Background sources in low-background experiments

Bachelor's thesis
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Table of Contents

1 Introduction

1.1 History

In the late 1960's, astrophysicists Raymond Davis Jr. and John N. Bahcall had a 380 cubic meter tank filled with perchloroethylene transported 1478 meters underground in the Homestake Mine in Lead, South Dakota. Why? They were preoccupied with one of two great mysteries baffling physicists, and the only way they stood a chance at discovery was to go underground.

Davis Jr.'s and Bahcall's purpose was to conduct an experiment to collect and count solar neutrinos. Their experiment required a big underground target with rock overburden to prevent interference from cosmic-rays (CR), as they were aware of how small the probability of neutrino capture is. The Brookhaven Solar Neutrino Experiment would later be known as the first deep underground measurement in the field of physics. [1].

1.2 Two great mysteries

Particle physicists are occupied by two major mysteries: neutrinos and dark matter. Our lack of full understanding of these concepts results in rather large holes in the Standard Model (SM) of physics. At first, neutrinos were only a theoretical idea. It appeared that the laws of conservation of energy and momentum did not apply to beta decay. Wolfgang Pauli proposed that there exists a particle not yet discovered, which would account for the discrepancy. He firmly believed that the existence of this particle could never be proven scientifically. [1].

It took only 20 years for science to do the impossible — the neutrino was found. As it turns out, they are so plentiful that there are more neutrinos in the Universe than any other particle. They pass through our world at the speed of light, and even now trillions of neutrinos are passing through us every second [2]. There are neutrinos that have seen the beginning of time, as well as, new neutrinos, which are byproducts of nuclear reactors and muon and beta decay. [3].

The second mystery also began as a conflict between theory and practice. In the early 1930's, Swiss astronomer Fritz Zwicky observed the galaxies in the Coma cluster. He discovered that the velocities of these galaxies exceeded theoretical expectations. Galaxies should spin at velocities proportional to their mass, with the central mass' gravitational pull preventing it from spiraling apart. In contrast, what was observed was that the outer regions of galaxies were spinning faster than expected. For them to spin that fast and stay on their track, there had to be additional invisible mass that had not been accounted for in calculations. Again, there is something that we do not see and cannot account for. That something does not reflect, does not radiate and does not absorb light. This mystery material is appropriately called dark matter. According to certain estimates, it could make up to 27% of our Universe. [3].

Considering that neutrinos and dark matter make up a significant amount of our Universe, they are surprisingly elusive and difficult to study. Why is it not possible for your particle detector to only detect the particles you want? It is not the actual particles you detect, but the traces they leave when they interact with the target medium. These traces are similar to those left by many other particles, and these undesirable sources of traces are known as background. It is like finding a needle in haystack, but in nanoscopic terms. What is the solution? The haystack needs to be obliterated or mitigated as much as techniques and budgets permit until nothing but the needle remains. In other words, we need low-background experiments.

In this thesis I study the major sources of background in low-background experiments: muons, neutrons, neutrinos, and radioactive impurities. I will present a summary of their history, followed by the characteristics and common interactions of these different sources. In addition, I will review what options exist for reducing backgrounds or mitigating their effects. I have included examples of deep underground laboratories and how they differ from each other. To recap how knowledge of backgrounds can be implemented for real-life use, I will present a working example of the thorough natural background characterization done in Callio Lab in the Pyhäsalmi Mine in Finland.

1.3 Deep underground laboratories

Where do we look for low-background experiments? We must look underground at so-called deep underground laboratories (DUL's) where the rock overburden serves as an effective barrier for high energy particles. It is no coincidence that experiments studying neutrinos, such as JUNO, SNO+, Super-Kamiokande, and DUNE, to name a few, are located underground or within mountains. DUL's can refer to laboratories located deep underground but also to laboratories that are built inside mountains and have horizontal access routes. [4, 5].

Although the Brookhaven Solar Neutrino Experiment, later referred to as the Homestake experiment, is thought of as the first deep underground experiment, the first official deep underground laboratory is the Baksan Neutrino Observatory (BNO). It is made up of multiple laboratories situated at different levels and is located beneath the Mount Andyrchi in the Baksan valley in Russia. Construction began in 1967, and 10 years later the first neutrino telescope began operating. Experiments are still underway at BNO and it is operated by the Institute of Nuclear Research of the Russian Academy of Sciences. [4, 6].

For successful and continuous experimentation, a simple hall in a mine or cavern is not enough but working infrastructure both above and underground is required [7]. This includes but is not limited to continuous quality electric power, proper air ventilation, and safe access shafts and/or tunnels. It should also be taken into account whether access is via horizontal or vertical tunnels, as this may affect transportation of materials. Support infrastructure should include mechanical and electrical workshops, storage facilities, offices, a clean room, a low-background gamma radiation laboratory, and IT services. Geographical access to the location, such as is it along highway routes, or close to airports or train stations, must also be taken into consideration. [5, 7].

DUL's can be excavated and designed from scratch, as was the case with the Baksan Neutrino Observatory in Russia, which was built independently of other projects. Most DUL's are built within existing mines, as is the case with Callio Lab in Pyhäsalmi Mine in Finland, or in tandem with underground civil engineering projects. One example of the latter is the Laboratori Subterrano Canfranc (LSC) in Spain, which was built during the construction of nearby highway tunnels. DUL's also have applications for use in other fields, such as biology, cybersecurity, food production, and

Table 1. Summary of access type and depth m.w.e. of selected DUL's. Data collected from Ref. [5, 6, 8].

DUL	**Location**	**Site and access**	**Depth** [m.w.e.]
BNO	Andyrchi, Russia	Mountain, horizontal tunnel	4700
Callio Lab	Pyhäsalmi, Finland	Flat, vertical tunnel/shaft	4000
CJPL	Sichuan Province, China	Mountain, horizontal tunnel	6700
Kamioka Observatory	Hida, Japan	Mountain, horizontal tunnel	2700
LSC	Canfranc, Spain	Mountain, horizontal tunnel	2400

underground building. Callio Lab is an excellent example of such a multidisciplinary working environment as it is exploring the many uses an underground laboratory can have during its lifetime. To date, Callio Lab has hosted experiments in the fields of physics, biology, agriculture, and geology [9]. [5, 6, 10].

Currently, there are tens of underground laboratories worldwide ranging from depths of a few meters to over several kilometers. Table 1 shows a brief summary of selected DUL's access type and depth in meters water equivalent (m.w.e.). Bedrock varies greatly in density, so depth gives an insufficient analysis of the effectiveness of the rock barrier. Meters water equivalent is a term often used to compare cosmic-ray penetrativeness between underground laboratories. At present, the China JinPing Underground Laboratory (CJPL) is the deepest laboratory in the world, located in the Jinping Mountains of Sichuan, China. It has a rock overburden of 2400 meters, corresponding to 6700 m.w.e. [8, 11].

2 Background sources in low-background experiments

2.1 Muons

2.1.1 History

Muons were first discovered in 1936 by Carl Anderson and Seth Neddermeyer. They observed that this new particle had a negative electrical charge and that mass-wise, it was lighter than a proton, but significantly heavier than an electron. The muon was first mistaken for the Yukawa meson, which physicists at that time were intensely searching for. Japanese physicist Hideki Yukawa had proposed a particle to explain the forces binding neutrons and protons to nuclei and the particle that Anderson and Neddermeyer found, roughly fit the estimated characteristics predicted by Yukawa. The actual Yukawa meson was discovered in 1947 and is what we now know as pions or pi-mesons. [12].

2.1.2 Characterization

Anderson and Neddermeyer were on the right track, as the decay of charged Yukawa mesons, or pions, is the main source of muons. Pions are first created in the upper atmosphere by cosmic-rays crashing and interacting with particles. In these interactions the high energy primary particles collide with nuclei in the upper atmosphere, producing a spray of new secondary particles. These secondary cosmic rays consist of protons, neutrons, pions, kaons, electrons, and photons. Pions are very short-lived, and either positive (π^+) or negative (π^-), and they decay into positive (μ^+) or negative muons (μ^-). Neutrinos (ν) or antineutrinos ($\bar{\nu}$) are created in the process. Charged pion decay is characterized as

$$\pi^+ \rightarrow \mu^+ + \nu \tag{1}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu} \tag{2}$$

Muons have a mass of 105.7 Mev/c^2, which is 207 times larger than the mass of electrons, a half-life of 1.56 μs and travel near the speed of light. Although a muon's lifetime of 2.2 μs may seem short, due to the relativistic effect it is sufficient time to travel from the atmosphere to Earth's surface and beyond. [3, 13].

Muons and neutrinos are the only particles capable of penetrating over 2000 m.w.e. underground: muons pass straight through ordinary matter, traveling through space at almost the speed of light, continuing their journey deep into the earth unhindered. Muons do not travel indefinitely: atmospheric muons can reach depths of up to 14 km.w.e. [14]. They lose energy through continuous and discrete processes. As mentioned before, muons can be either positive or negative, meaning they have an electrical charge. This means they constantly lose energy in small increments through ionization. At greater depths, discrete energy loss processes, such as bremsstrahlung, pair production, and photo-production are more prominent. As the name suggests, in these discrete process's muons lose energy in bursts. On average, the net flux of muons, which above ground at Pyhäsalmi, Finland (63.6812° N, 25.9815° E, WGS84) has been measured to be 180 muons per square meter per second, decreases every 1500 m.w.e. by one order of magnitude [15]. This relation is illustrated in Figure 1. [5, 16].

2.1.3 Neutrino-induced muons

Muons are also products of neutrino interactions, and these muons emanate from all directions inside the Earth. In inverse muon decay a neutrino scatters off of a free electron via charged current (CC) interaction producing a muon and an electron-neutrino. Neutrinos produce muons also through CC quasi-elastic scattering, where a muon-neutrino and neutron collide, creating a muon and a proton. At depths of under six kilometers m.w.e. cosmic-ray muons appear at rates of three to five orders of magnitude greater than neutrino-induced muons [16]. At depths of over ten kilometers m.w.e. neutrino-induced muons dominate over CR muons, and beyond 14 km.w.e. the muons observed are solely products of neutrino interactions. The total rate of neutrino-induced muons is $4.8 \times 10^{-8}\mathrm{m}^{-2}\mathrm{s}^{-1}$ and it is not depth-dependent. [5, 16, 17].

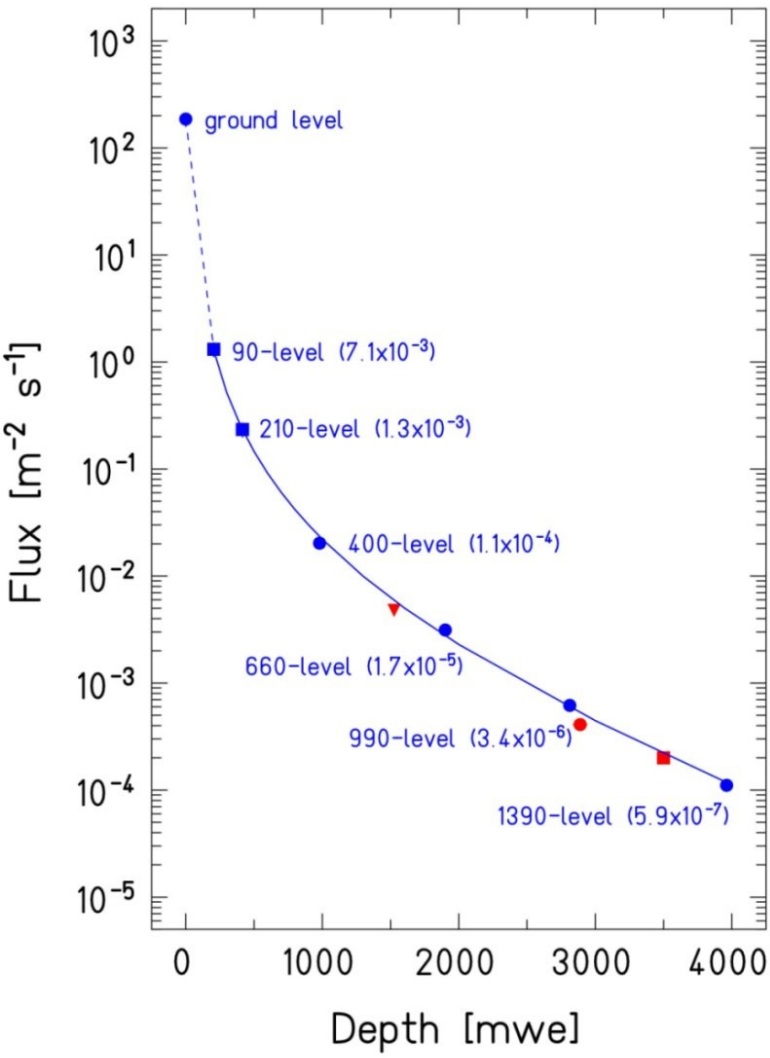

Figure 1. Muon flux depth relation at Pyhäsalmi Mine. Fig. from Ref. [15]. Published with permission. Since the measurements have been completed, the overburden from 1000-1400 meters underground has changed to some extent due to ore being mined and replaced with backfill [19].

2.1.4 Background reduction

There are two main methods to shield low-background experiments from muon interference. One is to situate the experiment deeper, as the muon flux decreases as the depth m.w.e. increases. Currently, there is no DUL deep enough that the muon flux would be zero, so additional measures must be taken. These additional measures are veto detectors. The principle is simple: veto detectors situated before the main detectors observe a muon, and incidentally, data collected while veto is active can be discounted from analysis. This ensures that final data does not include the passing muon or interactions it may have caused. [5, 18].

2.2 Neutrons

2.2.1 History

The neutron was discovered relatively late in 1932 by James Chadwick, who used data from scattering measurements to calculate the mass of a neutron. Two years before physicists Bothe and Becker had observed, that when beryllium was bombarded with alpha particles, it produced a form of penetrating but non-ionizing neutral radiation. Intrigued by these findings, Rutherford's assistant and pupil Chadwick proved that this neutral particle was not a gamma-ray or a photon through additional target experiments. In order to determine the mass of this unknown particle, he bombarded a boron target with alpha particles. The subsequent reactions caused neutral particles to be emitted, and Chadwick analyzed the interactions between these particles and nitrogen. Applying the conservation of energy theorem to the observed reactions, he was able to calculate the mass of the neutron as 938$\pm$1.8 MeV, which is closely consistent with the current defined value of 939.57 MeV. [3].

2.2.2 Neutron background sources

Local radioactivity The neutron flux around us originates from two major sources. One source is local radioactivity. The fission of ^{238}U, ^{235}U, and ^{232}Th in surrounding rock and detector materials contribute heavily to the local neutron flux. In 1938, Lise Meitner discovered a way to disrupt the heavy nucleus of $^{235}_{92}$U to its breaking point. The uranium isotope underwent fission when hit by a neutron, but not from the force of impact. The ^{235}U absorbs the neutron, growing in mass number A, which leads it to become so unstable it shatters at once, splitting into two fragments which immediately emit several neutrons (neutron emission). [3].

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U}^{*} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + {}^{1}_{0}\mathrm{n} + {}^{1}_{0}\mathrm{n} \qquad (3) $$

^{238}U which makes up 99.3 percent of all naturally occurring uranium, is the most significant of the three mentioned nuclides due to its relatively short fission half-life. In Callio Lab 2 (1436 meters underground) at Pyhäsalmi Mine the average production rate of neutrons through fission is approximately 12.2 neutrons/year/g of rock per ppm of ^{238}U and ^{232}Th, which where measured to be 3.69 ppm and 6.22 ppm respectively. The bedrock in Pyhäsalmi Mine at depths greater than 1400 meters is mafic volcanic rock with layers of felsic volcanic rocks. [3, 9, 19].

Muon interactions The second source of neutrons is muon interactions (muon-induced spallation). Neutrons are created by cosmic muons passing through matter and undergoing energy losses. This ultimately leads to nuclear breakup, or spallation, processes, of which muon capture is most common. Muon capture is as follows

$$ \mu^{-} + p^{+} \rightarrow n^{0} + \bar{\nu} \qquad (4) $$

The negatively charged muon is attracted into the Coulomb field of a nucleus and “captured” by a proton. This results in a neutron and a neutrino being emitted. The neutron flux originating from muon interactions is depth-dependent and requires thicker shielding because they can have energies up to several GeV [7]. [5, 20].

2.2.3 Background reduction

The neutron background is problematic due to its large energy range, as cosmic muon-induced neutrons have energies of up to several GeV, whereas neutrons from local radioactivity have energies of up to 10 MeV. At depths of over 100 meters rock overburden, the total neutron flux is largely depth- independent. At these depths, the neutron flux resulting from local radioactivity is 100-1000 times more significant than the neutron flux caused by cosmic radiation. [7].

Situating the experiment deeper underground, where there are fewer muons, decreases the neutron flux from cosmic radiation. While the remaining cosmic-induced neutrons can be tagged out using veto detectors, other shielding methods are needed in eliminating neutrons produced within the detector setup or surrounding rock. Neutrons can be slowed down by hydrogen-rich materials. A hydrogen nucleus consists of only one proton, and since protons and neutrons have near-identical masses, all of the neutron's kinetic energy can be transferred to a proton in one single collision, resulting in slowing or stopping the neutron. [3, 5].

Shield materials made of elements of a high atomic number, such as lead, will prove ineffective in slowing neutrons, as the neutrons will simply bounce off in elastic collision (neutron mass«heavy nuclei). An all-round effective hydrogen-rich shield is water, with a neutron capture cross-section of 0.3 barns. Other materials with high neutron capture cross-sections are boron and cadmium, but as these are toxic materials, their use may be restricted. It is important to note that the absorption of neutrons causes gamma-rays to be emitted and proper measures will have to be taken to shield from these subsequent gamma-rays. [3, 5].

2.3 Neutrinos

2.3.1 History

Deep underground detectors were the first to find cosmic-ray neutrinos. Muons were found to be emanating from the surrounding rock at angles so large, that they could not possibly be atmospheric muons from up above. This mystery was solved when muon-neutrinos were discovered through pion decay, in an experiment in 1962 where pions were created by shooting high energy protons at a metal target. What was noticed, was that the subsequent interactions, which were traceable to neutrinos, did not produce electrons, like in inverse beta decay, but muons. It followed, that these neutrinos must differ from those associated with beta decay. Later, the existence of three different types of neutrinos and their antiparticles, antineutrinos, would be confirmed. [3, 21].

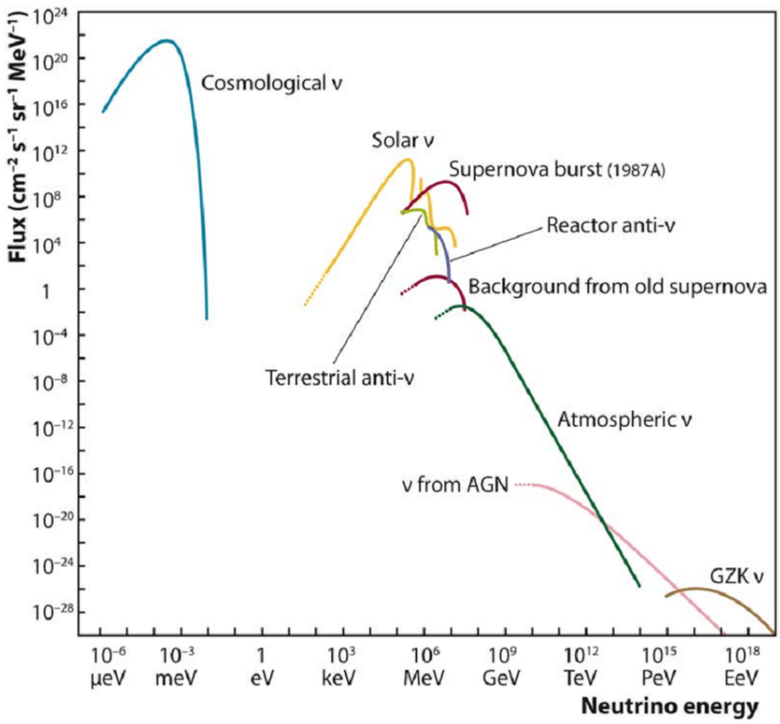

Figure 2. Energy ranges and relative intensities of neutrinos according to source of origin. Fig. from Ref. [23]. Published with permission.

2.3.2 Characteristics

Neutrinos are categorized into three distinct flavors, tau, muon, and electron, and differ greatly by their respective energies depending on their place of production (see Fig. 2 for overview on neutrino energy ranges). Neutrinos and antineutrinos differ in spin: a neutrino spins in the opposite direction of its direction of motion, while the antineutrino spins in the same direction as its motion. Neutrinos have no charge, and the Standard Model of particle physics defines them to be massless. However, neutrino oscillation experiments disagree with this assumption of no mass. This was discovered in 1998 by the Super-Kamiokande experiment, and it proved the existence of neutrino oscillation with atmospheric neutrinos. This discovery verified that neutrinos have a minute rest mass. The SM fails to explain this, and as such, displays the incompleteness of the SM. [3, 7, 22].

2.3.3 Interactions

Neutrinos interact only through weak nuclear force and gravity, and because of this, they hardly interact with matter. The short span of weak force requires particles to come incredibly close to each other for it to have an effect. Due to their stable nature and low probability of interaction, according to estimates, neutrinos make up most of the Universe's particles, outnumbering protons a billion (10^9) to one. [3, 16].

2.3.4 Background reduction

Due to their elusive nature, all neutrino signals are welcome. Neutrino cross sections, which describe the probabilities of a nuclear reaction occuring, are minimal. To scale, there is a one in 10^5 chance that a 100 TeV neutrino interacts while traversing one kilometer of ice, but the probability increases with energy. As stated previously, cosmic-ray induced muons can reach depths of 14 km.w.e., so any muons detected beyond that are from neutrino interactions. [16].

Neutrinos are observed either by detecting a neutrino interaction happening in the detector, or by detecting subsequent muons from neutrino interactions that happen outside of the detector. When searching for a specific type of neutrino, neutrinos of other energies can be disruptive to the experiment. For example, experiments studying geoneutrinos can detect neutrinos emanating from nuclear reactors, since the energy ranges of geo- and nuclear-based neutrinos overlap. The neutrino energy range is vast, from cosmological neutrinos having energies below 10 meV to galactic neutrinos in the TeV and PeV range [23]. [5, 16].

2.4 Radioactivity

2.4.1 Theory

Radioactivity is all around us, emanating from space, from the Earth, from buildings, even other humans. The geological history of the Earth has been determined almost completely by the continuous energy released from the decay of radioactive uranium, thorium, and potassium isotopes. This is possible due to their long half-lives. Measurements have shown that the radioactivity of samples decrease exponentially in time. A half-life is the time it takes for an initial measured radioactivity (N_0) to decrease by half. According to the activity law

$$N = \mathrm{N_0 e^{-\lambda t}} \tag{5}$$

Each radionuclide has a unique value for λ, the decay constant and subsequently for the half-life as well. The half-life of the samples is as follows

$$\mathrm{t}_{1/2} = ln2/\lambda \tag{6}$$

Half-lives can range from very fast decay (fractions of seconds) to even billions (10^9) of years (such as ^{232}Th) [3].

Radioactivity is measured in Becquerels (Bq/s), which defines how many nuclei in a quantity of radioactive material decay in a second. Another term used is sieverts. Sieverts describe the equivalent biological effect a dose of radiation has, and it has been roughly defined to be equivalent to one gray of gamma radiation. One gray is the equivalent biological effect one joule of radiation energy has on one kilogram of human tissue. In Finland, the effective radiation dosage a person gets per year is 4 mSv. To compare, in Poland the yearly effective dosage is only 2,48 mSv [24]. This difference of nearly half is due to the difference in bedrock, as Finland's bedrock is predominantly granite with high uranium and thorium content. [3].

Alpha, beta, neutron, and gamma decay are all ionizing radiation, meaning they produce ions in the medium they interact in and remove electrons from the orbit of a nucleus. The nuclide undergoing decay is called the parent, and the resulting nuclide is called a daughter or progeny. These progenies can decay further, until the nucleus reaches its stable state at its lowest possible energy level. [3, 25].

2.4.2 Gamma decay

When a nucleus decays, absorbs energy in the form of a photon or undergoes fission it is left in an excited state. An excited nucleus, often denoted with an asterisk (See eq.3), is unstable and aims to return to its ground state. This can be achieved by emitting photons, which are traditionally called gamma-rays. Nuclei can undergo multiple gamma decays. Most excited nuclei decay fast to their ground state through gamma decay, but some nuclei can stay in an excited state for several hours. An example is $^{87}_{38}\mathrm{Sr}^*$, which is an isomer (long-lived excited nucleus) of $^{87}_{38}$Sr. [3].

2.4.3 Alpha decay

Isotopes with heavy nuclei, characterized as having an atomic number (Z) greater than 83, decay typically through alpha-decay, where the nucleus emits an alpha particle. When a nucleus has a large ratio of protons to neutrons, it is unstable, and alpha decay is a means to stabilize it. The alpha particle corresponds to a ${}^{4}_{2}\mathrm{He}$ nucleus consisting of two protons and two neutrons. When the nucleus emits the alpha particle, it decays into an element with an atomic number corresponding to Z - 2, and its mass number (A) decreases by four. Below is the reaction for alpha decay of ${}^{238}\mathrm{U}$

$$ {}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} \tag{7} $$

Because alpha particles are heavy and have an electric charge, they ionize plenty of molecules around them, and so their mean free path in air is very limited, only a few centimeters. [3].

2.4.4 Beta decay

Unstable nuclei decay towards equilibrium by evening out their ratio of protons to neutrons. In negative beta decay, a neutron becomes a proton, and subsequently, an electron and an antineutrino are emitted (See eq. 8). Positive beta decay is also called positron emission (See eq.9). In positron emission, a proton becomes a neutron resulting in a positron and a neutrino being emitted. These resulting electrons and positrons, referred to as beta particles, can ionize other nuclei.

$$ n^0 \rightarrow p^+ + e^- + \bar{\nu} \tag{8} $$

$$ p^+ \rightarrow n^0 + e^+ + \nu \tag{9} $$

The third form of beta decay is electron capture (EC). As the name suggests, a nucleus can capture an electron from one of its inner layers. The electron reacts with a proton, resulting in a neutron being added to the nucleus. This interaction releases an electron neutrino and energy in the form of gamma radiation. Electron capture probability increases with atomic number, as the larger the atomic number, the greater the nucleus electric field, and the closer the electrons are to the nucleus.

$$p^{+} + e^{-} \rightarrow n^{0} + \nu \tag{10}$$

The resulting nuclides in beta decay are isobars of the original unstable nuclides, as the mass number remains unchanged. [3].

2.4.5 Neutron radiation

Neutron radiation manifests as free neutrons released through nuclear fission. Free neutrons are unstable, with an average half-life of 611 seconds, quickly decaying through beta decay into an electron, a proton, and an antineutrino (See eq. 8). Neutrons are neutral, i.e., free of electric charge. Neutron radiation is often called ionizing radiation, when a more accurate definition is indirect ionizing radiation. The neutron itself does not ionize atoms in the same way as charged particles, but neutron interactions can lead to ionization. For example, a nucleus can absorb a neutron, resulting in a gamma-ray being emitted, which can ionize other nuclei. [3, 25].

2.4.6 Impurities in low background experiments

Radioactivity poses challenges in low background experiments. In addition to the previously mentioned radioactivity, the detector setup itself can be a source of radioactivity producing false signals. The detector materials and shielding may contain radioactive impurities, or it may have been contaminated during installation through air (e.g. radon) or touch (oils from fingers attract impurities from the air). [5, 7].

2.5 Radon

Radon is a significant source of radioactive background, especially in Finland, where the bedrock is high with uranium and thorium. The decay chains of ^{238}U, ^{232}Th, and actinium produce three of the naturally occurring radon isotopes, ^{220}Rn, ^{222}Rn, and ^{219}Rn, respectively. These first decay into radium, which when it decays produces radon (See eq. 11).

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He} \tag{11}$$

Radon, colorless and odorless, is highly mobile, as it can travel through air, water, and attached to matter. Radon decays through alpha decay, producing long-lived progenies such as ^{210}Pb and ^{210}Po which can disturb measurements for a long period of time, if gained access into the detector system. Radon's progenies are electrically charged and solid in nature, so they can attach themselves onto surfaces. [25, 26, 27].

For low background experiments, physicists strive to achieve radon concentrations in the mBq/m^3 or even μBq/m^3 ranges. In underground, enclosed spaces, radon concentrations can be more than one hundred times greater than above ground, where it is around 10-20 Bq/m^3. Due to this, further protective measures need to be taken, such as ventilation, fresh air supply, or radon traps. Surface contaminations can be removed through mechanical and chemical cleaning, but to prevent recontamination while cleaning is near impossible unless performed in a clean room. [5, 28].

2.5.1 Radon removal

Preventative measures can be taken to minimize the radon effect. These include using materials with low uranium and thorium content, using fresh air supply from above ground or from bottles, and/or flushing the experiment with a source of contaminant free gas, such as gaseous nitrogen. To prevent radon from entering via airways, systems can be pressurized or the incoming air can be filtered, for example, using radon traps. Carbon filtering involves directing air through an active carbon bed, which traps radon into its carbon pores. Other filtering techniques involve trapping the radon infused air in a buffer tank or charcoal bed until the radon has decayed enough. This aged air is subsequently filtered in order to remove any remaining solid impurities before being allowed to flow to the experiment. Radon's daughter nuclei have an electric charge and easily attach onto solid particles within the air. [5, 29].

Larger scale radon removal systems or radon traps implement multiple radon removal techniques. The basic idea is to get air from outside (with radon activity around 20-30 Bq/m^3) clean it from dust and other contaminations and dehumidify it. Next begins the radon removal, with the air being blown through a carbon bed, and additional filtering. A good example of successful radon removal is the Super Kamiokande experiment. Radon is a genuine challenge in Kamioka, where during the warm summer months, radon levels in the mine can reach 2-4 kBq/m^3. By implementing radon removal systems, they have gotten the concentrations down to 2-3 mBq/m^3. [5, 29].

3 Callio Lab

3.1 Callio Lab 2 and Lab 5

Pyhäsalmi Mine in Finland, with a maximum depth of 1444 meters, is Europe's deepest base metal mine. Mining activity is expected to end in spring or early summer 2021, and numerous projects are underway planning for reuse of the mine, and its excellent infrastructure. Callio Lab is a unique underground research environment with repurposed underground facilities in the mine. [5, 9].

Natural background radiation (NBR) characterization has been done in two underground spaces: Lab 2 and Lab 5. Lab 2 is reachable by vehicle and is located 1430 (1436 in fact) meters below ground. It was the primary location for planned low-background activities until a new space, now named Lab 5, was acquired on the main level at 1410 meters underground. Lab 5 has almost direct access to the lift since it is within 100 meters walking distance. Even more notable is that the levels of gamma-ray background were found to be considerably lower in Lab 5 than Lab 2, proving it to be a more opportune space for low background activity. The radon level as well differed greatly, at Lab 5 it is a mere 21.9 ± 1.1 Bq/m^3, while the results of measurements conducted at Lab 2 ranged from 50 - 300 Bq/m^3 [30]. [19].

3.2 Baltic Sea Underground Innovation Network

Callio Lab is part of the Baltic Sea Underground Innovation Network (BSUIN), which consists of six underground laboratories or conceptual laboratory designs, and the project has over fourteen partner organizations. The main objective of BSUIN is to make underground laboratories in the Baltic sea region more accessible to science and research. This involves thorough and methodologically consistent geophysical, organizational, structural, and NBR characterization. These characterizations provide current and future users and site managers with essential information on the usability and accessibility of the underground laboratory in order to develop their working environment and experimental setups. New users are given comparable data to choose a location most appropriate for their purposes. [10].

3.3 Natural Background Radiation Characterization

NBR characterization (i.e., the mapping of local background sources) is needed to decide what research or experiments are feasible to conduct at a certain location. It is used to ascertain the local NBR sources and activity. NBR characterization can be considered essential in order to utilize an underground laboratory as a low-background environment. [10, 11].

Pilot NBR characterization of the selected BSUIN underground laboratories has been successfully completed as of January 2020. The measurement methodology is designed to be consistent laboratory-specifically as well as from laboratory to laboratory. Emphasis has been placed on detailed documentation in order to ensure that measurement setups can be easily recreated. This provides an opportunity to compare results between laboratories and also in-time within the laboratory. [10, 11, 31].

3.4 Setup and methodology

For comparable and reliable NBR characterization, the pilot measurements followed set guidelines. This included a detailed description of the underground space including the depth and m.w.e., temperature and relative humidity, area and volume of space, air ventilation methods used, geology of the local bedrock as well as what materials are used in surrounding walls and floors. The physical locations of measuring points were documented and included was the height and orientation of measuring devices. [11, 31].

The gamma-ray background was measured with a low-background HPGe spectrometer with additional measurements done with portable HPGe, scintillation, and CZT gamma-ray spectrometers. Radon was measured with a Rad7 radon detector. When radon decays, it produces progenies, such as ^{214}Pb and ^{214}Bi, which affect the local gamma-ray background (GRB) when they decay and emit gamma-rays. Because of this, the HPGe spectrometer measurement was repeated while the measuring chamber was purged with vaporized liquid nitrogen, in order to analyze the significance of radon on the local GRB. [11, 31].

The radioactive content of the materials in the surrounding environment was determined through radionuclide analysis of rock, concrete, and shotcrete samples using the HPGe spectrometer. The samples were crushed to approximately the same size (5 mm diameter) and fit a 1 liter Marinelli vessel. Neutron flux measurements were conducted with proportional ^{3}He counters. [11, 31].

4 Conclusions

Backgrounds in a low-background experiment consist of muons, neutrinos, neutrons, and radioactivity. These all can affect negatively an experimental set-up and cause additional work. Proper research and measurement of these backgrounds is an essential part of low-background experimentation. After mapping of the backgrounds is completed, measures can be taken to mitigate their effects. This will aid in analysis of data and ensure the repeatability of the experiment.

Backgrounds are geology-, depth-, and material- dependent, and no DUL is the same. Measurements to assess the background flux of a laboratory can be conducted through neutron- and muon flux, gamma-ray spectrum, and radon measurements. Detailed documentation should be kept for later use as these can be used for comparing the effectiveness of different background reduction methods, such as gaseous nitrogen flushing and veto detectors.

Whether a physicist has the opportunity to decide the location of a new DUL freely, as was in the case with the Baksan Neutrino Observatory, or repurpose an abandoned mining tunnel, they have plenty of opportunities to affect the significance of backgrounds in their experiments positively. The work begun by Raymond Davis Jr. and John N. Bahcall is far from done, and although they led the way underground, particle physics still has much farther to go. Well-executed low-background experiments will continue leading the way.

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