Deeper understanding at Lab 2: the new experimental hall at Callio Lab underground centre for science and R & D in the Pyhäsalmi Mine, Finland

Master’s thesis

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Contents

1 Introduction ................................................................. 5
  1.1 History ................................................................. 5
  1.2 Motivation ............................................................. 6

2 Deep underground physics laboratories (DULs) ....................... 9
  2.1 Why to go deep? ......................................................... 9
  2.2 Deep (>2 000 m.w.e.) underground laboratories ................ 10
  2.3 Callio Lab (CLAB), Finland ........................................ 15

3 Background sources for underground laboratories .................. 21
  3.1 High-energy cosmic muons ........................................... 21
    3.1.1 Muon Depth-Intensity-Relation (DIR) ....................... 21
    3.1.2 Methods to reduce muon background ......................... 23
  3.2 Neutron background .................................................. 23
    3.2.1 Neutrons from local radioactivity ......................... 24
    3.2.2 Cosmic ray muon induced neutron background ............ 24
    3.2.3 Reduction on neutron background ............................ 25
  3.3 Neutrino background ................................................ 26
    3.3.1 Neutrinos interfering with experiments ................... 28
  3.4 Radioactive impurities ............................................ 29
    3.4.1 Radioactivity .................................................. 30
    3.4.2 Radioactive decay law ...................................... 31
    3.4.3 Alpha decay .................................................. 32
    3.4.4 Beta decay .................................................. 34
  3.5 Problematic radon .................................................. 34

4 Radon ................................................................. 39
  4.1 History ............................................................... 39
  4.2 Properties of radon ................................................ 39
  4.3 Radon transport mechanisms ...................................... 40
  4.4 Radon contamination ............................................. 41
  4.5 Radon mitigation .................................................. 42
5 About activated carbon-based radon removal systems 43
  5.1 Adsorption of radon with activated carbon 43
      5.1.1 Principles of adsorption 43
  5.2 Activated carbon as adsorbent 44
  5.3 Radon removal systems 45
      5.3.1 How to design a radon trap? 47
      5.3.2 Examples of radon traps used in some of the DULs 51
6 Radon and radon mitigation in the CLAB Lab 2 57
  6.1 Current situation 57
  6.2 Options for radon mitigation in the Lab 2 57
      6.2.1 Separating the experiments from the atmospheric impurities 57
      6.2.2 Changing the air intake from the elevator shaft to fresh air shaft 59
  6.3 A radon trap for the Lab 2 60
7 Results and discussion 63
1 Introduction

In the present work Callio Lab, an underground centre for science and R & D in the Pyhäsalmi Mine, Finland, and the new underground measurement hall, Lab 2, are introduced. The world’s deep underground laboratories (DULs), including Callio Lab as one of them, are presented. The main sources of the background radiation for underground laboratories are introduced including their effects to specific low background research topics. As a case study the required steps for the concretisation of a deep underground measuring hall and the methods to reduce the radiative background in Lab 2, especially related to radon, are described.

1.1 History

Callio Lab (CLAB) was established in 2015 to market and promote the available underground spaces in the Pyhäsalmi Mine for many purposes such as scientific research and commercial use. Pyhäsalmi Mine is 1.4 km deep base metal mine located in Pyhäjärvi, Finland. The mine has more than 250 km of tunnels and various size caverns (see Fig. 1).

The history of Pyhäsalmi mine started already in 1958 when a local farmer found a piece of ore while digging a well. Mining started in 1962 as an open pit and soon continued as underground mining. The known ore body went down to the depth of one kilometre. During the middle of 1990’s it was realised that the mine would close down at the end of the decade. Therefore the local community started looking for new usage and new users for the mine – the Centre for Underground Physics in Pyhäsalmi (CUPP) was established.

First (geo)physics experiments were conducted already in the end 1990’s and the first long term experiment Muons UnderGround, MUG, started in 2000. A new ore body was found beneath the old one and the new mine started operating in the beginning of 2000 thus providing future for the science as well. The MUG experiment was followed by the design of the Experiment with MultiMuon Array, EMMA, in 2003. EMMA consists now of 11 detector stations (15 m² each) located at the depths of 45 (two satellite) and 75 (nine detector stations) metres. During 2004 the muon fluxes were measured throughout the mine using a movable underground detector, MUD.

During the two LAGUNA (LAGUNA 2003 - 2007 and LAGUNA - LBNO 2007 -
2013) design studies seven European underground sites, Pyhäslami Mine being one of them, were investigated to host future large scale underground detectors [6, 7]. More in depth information of the constructability of the Pyhäslami bed rock was gathered with extensive site investigations by means of underground drilling and analysis (mechanical and chemical) of borehole samples. The site investigation was funded by the town of Pyhäjärvi, Pyhäslami Mine and the European Regional Development Fund (ERDF) from European Union. From the results of the design studies and the site investigations it is known that the good quality of the bed rock and the infrastructure of Pyhäslami Mine makes it possible to host large scale (tens, even hundreds of kilotons) detector installations [8].

The above results made it possible to start the planning and construction of a new deep underground measuring hall at the depth of 1 430 metres (approx. 4 000 m.w.e.) - CLAB Lab 2. The C14 experiment [9] is the first experiment to use the new hall.

1.2 Motivation

Particle accelerators and colliders, like LHC in Cern, are producing various scientific results from the early stages of the Universe (behaviour of the quark-gluon plasma produced in heavy ion collisions) to finding the new particles, like the Higgs boson in 2012. Through the high energy, high intensity interactions it is possible to get the statistics needed for scientific conclusions. But when studying extremely low rate, energetic phenomena, like proton decay or double beta decay, or when studying extremely rarely interacting particles like neutrinos or dark matter candidates, deep underground detectors are needed. Underground physics laboratories provide the necessary low background environment to study these processes.

Centre for Underground Physics in Pyhäslami (CUPP) has used the mine infrastructure for experiments since 2003. The experiments have been and are located in old tunnels and rooms not used by the mine any more. These places required separate housing for the detector setups varying from a weather proof box, to roofed trailer and finally to dedicated detector stations to protect the experiments from the mine environment. The aim of the Callio Lab is to offer underground facilities and spaces for different types of users, such as physicists and biologists. An example case of how to transform an existing tunnel end into deep underground measuring hall was needed. A mine exploration tunnel at the depth of 1 430 m was chosen for the transformation. The massive rock over-burden, approximately 4 000 m.w.e., makes the chosen location ideal
The underground sites including the deep underground laboratories have to find ways to reduce the presence of radon (especially the $^{222}\text{Rn}$). The gaseous form and the relatively long half-life (3.8 days) of the $^{222}\text{Rn}$ allow the radioactive gas to advance long distances and find its way to every detector system [10]. What makes the radon even more problematic is that its decay products are also radioactive producing gamma rays and alpha particles in the range of several MeV (an electron volt $\sim 1.6 \times 10^{-19}$ J).

Radon is exceptionally crucial (even for everyday life, radon accumulation in dwellings and work places) in Finland where the bed rock is mostly granite thus containing uranium [11] – the father of radon so to speak.
2 Deep underground physics laboratories (DULs)

2.1 Why to go deep?

The highest energy particle accelerated by the mankind can reach energies up to several TeV. However, the highest energies measured for the cosmic rays have been above $10^{19}$ eV, several orders of magnitude higher than those produced by the mankind [12]. When the high energy cosmic rays (above $10^{15} - 10^{20}$ eV) interact with the Earth’s atmosphere, new particles emerge from the interactions producing eventually high energy muons ($\sim$200 times the mass of electron, half-live of 2.2 $\mu$s, travelling almost at the speed of light). These high energy, luminous muons interact with the matter only through weak and electromagnetic forces. These characteristics enable the muon pass through substantial depths of matter (expressed in g/cm$^2$, the vertical thickness of atmosphere is approx. 1 000 g/cm$^2$ equals to muon energy loss of 2 GeV [13]). Natural background sources, such as gamma, alpha, beta and neutron radiation from building and detector materials, can be suppressed with proper shielding materials. However, for the high energy muons the only way to reduce the background is to locate the experiments deep underground thus increasing the depth of matter. [14, 15].

Low background environments are needed for the experiments studying rare phenomena, like the interactions of neutrinos or of the dark matter. For extremely low rate interactions the deep underground laboratories (DUL) provide surroundings where the flux of easily penetrating high energy muons is close to zero. The rock-overburden, in astroparticle physics presented in metres of water equivalent (m.w.e.), acts as a barrier for the high energy particles. The over-burden can also be considered as a calorimeter (e.g. the rock-overburden (210 m.w.e.) of EMMA-experiment causes an energy cut-off of 45 GeV for vertical high energy muons [4]).

In addition to physics research DULs offer research possibilities to other fields as well [1]. Geologists and geophysicists benefit from the access to already large depths enabling the study of deep rock mechanics and transformations. Chemists and biologists make the most of the possibility to study chemistry of and the biological agents living in the underground rock and water deposits, research that has already been done in the Pyhäsalmi Mine [16]. Underground facilities can also be valued by the field of
food production in form of steady conditions for growing and storage environments. Underground facilities offer secure sites for future data centres and test areas for different fields of material development such as development of corrosive resistant coatings for metals. [17].

Deep underground laboratories are either built within existing underground facilities like mines (e.g. Callio Lab in the Pyhäsalmi Mine, CLAB, Finland [1]) or they are built during the construction of underground civil engineering works like construction of highway tunnels (e.g. Laboratori Subterrano Canfranc, LSC, in Spain [14]). Taking advantage of existing access tunnels or excavation equipment at the site, the building cost can be kept reasonably low. There are only a few exceptions that only the underground laboratory has been built alone without any accompanying civil engineering works (e.g. Baksan Neutrino Observatory, BNO, Russia [18]).

The DULs built inside mountains have horizontal access to the facilities thus making it possible to transport the materials and detector components using normal vehicles. Horizontally accessible facilities require less rock excavations, which lower building costs, in relation to the desired rock-overburden compared to vertical access facilities. However, in the horizontal access DULs the rock-overburden depends on the shape of the mountain. DULs with vertical access are usually build into closed or still active mines or other types of infrastructures already reaching required depths. In these facilities the rock-overburden is depth dependent. The deepest vertical access underground laboratories have overburden in terms of metres of water equivalent of more than 6 000 m.w.e. like SNOlab in Canada and China Jinping UnderGround Laboratory (6 720 m.w.e being the deepest located laboratory in the world). [15, 19].

2.2 Deep (>2 000 m.w.e.) underground laboratories

In the following review of currently operational deep underground laboratories with rock-overburden of more than 2 000 m.w.e are presented (see Fig. 2 for their locations on the world map). The physical characteristics of selected DULs are presented in the Table 1 on page 19.

Baksan Neutrino Observatory (BNO), Russia

The first deep underground measurements date back to the 1960s when empty cavities of mines were used for neutrino experiments. The most famous of them is R. Davis’
experiment with solar neutrinos. However, a hall in a mine is not a laboratory, as stated by A. Bettini in Ref. [15]. The building of the first dedicated deep underground laboratory, the Baksan Neutrino Observatory (BNO) under the mount Andyrchi in the Russian Caucasus, began in 1967. The first experiment began only in 1973 which was a ground-based detection facility Carpet. [15, 18].

The BNO consists of several underground measurement halls and dedicated low-background laboratories. In addition, underground facilities there are surface detector arrays situated at the mountain slopes. Housing and supporting services for the DUL are provided in the village named Neutrino. The laboratory is operated by the Institute of Nuclear Research (INR) of the Russian Academy of Sciences. [15, 18].

**Boulby Underground Science Facility (BUL), United Kingdom**

The Boulby underground laboratory (BUL) is located 1,100 m (2,800 m.w.e.) below the ground in the Boulby Mine in UK. The Boulby is active potash, polyhalite and rock-salt mine operated by Cleveland Potash Ltd. [19].

Surrounding rock-salt is naturally low in background radioactivity which make the site ideal for ultra-low background and deep underground science projects. The total underground laboratory floor space is 1,500 m² including the Palmer laboratory which has more than 750 m² of clean-room floor space with air filtration and conditioning, craning facilities and telecom access. The mine operators at site provide additional essential support facilities such as cavern reinforcing [19].
Ongoing studies at Boulby range from dark matter search (currently DRIFT-II), cosmic ray research to life in extreme environments and development of techniques for deep 3D geological monitoring. The Boulby Underground Science Facility is funded by the UK’s Science and Technology Facilities Council (STFC) and operates in close partnership with the Boulby mine operating company Cleveland Potash Limited [19, 20].

**Laboratori Nazionali del Gran Sasso (LNGS), Italy**

Laboratori Nazionali del Gran Sasso (LNGS) is located 1 400 m beneath the rock under the Gran Sasso mountain in Italy along the 10-kilometre long highway tunnel. The underground complex consists of three large experimental halls, each 100 m × 20 m × 18 m (h), and bypass tunnels thus making it the largest in the world [21].

Surrounding rock (dolomite calcreous rock) contains very small amounts of uranium and thorium thus keeping the neutron flux in the underground halls about thousand times less than on the surface. Low muon flux together with low neutron flux makes LNGS ideal for low background experiments. Besides being the largest operational facility in the world LNGS is also serving large and the most international scientific community in the fields of neutrino physics (e.g. Borexino), dark matter and nuclear astrophysics [21].

The LNGS is funded by the National Institute for Nuclear Physics (INFN), the Italian Institution in charge of coordinating and supporting research in elementary particle physics, nuclear and sub nuclear physics [21].

**Laboratorio Subterraneo de Canfranc (LSC), Spain**

The Laboratorio Subterraneo de Canfranc (LSC) is located under the Pyrenees Mountains in Spain. The first underground facility was built in the 1980s nearby to a dismissed railway tunnel. Building a new laboratory space became possible when a highway tunnel between Spain and France was planned. The laboratory consists of two halls, a low background counting room and workshops for the users [14].

Current experiments are related to fields of dark matter (e.g. ArDM), neutrino physics and geodynamics. LSC is managed by a consortium between the Spanish Ministry for Education and Science, the Government of Aragon and the University of Saragossa [14].
**China JinPing Underground Laboratory (CJPL), China**

The China JinPing Underground Laboratory (CJPL) is located under a 2 400 m rock-overburden (6 720 m.w.e.) in Sichuan province, China. The laboratory is the deepest in the world and yet it has a horizontal access, which allows the transportation of equipment by trucks. Laboratory facilities were built together with the construction of the Jinping-II Dam hydroelectric power plant. The first phase, CJPL I, was officially opened in 2010 and it consisted of a single 42 m × 6 m × 6 m (h) hall. The following expansion, CJPL II, consisted of four large experimental halls 130 m × 14 m × 14 m (h), will make it larger than the LNGS, but LNGS is designed as a laboratory making it more suitable for hosting experiments. [22].

The marble bed rock has low level of uranium and thorium making it an ideal site for low background measurements. CJPL also has a low background facility using high purity germanium detector. Current experiments are related to dark matter research (e.g. China Dark Matter Experiment, CDEX). CJPL is operated by Center for High Energy Physics, Tsinghua University. [22].

**Kamioka Observatory, Japan**

Kamioka observatory is located in Japan under the Mount Ikenoyama with maximum rock-overburden of 1 000 m (2 700 m.w.e.). The observatory was established in 1983 to host the Kamiokande experiment. The current observatory was established in 1995 after finishing the excavations for the Super-Kamiokande project. The observatory has a horizontal access enabling transportation of equipment by trucks. [21].

Kamioka observatory hosts experiments related to neutrino physics (e.g. Super-Kamiokande), dark matter research and gravitational wave measurements. The observatory belongs to the Institute for Cosmic Ray Research (ICRR). [21].

**Laboratoire Souterrain de Modane (LSM), France**

The Modane Underground Laboratory (LSM) is located 4 800 m.w.e below the Fréjus mountain the middle of the Fréjus road tunnel between France and Italy. It has shared access through the highway tunnel. The LSM is currently the deepest DUL in Europe [23].

All the surfaces of the laboratory were covered with low U/Th content concrete.
This together high air renewal rate allowed the radon level to drop down to 5-15 Bq/m$^3$. With additional radon removal facility the radon level of the air supplied to the experiments has been suppressed even further (10 mBq/m$^3$). The LSM activities are in the fields of neutrino physics, dark matter -search (e.g. EDELWEISS) and low radioactivity measurements. The LSM is jointly operated by the Centre National de la Recherche Scientifique (CNRS) and the Commissariat á l’Energie Atomique et aux Energies alternatives and in partnership with University of Savoie. [23].

Sanford Underground Research Facility (SURF), United States

The Sanford Underground Research Facility (SURF) is located at the former Homestake Gold mine, in South Dakota in the United States. The Homestake Gold mine is not an operational mine enabling the total control of the working environment. The mine is famous for the solar neutrino experiment conducted by R. Davis. Current laboratory modules are located at the depth of 4 200 m.w.e. [24].

SURF is managed for the US Department of Energy by the Lawrence Berkeley National Laboratory. The South Dakota Science and Technology Authority owns and operates the facility. [24].

SNOLab, Canada

The SNOLab is located under a 2 000-meter rock-overburden in the Vale Inco Creighton Mine in Canada. The current experiment hall is an extension to the hall done for the SNO experiment. Current research topics includes neutrino physics (e.g. SNO+) and search for dark matter and neutrinoless $\beta\beta$ decay. [25].

Oversight and governance of the SNOLAB facility and the operational management is performed through the SNOLAB Institute Board of Directors, whose member institutions are Carleton University, Laurentian University, Queens University, University of Alberta and the Université de Montréal [25].

Soudan Underground Laboratory (SUL), Soudan mine, the United States

The Soudan Underground Laboratory is located in the Soudan underground mine State Park and it is run by University of Minnesota (USA) [21]. The depth of the mine is 713.5 m.
The first scientific activity started in 1980 with Soudan 1 studying proton decay. There are two major experiments in the Soudan Underground Lab: the MINOS studying the long-baseline neutrino oscillations and CDMS II studying dark matter by looking for signals from Weakly Interacting Massive Particles (WIMPS). The laboratory also has a low background counting facility (LBCF). [21].

2.3 Callio Lab (CLAB), Finland

Callio Lab is located in the Pyhäsalmi Mine, Pyhäjärvi, Finland. The mine is the oldest still operating mine in Finland with a depth of 1444 m (bottom of elevator shaft). The mine produces zinc, copper and pyrite and it is currently owned by Canadian First Quantum Minerals Ltd.

Scientific work and mining have coexisted since the opening of the new mine reaching from 1000 down to 1420 meters below the surface. As the new mine is located below the old one all the supporting infrastructure, like the inclined tunnel, is still maintained. The old service halls and tunnels, which are not used for mining nor any mining supporting activities, have been given and are still giving locations for scientific experiments in many fields of science like particle physics, geophysics, geology and chemistry. The oldest still running experiment is the cosmic ray experiment EMMA at the depth of 75 m (210 m.w.e.) [4]. It is the first large scale experiment in the Pyhäsalmi Mine and therefore the cavern has been renamed as Lab 1.

The new mine was built the new main level was built below the ore body at the depth of 1420 m. The main level can be accessed by a lift just in three minutes or by a car through the inclined tunnel in 30 minutes. Access to the mine is allowed between 6 am and 10 pm. Working during weekends is possible with special permit. The main level hosts maintenance halls for mining equipment, storages facilities, electrical workshop, offices, a restaurant and a sauna. [17].

Within a walking distance from the lift at the depth of 1430 m (4000 m.w.e.) is located the newly build deep underground experimental hall Lab 2. The Lab 2 is built into an existing tunnel used previously for ore exploration. The actual experimental hall has a floor area of 120 m² with max. height of nine meters. The entrance hall is similar in size. The entrance and the experimental halls are separated from each other, and from the mine, by blast doors made from pulver painted steel (see Fig. 4). The entrance hall is used for loading and unloading of equipment from the trucks, thus reducing the amount of dust and dirt from entering the experimental hall. For handling heavier (> 20
kg) equipment there are currently no cranes but fortifications for installing e.g. boom cranes were done during casting the concrete in both, the entrance and the experimental, halls. Currently lifting of any larger components is done by using the machinery of a local subcontractor operating in the mine. [28].

Two types of concrete have been used in the transition of the space from ore exploring tunnel into measuring hall. The hall walls and the roof had already been sprayed with 5 cm thick layer of iron fiber reinforced shotcrete. From safety point of view, the shotcrete was, and still is, in good condition. From the low background point of view the shotcrete used was not optimal due to relatively high activity of the additive of the cement ($^{40}$K 140 Bq/kg, $^{226}$Ra 160 Bq/kg, $^{232}$Th 240 Bq/kg). The floor slabs for both the experimental hall and for the entrance hall were made from relatively low active acid proof concrete. As the ore contains pyrite (sulphur) the general environment is acid. The main emphasis was put on the floor because the C14 experiment is placed on the floor. The sufficient shielding from the radioactivity from the surrounding materials can be achieved through materials like lead, copper and paraffin.

Electric mains for the Lab 2 can provide up to 160 kVA of power and that can even be increased. For the experimental hall there is currently available 25 kVA from which 3 kVA is filtered and backed-up by an online-ups setup. For safety and for general
Fig 4. A 3D model of the built CLAB Lab 2. The experimental hall has floor area of 120 m² with max. height of 9 meters. The entrance hall is similar in floor area. Model by author.

Communications, between the operators underground and on the surface, there is a two-way radio in use. Connectivity for the experimental hall is provided through an optical 1 GBLan. Current connection to the internet is through 100 MB connection, but increasing it to one or several GB connection is possible. Discussion for joining the FUNET (Finnish University and Research Network) has been established, as it would also give direct access to supercomputers at CSC facilities in Finland (CSC - IT Center for Science Ltd. is a non-profit, state-owned company administered by the Ministry of Education and Culture). [28].

The air flux to the whole mine is 130 m³/s. The air is blown to the main level of the mine. A separate air line from the bottom of the pitch shaft to the experimental hall has been built. Secondary fans provide an air flux of 10 m³/s prior to air filtration unit. The air filtration is located in the entrance hall for the convenience of maintaining. Air is filtered through double phase filter package to meet the Euro-3 level air purity for the air entering the experimental hall. This corresponds to a normal office air quality. After the filtering the air is finally guided to the end of the laboratory hall from where it will be blown towards the entrance doors. This way the air flow will be natural and no air
barriers are formed. The experimental hall has higher pressure than the entrance hall and the entrance hall will have higher pressure than the nominal air pressure at that depth. This way the air flow will keep the mine air from entering the halls thus providing a natural barrier for impurities. [28].
Table 1. Summary of physical characteristics of the selected deep underground laboratories.  
Data collected from Ref. [2, 22, 26, 27]

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Surface and access</th>
<th>Depth [m.w.e.]</th>
<th>Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNO</td>
<td>Andyrchi, Russia</td>
<td>Mountain; horizontal tunnel</td>
<td>4 700</td>
<td>Norite rock</td>
</tr>
<tr>
<td>BUL</td>
<td>Boulby mine, United Kingdom</td>
<td>Flat; vertical tunnel</td>
<td>2 800</td>
<td>Salt</td>
</tr>
<tr>
<td>CJPL</td>
<td>China</td>
<td>Mountain, horizontal tunnel</td>
<td>6 800</td>
<td>Volcanogenic massive sulfide ore body with pyrite and zinc ore</td>
</tr>
<tr>
<td>CLAB</td>
<td>Pyhäsalmi Mine, Finland</td>
<td>Flat, vertical tunnel</td>
<td>4 000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kamioka</td>
<td>Japan</td>
<td>Mountain, horizontal tunnel</td>
<td>2 700</td>
<td>Lead and zinc ore</td>
</tr>
<tr>
<td>LNGS</td>
<td>Gran Sasso, Italy</td>
<td>Mountain, horizontal tunnel</td>
<td>3 200</td>
<td>CaCO₃ and MgCO₃</td>
</tr>
<tr>
<td>LSC</td>
<td>Canfranc, Spain</td>
<td>Mountain, horizontal tunnel</td>
<td>2 400</td>
<td>Limestone</td>
</tr>
<tr>
<td>LSM</td>
<td>Modane, France</td>
<td>Mountain, horizontal tunnel</td>
<td>4 800</td>
<td>Calcitic schists</td>
</tr>
<tr>
<td>SNOLAB</td>
<td>Creighton mine, Canada</td>
<td>Flat, vertical</td>
<td>6 000</td>
<td>Norite, Granite gabbro</td>
</tr>
<tr>
<td>SUL</td>
<td>Soudan mine, United States</td>
<td>Flat, vertical</td>
<td>2 000</td>
<td>Salt</td>
</tr>
<tr>
<td>SURF</td>
<td>Homestake mine, United States</td>
<td>Flat, vertical</td>
<td>4 400</td>
<td>Metasedimentary</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(7 000)</td>
<td></td>
</tr>
</tbody>
</table>
3 Background sources for underground laboratories

During the past centuries experiments performed in world’s underground laboratories have produced some of the most significant new results in the physics. In order to observe rarer phenomena the detectors have to become more and more sensitive. The biggest challenge is the radioactive background, which is produced in the surrounding rock. Thus making every DUL unique from the background characteristics point of view [29]. The unique nature of the DULs means that some of the experiments are more feasible in one location compared to another. The background characteristics of previously introduced DULs are presented in the Table 3 on page 37.

3.1 High-energy cosmic muons

3.1.1 Muon Depth-Intensity-Relation (DIR)

Only muons and neutrinos are able to penetrate to significant depth (< 2 000 m.w.e.) underground. Muons produce tertiary fluxes of photons, electrons and hadrons [30]. Muon energy losses are usually divided into continuous and discrete processes. The former is due to ionisation, which depends weakly on muon energy and can be considered nearly constant for relativistic particles. For muons reaching large depths, discrete energy losses become important: bremsstrahlung (br), direct electron-positron pair production (pair) and electromagnetic interaction with nuclei (photo production, ph). In these radiative processes the energy is lost in bursts along the muon path. The mean stopping power for high-energy muons in matter can be described as

\[
\frac{dE}{dx} = -\alpha - \beta E, \quad (1)
\]

processes \( \beta_{\text{br}} + \beta_{\text{pair}} + \beta_{\text{ph}} \) [31]. The thickness dx is commonly given in units of metres of water equivalent (1 m.w.e. = 102 g cm\(^{-2}\)). The factors \( \alpha \) and \( \beta \) in Eq. (1) are slightly energy dependent as well as dependent upon the chemical composition of the medium: in particular \( \alpha \propto Z/A \) and \( \beta \propto Z^2/A \). Typical values are for \( \alpha \approx 2 \text{ MeV g}^{-1} \text{ cm}^2 \) and for \( \beta \approx 4 \times 10^{-6} \text{ g}^{-1} \text{ cm}^2 \) [31].

For muons travelling in the standard rock density \( \rho = 2.65 \text{ g cm}^{-3} \), atomic mass \( A = 22 \) and charge \( Z = 11 \) the quantity \( \varepsilon \equiv \alpha / \beta \approx 500 \text{ GeV} \) defines the critical energy.
below which the continuous ionisation is the dominant energy loss process. After that
the contributions of direct bremsstrahlung, pair production, and nuclear reactions take
over from ionization losses. A rule of thumb is that the net flux of muons underground
decreases by an order of magnitude for every 1 500 m.w.e., or about 500 m of standard
rock [30, 31].

Groom et al. proposed a model [13] to fit the experimental data to a Depth-Intensity-
Relation (DIR), appropriate for the range (1 - 10 km.w.e.):

\[ I(h) = (I_1 e^{-h/\lambda_1} + I_2 e^{-h/\lambda_2}), \]

(2)

where \( I(h) \) is the differential muon intensity corresponding to the slant-depth, \( h \) [32].
Parameters for the equation have been determined in [32] as following: \( I_1 = (8.60 \pm 0.53) \times 10^{-6} \text{ sec}^{-1} \text{cm}^{-2} \text{sr}^{-1} \), \( I_2 = (0.44 \pm 0.06) \times 10^{-6} \text{ sec}^{-1} \text{cm}^{-2} \text{sr}^{-1} \), \( \lambda_1 = 0.45 \pm 0.01 \text{ km.w.e.} \), \( \lambda_2 = 0.87 \pm 0.02 \text{ km.w.e.} \) [32]. For an underground laboratory with flat
overburden it is straightforward to calculate the total muon intensity arriving below the
surface at a vertical depth, \( h_0 \). In the flat earth approximation, the through-going muon
intensity \( (I_{th}) \) for a specific slant-depth, \( h \), in the direction of zenith angle, \( \theta \), reads [32]:

\[ I(I_{th}, \theta) = I(h)G(h, \theta), \]

(3)

where \( G(h, \theta) = \sec(\theta), h = h_0 \sec(\theta) \), and \( I(h) \) is the DIR expressed in Eq. (2). Equation
(3) now becomes

\[ I(I_{th}, \theta) = (I_1 e^{-h_0 \sec(\theta)/\lambda_1}) + I_2 e^{(h_0 \sec(\theta)/\lambda_2)} \sec(\theta). \]

(4)

Integration over the upper hemisphere using Eq. (4) then provides the total muon
intensity for an underground site with flat overburden positioned at a vertical depth \( h_0 \)
[32]. Using the free parameters and applying muon flux data of sites with flat overburden,
a fit-function have been defined by Mei and Hime [32] which is similar to the muon
intensity function

\[ I_\mu(h_0) = 67.97 \times 10^{-6} e^{-h_0/0.285} + 2.071 \times 10^{-6} e^{-h_0/0.698}, \]

(5)

where \( h_0 \) is the vertical depth in km.w.e. and \( I_\mu(h_0) \) is in units of \( \text{cm}^{-2} \text{ s}^{-1} \), appropriate
in the flat-earth approximation [32].

Using the depth of CLAB Lab 2 (4 000 m.w.e) as \( h_0 \) the above equation would give
\( 6.775 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \) which is approximately 50% of the flux measured by the MUD
experiment in 2004 (\( 6.775 \times 10^{-5} \text{ m}^2 \text{ s}^{-1} \) vs. \( 1.1 \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \) [5]).
3.1.2 Methods to reduce muon background

The overburden is often important feature in experiments focused on measuring low-energy events: penetrating muons themselves can often be vetoed by turning off the detector after a muon is detected. In Kamiokande, for example, had about a 10% dead time due to this technique for background suppression [14]. But muons, in addition to producing prompt secondaries, like knock-out neutrons, can also activate nuclei in the detector that, sometime later, decay to produce a signal. In the case where there is a long delay before the induced activity is detected, conventional vetoing techniques can lead to an unacceptable dead time. In such case there is no alternative but a large depth to remove the initiating muon events. Laboratories build inside the mountains the muon flux is strongly affected by the angular dependence caused by the profile of mountain. In both cases the muon flux has to be measured to provide the input to the background simulations needed by the most sensitive experiments. The flux is time dependent with the seasonal variations of several percent [14, 29].

3.2 Neutron background

The neutron background in deep underground laboratories arises from two sources: local radioactivity (up to 10 MeV) and cosmic-ray induced electrons (up to few GeV). This huge range of neutron energies causes extremely challenging backgrounds to sensitive rare event searches. In dark matter experiments looking for direct interactions of WIMPs (Weakly Interacting Massive Particles), neutron background is critical because elastic interactions of fast neutrons give the very same signature as the signal, namely the WIMP elastic scattering off a nucleus. For double-beta decay experiments the high-energy neutrons (about a few MeV and above) produce background gamma-rays via inelastic scattering while thermal neutrons contribute to the gamma-ray background via neutron capture accompanied by (prompt or delayed) gamma-ray emission. Neutrons at MeV energies and above also mimic neutrino detection in scintillators via inverse beta decay posing a severe threat to low-energy neutrino experiments (reactor and geoneutrinos). Neutrons at sub-GeV and GeV energies contribute to the background for proton decay and atmospheric neutrino experiments. [20, 33].
### 3.2.1 Neutrons from local radioactivity

Neutron flux through local natural radioactivity, in the surrounding rock and in the detector materials used, is produced by spontaneous fission of \(^{238}\text{U},^{235}\text{U}\) and \(^{232}\text{Th}\). The most important source of neutrons is the \(^{238}\text{U}\), because of the long fission half-life of the other two nuclides compared to that of \(^{238}\text{U}\). Second production way is the \((\alpha,n)\) initiated by \(\alpha\)-particles \((E_\alpha < 10\text{ MeV})\) from natural \(\alpha\)-emitters interacting with light target nuclei. For heavy nuclei the \((\alpha,n)\) cross section is suppressed by the Coulomb barrier. The neutron energies from decay of \(^{238}\text{U}\) series nuclides range from thermal to several MeV and are consequently not difficult to shield. [14, 29, 33].

The spectrum of the emitted neutrons follows the Watt spectrum [34]:

\[
N(E) = C \frac{E}{\sinh(bE)}
\]  

(6)

The parameters \(a\) and \(b\) for the Watt spectrum are from the Los Alamos model as stated in the reference [34], where \(a = 0.7124\text{ MeV}\) and \(b = 5.6405\text{ MeV}^{-1}\). The rate of spontaneous fission of \(^{238}\text{U}\) is 0.218/year/g of rock (concrete) for 1 ppm of \(^{238}\text{U}\) and the average number of neutrons emitted per fission event is 2.4 ± 0.2 [34]. This gives 0.52 neutrons/year/g of rock (concrete)/ppm \(^{238}\text{U}\) [34].

In the Callio Lab in the Pyhäsalmi Mine the average uranium and thorium contents are 0.8 ppm and 3.2 ppm respectively. Based on the model in reference [34] the average rate of spontaneous fission of \(^{238}\text{U}\) in the Pyhäsalmi rock would be 0.174/year/g of rock (concrete) and the average number of neutrons emitted in the fissions would be 0.42 neutrons/year/g of rock (concrete) per ppm of \(^{238}\text{U}\). [2, 34].

### 3.2.2 Cosmic ray muon induced neutron background

The muon interactions (muon-induced spallation) in the rock produce energetic neutrons at a depth dependent rate. At depths greater than several tens of meters, the local radioactivity processes dominate the total neutron production rate. However, the neutron spectrum from spallation is significantly harder, extending up to several GeV in neutron energy, demanding thicker shields. Furthermore the high-energy spallation neutron component is in equilibrium with the muon and hadron flux in the rock thus attempting to shield against it will only produce more background at about the same rate as it is removed. [14, 35, 36]
The cosmic ray muons produce neutrons through several different mechanisms from which the muon capture is the most significant [14, 35, 36]. Once a negative muon is low on energy, it can be attracted into the Coulomb field of a nucleus, forming a “muonic atom” bound state. The bound state cascades down to the 1s state, where it will either decay:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

(7)

or else undergo nuclear capture via weak charged-current process:

$$\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z - 1,N + 1).$$

(8)

The number of neutrons from muon capture can be computed from the following expression:

$$N_n(h) = I_\mu(h) \times P_{\mu^-} \times P_c \times P_n;$$

(9)

where $N_n(h)$ is the number of neutron produced by stopped muons at a depth $h$, $I_\mu(h)$ is the flux of negative muons stopping at the given depth, $P_{\mu^-}$ is the relative charge fraction of cosmic ray muons, $P_c$ is the capture probability, and $P_n$ is the neutron multiplicity following the capture [36].

The neutron yield from cosmic-ray muons depends strongly on the depth of the underground laboratory. It is obvious that suppression of the muon flux by a large thickness of rock will also reduce the neutron yield. The dependence, however, is not linear. In general, at a depth of 3 000–4 000 m.w.e., where many of the rare event experiments are located, the flux of neutrons from activity of the experimental environment is two to three orders of magnitudes higher than the flux of neutrons from cosmic ray muons [14, 29, 34, 36, 37].

### 3.2.3 Reduction on neutron background

The neutron production rate due to muons at large depths is, in general, about three orders of magnitude less than that of neutrons arising from local, depending strongly from the depth and U/Th contamination, radioactivity. The neutrons produced by muons going through a detector setup can effectively be tagged-out using an external veto detector surrounding the actual detector setup. The neutrons created in the rock or surrounding detector materials, missing the veto, are more difficult to separate from actual data as these events do not appear in coincidence with the primary muons, due to the hard energy spectrum of neutrons and long propagation range [14, 32].
Hydrogen rich materials are used to slow down neutrons. Hydrogen nucleus contains only a proton and since proton and neutron have almost identical masses, in neutron scattering on a hydrogen nucleus, even the entire kinetic energy of a neutron can be transferred to a proton after one collision. Water, as hydrogen rich material, is commonly used for absorbing thermal neutrons. Hydrogen in form of water has a neutron capture cross-section (probability that a nuclear reaction will occur) of 0.3 barns (a barn is approx. the cross-sectional area of a uranium nucleus, \(10^{-28} \text{ m}^2\)) but the thickness of water can easily and cost effectively be increased. If a high atomic number material is used as a neutron shield, the neutron will just bounce off in elastic collision (the mass of the neutron is approx. the mass of a proton). Therefore lead (Z=82) is quite ineffective for blocking neutron radiation, as neutrons are uncharged and can simply pass through dense materials. In low-background experiments, neutron flux from the rock has to be suppressed by means of dedicated thick shielding (polyethylene, water, etc.). A shielding thickness of about 55–60 g/cm\(^2\) of polyethylene (CH\(_2\)) is sufficient to suppress the external neutron flux by six orders of magnitude. Similar suppression can be achieved by using 45–50 g/cm\(^2\) of CH\(_2\) together with 20–30 cm of lead placed between the rock and CH\(_2\). If the neutron passive shielding is in place, the dominant sources of neutron background from radioactivity are the detector components, giving \(10^{-8}–10^{-10} \text{ neutrons/(cm}^2\text{s)}\). [33].

Thermal neutrons can easily be absorbed by neutron capture in materials with high neutron capture cross-sections like boron, lithium, cadmium or gadolinium. These materials have neutron capture cross sections of thousands of barns (gadolinium 259,000 barns). Therefore, only a thin layer of such absorber is to enough to shield from thermal neutrons. However, if using cadmium, boron or gadolinium the absorption of neutrons is accompanied by emission of gamma radiation thus additional shielding is needed to attenuate gammas [33]. Underground laboratories provide the overburden necessary for experiments sensitive to cosmic-ray muons and their progenies. Qualifications for the location (low U/Th contamination), using hydrogen rich passive shielding and/or adding an active veto rejecting all events associated with passing muons detector can help to reduce the neutron background significantly [14, 32, 37].

### 3.3 Neutrino background

Neutrinos being the hot topic for particle physics research all observations of neutrinos can be considered as wanted signals. Most of the neutrinos around us have been born in
the Sun (solar neutrinos), in the rocks of Earth due to radioactivity (geoneutrinos) and as a by-product of nuclear power (reactor neutrinos). In addition to these large numbers of neutrinos are produced in the cosmic ray induced extensive air showers (atmospheric neutrinos). In some neutrino experiments, neutrinos with different origin can interfere (cause background) with the measurement of neutrinos of another source due to the overlapping energy ranges.

There are three types of neutrinos: electron, muon and tau neutrinos. They interact with matter through gravity and weak nuclear force. They do not interact with the electromagnetic force as they have no electrical charge. In minimal Standard Model (SM) neutrinos are massless; however, experimental results from solar, atmospheric and reactor neutrino experiments proves that neutrinos oscillate. The theory of neutrino oscillations require that neutrinos must have mass. The neutrino energy depends from their source (see Fig. 5. The residual neutrinos dating back to the birth of the Universe have energies down to 10 meV. Geoneutrinos produced by the radioactivity of the Earth ($\beta$ decay) have energies up to 10 keV. Solar neutrinos (produced in the pp fusion and CNO cycles in the Sun) have energies up to one MeV. [38, 39].

The neutrinos from the progeny of cosmic rays and those originating from the Sun have two major differences. The atmospheric neutrinos have energies from tens to many hundreds of times greater than their solar counterparts. Solar neutrinos (like geo- and reactor neutrinos as well) are electron (anti)neutrinos ($\nu_e$) but those atmospheric (anti)neutrinos are predominantly muon neutrinos $\nu_\mu$ [39].

Atmospheric neutrinos are produced through several reactions: first in the interactions of cosmic rays with the atmospheric nuclei pions and kaons are born. As pions (see Eq. 10–13) and a positive charged kaon (see Eq. 14) decay neutrinos are emitted. Through some decay channels of pions and kaons muons are also emitted. When the muons decay (see Eq. 16–17) they produce both muon and electron neutrinos. The main decay channels for pions, kaons and muons are the following [41]:

Pions:

\[
\begin{align*}
\pi^+ &\rightarrow \mu^+ + \nu_\mu \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\
\pi^+ &\rightarrow e^+ + \nu_e \\
\pi^- &\rightarrow e^- + \bar{\nu}_e
\end{align*}
\]
Kaons:

\[ K^\pm \rightarrow \mu^\pm + \nu_\mu \]  \hspace{1cm} (14)

\[ K^\pm \rightarrow \pi^\pm + \pi^0 \]  \hspace{1cm} (15)

Muons:

\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]  \hspace{1cm} (16)

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]  \hspace{1cm} (17)

3.3.1 Neutrinos interfering with experiments

Even the experiments which have not been specifically designed for measuring high-energy neutrinos are exposed to the neutrino background. The neutrino interactions
within the detector can cause various backgrounds:

\[ \bar{\nu}_l + p \rightarrow l^+ + n \] \hspace{1cm} (18)

\[ \bar{\nu}_l + n \rightarrow l^- + p \] \hspace{1cm} (19)

\[ \bar{\nu}_l + N \rightarrow \bar{\nu}_l + N^* \] \hspace{1cm} (20)

where N stands for the target nucleus [36].

However, the rate of neutrino interaction is really small, typically on the order of \( \sim 0.2 \text{ events/ton/year} \) (on \(^{16}\text{O}\)), dominated mainly by the quasielastic nuclear scattering. There is no way to shield from this background [36].

The muonic background caused by the cosmic ray can reach up to the depths of 14 km.w.e. Beyond this the muons observed are produced by the neutrino interactions with matter:

\[ \bar{\nu}_\mu + N \rightarrow \mu + X. \] \hspace{1cm} (21)

where N stands for the target nucleus and X produced progeny [36].

For geoneutrino experiments the biggest source of background are the reactor neutrinos as their energies overlap with the neutrino energies produced by the natural radioactivity (see Fig. 6 on page 30 for reactor neutrino background in Europe). Events (Terrestrial Neutrino Unit (TNU) from the nuclear reactors using load factors of year 2014 are presented in the Table 2. Besides causing a background, the reactor neutrinos can be used to study neutrino-oscillations providing appropriate distance between the reactor and the neutrino detector (in JUNO \( \sim 50 \) km). The constant flow of reactor neutrinos can be also used to monitor the power of the reactor [39, 42]

### 3.4 Radioactive impurities

Radioactive impurities especially within detector setup can cause severe background for the experiments. It is not only the radioactivity of the rock or the cosmic ray muons that contribute to the radioactive background, but also the radioactivity within detector materials, support structures, shielding, electrical connections and even in the air (e.g. radon gas) [36]. These impurities produce alpha, beta, gamma and neutron radiation thus producing false signals in the experiments.
Table 2. Calculated reactor neutrino background in four European deep underground laboratories. The Terrestrial Neutrino Unit (TNU) is defined as one neutrino flux induced event per year per every $10^{32}$ protons. Table data from Ref. [38]. Published with permission.

<table>
<thead>
<tr>
<th>Locations</th>
<th>Events (TNU)</th>
<th>Events w/ 2014 load factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAB</td>
<td>90.7 ± 3.1</td>
<td>72.4 ± 3.1</td>
</tr>
<tr>
<td>LSC</td>
<td>290.2 ± 9.8</td>
<td>222.3 ± 8.4</td>
</tr>
<tr>
<td>LSM</td>
<td>738.3 ± 33.6</td>
<td>550.6 ± 19.5</td>
</tr>
<tr>
<td>BUL</td>
<td>1647 ± 144</td>
<td>1005 ± 119</td>
</tr>
</tbody>
</table>

Fig 6. Sum of the contributions coming from the nuclear reactors of the world. Fig. from Ref. [38]. Published with permission.

3.4.1 Radioactivity

Alpha, beta, gamma and neutron radiations interact with the matter in different ways and they can have different energies. Each type of radiation is capable of removing electrons from the orbit of a nucleus in a process called ionisation. Ionising radiation is detected through the highly reactive ions produced in the interactions. If a nucleus receives
energy, an electron can be moved to an orbit further, but still being bound to, the nucleus, the atom is said to be in an excited state. The atom will decay when the electron returns to the lower orbit. The de-excited energy is emitted as electromagnetic radiation. [10].

If a nucleus can move to lower energy state in which the protons and neutrons are more tightly bound in the nucleus by emitting radiation, it will. Such a nucleus is unstable, radioactive. Stable nuclei are unable to loose energy by emitting radiation as they already are at the lowest possible energy level. Due to the fact that nuclear systems tend to seek stability and because of the nature of nuclear forces, the most likely radiations to be emitted are an alpha particle (two neutrons and two protons - a helium nucleus); an beta particle (an electron or its antiparticle positron); and a type of high energy X-rays called gamma rays [10]. The process of alpha and beta decay leads to the formation of a different element, whereas gamma decay does not. The isotope that decays is called the parent. The resulting isotope, is a different element, is called progeny. [41].

### 3.4.2 Radioactive decay law

The statistical nature of radioactive decay was understood already in the late 19th century by the early researchers of radioactivity: it is impossible to predict when a specific nucleus would disintegrate to form another. This led to the following deduction; if there exists at a certain time t, a number N of radioactive nuclei and no new nuclei are being formed, then the decay (dN) in the sample in a certain time (dt), would be proportional to the total number of nuclei N in the following way:

\[
\frac{dN}{dt} = -\lambda N, \tag{22}
\]

where \( \lambda \) (s\(^{-1}\)) is called the decay constant of a specific radioactive species [41]. The Eq. (22) can be rewritten as

\[
\lambda = -\left(\frac{dN}{dt}\right) / N. \tag{23}
\]

In the Eq. (23) the \( \lambda \) is the probability per unit time for the decay of a nucleus and it is different for every nuclide. The solution of the Eq. (23) is called the exponential law of radioactive decay.

\[
N(t) = N_0 e^{-\lambda t}, \tag{24}
\]
where \( N_0 \) is the number of nuclei present at time \( t=0 \).

The time when half of the nuclei have decayed is called the half-life \((t_{1/2})\) of a species. Often also the mean lifetime \((\tau)\) is used to express the predictions of decay. The relation between half-life and mean lifetime is \((t_{1/2} = \tau \ln 2)\). To get \((t_{1/2})\), \( N = N_0 / 2 \) is substituted in Eq. (24) to give

\[
t_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln (2),
\]

Half-lives vary from fractions of seconds (e.g. \(^{213}\)Po, \(t_{1/2} = 4.2 \times 10^{-6}\) s) to billions of years (e.g. \(^{232}\)Th, \(t_{1/2} = 14.1 \times 10^9\) years).

Activity \((A)\) of a sample is determined by the number of decays within a time unit. The activity is expressed in SI units as Bq (unit is Becquerel, named after Henri Becquerel) and is defined as one disintegration per second [41]

\[
A = \frac{dN}{dt} = \lambda N.
\]

### 3.4.3 Alpha decay

In heavier nuclei (almost exclusively atomic numbers 83 or higher) the proton repulsion (like charges repel each other) within the nuclei makes the nuclei barely stable of even unstable. In order to increase the binding energy per nucleon the nucleus could shed a proton away. But as the nucleus has less mass than the sum of the masses of the particles within it, the shedding cannot take place. This is due to the attractive nuclear forces creating the binding energy between nucleons. If a proton would be ejected, the nucleus would have had to come up with energy to provide the proton its free mass. For the conservation of energy point of view this is not possible. However, if the nucleus ejects two protons tightly bound to two neutrons (an alpha particle) then the shedding of extra protons is possible due to the fact that bound nucleons have less mass than they would have as a free [10, 41].

The reason for the generally long half-lives of alpha decaying heavy nuclei is that there is a delicate balance between the electromagnetic force and the nuclear force. In the classical world alpha particles would not have enough energy to escape the potential barrier created by the strong force inside the nucleus. However, the quantum tunnelling effect allows alphas to escape even though they do not have enough energy (typically in the range of 4–9 MeV) to overcome the nuclear force (typically 6–7 times
the decay energy). Due to the wave nature of matter there is an infinite probability for the alpha particle to be in a region far enough from the nucleus that the potential from the Coulomb repulsion is equal to the attraction of the nuclear force. With enough time an alpha decay will take place. The emission of \( \alpha \) particles in this case is spontaneous and can be stated in the following way:

\[
\frac{AX}{Z} \rightarrow \frac{A-4}{Z-2}Y + \alpha,
\]  

(27)

where \( A \) is the mass number, \( Z \) is the atomic number and \( N \) is the number of neutrons. \( X \) is the decaying parent nucleus and \( Y \) is the final state, and \( \alpha \) is the emitted particle \([10, 41]\).

From the quantum mechanical point of view the \( \alpha \) particle within a nucleus has a wave nature and therefore a wave function to describe its probability to be at specific location at specific time \( t \). Whenever the potential barrier within the \( \alpha \) particle is of a finite size the wave function solution will have its main component inside the potential well (created by the potential barrier), a finite (greater than zero) part inside the barrier and another finite part outside the barrier. The half-life is dependent on two aspects: i) the closer the energy of the \( \alpha \) particle is to the barrier height, the more likely the particle will pass the barrier. ii) The more energetic the \( \alpha \) particle is in relation to the barrier height, the more frequent there will by trials to pass the barrier and therefore the particle is more likely to escape. Given enough trials the \( \alpha \) particle can be found outside the potential barrier and the \( \alpha \) decay has occurred \([41]\).

A simple formula to approximate the half-life for a \( \alpha \) decaying nucleus was created already a century ago by Geiger and Nuttal. They had found a linear proportionality between the logarithm of the decay constant and the logarithm of the range of a \( \alpha \) particles from a given natural radioactive decay series.

\[
\log(t_{1/2}) = A + \frac{B}{Q_{\alpha}},
\]  

(28)

where the constants \( A \) and \( B \) are atomic mass dependent. The equation (28) shows that the half-lives are exponentially dependent on the decay energy thus the energy of the \( \alpha \) particle. Although the \( \alpha \) emitting isotopes have about the same decay energies the difference in half-lives is in orders of magnitudes. Approximately change of one MeV in the \( \alpha \) decay energy results in a change of \( 10^5 \) in the half-life. The Geiger-Nuttal law of \( \alpha \)-decay is good approximation for the half-lives still but it has been replaced by modern experimental representation. \([43]\).
3.4.4 Beta decay

In beta decay an electron ($\beta^-$) or its antiparticle positron ($\beta^+$) is ejected from the nucleus when a neutron is transformed into proton, or vice versa. Through the transformation the nucleus moves closer to the optimal ratio of protons and neutrons. From the general beta decay (see Eq. 29) can be seen that in the beta decay both the atomic number $Z$ and the neutron number $N$ changes. However, the mass number $A$ remains unchanged. The energy spectrum of beta particles is continuous. Beta decay is mediated by the weak force [41].

$$^{\text{A}}ZX_N \rightarrow ^{\text{A}}Z\pm1Y_{N+1} + \beta^\pm$$  \hspace{1cm} (29)

There are three processes for the beta decay to take place:

$$n \rightarrow p + e^- + \bar{\nu}_e \hspace{1cm} (\beta^-) \hspace{1cm} (30)$$

$$p \rightarrow n + e^+ + \nu_e \hspace{1cm} (\beta^+) \hspace{1cm} (31)$$

$$p + e^- \rightarrow n + \nu_e \hspace{1cm} (EC) \hspace{1cm} (32)$$

In the electron capture (EC, Eq. 32) a proton rich nucleus of an electrically neutral atom absorbs an inner atomic electron. In the absorption a nuclear proton converts into a neutron and simultaneously causes the emission of an electron neutrino. The emitted neutrino is mono-energetic. In nuclei where the energy difference between initial and final states is less than $2m_e c^2$, the $\beta^+$ decay is not energetically possible and therefore the electron capture is the sole decay mode [41].

3.5 Problematic radon

For the low background experiments radon as radioactive noble gas, is a major challenge. Radon activity, which is typically 10–20 Bq/m$^3$ in open air, is larger by two orders of magnitude or more in closed underground cavities. Radon and especially its isotope $^{222}$Rn (half-life of 3.823 days) can mitigate long distances and diffuse into any cavity before decaying, leaving its long-lived progeny behind (e.g. $^{210}$Pb, 22.3a; $^{210}$Po, 138 days). (See Fig. 7 for the total decay chain of uranium). These long-lived daughters produce an accumulation of the local background disturbing the measurement for a long time. Radon decays through $\alpha$ decay into isotopes of polonium:
Therefore, for the low background measurements, it is important to reduce the radon not only at the experimental areas but also in facilities leading to the full assembled detector. For comparison the isotopes of radon from the thorium series ($^{222}_{86}\text{Rn}$, 55.6 s) and actinium series ($^{219}_{84}\text{Rn}$, 3.96 s) and their daughter nuclides do not pose similar background accumulation as $^{222}_{86}\text{Rn}$. Due to the comparable shorter half-lives the $^{220}_{86}\text{Rn}$ and $^{219}_{84}\text{Rn}$ isotopes are not able to travel long distances from their birth place resulting that their concentrations rarely increase inside. In addition to the short half-lives of these isotopes of radon also their progenies are short-lived (seconds to minutes) compared to the long-lived progenies of $^{222}_{86}\text{Rn}$ (days to years). Therefore, any contamination from these isotopes will decay away briefly. [44, 45].
Fig 7. Uranium-238 decay chain from Wikipedia under CC-licence.
Table 3. Summary of the unique background characteristics of the selected DULs.

<table>
<thead>
<tr>
<th>Site</th>
<th>Muon flux [μ m⁻² s⁻¹]</th>
<th>Radon [Bq m⁻³]</th>
<th>Neutron flux [10⁻³ m⁻² s⁻¹]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNO</td>
<td>3.03±0.19×10⁻⁵</td>
<td>40</td>
<td>2.2 (1–11 MeV)</td>
<td>[46]</td>
</tr>
<tr>
<td>BUL</td>
<td>4.09±0.15×10⁻⁴</td>
<td>1-5</td>
<td>17.2 (&gt;0.5 MeV)</td>
<td>[47, 48]</td>
</tr>
<tr>
<td>CJPL</td>
<td>2×10⁻⁶</td>
<td>50</td>
<td>4.0 (th)</td>
<td>[22, 49]</td>
</tr>
<tr>
<td>CLAB</td>
<td>1.1±0.1×10⁻⁴</td>
<td>&lt;70</td>
<td></td>
<td>[2, 5, 50]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>660 m:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20.8 (&lt; 1.5 MeV)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>5.6 (1.5–12 MeV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>990 m:</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>37.5 (&lt; 1.5 MeV)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>9.5 (1.5–12 MeV)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>1410 m:</td>
<td></td>
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<td>42.2 (&lt; 1.5 MeV)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>16.8 (1.5–12 MeV)</td>
<td></td>
</tr>
<tr>
<td>Kamioka</td>
<td>3×10⁻³</td>
<td>20-60</td>
<td>82.5 (th)</td>
<td>[51]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>115 (fast)</td>
<td></td>
</tr>
<tr>
<td>LNGS</td>
<td>3×10⁻⁴</td>
<td>50-120</td>
<td>Hall A:</td>
<td>[51, 52]</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3.81 (0–10 MeV)</td>
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</tr>
<tr>
<td>LSC</td>
<td>2.4×10⁻³</td>
<td>50-80</td>
<td>3.44 (0-10 MeV)</td>
<td>[51, 53]</td>
</tr>
<tr>
<td>LSM</td>
<td>5.76×10⁻⁵</td>
<td>15 (0.01 filtered)</td>
<td>19 (th)</td>
<td>[46]</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>11 (&gt; 1 MeV)</td>
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<tr>
<td>SNOLAB</td>
<td>3×10⁻⁶</td>
<td>120</td>
<td>47 (th)</td>
<td>[51, 54]</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>46 (fast)</td>
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<tr>
<td>SUL</td>
<td>2×10⁻³</td>
<td>300–700</td>
<td>0.7 (th)</td>
<td>[55]</td>
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<tr>
<td>SURF</td>
<td>4.4×10⁻⁴</td>
<td>40-200</td>
<td>4100L: 9.9 (th)</td>
<td>[55]</td>
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<td>Davis: 1.7 (th)</td>
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<td>TCR: 8.1 (th)</td>
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4 Radon

4.1 History

Friedrich Dorn was one of the pioneers working, in the turn of the 20th century, with the newly discovered radiation along with Marie and Pierre Curie, Ernest Rutherford and Henri Becquerel to name a few. Dorn established that radium emitted a radioactive gas Niton. William Ramsay and Robert Whytlaw-Gray isolated radon in 1910 and they found that it was the heaviest of the known gases. Radon (still under the name Niton) was accepted as a new element in 1912 by the International Committee for Atomic Weights. It was not until 1923 when the name Radon was accepted officially. [56].

Increased risk for respiratory diseases among miners was reported as early as in the 16th century by Paracelsus. But it was not until the 1950s when the connection between radon and lung diseases was epidemiologically proven. Since then there are set limits for radon levels both for homes and work places. Current limits in Finland are 400 Bq/m$^3$ for work places, including underground sites like mines, and 200 Bq/m$^3$ for new accommodations and buildings. [45, 56].

Radon is not only hazardous for personnel, but it can cause severe background issue to low background experiments. In low background environments physicists and engineers are developing methods to reduce the radon levels from single digit values to down to mBq/m$^3$ or even to $\mu$Bq/m$^3$ ranges.

4.2 Properties of radon

Radon is constantly produced by the decay of radium in the rock and in the soil. There are three naturally occurring radioactive isotopes from the decay chains of uranium-238 ($^{222}$Rn), thorium-232 ($^{220}$Rn) and actinium ($^{219}$Rn). The $^{220}$Rn has the longest half-live (3.8 d) and is therefore the most important radon isotope in terms of radiation exposure. It is measured to determine its contribution to human radiation exposure. It contributes about half (2 mSv) of the annual radiation exposure in Finland of the total annual average dose (4 mSv). [45].

Although radon is a significant contributor to the annual dose the radon isotopes themselves are not dangerous (until the moment they decay), but due to their mobility as gases they act as transport service for their alpha-emitting progenies. The decay
products of radon are solid and most of the electrically charged progenies tend to attach to surfaces and dust particles in the air, but some remain unattached. The unattached ones are predominantly positively charged and are typically found in the 0.5 to 1.5 nm size range. The attached ones will have a size range and state of charge which reflects the characteristics of the aerosol particles to which they have become attached to. The most dangerous radon progenies from the decay energy point of view are $^{218}$Po and $^{214}$Po which are alpha emitters with energies of 6.00 and 7.69 MeV, respectively. [45, 57].

Chemically radon is almost inert (no chemical reactivity under normal conditions), colourless and odourless gas. Besides being transported through the air radon is soluble in water and thus can be transported through ground water streams for long distances in high concentration solutions. However, the solubility of radon decreases with increasing temperature thus causing the radon to be released during water-related activities. [45, 57].

### 4.3 Radon transport mechanisms

Radon is constantly produced by the $\alpha$ decay of radium in the rock, soil and building materials. Radium is usually in balance with uranium thus they both have the same activity concentration. However, due to the difference in solubility of uranium and radium (chemical) compounds there can exist local unbalances in the activity concentrations. During the decay of radium some of the radon atoms are freed from the crystal structure of the rock through recoil into the pores of the rock. This is called radon emanation. After the decay of radium isotopes ($^{226}$Ra and $^{224}$Ra), radon atoms ($^{222}$Rn and $^{220}$Rn) have kinetic energies of 86 and 123 keV. With the kinetic energy the isotopes can reach distances from 0.04 to 0.06 $\mu$m in the granular material and up-to 60 $\mu$m in the pore space [58].

Radon emanation coefficient (dimensionless value) gives an indication of the fraction of the produced radon atoms that leave the material itself. Water in the pores can enhance the radon release from the crystal structures (radon is soluble to the water), but it can also prevent the pore air and thus radon from leaving the pore. In general, the air and the water flow within the pore structure can transport the radon for long distances. Two principal mechanisms are very important for the $^{222}$Rn transportation into air: the diffusion length and the convection flow. The exhalation rate from soil depends on the emanation fraction, the radium activity mass concentration of the material, the density of
the material, the decay constant of the radon isotope and the diffusion length of isotopes in soil; and it is expressed in Bq/m$^{-2}$s$^{-1}$. Only a fraction of radon produced in the rock can reach the pore space and a fraction from that to the free air. Many external factors can influence the diffusivity and through this the rate of exhalation; increasing the atmospheric pressure decreases the rate of exhalation, while increasing the wind speed and temperature can enhance it. In addition, these parameters may forecast convection due to a flow of air in the pore space, and thus changing the radon flow in the soil. Previous studies have shown that the exhalation rate is governed by the diffusion length [58].

### 4.4 Radon contamination

The main source for atmospheric contamination comes from $^{222}$Rn and its progeny. Both the radon and the progeny emitted in the atmosphere are electrically charged thus enabling them to stick on detector surfaces with a relatively high probability to remain fixed. $^{222}$Rn can emanate from materials where there are traces containing traces of $^{238}$U (see Fig.7) for a complete $^{238}$U decay chain). Surface contaminations are taking place during the construction, handling, storing and setting up phases of the detector production and assembly. Surface contaminations can however, be removed by mechanical or chemical treatments, but preventing the surfaces from re-contamination is basically impossible. The detector surfaces will be in contact of air or a gas atmosphere and thus being in contact with radioactive impurities. Therefore, extra care has to be taken into air and gas purities of the post-cleaning facilities and areas. [59].

As an example case for radon contamination imagine building a low background scintillator experiment. All the materials used for the setup are manufactured and stores in atmospheric conditions ($^{222}$Rn in the air). Surfaces of detector materials have now been exposed radon which decays through alpha decay. The $^{218}$Po ions plate out on the surfaces and eventually decay into long-lived $^{210}$Pb (t$_{1/2}$ 20 years). Once the all the detector materials are assembled into a working detector $^{214}$Pb or its daughters on the inner surface of the detector could then wash off into the scintillator. $^{214}$Bi and $^{214}$Po nuclides could also recoil into the scintillator at the time of the decay that produced them. When studying the decays of $^{14}$C (β end-point 0.156 MeV), particular concern is the β-decay of $^{214}$Bi with an end-point of 1.14 MeV. [59, 9].
4.5 Radon mitigation

There are four possible means of reducing radon in the underground air. The simplest way to mitigate radon is to change the air supply from radon-loaded into fresh supply of atmospheric air as it usually has radon levels only of 10-20 Bq/m$^3$. If air and its oxygen is necessity, then using pure synthetic air (compressed or liquid) can be used as the air is storage for several half-lives of radon between packing and delivering to the users. If oxygen is not vital then the detector setups can be purged with ultrapure instrumental gases like nitrogen or argon thus providing a gas sphere preventing the air impregnated with radon from entering. [44].

Second option would be the selection of materials (especially rock and concrete) with low U/Th content (respectively low $^{220}$Rn and $^{222}$Rn content as well). Third option would be blocking the radon entry points. In underground construction radon barriers are used to prevent radon entering the air and it is guided through active measures somewhere else (like depressurizing the barrier zone with suction etc.). Radon barrier materials are usually only millimetres in thickness as the barrier has to be, at least, three radon diffusion lengths thick. Barrier membranes can be made e.g. from polyethylene foils of high, low and very low density (HDPE, LDPE and VLDPE). [14, 44, 60].

Fourth option would be the removal of radon and its decay products. As mentioned in the previous section radon and its progenies can be removed from the surfaces through chemical or mechanical treatment. In deep underground laboratories the radon in the air is the biggest source of contamination. Therefore, different methods have been developed to reduce the radon content in the air thus reducing the number of contaminants in the detector setups. Most common way is to use active carbon filtering in which air is blown through the active carbon bed (or series of beds) and radon gets trapped into the pores of carbon. In “aging” systems the input air flow is passed through a charcoal bed which big enough to retain radon front for a time equal to many half-lives: the radon decays before it can emerge from the column. This kind of system was used in Super-Kamiokande experiment. More on the systems used in the following chapter. [44].
5 About activated carbon-based radon removal systems

Although radon ($^{222}\text{Rn}$) is quite short lived (half-life of 3.8 days), it can as a gas propagate large distance. Its decay products are also radioactive and therefore it is important to prevent radon from entering the wanted radon-free areas. Different techniques from simple aging (letting the radon decay in a buffer tank) to on-line measures using active carbon filters are used to produce radon-reduced air.

5.1 Adsorption of radon with activated carbon

5.1.1 Principles of adsorption

Adsorption takes place when molecules or atoms sorbed are concentrated only at the surface of the solid. In the adsorption particles in the gas phase experience a drop in potential energy associated with their interactions with a solid surface. The adsorption is spontaneous process accompanied by reduction of the surface free energy of the adsorbing surface. Adsorption can take place through a number of chemical and physical interactions, depending on the chemical and physical structure of the atoms adsorbed and of the adsorbent material. This allows the particles to concentrate and stay onto the surface. As the particles leave the gas phase they form a new denser phase (adsorbed phase or sorbate). [61].

If in the adsorption only weak interactions such as Van der Waals or dipole and quadrupolar electrostatic interactions are present, the process is called physical adsorption. In the phenomena gases tend to be adsorbed on a solid if the temperature is sufficiently low (adsorption is an exothermic process) or the gas’ partial pressure is high enough. The efficiency of filtration is determined by the strength of the interactions and the number of active sites available for the interactions to take place between the sorbate and the particles. [62].
5.2 Activated carbon as adsorbent

Radon is a non-polar atom, as is carbon, and it is the Van der Waals interaction that binds the atom to the surface in this case. Therefore, an effective filter medium requires a very large surface area. This makes the activated carbon an ideal filter material as it has high surface area to mass ratio (usually around 50 m$^2$/g, but can be up to 1 000 m$^2$/g). For capturing $^{222}$Rn the most effective and economic way is to use activated carbon filters. Activated carbon is widely commercially available and for low background purposes also synthetic activated carbon is available [44].

Within an activated carbon filter the favouring of radon capture with respect to carrier gases is due to the following; N$_2$ ($r_w$=1.55 Å), O$_2$ ($r_w$=1.52 Å) and Ar$_2$ ($r_w$=1.88 Å) have similar polarizabilities ($\alpha$) as carbon ($r_w$=1.70 Å), so they are not separated by the activated carbon. Radon, however, has a much higher polarizability ($r_w$=2.2 Å) and therefore it is much more likely to be trapped by the activated carbon. Polarizability is proportional to the Van der Waals radii through the following relation [62, 63]:

$$ r_w = \left(\frac{\alpha}{4\pi\varepsilon_0}\right)^{1/3}. \tag{34} $$

Addition to radon the pores of activated carbon can be occupied by water vapour ($r_w$=2.75 Å) thus inhibiting the radon adsorption. The effect of water vapour on the adsorption coefficient (K) is inverse proportional to the increase of relative humidity. However, the effect of actual measurements is relatively small. It has been observed that radon penetrates the active carbon at faster rate than the water vapour. Therefore, radon diffuses mostly through dry carbon even when within high relative humidity carrier gases. [63, 64]

The ability of radon to be adsorbed (expressed by the adsorption coefficient K) onto the carbon is temperature and pressure depended. The higher pressure and lower temperature will result in more atoms to be adsorbed onto the activated carbon. However, the increase in pressure will actually reduce the K and therefore the breakthrough time of radon. The coefficient K is depended from the volume flow rate instead of mass flow rate. Therefore at higher pressure more radon per unit mass of carrier gas will be adsorbed than at lower pressures. This characteristic is used in pressure swing adsorption systems. [62, 63].

The dependence on the temperature is inverse proportional: the colder the carbon, the more radon it will adsorb. However, for the breakthrough time (the time for radon to cover the length of a column of activated carbon) the effect is exponential: the colder
the carbon, the longer it takes for radon to break through the filter at hand. Hence, with appropriate cooling the effectiveness of activated carbon filter can be increased by several orders of magnitude. Vice versa by heating up the filter it is easy to purge the filter from radon (reactivating the activated carbon). This characteristic is used in temperature swing adsorption systems. [62, 63].

5.3 Radon removal systems

Generally all radon removal systems (radon trap, anti-radon etc.) used in the underground laboratories are based on the same general concept (a schematic of a general radon trap can be seen in the Fig. 8). The air is obtained from the surface (outside), cleaned from dust and other pollutants, dehumidified, blown through a mass of carbon, filtered again to remove contaminants from the radon decay and from the carbon itself and finally the air is supplied to the underground hall. Differences between the systems arise from building and running costs, space requirements, needed order of magnitude for radon removal, different operating temperatures for the activated carbon adsorption phase and usage of different pressures from almost vacuum to 10 bars. [65].

There are four possible alternatives in designing a full-scale radon traps: firstly the system can be passive operating at room temperature, secondly passive system operating below the room temperature, thirdly an active system operating at the room temperature and fourthly an active system operating at lower than room temperature. The difference between passive and active systems is in the method of dealing with the radon after it is removed from the air stream. The passive systems keep the radon on the activated carbon until through decays the desired reduction in the radon level has been achieved. In active systems, however, the activated carbon mass is periodically purged to remove the radon in order to obtain free surface area for new radon atoms to be trapped [65].

In general, both active and passive systems can reach the same orders of magnitude in radon reduction. The differences come from the fact that passive holding tanks require large quantities of activated carbon and larger facilities to host the setup than the active ones. Building a large structure is expensive but also running active systems and especially running systems below the room temperature may bring significant operational costs compared to passive, room temperature ones [65].
Fig 8. Schematic view of general active-carbon based radon trap: Incoming air is filtered and dehumidified before blowing the air into column of activated carbon (GAC– granular activated carbon). Water in the air can reserve the surface space of carbon thus reducing available surface area for radon. The radon trapped on the activated carbon can be let to decay (passive system) or be purged (active system). The residual air is filtered and blown to the target area. For the operation valves are kept open (– open valve). The green color indicates radon-reduced air. The schematic is based on the description in Ref. [65].
5.3.1 How to design a radon trap?

While designing a radon trap for the first time, it is important to know all the effecting parameters like the air flow (m³/h), the holding time (t [h]) required for the radon reduction factor (R) to be achieved and the amount of activated carbon to be used (m [kg]) to get holding time at the wanted level. The retention time can be calculated [66]:

\[ t = K \times \frac{m}{f} \]  

where \( K \) [m³/kg] is the adsorption coefficient which is dependent from the activated carbon used (mesh size in particular) and from the temperature (inverse proportional) and pressure (proportional) of the system [44]. This gives good basis for estimating the cost and size needed for a passive holding tank and amount of activated carbon needed (see Table 4). With a passive system and with a large air flow the needed amount of activated carbon and space required by the retention tank becomes economically not feasible [65].

The temperature (T) dependence of adsorption coefficient is exponential as seen in Eq. (36). In this equation the characteristics of the activated carbon (\( \Lambda/T \) and \( K(T) \)) are separated into their coefficients compared to the Eq. (35). Therefore, with appropriate cooling equal reducing factors could be obtained with much less use of activated carbon. See Tables 4 and 5 on pages 48 and 48 respectively, for mass evaluation of different passive systems.

\[ t = \frac{K(T)e^{(\Lambda/T)m}}{f} \]  

When using a single holding tank passive system, the activated carbon has to be changed (or purged in active systems) every now and then to remove any contaminants. For this period the air supply to the experimental sites would be disturbed for the period of the maintenance to take place. One solution is to use two holding tanks in parallel allowing the change or purging the activated carbon in the other (see Fig. 9) while the other is producing radon-reduced air. Purging such a setup is also possible by using a separate air or gas flow or to use the output of the second system to purge the used one [44].

Purging can be done through temperature or pressure swing systems thus enabling the radon trap to operate continuously. In temperature swing systems the carbon column
Table 4. Estimated amount of activated carbon needed to achieve desired reduction factor R for $^{222}\text{Rn}$ in a passive holding tank at room temperature, when air flow (m$^3$/h) is 500 m$^3$/s (approx. one volume of CLAB Lab 2 to be changed in one hour). Using values for adsorption coefficient from Ref. [66].

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<td>4</td>
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<td>4</td>
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<td>606</td>
<td>4</td>
<td>75739</td>
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<td>1000</td>
<td>909</td>
<td>4</td>
<td>113609</td>
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Table 5. Estimated amount of activated carbon needed to achieve desired reduction factor R for $^{222}\text{Rn}$ in a passive holding tank at -40 °C, when air flow (m$^3$/h) is 500 m$^3$/s (approx. one volume of CLAB Lab 2 to be changed in one hour). Using values for adsorption coefficient from Ref. [66].

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is appropriately cooled below the room temperature (the adsorption coefficient is exponentially dependent on the temperature, see Eq. (36), and the purged column is at the room temperature. With the temperature difference and therefore the difference in the adsorption coefficient it is possible to purge the warmer system with purified air from the cooled down system. When changing the system oppositely the former can be purged and the other act as a filter. [44, 62].

In pressure swing the feeding side will be in higher pressure than the purging side. The effectiveness of the pressure swing is based on the pressure differences of each side. The lower the pressure, the lower is the absorption coefficient and therefore less radon is
adsorbed by the surface of activated carbon. Hence, as with the temperature swing systems, the difference in adsorption coefficients makes it possible to purge the lower pressure system with purified air in order to remove the excess radon from the activated carbon. [44].
Fig 9. Using two activated carbon columns in parallel: incoming air is dehumidified in the air drier before blowing the air into column of activated carbon (GAC—granular activated carbon). Only one carbon column is used at a time so that changing the carbon in one would not disturb the air flow into the laboratory area. Columns are separated by valves (— open valve, X closed valve). Green color indicates radon-reduced air. The schematic is based on the description in Ref. [44, 65].
5.3.2 Examples of radon traps used in some of the DULs

Kamioka radon trap

In Kamioka the radon levels in the mine tunnel air near the Super-Kamiokande detector typically reach 2 - 4 kBq/m³ during the warm season (May until October) and during the cold season (November to April) the radon level is 100 - 300 Bq/m³. The large variations are due to the natural ventilation (wind direction). During the cold season the fresh air blows into the tunnel system and during the warm season from the tunnel transporting the radon-loaded air from the depths of the mine. [67]. The air purification room is separated from the mine with normal doors, therefore the variations in the tunnel radon levels are proportional to the radon levels inside the room (500 Bq/m³ and 40 Bq/m³, respectively) [68]. The detector dome however, is separated from the mine by air-tight door keeping the radon level approx. at 40 Bq/m³. [68].

The radon trap used in Kamiokande is both room (old radon trap) and below the room temperature (the new, added radon trap) passive system (see Fig.10 for a schematic view). The air is compressed to approx. 7 bars after which it is dried to a dew point of -24 °C before entering the activated carbon columns. The four columns (each 0.8 m diam. × 4 m height, labelled GAC in the Fig. 10) hold in total of four tons (8 m³) of activated carbon. As the adsorption is an exothermic process there is a heat exchanger in between the set of two columns. Radon reduction factor of 1 400 has been reported between the inlet and the outlet of the first two columns of activated carbon. Between the heat exchanger and the second set of two columns the radon reduction factor of 30 has been reported. The pressure of the air after the columns has dropped down to approx. 1 bar at the air flow of 10-15 m³/h. [65].

In March 1998 an external radon trap was added to the purification system which consists of 50 ℓ of activated carbon cooled down to -40°C. Typical radon levels for the purified air were approx. 20 mBq/m³ (before March 1998) and after the installations of additional cooled (-40 °C) column of activated carbon between 2 – 3 mBq/m³. The output of this system is Rn-reduced-air with a typical flow rate of 15 m³/h with a dew point of -50 °C. [68].
Fig 10. The Kamiokande radon trap: Incoming air (blue) is dehumidified in the membrane air dryer before blowing the air into column of activated carbon (GAC – granular activated carbon). In the carbon columns takes place most of the radon reduction (light green). The residual radon is filtered in the cooled (-40 °C) activated carbon columns to reach the radon activity concentration of few Bq/m³ (green). The schematic is based on the description in Ref. [67]
**Borexino radon trap and Princeton clean room radon trap**

In the Borexino experiment two types of radon traps have been used, a pressure swing system and a vacuum swing adsorption system. The latter one was used in Princeton where the Borexino nylon vessel was assembled and the former one at the Borexino experiment. With both systems radon reduction factors of approx. 100 were obtained [44].

The pressure swing adsorption system relies on the pressure-dependent adsorption properties (the higher the pressure the higher adsorption coefficient) of the activated carbon. The system uses two activated carbon columns connected in parallel. In the feeding cycle fresh air is pumped through one of the columns to produce radon-reduced air. This is called the feed cycle. The duration of the feed cycle is smaller than the diffusion time of radon through the column (breakthrough time). As the air passes through the column the output is radon-reduced air. [44].

At the same time with the feeding cycle the other column goes through a purging cycle. A fraction of the radon-reduced air is extracted and expanded to lower pressure. The lower pressure air is then used to purge the second column contaminated during the previous feed cycle. Due to the expansion, the purge air has a lower radon concentration that the output air from the feed column, by an amount equivalent to the ratio of the pressures. After the depressurisation of the column part of the radon adsorbed during the feed cycle will be desorbed. The direction of the purged air flow is towards the columns feed cycle input thus the desorbed radon has the same direction. In order to the purging to work the flow rate of the purging air has to be higher than the flow rate during the feeding cycle. Otherwise the radon front within the column would advance and eventually break through after number of feeding cycles thus contaminating the output air with radon. See Fig. (11) for the schematic view of the pressure swing system. [44, 62].
Fig 11. Borexino radon trap: A schematic of the Pressure Swing Adsorption (PSA) radon filter [44]. It is an active radon trap in which the air to be purified is fed (feeding cycle) into the columns (tanks) filled with activated carbon. In the picture air is blown through the tank one (– open valve, X closed valve) at high pressure. The second column takes a fraction of the radon-reduced air which is expanded (pressure is lowered) and is pushed through the tank towards the feeding inlet (purging cycle). The cycles are switched from one tank to another providing continuous supply of radon-reduced air. Air quality is indicated by colors: blue is inlet air, green is radon-reduced air and red is purged air. The schematic is based on the model in Ref. [44].
The Vacuum Swing Adsorption (VSA) based radon trap is in principle similar to the Pressure Swing Adsorption trap introduced in the previous paragraph. In the feeding cycle the air feed is at the atmospheric pressure. On the purging side the pressure is significantly lower, practically between 5 to 20 mbars. [44].

As in the PSA the ratio between the purge and feeding flows determines the radon filtering efficiency. Like the PSA this also used two columns of activated carbon. Instead just having the cycles (feeding and purging) the purged column which is pumped down to mbars has to be re-pressurised (approx. one minute) afterwards the purged column will be brought back to the feeding pressure (atmospheric, in few seconds). Then the feeding is changed to the purged one and the previously feeding column begins the with purging cycle. See a Fig. 12 for a diagram of the VSA radon trap. [44].

As the system itself is rather small, the columns used were just 1.4 m in height and less than 1.0 m in diameter, pumps and other main components taking few square meters, it could be fit into almost every cavern or maritime container. The amount of activated carbon used was half a ton. The total cost for the main components including the carbon were 53 000$ (in 2003). [44].
Fig 12. Princeton radon trap for the Borexino nylon vessel assembly: A diagram of the full-scale Vacuum Swing Adsorption (VSA) radon filter. It is an active radon trap in which the purging of the active carbon is done through de-pressurisation of the tank to be purged. During the purging phase the purged column of activated carbon is pumped down just to few mbars causing the radon to desorb from the surfaces of the activated carbon. After purging the column is re-pressurised and returned to the feeding pressure (atmospheric). The valve operations are indicated as following: (–) an open valve, (X) a closed valve. The cycles were computer controlled through a Labview user interface. Air quality is indicated by colours: blue is inlet air, green is radon-reduced air and red is purged air. The schematic is based on the model in Ref. [44].
6 Radon and radon mitigation in the CLAB Lab 2

6.1 Current situation

Currently the Lab 2 has an air exchange rate of 10 m$^3$/s, thus the total air volume to be exchanged will take roughly two minutes. Therefore, the accumulation of radon or other impurities emanating from the surrounding rock and construction materials will be minimal. With the air exchange the radon level has been dropped from 300 Bq/m$^3$ down to 50 Bq/m$^3$. Although the surface air has radon activity concentration less than 20 Bq/m$^3$, the air travels 1 400 m in elevator shaft, through a loading area of crushed ore and 500 meters in a ventilation pipe made out of fabric, thus contaminating the inlet air not only with radon but also with fine particles from the mine air.

6.2 Options for radon mitigation in the Lab 2

There are several options to mitigate the radon and its effects to the experiments. In the following paragraphs four different methods are introduced.

6.2.1 Separating the experiments from the atmospheric impurities

The experiments taking relatively small volumes, less than a cubic meter, the most practical way is to separate the experiment from the surrounding atmosphere. Although this is not mitigation the radon from the Lab 2, but this way also low background experiments can be operated in approx. radonless environments. This separation can be done by sealing the experiment within walls made of e.g. plexiglass and the inner volume would be flushed with pure (type 4.0, 99.99 % pure) or ultra-pure (type 5.0 or higher purity) gases to remove air and impurities including radon with the output flow. In the Fig. (13) is an example setup from germanium farm at the LSC, Spain. The germanium detector is shielded with ultrapure copper and lead, and the whole setup is installed within plexiglass cube. When in operation the inner volume of the cube is flushed with pure nitrogen produced by the boiling pf liquid nitrogen used to cool down the germanium detector. The gas can be from bottles as well.
This solution is rather inexpensive as long as the experimental setups are small in volume. In case of germanium detectors, the flushing gas is a by-product of the cooling process thus not producing any additional costs. If the no liquid cooling is needed, then the gas has to be bought separately thus increasing the running costs. For example, in case of C14 experiment the flushing will be done using bottled nitrogen. The purity of the nitrogen to be used is not yet decided therefore the price range is not yet known.

The separation of experiments into their own gas sphere does not come without a risk. When handling potentially oxygen displacing gases it is important that all the personnel are aware of the risk and know to how operate in case of gas leak or a system failure. As gases used in science cannot contain impurities, odorised gases cannot be used to inform the users of possible leaks. For this reason it is vital that areas, where the gases are handled and where the flushed gases are purged, are equipped with oxygen level sensors or monitors.

Fig 13. High sensitivity germanium detector sealed within plexiglass cube. The cube is flushed with pure nitrogen (gas) produced from the liquid nitrogen used to cool the germanium detector. Thick layer of lead and ultrapure copper reduces the surrounding gamma background significantly and the gas flushing prevents radon from entering the cube. Picture is from the germanium farm of LSC, Spain. Photo by author.
6.2.2 **Changing the air intake from the elevator shaft to fresh air shaft**

The air currently taken from the bottom of the elevator shaft is reasonable in air quality. The piston type of movement of the elevator accumulates impurities from different levels due to pressure differences thus contaminating air. The air radon levels at the intake vary from less than 50 to 300 Bq/m$^3$ which is also the range of radon level variation in the Lab 2 [69].

![Fig 14. An illustration on the current air intake from the bottom of the elevator shaft (doors on the right) leading fresh air to the Lab 2 at the Pyhäsalmi Mine. Illustration by author.](image)

The mine has a fresh air intake from the surface of roughly 100 m$^3$/s. The fresh air is blown with fans to the new mine (depths 990 to 1 420 m). Areas which are connected to fresh air shaft through ventilation pipes have in general radon levels less than 20 Bq/m$^3$, a typical value for the air outside. If the Lab 2 would also be connected to the fresh air shaft, the radon levels would decrease by several-fold.

Although the main level (1 420 m) has a vast fresh air inflow the closest access to the fresh air shaft from the Lab 2 (1 430 m) is from the level of 1 390 m. The pipe connection could be done using ventilation pipes installed onto the ceiling of the inclined tunnel. The length of the pipeline would be 700 meters if connected to the current intake line. As the inclined tunnel is used by the large mining equipment there will collisions to the pipelines causing breaks into the fresh air supply. The cost estimate for the connection from fresh air shaft to the Lab 2 would be around 10 000 € including the labour costs.
Anti-radon coating

In the Lab 2 the source of radon could be blocked by using anti-radon coating not only on the walls and ceiling but also to the floor slab. This would enable significant reduction on the radon levels emanating from the surrounding rock.

Radon filtering system

If the whole Lab 2 would require less than 10 Bq/m³ radon levels then in addition to above an active carbon based filtering system would be needed for the inlet air to produce radon-reduced air. In the following section the preliminary design will be described for a pressure swing filtering system with regeneration for the active carbon.

6.3 A radon trap for the Lab 2

Based on the example cases presented in the previous chapter there are several options from which to select when designing a radon trap for the Lab 2. With a radon reduction factor of 10 a passive radon trap (room temperature) would need activated carbon in tens of kilotons. Therefore, the size and space requirement which it brings, there is no available location to host the activated carbon columns inside the Lab 2. Also the adsorbed radon and its progeny would impose a source for radiation exposure both for personnel and especially for the experiments through gamma radiation within the decay chain of radon. If the passive system were cooled down to -40 °C then the amount of activated carbon would be in range of few tons. This would be manageable both from the cost and space point of view. However, the constant cooling would require either vast amounts of electrical power (increasing running costs and challenges with the heat load) or use of gases on liquid phase thus raising personnel safety issues.

From the active radon traps both (PSA, VSA) designs are practical and are based on commercial products thus maintenance would be possible. Also both systems require installation area of few square meters so they would be possible to install inside a marine container. This would be economically practical place of installation as it provides cover from the mine air and also from the possible sulphur explosions and it would be easy to transport the system where ever it would be needed. As based on the schematics of the PSA it seems to be less complex to operate than the VSA.

As the purging of the activated carbon columns causes an accumulation of radon and
its progenies near the purging vent, it is important to divert the purged gases away from the Lab 2 and from the tunnel leading to the Lab 2. This would have to be done with a pipe connection to the exhaust shaft, thus increasing the installation costs.
Fig 15. Schematics for the PSA radon trap for LAB 2. Inlet air (blue) would arrive from the fresh air shaft. The air would be pushed through a dehumidifier and then through a column of activated carbon at high pressure. After the column the radon-reduced air (green) would be pushed to the air outlet and to the experimental hall of Lab 2. A fraction of the radon-depleted air would be diverted to an expansion chamber were the pressure is lowered close to the atmospheric pressure. With a flow rate higher than the inlet flow rate the depressurised air would be pushed into the second column through the exit towards the air inlet. The valve operations are indicated as following: (–) an open valve, (X) a closed valve. The radon-loaded air (red) would then be diverted to the exhaust shaft to prevent contamination of other facilities in the mine. The schematic is adapted from the description in Ref. [44].
7 Results and discussion

Callio Lab 2 now exists at the depth of 1 430 meters in the Pyhäсалми Mine Ltd. It provides the much needed addition to the available spaces not only for the Callio Lab itself but also for the scientific community looking for deep underground measuring halls and laboratories to conduct their experiments. Massive overburden, approx. 4 000 m.w.e. makes the Lab 2 ideal for low (muon) background experiments (see Table 6). Shielding from local radioactivity can be done by using shielding materials and active-carbon based passive or active filtering system to reduce the radon level in the experimental hall.

Table 6. CLAB Lab 2 characteristics for scientists.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>1 430 m ~ 4 000 m.w.e.</td>
</tr>
<tr>
<td>Muon flux</td>
<td>$1.1 \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1}$</td>
</tr>
<tr>
<td>Radon</td>
<td>50 – 300 Bq/m$^3$ preliminary results due to the challenges with the air blower</td>
</tr>
<tr>
<td>U/Th</td>
<td>U (0.8 ppm), Th (3.2 ppm) (whole mine average)</td>
</tr>
<tr>
<td>Connectivity</td>
<td>GBLan, 100 MB internet connection (upgradable)</td>
</tr>
</tbody>
</table>

As for all the other DULs their experimental halls have been characterised by their backgrounds making the comparison between the sites possible. Without characterisation it will be difficult to market the available space(s). Therefore, the following steps should be taken concerning the characterisation of Lab 2. A muon flux (generally effecting low background experiments) measurement with angular accuracy should be performed in order to know the exact rock-overburden and the angular dependence of it. The neutron background (effects e.g. dark matter and $\beta\beta$ experiments) measurements should also be performed using dedicated experimental setups to measure the neutron flux produced by the local radioactivity (<10 MeV) and by cosmic ray induced air showers (up to few GeV). Determining the gamma ray spectrum is also vital to understand the background due to radioactive decays in the materials within the Lab 2 and within the detector materials in order to define the needed thickness of radiation shielding, or in worst case state that the site cannot be used for specific low background experiments at all.

As mentioned in the section 2.3. the additive to the cement (used in walls and ceiling)
has a relatively high concentrations of $^{40}$K, $^{226}$Ra and $^{240}$Th that causes accumulation to the background. This might be a show stopper for some more demanding low background experiments. Therefore the background measurements are vital when looking for a hosting site among the DULs. If a dedicated low background counting facility would be needed, my recommendation would be to construct a dedicated low background (low radioactivity) laboratory using low radioactive materials and techniques from the beginning to prevent or at least reduce the contamination of detector materials while handling, installing and running the detector setups.

This work has proven that it is possible to upgrade an exploring tunnel into measuring hall with reasonable costs. One of the major delaying components in the construction of Lab 2 was the constant lack of available resources committed to the project. Although the designs were accepted in various levels and pressure was given to proceed with the construction no resources were allocated at the same rate. The cost estimate, which was quite well kept at the end, was done using the expertise of mine personnel and underground mine operators. Their insights and knowledge proved to be extremely valuable. During the design phase there were several detailed discussions with the Finnish underground infrastructure constructors and material suppliers. The suppliers shared also their results of radiological analyses of their products. The openness and expertise of regional and other Finnish companies could be valuable asset for future development projects of Callio Lab. It is important to realize that without the contributions and flexibility of companies and their representatives the Lab 2 would not have been achieved with the resources allocated.

Although the Lab 2 is now finished according to the budgetary limits some thoughts have arised concerning the future transformations of existing tunnels or building totally new underground facilities whether for science or commercial use. In an ideal case project of this magnitude and importance should have a project plan and a professional project management. The project should start with planning phase, learning from the successes and failures of other DULs. It is important that already from the beginning of the project the design is done from the user, not from the constructor point of view. The resources, both financial and personnel, should be already available from the stakeholders to take this phase through.

With the preliminary design the project management could continue with obtaining more stakeholders and have them committed (Letter of Commitment, Memorandum of Understanding) into the coming project. This would ensure that there would be both financial and human resources to realize the planned building project. With secured
resources it will be possible for the project management to hire experts (in publicly funded projects through competitive bidding) to do the designs and help with the competitive bidding for the actual construction project. After this it would just be overseeing the project and make sure everything will be done in time according to the agreed plan and budget. This way the construction can proceed according the planned schedule and resources will be available for each steps of the way. And as a result there will be satisfied users starting their activities on time.
References

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