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Editorial: Science and technology in deep underground laboratories

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Editorial on the Research Topic
Science and technology in deep underground laboratories

Deep Underground Laboratories (DULs) are **multidisciplinary research infrastructures** with a rock overburden that goes from a few hundred metres to a few kilometres. There are 13 laboratories in operation on three continents (North America, Europe, Asia, Australia) giving a global excavation volume of over a million cubic metres. The science enabled by DULs is growing in both depth and breadth. New laboratories are being constructed/proposed including a new one in South Africa.

This Research Topic collects contributions on the construction, exploitation and safety aspects of four DULs. It includes the excavation of one of the world's largest underground caverns to accommodate the Hyper-Kamiokande detector Abe et al., a world-leading international neutrino and nucleon decay experiment comprising the next-generation underground water Cherenkov detector (about 250 kton) and utilising the upgraded Japan Proton Accelerator Research Complex (J-PARC) neutrino beam. The scientific program of the next-generation neutrino experiments is very broad. In particular, near detectors offer opportunities to further test our understanding of particle physics. An example is presented with the search for heavy neutral leptons in the DUNE near detector Carbajal and Gago. The Research Topic also includes the new underground laboratory, Yemilab Park et al., which was completed in Jeongseon, Gangwon Province, with a depth of 1 km and an exclusive experimental area spanning 3,000 m^3, where the Yangyang Underground Laboratory facilities will be relocated. Additionally, Yemilab includes a cylindrical pit with a volume of approximately 6,300 m^3, designed as a multipurpose laboratory for next-generation experiments involving neutrinos, dark matter, and related research. A third underground laboratory is discussed, Callio Lab Joutsenvaara et al., which is a versatile multidisciplinary research platform, project-based, pay-by-service approach to organising and economically running the research activities, a mandatory approach for a platform operating without governmental funding. Improving safety underground is one of the necessary actions in DULs. The Gran Sasso National Laboratory (LNGS) is, at present, the largest deep underground laboratory in operation for astroparticle physics and rare event research. Cavalcante and Bucciarelli shows the study of an adaptive evacuation system for LNGS to improve the evacuation performance in underground laboratories, which is composed of a combination of passive, dynamic, and adaptive signage that can adapt itself to lead the laboratory occupants to the safe location for evacuation.

The main reason to develop an underground infrastructure is to operate in a very low radioactive environment where muons from cosmic rays are strongly suppressed. This singular environment opens the possibility to search for very rare events such as low energy neutrino interactions, dark matter direct detection, and neutrinoless double beta decay, crucial to enhance our understanding of the Universe. Different naturally occurring radioactive products which lead to decay products and decay emissions on a wide spectrum of energies may adversely impact the sensitivity of a running particle physics detector. This Research Topic collects contributions on various efforts to monitor background levels in experiments. The Boulby UnderGround Screening (BUGS) Facility Scovell et al. comprises an array of germanium detectors, two XIA UltraLow-1800 surface-alpha counters, two radon emanation detectors and an Agilent ICP-MS system. Agrawal et al. presents the design and the construction materials used to build the AMoRE-II detector, an experiment to search for the double beta decay of ^{100}Mo nuclei using molybdate crystal scintillators, operating at milli-Kelvin (mK) temperatures and shielding system, including active and passive shielding, the cryostat, and the detector holders and instrumentation. The Global Argon Dark Matter Collaboration (GADMC) contribution Agnes et al. shows their efforts to reduce and monitor the ^{39}Ar activity in atmospheric argon, which is mainly produced and maintained by cosmic ray induced nuclear reactions and limits the ultimate size of argon-based detectors and restricts their ability to probe very low energy events. The discovery of argon from a deep underground well with significantly lower activation than atmospheric argon and a dedicated experiment to monitor the radioactive level are important steps in the development of direct dark matter detection experiments using argon as the active target. Devices based on superconductivity and superfluidity, low-temperature phase transitions or the low heat capacity of non-metals in the milli-Kelvin range are often sensitive to small energy depositions as can be caused by environmental radiation. Camus et al. shows the main design features and operating parameters of The Cryogenic Underground TEst facility [CUTE (Agnes et al.)] at SNOLAB, a platform for testing and operating cryogenic devices in an environment with low levels of background.

Several challenges faced by DUL science are dealt with using new technological infrastructures and technological applications. This Research Topic collects contributions such as the presentation of the Nuova Officina Assergi (NOA) Consiglio et al., a new facility for the production and integration of large-area silicon photodetectors operating at cryogenic temperatures. Silicon photomultipliers are proving to be a promising technology for next-generation experiments searching for rare events in underground laboratories. To overcome the issues in terms of the extreme radio-purity, costs, and technological feasibility of the future dark matter experiments, the novel silicon photomultiplier (SiPM)-based photodetector modules Razeto et al. seem to be promising candidates, capable of replacing the present light detection technology. However, the intrinsic features of SiPMs may limit the present expectations. It also collects the presentation of the **Bellotti Ion Beam Facility** (IBF) Junker et al. at LNGS which stands out as the worldwide only ion beam user facility deep underground. As this, it aims to provide the scientific community with access to intense proton, ^{4}He and ^{12}C ion beams in a low radiation environment achievable only in a deep underground site. The intense carbon beam and, more in general, the excellent long-term stability of the beams produced by the 3.5 MV Singletron™ accelerator are unique features of the Bellotti IBF. As an example of a technological application, Daniels et al. shows the potential of the DULs as a battery to store compressed air, using off-peak surplus energy. Natural accumulations of salt (halite deposits) in the UK represent a large and untapped natural storage reservoir for compressed air with the ability to provide instantaneous green energy to meet peak demand. To realise the potential of this emerging technology, a detailed knowledge of the relationship between mechanics, chemistry and geological properties is required to optimise cavern design, storage potential and economic feasibility.

In addition, the special environments in which DULs are located provide opportunities to carry out many and varied studies on geology, geophysics, biology and planetary exploration of significant interest and impact in both pure and applied science. Several investigations have evaluated the effects of low background radiation environments on living organisms. With this purpose, the Canfranc Underground Laboratory (LSC) launched the **Biology Platform** in 2021 Hernández-Antolín et al., joining efforts with other DUL by providing laboratory space for biology experiments. Two identical laboratories have been built (underground and on surface) to replicate biology experiments under the same conditions, with the main difference being the cosmic radiation background. A number of diverse biology experiments are ongoing in LSC, LNGS, SNOLAB, WIPP, and other DULs. DISCOVER22 (DNA Damage and Immune System Cooperation in VEry low Radiation environment 2022) Morciano1 et al. aims at investigating how the low radiation background modulates the Immune System (IS) response *in vitro* and *in vivo* models, linking physical microdosimetric measurements and the corresponding biological radiation responses by using radiation biophysical models. In determining the response of biological systems, the external and underground laboratories must be characterised and equipped to perform radiobiological studies Ampollini et al. aimed at understanding the involvement of the different low linear energy transfer components.

An emphasis on outreach and education is addressed in underground labs to inspire learning across generations. To achieve this mission, SURF Horn and Woodward operates an open-to-the-public visitor centre, hosts multiple public outreach events per month and an annual city-wide science festival, trains science educators, develops school curriculum units, and provides classroom materials, based on science researched at the laboratory. The strategic approach, specific methods, and successful outcomes of these programs may serve as examples for effective science education, public outreach, and community engagement. Underground laboratories are working on many different fronts to improve **Equity, Diversity, and Inclusion** (EDI) in their host countries and within particle physics collaborations. Laboratories can institute in their teams and also encourage the scientific collaborations they host to have policies and plans for increasing

EDI. North American underground laboratories Caden et al., SNOLAB and SURF, are each supporting their employees and user-bases in targeted outreach, consultation with experimental collaborations on their own policies, EDI training, and Indigenous cultural recognition.

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