The SNOLAB underground laboratory

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Abstract. The SNOLAB laboratory is 2 kilometers underground in Sudbury, Ontario, Canada. The depth of this location results in a reduction of cosmic-radiation induced muons to the negligible level of one muon per square meter per day. The laboratory maintains cleanliness standards to control the radioactivity from dust falling out of the air, from human activity, and from research equipment brought into the lab. The resulting low-radiation environment enables a variety of research, and SNOLAB is focused on rare-event searches such as dark matter searches and nuclear decay studies. In order to enable and advance these research topics, SNOLAB is conducting research and development into cleanliness, low-level assay, radioactive gasses and cryogenics. SNOLAB collaborates, and competes, with other underground laboratories on these research and development topics, as well as operational topics, to support the global research community.

1. Introduction
Since the discovery of ionizing radiation, researchers have been investigating and studying the sources of ionizing radiation. The majority of ionizing radiation is due to astrophysical phenomena, from the high-energy cosmic rays accelerated in jets to the radioactive decay of elements created in supernovae. Many modern research topics require laboratory environments as free as possible from cosmic radiation and radioactive isotopes. High-energy cosmic rays create showers of particles as they interact in the atmosphere. These secondary particles are often easy to shield; a few meters water equivalent of shielding will reduce the neutrons, protons, and electron secondaries by many orders of magnitude. However, the muons created in cosmic-ray showers can penetrate kilometers of rock, so research and applications with muon-related backgrounds require deep underground facilities.

SNOLAB, situated 2 km underground in Sudbury, Ontario, Canada, is one of the preeminent deep underground laboratories [1, 2]. The research enabled by utilizing the Canadian Shield as a radiation shield has resulted in world-leading results in studying the nature of matter, particularly the nature of dark matter, and the fundamental properties of neutrinos.

2. The current scientific program
The properties of neutrinos and the nature of dark matter are the current scientific drivers for most of the scientific program at SNOLAB. The scientific program continues to broaden and includes astrophysics, genomics, occupational health, mining and nuclear non-proliferation.

The properties of the neutrino are at the forefront of particle physics. The discovery that these particles oscillate between flavors, and the conclusion that neutrinos have mass, has made...
neutrinos an outlier in our understanding of particle physics. The search for neutrinoless double-beta decay is one of the most sensitive experiments probing the nature of the neutrino. These experiments have sensitivity to Majorana neutrinos above some mass threshold, so a detection or null-result will add to the knowledge of the neutrino. For example, if cosmological probes measure the neutrino mass, then a null-result in a neutrinoless double-beta decay experiment would strongly favor the Dirac nature of the neutrino. SNO+ is a flagship experiment at SNOLAB focused on a search for the neutrinoless double-beta decay of $^{130}$Te that will have world-leading sensitivity to neutrino properties. Furthermore, the LEGEND-1000 and nEXO Collaborations, designing two leading experiments for a next generation neutrinoless double-beta decay search, are investigating the possibility of siting their experiments at SNOLAB. SNOLAB has allocated the cryopit, the last unoccupied large experimental hall, to a tonne-scale neutrinoless double-beta decay experiment.

Dark matter is one of the mysteries of cosmology. The modern theory of cosmology tells a compelling, quantitative description of our Universe’s history. However, the two main components in the current cosmological picture, dark matter and dark energy, remain a complete mystery. Dark matter is observed in gravitational measurements from dwarf galaxies to the largest scale structures in the Universe, but baryonic matter thermally formed during the Big Bang just cannot form large-enough gravitational wells to explain the structures observed in our Universe. SNOLAB hosts a number of experiments probing the hypothesis that there is a fundamentally new particle, perhaps part of a dark sector of particle physics, that has very low cross-sections for interactions with baryonic matter. The diversity of these experiments at SNOLAB reflects the diversity of ideas regarding the nature of dark matter. SNOLAB hosts NEWS-G, miniCLEAN, DAMIC, DEAP-3600, SuperCDMS-SNOLAB, PICO-40L and PICO-500 and SENSEI, all with the primary goal of searching for dark matter interactions in ultra-sensitive detectors.

The scientific program continues to broaden and include more multi-disciplinary and applied research. SNOLAB is hosting REPAIR, studying the effects of low-level radiation on cell repair mechanisms. The FLAME experiment is collecting data on the impacts on metabolism from working deep underground. A group is constructing a 15 m xenon distillation column to study the performance of distillation packing materials and the relative volatility of noble element isotopes.

A number of researchers at SNOLAB are still sensitive to, and actively searching for, neutrinos from various astrophysical sources. This was the original goal of the SNO experiment that started research at the SNOLAB site, studying the fluxes of various neutrino flavors emanating from the Sun. The HALO lead-based detector is a detector sensitive to neutrinos from supernovae in the local Galaxy. Although not the focus of those efforts, the extraordinary sensitivity of many of the dark matter experiments, and the neutrinoless double-beta decay experiments, is enough to detect neutrinos from galactic supernovae as well. Although it is interesting that the lead-based technology is less sensitive to anti-neutrinos than most technologies for observing neutrinos, so HALO is poised to make a unique contribution to supernova observations.

3. Research and development on capabilities that enable research

Research and development is lower in priority at the laboratory than supporting the experimental construction and operational requirements. However, SNOLAB does conduct research and development to improve the capabilities and services at the laboratory. Research and development projects are investigated if they align with active experimental needs and/or they improve the SNOLAB capabilities to serve researcher needs. Based on a survey of user strategies and potential future projects, SNOLAB has identified cryogenics and low-background assay, materials and assembly as critical development needs.

Underground physics detectors are typically cryogenic, liquid xenon down to millikelvin
temperatures, so SNOLAB is focusing research and development on cryogenic infrastructure. The laboratory is currently using ~ 2000 litres of liquid nitrogen, so we are developing a project to meet this need through underground nitrogen generation rather than shipping dewars full of liquid nitrogen. This will have the impact of reducing the logistical work in supplying required cryogens to the point of use. Additionally, SNOLAB scientific, engineering and operations staff will continue to develop their skills and knowledge related to medium sized cryogenic infrastructure to meet future experiment needs.

Underground, rare-event searches continue to push the boundaries of low ionizing radiation specifications. Many of the R&D projects at SNOLAB focus on enabling researchers with extraordinary low background requirements. There are a few threads of development that are in various stages at SNOLAB. The radiation counting capability at SNOLAB has grown significantly over the past few years. Clean construction is an area of interest, because it is a broad need that reoccurs for most experiments. Finally, SNOLAB is improving the data available to researchers, including radon levels, particulate levels and analysis.

Pacific Northwest National Laboratory and SNOLAB are developing an assay protocol to understand the radioactive fallout during routine operations and critical detector assembly [3]. A container is exposed to fallout for a period of time, say one month, and then ICP-MS is used to measure the uranium, thorium, potassium, and lead fallout. This has led to a dramatic change in the understanding of radioactivity from particulates in the air at SNOLAB, because we assumed particulates were contaminated at levels similar to dust in the mine environment. The particulates collected in SNOLAB are lower than mine dust by a few orders of magnitude with respect to mine dust. This research has also made clear that the nature of fallout in the laboratory is directly related to activities in the laboratory. For example, lead levels in the air are elevated when we are moving lead stacks. With a baseline technique to measure radioactive fallout during operations, we plan on both researching assembly techniques that minimize radioactive contamination and continuously measuring radioactive fallout throughout the laboratory so users can have access to those data.

Radon is a significant issue for many experiments, so radon measurement and removal is a research and development topic at SNOLAB. Underground sites have the potential of significantly elevated radon levels, exacerbating the issues; the radon activity in SNOLAB air is typically 100 to 150 Bq/m$^3$. We are currently developing a project to supply low-radon air for critical operations and samples that are impacted by the deposition of radon daughters. Additionally, SNOLAB is continuously monitoring the radon levels at a number of locations throughout the laboratory. Also, SNOLAB has a radon emanation capability and we are improving the process systems and detectors to improve the sensitivity of that capability. Finally, we are implementing the ability to measure surface alpha activity for research and quality control.

4. Final remarks
SNOLAB is now full of experiments focused on a number of areas of research. Most experiments are focused on neutrino properties and the nature of dark matter, but the experimental portfolio has been diversifying and now includes genomics, national security, and the effects of underground work. SNOLAB is focused on improving services and capability for cryogenics and low-background materials/assay/assembly. It is clear that there is a large amount of interest in future research projects that require deep underground sites. SNOLAB anticipates working with the research community to maximize the scientific impact of the current suite of experiments, to plan next generation efforts, and to explore new research topics.

Partnerships with other particle physics laboratories is critical to the continued success of underground physics. The large laboratories, traditionally focused on accelerator based particle physics, have become key partners due to the confluence of the scientific motivations and a
need for expertise in building large detectors. The underground laboratories all compete for status and science, but also collaborate on sharing best practices, research and development, and evaluating the need for underground space. These partnerships, both in collaboration and competition, make the underground science more dynamic and productive.

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References
[1] Smith N J T 2012 *The European Physical Journal Plus* **127** 108 ISSN 2190-5444 URL https://doi.org/10.1140/epjp/i2012-12108-9
[2] Duncan F, Noble A and Sinclair D 2010 *Annual Review of Nuclear and Particle Science* **60** 163–180 URL https://doi.org/10.1146/annurev.nucl.012809.104513
[3] di Verci M 2019 Study of surface contamination in ultralow background (ulb) materials URL https://indico.cern.ch/event/806050/contributions/3502706/