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Low Background Measurement Program at SNOLAB

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Experiments studying rare event searches, such as dark matter interactions and neutrinoless double beta decay, require ultra-low levels of radioactive backgrounds in their own construction materials, shielding and in the surrounding environment. As the next generation of experiments are becoming even more sensitive, material selection has become one of the most crucial components of the design process for these experiments to reduce these backgrounds to be as low as reasonably achievable. The SNOLAB low background counting program has developed several different methods to directly measure these experimental backgrounds. This proceedings will review the low background measurement facilities at SNOLAB currently used to measure these backgrounds, describe the data analysis techniques and present the capabilities of these detectors. Furthermore, plans and options to expand these facilities will be discussed and a program to measure environmental backgrounds at the SNOLAB underground laboratory will be described.

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1. Introduction

SNOLAB has developed a world class low background measurement facility to search for low background materials which can be used in the construction of highly sensitive neutrino and dark matter search experiments, and biological projects studying the effects of reduced radioactive dose rates in underground laboratories. The low background counting laboratory is located in the underground SNOLAB facility which is 2 km (6000 m water equivalent) below surface at the Vale Creighton Mine, located in Greater Sudbury, Ontario Canada [1]. The counting facility's primary goal is to find and quantity materials which have low concentrations of the radioactive chain elements, ^{238}U, ^{232}Th and ^{40}K, often well below ppt levels. These radioactivity levels are below what is generally accessible by chemical and analytical techniques, therefore assay methods are often performed through radiation counting.

Furthermore, the counting detectors themselves must be very low in background contamination levels, which requires them to be radioactively clean and underground, and fabricated and shielded with low background materials, therefore the search for cleaner materials is ongoing for the next generation of low background detectors. In addition to the underground laboratory, there are surface laboratories which also have counting facilities, such as inductively coupled mass spectrometry (ICP-MS) which do not require the low cosmic-ray background environment. Table 1 summarizes the counting methods used and shows the current sensitivity levels for each technique.

Measurement Method	Backgrounds Detected	Sensitivity
Ge spectrometry	γ emitting nuclides	10 – 100 μBq/kg
Rn emanation assay	^{226}Ra, ^{228}Th	0.1 – 10 μBq/kg
Neutron activation	primordial parents	0.01 μBq/kg
Liquid scintillation counting	α, β emitting nuclides	1 mBq/kg
Mass spectrometry (ICP-MS; AMS)	primordial parents	1 – 100 μBq/kg
Graphite furnace AAS	primordial parents	1 – 1000 μBq/kg
Röntgen Excitation Analysis (XRF)	primordial parents	10 mBq/kg
α spectrometry	^{210}Po, α emitting nuclides	1 mBq/kg

Table 1: Techniques to measure radioactive backgrounds. The sensitivity shown is for the U and Th chains and it is assumed that the chains are in secular equilibrium.

2. Backgrounds at the SNOLAB Underground Laboratory

Underground laboratories have very low levels of cosmogenic backgrounds, however, the dominant backgrounds for experiments located in these laboratories now arises from the experimental construction materials and the surrounding environment, such as the concrete, shotcrete and rock. These backgrounds must be well understood in order to build an experiment that can be shielded from these backgrounds as well as possible. SNOLAB is embarking on an extensive program to measure the neutron and gamma backgrounds throughout the underground laboratory facilities to allow for a better understanding of these backgrounds in the different laboratory areas. Measurements of the rock, shotcrete and concrete have been done using gamma counting and using ICP-MS, ICP-AES and XRF. The results showed that the Norite rock had ^{232}Th and ^{238}U concentrations levels of 5.1 ppm and 1.1 ppm, respectively; and the shotcrete had ^{232}Th and ^{238}U concentration levels

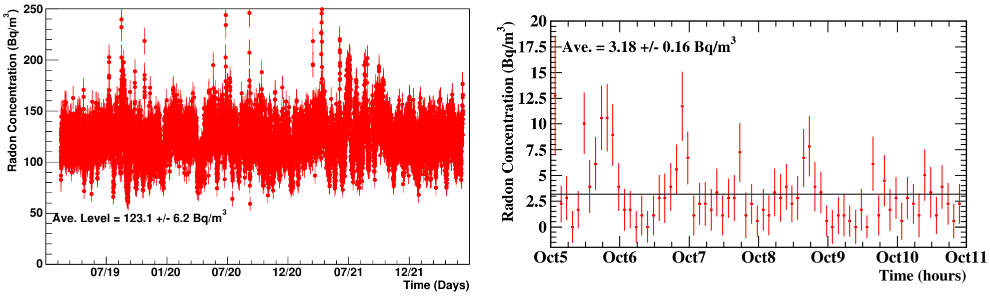

Figure 1: The left plot shows the radon levels in the underground SNOLAB laboratory air. The right plot shows the radon levels in the SNOLAB compressed air supply.

of 2.4 ppm and 1.2 ppm, respectively. The neutron flux from this type of rock and shotcrete was previously measured to be 9.45×10^{-6} cm^{-2} s^{-1} [2]. These results are from only one location in the laboratory, therefore a program to collect new data in different locations is now underway.

A similar study of the gamma background below 3 MeV is also underway at SNOLAB to characterize the gamma background environment. The spectra are expected to vary throughout the laboratory as they depend on the local rock composition and the materials in the laboratory. The measurements are being done with two NaI(Tl) detectors in order to decrease the time required to collect the data from different locations throughout the underground laboratory.

Most low background experiments are very sensitive to the progeny of ^{222}Rn and ^{220}Rn. There are several alphas and gammas created during the decay processes and many of these can mimic the expected signals which most experiments want to observe. SNOLAB has been using Durridge RAD7 radon monitors for several years to measure the radon levels in various locations in the underground laboratory [3]. Figure 1 shows the recent radon levels measured at SNOLAB, the average radon concentration is 123.1 ± 6.2 Bq/m^3, which is well below the radon levels measured without any ventilation to the underground laboratory which has been measured to be 589.8 ± 114.3 Bq/m^3.

However, the radon levels measured in the laboratory are orders of magnitude above what most low background experiments require. Therefore lower radon levels may be achieved at SNOLAB by using air from the compressed air supply from surface, as this air doesn't travel through the underground tunnel system and is therefore not exposed to the higher levels of radon present from the rock walls. Measurements have shown that the compressed air radon levels are 3.18 ± 0.15 Bq/m^3, see the right plot in figure 1. One can also use nitrogen gas to purge radon from small volumes or use radon scrubbing systems to reduce radon in larger volumes.

3. Measurement Methods

SNOLAB has developed several different measurement methods to quantify the amount of radioactivity in various materials as shown in table 1. One of the primary and most effective methods to measure the radioactivity in a material is to directly count the material using an ultra-low background semiconductor germanium spectrometer. These detectors use the purest shielding materials available, such as ancient or ultra-high pure lead and copper, to reduce backgrounds from the lab environment, and use nitrogen boil-off gas to purge any radon from the detector region.

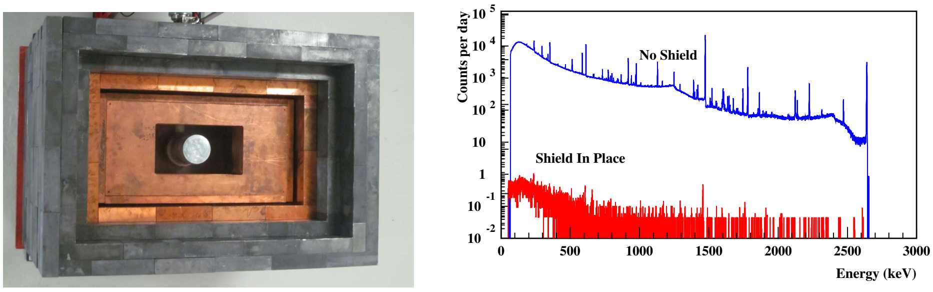

Figure 2: The left figure shows the SNOLAB VdA germanium counter, the high purity lead and copper shielding is shown surrounding the germanium detector. The right plot shows the gamma background spectra in the underground laboratory with respect to the fully shielded gamma spectra.

SNOLAB has five fully operational detector systems in the underground low background lab, an example of a detector showing its shielding layers is shown in figure 2. The detector designs can allow samples of up to several kilograms to be measured to improve the sensitivity of the measurements. The right plot of figure 2 shows a detector spectrum taken with the shielding removed compared to a spectrum with the full shielding in place and the nitrogen purge gas operational, this shows that with the full shielding in place the backgrounds in the detector chamber become negligible. The efficiencies of the detectors are measured using calibration samples which contain known quantities of various isotopes. To account for the different sample geometries and compositions, complete detector models have been developed in Geant4 [4], the efficiency is then corrected using the results of the simulation models.

To further enhance SNOLAB's gamma counting capabilities in cooperation with Health Canada's Radionuclide Laboratory CAL05, a new detector is now being installed and commissioned. This detector is being built as part of Canada's commitment to the Comprehensive Test Ban Treaty (CTBT) to search for rare radionuclides in the atmosphere. The detector system consists of two broad energy germanium (BeGe) detectors facing each other in a common shielding to allow for coincidence studies between the two detectors, thus enhancing the ability to search for very small signals. The gamma detectors can also be used with a small beta detector, which consists of two thin passivated silicon wafers sandwiched between the two BeGe detectors to search for beta-gamma coincidence events in gas samples.

Many isotopes can decay through alpha particle emission. The alphas can be counted using alpha spectrometers to identify and quantify the isotope based on the energy of the emitted alpha particles. Alpha counting is often used for material testing as a complementary method to gamma counting, in particular to measure surface contamination. Samples are generally machined into thin disks, or a liquid solution is placed on a metal disk and then allowed to dry to give a uniform coating. SNOLAB operates an XIA Ultra-Lo 1800 alpha counter in the surface clean labs which uses argon gas in the drift chamber, activities as low as 180 ± 30 nBq/cm^2 have been measured, small residual backgrounds are present from radon and cosmic rays. Further improvements to sensitivity could be achieved by moving the detector underground. Samples as large as 30 cm $\times$ 30 cm and less than 1 cm thick can be measured in this detector.

SNOLAB has long maintained radon emanation detection systems and is continuously im-

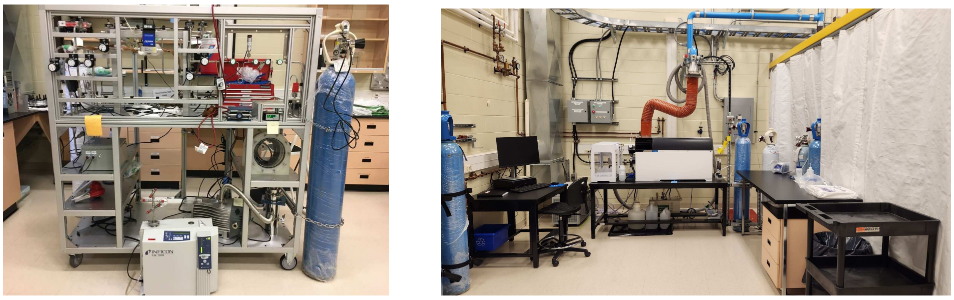

Figure 3: The left photo shows the new SNOLAB radon emanation chamber located in the SNOLAB surface laboratory. The right photo shows the new Agilent ICP-MS system in the SNOLAB surface laboratory.

proving existing systems and has built a complete new radon emanation board to increase our measurement capabilities. Radon emanation of a material is the process in which the radon atoms formed from the decay of ^{226}Ra escape from the decaying isotopes and move into the pore spaces of the molecule. Diffusion and advective flow then cause the movement of the radon atoms throughout the material and subsequently to the surface. Once the radon atoms reach the surface, they can be exhaled from the material (see e.g. [5]). These radon atoms and their progeny can be collected inside a radon exhalation chamber for several half-lives of the ^{222}Rn and then counted directly with a radon detector (e.g. Durridge RAD7 [3]) or using alpha spectrometry. The new SNOLAB emanation board, shown in figure 3, has achieved background levels as low as 2 radon atoms per day and the efficiency has been measured to be $199.23 \pm 4.46\%$, note that the efficiency is calculated relative to 3 alphas being released in the ^{238}U decay chain.

ICP-MS is a type of mass spectrometry which uses inductively coupled plasma to ionize the sample [6–9]. It is often used to identify metals and some non-metals which are dissolved in liquids at very low concentrations. The ions are then separated on the basis of their mass-to-charge ratio and a mass spectrometer then detects the ion signal, which is proportional to the concentration of the isotope. ICP-MS screening is useful for small samples or when a piece of a large sample can be used. SNOLAB has recently acquired a new ICP-MS measurement system from Agilent, the new system is installed in SNOLAB's surface clean laboratories [10]. It is now being commissioned using SNOLAB's ultra pure water as a test media and detection limits have been measured to be 0.109 ppt for ^{232}Th, 0.010 ppt for ^{232}U and 6.784 ppt for ^{210}Pb. Currently, methods are being developed to analyze analytes in isolation and to digest solid samples into aqueous solutions.

4. Summary

The SNOLAB Laboratory has developed several word-class low background counting facilities, many of which take advantage of the depth of the underground laboratory. The laboratory operates several high-purity germanium detectors, an alpha spectrometer, radon emanation chambers and is now developing the process to analyse samples using a new IPS-MS detector. Further developments are ongoing with the expansion of the germanium counting capabilities with the new dual detector being assembled and commissioned in the underground laboratory. These different background measurement capabilities can be used together to find and evaluate new lower background materials required for future low background experiments and to quantity environmental samples.

Acknowledgments

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References

[1] N.J.T. Smith, *The SNOLAB Deep Underground Facility*, *Eur. Phys. J. Plus* **127** (2012) 108.

[2] M. Browne, *Preparation for Deployment of the Neutral Current Detectors (NCDs) for the Sudbury Neutrino Observatory*, PhD Thesis, North Carolina State University (1999).

[3] Durridge Company Inc., http://www.durridge.com/.

[4] J. Allison et al., *Recent Developments in Geant4*, *Nucl. Instrum. Meth. A* **835** (2016) 186; J. Allison et al., *Geant4 Developments and Applications*, *IEEE Trans. Nuc. Sci.* **53** (2006) 270; S. Agostinelli et al., *Geant4 - A Simulation Toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250.

[5] A. Sakoda and Y. Ishimori, *Mechanisms and Modeling Approaches of Radon Emanation for Natural Materials*, *Japanese J. Health Phy.* **52** (2017) 296.

[6] A.L. Gray and A.R. Date, *Inductively Coupled Plasma Source-Mass Spectrometry Using Continuum Flow Ion Extraction*, *The Analyst* **108** (1983) 1033.

[7] R.S. Houk, *Mass-Spectrometry of Inductively Coupled Plasmas*, *Anal. Chem.* **58** (1986) 97.

[8] S.D. Tanner et al., *Reaction cells and collision cells for ICP-MS: a tutorial review*, *Spectrochimica Acta Part B: Atomic Spectroscopy* **57** (2002) 1361.

[9] B. Meermann and V. Nischwitz, *ICP-MS for the analysis at the nanoscale – a tutorial review*, *J. Anal. Atomic Spect.* **33** (2018) 1432.

[10] Agilent Technologies Inc., http://www.agilent.com.