detectors, and miniaturized proportional counters. Additionally, an overview of the existing radon screening infrastructures at different laboratories worldwide will be provided. The talk will conclude with a brief outlook on future developments in the production of reliable radon calibration sources, and studies of radon emanation from different materials.

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Reduction of radon in xenon-based experiments to search for rare events

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With the installation of rare event search experiments in underground laboratories, good passive and active shielding measures, careful material selection and surface treatments, radioactive isotopes in the xenon of xenon-based rare event search experiments have become the most important underground source in the search for rare events besides solar and atmospheric neutrinos. Particularly important are radioactive noble gases, especially Rn-222 because of its gamma and beta-emitting progenies Pb-214, Bi-214 and Pb-210, which cannot be removed by normal getters. In this talk, various methods for the continuous active removal of radon from xenon, in particular charcoal chromatography and cryogenic distillation, will be presented.
New records in the purity of Ar-39, Kr-85 and Rn-222 have been achieved with cryogenic "online

distillation”in the dark matter experiment XENONnT. The talk will also give an outlook on how these methods can be further developed to achieve the required purity of radioactive noble gases for the next generation of experiments such as DARWIN/XLZD. In particular, the developments just started within the ERC Advanced Grant project LowRad (no. 101055063) with a target radon purity of 1 radon atom per 160 mol xenon (or 0.1 μBq/kg) also aim at integrating the required very sensitive online diagnostic methods.

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Ultra Low Background Radon Measurement System and Radon Removal Techniques for Rare Event Experiments

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In the pursuit of ultra-low background experiments, minimizing radon levels is crucial. This research presents significant advancements in radon detector sensitivity, surface treatment technologies, and radon removal systems. We achieved a background level of 0.07 ± 0.03 mBq in a 7.4L chamber and 0.03 ± 0.01 mBq in a 12.33L chamber. Various surface treatments, including epoxy coating, mylar membrane covering, and teflon coating, were tested, resulting in up to a tenfold reduction in radon levels. Additionally, a cold trap enrichment method was developed, increasing radon measurement sensitivity by 30 times. A radon removal system with charcoal trap was designed and tested, demonstrating its effectiveness in reducing radon levels within nitrogen and xenon environments. These developments are essential for ensuring minimal radon background in experiments such as PandaX-4T.

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State-of-the-art surface coating for radon background mitigation

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For rare event searches using liquid xenon detectors, radon-induced background represents the most significant contribution. Specifically, 222-Rn, a decay product of 226-Ra found in all materials, enters the detector’s active region by emanation from the material surfaces. To meet the sensitivity requirements for the next generation of detectors, this background must be reduced by about one order of magnitude compared to the levels achieved by the current generation (XENONnT 222-Rn activity ~ 1 μBq/kg). The current radon mitigation techniques might not be sufficient to reach this goal, necessitating the exploration of alternative strategies.

At the Max-Planck-Institut für Kernphysik (MPIK), various surface coating techniques have been intensely studied as radon barriers. Among them, the electrodeposition of pure copper has emerged as a promising mitigation method. We achieved a thousandfold reduction in 222-Rn emanation on a 2×2 cm² stainless steel sample previously irradiated with 226-Ra at the ISOLDE facility at CERN. Following this successful small-scale test, the setup was upgraded to allow larger, vessel-like samples to be coated. Additionally, new 226-Ra implanted samples have been produced to validate the

reliability of the coating technique further. The current state of the coating project will be presented, along with a discussion of upcoming operations.

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Study and development of new radon adsorbents - the IRENE project

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Radon is one of the most important radioactive backgrounds in low energy and very rare events experiments in particle and astroparticle physics like neutrinoless double beta decay or dark matter direct research. A concentration of few radon atoms per m3 or per kg will be mandatory in future experiments. Capturing radon at these very low levels require the use of very effective adsorbents. At CPPM in Marseille we have been studying microporous radon adsorbents for over 10 years.
After an initial period during which we studied more than 50 samples of carbon-based adsorbents, both commercial and laboratory developed, from which we establish the optimum pore size for radon capture, we recently considered the radon adsorption as function of temperature in several commercially available silver zeolite. A very large radon adsorption capacity, 100 times higher than in the best reported materials, was observed for a titanium-silver zeolite.
A new consortium between CPPM and four physical chemistry and materials science laboratories has been setup in February 2024 to understand the origin of this excellent performance and to optimize it.
The goal of this unprecedented collaboration, named IRENE, is to develop in the next 4 years, innovative materials for extreme radon adsorption, in particular in xenon.
In this presentation we will report on the main results obtained up to now and we will present the IRENE project

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Radon daughter deposition modelling and measument

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This work summarize different approaches that were carried out in the Modane Underground Laboratory (LSM). In this work the simulation of Radon daughter implantation on different surfaces is presented. The work compares a Geant4 based approach to the SRIM code . This lies in the simulation of the nucllear recoil on a metal plate. The different materials are tested respectively to radon deposition. Mainly we try to simulate accurately the nuclear recoil and the different surface states that will govern the implantation depth. Moreover different material were tested in radon deposition chamber that allowed us to test different environmental possibilty. the main material and packing are tested and the accuracy of simulation is tested.In the conclusion a discussion is made to check if this simulation can be generalized to underground experiment and the surface lead 210 deposition background background contribution coming from the storage of materials before building the experiment.This work could be discuss as a possibility to anticipate the background coming by

monitoring the radon level or giving a radon budget for the experiment building and anticipate the lead 210 contribution.

Production of Radiopure Materials / **79**

Copper electroforming at Canfranc

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High purity copper continues to play an important role for ultra-low-background detectors on neutrino physics and dark matter experiments. Electroforming of copper is an electrochemical process that enables the manufacture of metallic parts with high chemical and radioactive purity, process reproducibility and good mechanical properties.
To support the construction of the ultra-low-background detectors, a Copper Electroforming Service (CES) is in operation at the Laboratorio Subterráneo de Canfranc (LSC). This work highlights the last electroformed copper pieces prepared and results, including plans to upgrade the setup.

Production of Radiopure Materials / **47**

Radiopure PEN for Rare-Event Searches

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Achieving the scientific goals of rare-event searches, such as dark matter and neutrinoless double-beta decay detection, hinges on stringent background reduction. Utilizing materials with outstanding radiopurity that can additionally self-veto internal background radiation is critical for meeting these requirements. Poly(ethylene-2,6-naphthalate) (PEN) has emerged as a highly promising candidate for cryogenic rare-event searches due to its intrinsic scintillation and wavelength-shifting properties, along with its structural stability at both room and cryogenic temperatures. In the LEGEND-200 neutrinoless double-beta decay experiment, commercial PEN has already been successfully implemented as an optically active and structural component. To meet the more demanding background reduction needs of future experiments, such as LEGEND-1000, we are advancing the self-synthesis of glycol-modified PEN (PEN-G). This presentation will cover the production of commercial PEN components and the synthesis of PEN-G, focusing on their optical properties, structural performance, and radiopurity. Additionally, we will explore the future applications of radiopure PEN in next-generation rare-event searches. This research is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Excellence Cluster ORIGINS EXC 2094-39078331; SFB1258-283604770.

Production of Radiopure Materials / **43**

On the manufacturing process of novel ultra-radiopure, high-strength, electroformed Cu-based alloys for rare event searches

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Near-future low-background experiments such as direct Dark Matter (DM) or Neutrinoless Double-Beta Decay search experiments require extremely radiopure detector materials and consistent manufacturing processes to achieve their physics discovery potential. Electroformed copper (EFCu) has been shown to achieve extreme radiopurity. However, its mechanical properties are limited due to high ductility and low strength.
Copper can be procured commercially at low cost and high purity and has no long-lived radioisotopes. Unfortunately, it may be contaminated during manufacturing and is activated by cosmogenic neutrons. In an effort to achieve even higher radiopurity, attention is focused on EFCu. To fulfil the unique radiopurity requirements, experiments pioneer large-scale, additive-free Cu electroformation, e.g. the former Majorana Demonstrator or the on-going NEWS-G collaboration ECuME project. Copper electroforming has been demonstrated to achieve extreme radiopurities with contamination below 10^{-14}g of ^{232}Th and ^{238}U per Cu gram. However, Cu is highly ductile and of low strength, limiting its use for moving mechanical, high-pressure, and load-bearing parts. The ECuME project would improve the capability for experiments such as DarkSPHERE [2], a large-scale electroformed underground spherical proportional counter. DarkSPHERE will operate under high pressure, to probe uncharted territory in the search for DM. This level of radiopurity is also vital for neutrinoless-double β-decay experiments e.g. nEXO, LEGEND, and NEXT to name a few.
To improve the strength of EFCu alloying has been investigated. The most promising alloying element is chromium (Cr). It has been demonstrated that small additions of Cr, combined with heat treatment and aging cycles, improve EFCu strength by 70% [3]. However, Cr additions lead to impurities, and a compromise between strength and radiopurity is required by exploring a complex parameter space of compositions and strengthening mechanisms [4]. Additionally, Cr solubility in Cu is very limited and small additions of titanium (Ti) can allow for even greater mechanical strengthening due to reinforced precipitation, achieved based on the Integrated Computational Materials Engineering (ICME) framework [5].
A systematic simulation study of manufacturing processes (additive-free electroplating and heat treatments) aiming to achieve homogenized alloy compositions is performed using DICTRA [6]. This will inform the achievable alloy compositions and an ICME approach will follow to enable rapid design of new, application-specific alloys.

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Archaeological Lead purification for RES-NOVA

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RES-NOVA is a newly funded project for the investigation of astrophysical neutrino sources with archaeological PbWO4 cryogenic detectors. RES-NOVA will exploit Coherent Elastic neutrino-Nucleus Scattering (CEνNS) as detection channel, thus it will be equally sensitive to all neutrino flavors produced by Supernovae.
In order to achieve the goal sensitivity, the crystal must be grown from highly radio-pure precursors. In this contribution, we will present an innovative atomization technique, mediated from the 3D printing technology, for the production of lead with impurity levels in fulfillment to the RES-NOVA requirements. After the successful production of 1 kg of atomized lead, RES-NOVA plans to scale the technology and produce 100 kg of atomized lead within the next year.
Such technique could be profitable for the production of other atomized materials for crystal growth, as well as for the purification of relatively large amounts of lead for the innermost shielding layers for low-background gamma spectroscopy.

Neutron Background Mitigation / 95

Measuring underground neutrons with the high-efficiency neutron spectrometry array (HENSA): current status and future prospects

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TBA

Neutron Background Mitigation / 62

Calculation and Mitigation of Neutron-Induced Backgrounds in Rare Event Search Experiments

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Neutron-induced backgrounds pose a significant challenge in experiments designed to detect rare events, such as dark matter interactions and neutrinoless double-beta decay. This talk discusses the characteristics of these backgrounds, focusing on neutron generation via spontaneous fission and

α,n reactions. These processes are particularly critical in underground experiments, where the continuous emission of radiogenic neutrons from the detector materials is, to some extent, unavoidable. We present the latest advancements in neutron yield calculations using new tools and updated cross-sections and discuss strategies for mitigating these backgrounds, including material selection and shielding optimization.

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Optimised neutron yield calculations from (α,n) reactions with the modified SOURCES4 code

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The sensitivity of underground experiments searching for rare events such as dark matter, neutrinoless double-beta decay or low-energy neutrinos is affected by the background due to neutrons from spontaneous fission and (α,n) reactions. Neutron yields and energy spectra due to these reactions can be calculated using a variety of codes. In this paper we present new calculations of neutron production using the modified SOURCES4A code with recently updated cross-sections for (α,n) reactions and the comparison of the results with available experimental data from alpha-particle beams and radioactive decay chains. The cross-sections for (α,n) reactions used in SOURCES4 have been taken from reliable experimental data where possible, complemented by the calculations with the recent versions of EMPIRE and TALYS codes or evaluated data library JENDL-5 where the data were scarce or unavailable.

Neutron Background Mitigation / 14

Development of a GAGG-based low-background neutron detector

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In rare events experiments, a precise knowledge of the environmental gamma and neutron backgrounds is crucial for the design of appropriate shieldings. The neutron component is often poorly known due to the lack of a scalable detector technology for the measurement of low-flux neutron spectra in a short time.
Thanks to their high gadolinium content, we are investigating the possibility of using scintillating $Gd_3Al_2Ga_3O_{12}$ (GAGG) crystals as portable neutron detectors, in alternative to 3He counters.
GAGG features a high scintillation light yield, good timing performance, and the capability of particle identification via pulse-shape discrimination. In a low-background environment, the distinctive signature produced by neutron capture on gadolinium, namely a γ-ray cascade releasing ~8 MeV of total energy, and the efficient particle identification provided by GAGG would yield a background-free neutron capture signal.
In this contribution, we will present the characterization of a first GAGG detector prototype in terms

of particle discrimination performance, intrinsic radioactive contamination, and neutron response. We will then discuss possible further developments of this detector technology towards the realization of a portable setup for the neutron spectrum measurement in various locations of the INFN Gran Sasso National Laboratory (LNGS) laboratory.

Neutron Background Mitigation / 4

Gd-PMMA: a novel neutron tagging technology for low background detectors

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Low background detectors, such as those used in direct dark matter searches, require high-efficient neutron veto to reject nuclear recoil backgrounds. Gadolinium-doped polymethyl methacrylate (Gd-PMMA) has emerged as a promising solid neutron tagging material, with high hydrogen content for moderating neutrons and gadolinium content for capturing thermal neutrons and exploiting subsequent emission of high-energy gamma rays. This talk introduces a novel Gd-PMMA material based on a complex compound called gadolinium methacrylate, which will be used in the DarkSide-20k experiment, a direct dark matter search experiment with liquid argon.
The Gd-PMMA will serve as both a neutron tagging material and the main structural material of the dual-phase argon Time Projection Chamber (TPC) in the DarkSide-20k detector. This design allows for the Gd-PMMA to be located as close as possible to the detector's active volume to tag any possible neutrons from intrinsic backgrounds. With liquid argon buffers on both sides of the Gd-PMMA, gamma rays released during neutron capture can be effectively detected. To maximize neutron veto efficiency, a ~1% gadolinium mass fraction with 15 cm thick Gd-PMMA surrounding the TPC's active volume is required. Radiopurity control of this material is also being studied to ensure its suitability for use in low-background experiments.

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Rare event search with cryogenic calorimeters

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Cryogenic calorimeters have emerged as powerful tools in the search for rare events, such as neutrinoless double beta decay and dark matter interactions, due to their exceptional energy resolution, low-energy threshold and versatility.
This contribution will provide an overview of the latest results from leading experiments based on these detectors.
A particular focus will be placed on background reduction techniques, which are crucial to improving the sensitivity of these searches.
Key advancements, including material purification, shielding strategies, and advanced signal processing methods, will be discussed, highlighting their role in achieving unprecedented sensitivity in rare event detection.
The implications of these results for future experiments will also be addressed, highlighting the potential of cryogenic calorimeters in pushing the frontiers of low-background physics.

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Development of a Silicon Bolometer for Rare Event Detection with LED Self-Calibration

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This research introduces a novel silicon bolometer, designed to dramatically enhance sensitivity for detecting ultra-low radioactive contamination of material surfaces. Targeting a sensitivity of 1 nBq/cm², the project integrates meticulous surface contamination control with advanced bolometric techniques. A central advancement is the implementation of a self-calibrating system using LED pulses, which simplifies detector operations and enhances stability, and eliminates the need for radioactive alpha sources or heater-based stabilization techniques. In this work, such a self-calibration has been successfully performed for energies up to 10 MeV. The calibration process involves developing an energy resolution curve from LED events, providing foundational data. LED pulses of varying amplitudes are used to linearize and calibrate the energy scale by using the Poisson statistics of the light itself. The accuracy of this model is verified through simulations that assess background levels, enabling more reliable measurements. The successful development of this novel detector will enable future projects for rare events to perform high-precision screening measurements of all the components prior to the experiment construction.

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Radioassays for the LEGEND 76Ge neutrinoless double beta decay experiment

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The LEGEND experiment searches for neutrinoless double beta decay in ^{76}Ge-enriched high-purity germanium detectors operating in liquid argon, whose scintillation acts as an active veto against external background events. Using specialized detector geometries, pulse shape discrimination is performed to further veto background events. LEGEND-200 has completed about one year of stable physics data-taking at Laboratori Nazionali del Gran Sasso (LNGS) in Italy, with the first data recently unblinded. With a planned ultimate exposure of 1 ton·yr and a target background index of 2×10^{-4} cts/(keV·kg·yr) at $Q_{\beta\beta}$ = 2039 keV, LEGEND-200 is expected to reach a 3σ discovery sensitivity of 10^{27} years half-life. The next generation experiment, LEGEND-1000, will operate 1000 kg of detectors and reach an expected discovery sensitivity of 10^{28} years half-life, covering the inverted neutrino mass hierarchy. To reach the required low background, LEGEND uses an extensive radioassay program, which will be discussed with highlights on recent measurements.

This work is supported by the U.S. DOE and the NSF, the LANL, ORNL and LBNL LDRD programs; the European ERC and Horizon programs; the German DFG, BMBF, and MPG; the Italian INFN; the Polish NCN and MNiSW; the Czech MEYS; the Slovak RDA; the Swiss SNF; the UK STFC; the Russian RFBR; the Canadian NSERC and CFI; the LNGS and SURF facilities.

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Analysis of the backgrounds in the LEGEND-200 experiment

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LEGEND-200 is an experiment designed to search for neutrinoless double beta decay ($0\nu\beta\beta$) in ^{76}Ge at LNGS in Italy. In this talk, we present a comprehensive analysis of the backgrounds in the LEGEND-200 experiment. This consists both of the results of several 'special background runs' where components of the experiment were removed to provide a model independent determination of their contribution to the background and in-situ γ screening measurement of their activities. In addition, we developed a Bayesian model of the data by fitting the experimental data over a wide spectral range and various event topologies to a sum of Monte-Carlo simulations. This model provides information on the activities of the various components in the experiment. This work informs future hardware upgrades of LEGEND-200 and the design of LEGEND-1000.
This work is supported by: U.S. DOE, NSF, LANL, ORNL, LBNL LDRD programs; European ERC, Horizon programs; German MPG, BMBF, DFG; Italian INFN; Polish NCN, MNiSW; Czech MEYS; Slovak SRDA; Swiss SNF; UK STFC; Canadian NSERC, CFI; LNGS, SNOLAB and SURF facilities.

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Latest results from the CUORE experiment

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The Cryogenic Underground Observatory for Rare Events (CUORE) is the first bolometric experiment searching for 0νββ decay that has successfully reached the one-tonne mass scale. The detector, located at the LNGS in Italy, consists of an array of 988 TeO2 crystals arranged in a compact cylindrical structure of 19 towers. CUORE began its first physics data run in 2017 at a base temperature of about 10 mK and has been collecting data continuously since 2019, reaching a TeO2 exposure of 2 tonne-year in spring 2023. This is the largest amount of data ever acquired with a solid state cryogenic detector, which allows for further improvement in the CUORE sensitivity to 0νββ decay in 130Te. In this talk, we will present the latest results of CUORE, based on the full available statistics and on new, significant enhancements of the data processing chain and high-level analysis.

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Exploring the keV scale energy spectrum of CUORE

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The Cryogenic Underground Observatory for Rare Events (CUORE) is the first tonne-scale experiment using cryogenic calorimeters. The detector is located underground at the Laboratori Nazionali del Gran Sasso in Italy and consists of 988 TeO2 crystals operated in a dilution refrigerator at a base temperature of about 10 mK. Thanks to the large exposure, sharp energy resolution, segmented structure and radio-pure environment, CUORE provided the most sensitive exclusion limit of the neutrinoless double beta decay of 130Te.
We are working towards demonstrating the potential of CUORE as a multipurpose detector over a broad energy range. In this contribution, we present a comprehensive study on low-energy events,

from a few to tens of keV, in the CUORE experiment. We profit from the very large amount of data collected so far (2 ton yr of exposure), to investigate the spectral features present at this energy scale to better understand the contribution from external radioactive sources and to study nuclear processes such as the 123Te electron capture.

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Backgrounds of the CUPID experiment

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Next generation neutrinoless double beta experiments aims at covering the inverted hierarchy region of the neutrino mass spectrum, with sensitivities on the half-lives greater than 10^{27} years. The CUPID experiment will exploit cryogenic calorimeters to search for neutrinoless double beta decay of ^{100}Mo. To reach the target sensitivities one of the key requirements is the understanding and control of the backgrounds. This talk will detail the background sources relevant to the CUPID experiment. We will show the estimation of the background index for each of the sources. The estimations of the background from the radioactivity in the detector set-up are based on detailed Monte-Carlo simulations and on backgrounds of past experiments. Other backgrounds are derived from detector performances in R&D tests.

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Updated background studies for the ANAIS dark matter experiment

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The ANAIS experiment is intended to search for dark matter annual modulation with ultrapure NaI(Tl) scintillators in order to provide a model-independent confirmation or refutation of the long-standing positive annual modulation signal in the low energy detection rate of the DAMA/LIBRA experiment at the Gran Sasso Underground Laboratory (Italy), using the same target and technique. ANAIS-112, consisting of nine 12.5 kg NaI(Tl) modules produced by Alpha Spectra Inc., disposed in a 3×3 matrix configuration, is taking data smoothly with excellent performance at the Canfranc Underground Laboratory (Spain) since August, 2017. Latest results corresponding to six-year exposure were compatible with the absence of modulation and incompatible with DAMA/LIBRA signal at 3.9sigma (2.9sigma) at [1-6] ([2-6]) keV; 5sigma sensitivity is expected for late 2025. Beyond ANAIS-112, the ANAIS+ project operating crystals at low temperature and replacing PMTs by SiPMs is in development.

The background model developed for all the nine ANAIS-112 detectors, based mostly on quantified activities independently estimated following several approaches, described well the measured spectra except for the very low energy region just above threshold. New filtering protocols based on machine-learning techniques have allowed to reduce the registered background in that region, but

an excess over the simulation still persists. The background model also allows to predict the evolution in time of the rates in different energy windows, considered in the annual modulation analysis. An updated model is under development using 6-year exposure aiming at improving the description of some components as tritium produced cosmogenically and 210Pb contamination on crystal surface; both contributions are relevant in the low energy region and affect the time evolution of the detection rates.

Here, after the general presentation of the experiment, methodology and preliminary results of this new background studies will be discussed.

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BINGO: Investigation of the Majorana nature of neutrinos at the few meV level of the neutrino mass scale

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BINGO is a project dedicated to explore and demonstrate new methods for background reduction in cryogenic calorimetric $0\nu\beta\beta$ searches. With a target background index at the level of 10^{-5} counts/(keV kg yr) it aims at providing a path towards a nearly background free $0\nu\beta\beta$ experiment with a tonne of the isotopes of interest ^{100}Mo and ^{130}Te. The major design aspects to achieve this goal are (i) a novel detector assembly reducing the exposed surface area of un-instrumented (passive) materials in the detector array by more than an order of magnitude, (ii) an additional tightly packed array of BGO scintillators that surrounds the detector array and acts as active cryogenic veto system and (iii) the use of enhanced Neganov-Trofimov-Luke based light detectors that help mitigate the pile-up background for ^{100}Mo and ensure the alpha-beta discrimination in $^{130}TeO_2$. In this talk, we will describe the technical design of these concepts, results from prototypes of the technologies in proof-of concept measurements and initial Geant4 based projections of the impact of these improvements in a CUORE/CUPID size experiment.

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The Background Control of PandaX-4T and A Low-background PMT for PandaX-xT

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The PandaX-4T experiment uses a liquid xenon time projection chamber (TPC) to search for dark matter and other rare events. To achieve this, PandaX employs various techniques to remove and precisely measure the radioactivity of detector components, such as radon detectors, krypton systems, alpha detectors, and HPGe detectors. The photomultiplier tubes (PMTs) significantly contribute to the background, especially for the next-generation PandaX-xT detector, making their control crucial. In collaboration with Hamamatsu, PMT components are screened using HPGe detectors, leading to the development of the low-background R12699 PMT. This PMT achieves extremely low levels of Co-60 (~0.6 mBq/pc), Th-232, and U-238 (~0.1 mBq/pc). Additionally, its dark noise, position reconstruction accuracy, afterpulse probability (APP), and quantum efficiency (QE) meet high standards, making it suitable for next-generation rare decay detection experiments.

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Environmental radioactivity background control at JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kt liquid scintillator detector under construction at 700 m underground. It will enable studies of various neutrino physics topics, and the level of radioactive background is an essential factor for achieving the desired sensitivities. The raw materials of the JUNO detector have already been screened and met the radio purity requirements. The detector is presently being installed in the underground experimental hall, and during these operations the radioactive control of the environment is crucial . The whole underground space at the JUNO site is about 300,000 m^3, including the 120,000 m^3 main hall and several attached halls and tunnels, such as the liquid scintillator room and the liquid scintillator filling room, making it the largest underground laboratory in the world. As in every underground laboratory, the rocks and water will release large amounts of ^{222}Rn into the air. The detector components are exposed to air during the installation, so radon and its daughters can attach to their surfaces. This is particularly critical for materials directly contacted with the liquid scintillator since the radioactive contaminants could leach into the liquid and mimic the physics signals. Therefore, the controlling the radon concentration in the experimental hall is a critical issue. Moreover, dust in the air is rich in ^{238}U, ^{232}Th and ^{40}K, so the residual dust is another source of radioactive background. The cleanliness inside the experimental hall should reach the level of Class 100,000 or better. To achieve an installation environment with a low radon concentration and cleanliness level, a lot of effort was put into optimizing the ventilation system in the experimental hall. Additionally, the sources of radon in the underground air have been carefully studied. The radon concentration in the experimental hall has been stabilized at about 180 Bq/m^3 after great efforts. Both the radon and the cleanliness level have now met the requirements.

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Studies of radioactive background from environment for a potential LXe dark matter experiment at Boulby

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Rare event searches, such as those targeting dark matter interactions and neutrinoless double beta decay (0νββ), face challenges from gamma-rays originating in rock, contributing to electron recoil background. This report presents a dual investigation: measurements of natural radioactivity in rock samples from Boulby Mine and a simulation assessing shielding thickness for a future detector. The measurements provide data for normalising conditions in prospective experiments at Boulby. The simulation studies the effectiveness of water shielding around a detector, focusing on the Weakly Interacting Massive Particle (WIMP) energy range (0 –20 keV) and the energy range near the 0νββ Q-value (2.458 MeV for Xe-136).

The study design features a simplified xenon-based detector with a 70-tonne active mass, encompassed by veto systems and water shielding. Our findings indicate that the gamma-ray background from rock is unlikely to persist through analysis cuts in the WIMP energy range with water/scintillator

thickenss of > 3 m thanks to a powerful discrimination between potential WIMP signals and gamma-ray background. For $0\nu\beta\beta$ decay signal searches fiducial mass of the detector may need to be reduced to keep the background from rock below 1 event in 10 years of running.

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Environment background at HADES

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The HADES underground research facility, located in a clay formation at a depth of 225 meters, is operated by Euridice. The ultralow background gamma-ray spectrometry laboratory is operated by the Joint Research Centre of the European Commission (JRC) for radioactivity measurements, made possible by a significant reduction in muon flux (secondary cosmic rays) by a factor of 5000 compared to above ground. Eleven specially designed high-purity germanium detectors are used for sub-mBq measurements. There is also a scanning station through which the homogeneity of dead layers in HPGe detectors can be studied. Among the many topics addressed in HADES, priority is given to the characterization of reference materials, tracing processes in nature (such as ocean currents, uptake in the food chain, and anthropogenic activities related to nuclear operations), and quality control. Basic physics experiments (e.g., the search for neutrinoless double beta decay and other rare processes) are also strongly supported through assays for material selection, storage of radiopure materials, detector testing, studies of rare nuclear decays, and methods for low-level applications. The status of the laboratory and selected aspects of the successful operation of the first SAGe and BEGe detectors in the world will be presented.

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