Possibilities for Underground Physics in the Pyhasalmi mine

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The Pyhasalmi mine is uniquely suited to host new generation of large-scale underground experiments. It was chosen both by the LAGUNA-LBNO and by the LENA Collaboration as the preferred site for a giant neutrino observatory. Regrettably, none of these projects got funded. The termination of the underground excavations in the fall of 2019 marks an important milestone. To maintain the infrastructure in good condition a new sponsor must be found: either a large-scale scientific project or a new commercial operation. The considered alternatives for the commercial use of the mine include a pumped-storage hydroelectricity plant and a high-security underground data-storage centre. Without a new sponsor the ongoing experiments, including the cosmic-ray experiment EMMA and the study of C14 content in liquid scintillators, have to be completed within the next few years.

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1 Introduction

Earth’s atmosphere is exposed to a steady flux of energetic particles known as cosmic rays [1]. Cosmic-ray interactions with nuclei in the atmosphere induce intense showers of secondary particles. Most of them won’t even reach the ground, but the high-energy muons created at the early stages of the shower cascade will penetrate deep under the surface of the Earth. These muons are the leading source of background [2] e.g. in experiments searching for dark matter or aiming to detect neutrinoless double beta decay. To reduce this background, one has to place the measuring setup deep underground and assure long acquisition times. The growing interest in low-background measurements generates demand for well-equipped underground laboratory space able to accommodate the detectors, auxiliary equipment and the supporting infrastructure. Such facilities are usually located in unused sections of a mine or as an annex to a road or a railroad tunnel. The Pyhasalmi mine in Finland offers an excellent location to host a variety of deep-underground experiments. As it was documented during the LAGUNA-LBNO design study [3], the exceptional quality of the surrounding rock combined with a modern mining infrastructure make Pyhasalmi an ideal location for the construction of gigantic caverns even at the maximum depth of 1400 m below the ground.

2 The Pyhasalmi mine

During the second half of 2019 the underground operations in the Pyhasalmi mine are coming to an end while the reprocessing activities at the surface will still continue for a few more years. As a legacy of nearly 60 years of operation and especially thanks to the technological upgrades realized within the past two decades, the infrastructure of the mine is in excellent condition including modern communication services and safety procedures. The main level of the mine, where all the major facilities are located, is at 1400 m underground. These facilities, now scheduled for gradual decommissioning, include four large halls designed for storage, service and maintenance of mining machinery. There are also control rooms, social areas and a restaurant. The 1400 m level is accessible from the ground level by an elevator and by a 12-km long truck-size decline. The elevator ride takes about three minutes while a car ride lasts about half-an-hour. In addition to the main level, there are additional large caverns at the depths of 990, 660 and 400 m.

To promote, maintain, and operate the underground premises throughout the transition period and after the closure of the mine, an organization called Callio has been established [4]. The largest of the considered commercial alternatives is a pumped-storage hydroelectricity (PSH) plant [5]. If realized, it would be the first PSH in Finland. With the hydraulic head of 1400 meters and the storage volume of 162,000 m$^3$
it would have the effective capacity of 1 GWh and utilize one or two 75 MW turbines. The other large-scale alternative is an underground data centre. If one or both of these projects were realized, the future of the mine underground infrastructure would be secured, making a continuation of smaller, both scientific and commercial projects possible.

![Image](image_url)

Figure 1: A photograph of the C14 setup in the main hall of Lab2 at the depth of 1430 m (4100 m.w.e.) in the Pyhasalmi mine.

## 3 Deep-underground laboratory

The deep-underground laboratory in the Pyhasalmi, known as Lab2, is located at the depth of 1430 m corresponding to 4100 m.w.e. The area of the main hall of Lab2 is about 120 m² and the maximum height is about 7.5 m. The area of the adjoining entrance hall is about 100 m² and has the height of about 5 m, sufficient to accommodate a delivery truck. Lab2 is situated about 500 m away from the elevator shaft and is accessible also on foot. The laboratory space is equipped with the ventilation, the optical fibre, and a 1 GB internet connection. Currently the flux of fresh air to the laboratory is maintained at the level of about 10 m³/s. For the electric power...
there is a 160 kVA line at the entrance hall and a 25 kVA and a 3 kVA (UPS) lines in the laboratory hall. The radon level in Lab2 is about 240 Bq/m$^3$ and the temperature is about 26 °C. Figure shows the main hall of Lab2. The available space is sufficient to accommodate small- to medium-size experiments and would be well suited e.g. for low-background measurements.

3.1 Muon and neutron background in Lab2

The knowledge of the neutron background, originating from radioactive decays and induced by muons, is important for many experiments. The first muon flux measurements in the mine date back to 2005. The measured flux at the depth of 1390 m (4000 m.w.e.) was $(1.1 \pm 0.1) \times 10^{-4}$ m$^{-2}$s$^{-1}$ [6]. The neutron background measurement in Lab2 was performed in July 2018. The setup consisted of $^3$He counters and $^{10}$B-loaded plastic scintillation detectors. The results are scheduled to be published soon, but there are already indications that the flux of thermal neutrons in the Pyhäsalmi mine is higher than in Gran Sasso. The current measurements are part of the Baltic Sea Underground Innovation Network program (BSUIN) [7].

4 Ongoing physics experiments in the mine

Currently there are two physics experiments taking data in the mine: the cosmic-ray experiment EMMA at the depth of 75 m and the C14 experiment probing the concentration of $^{14}$C in liquid scintillators in the main hall of Lab2.

4.1 EMMA

EMMA (Experiment with Multi-Muon Array) [8] is a dedicated underground cosmic-ray experiment studying the mass composition at the knee region. The setup consists of 11 nearly completed detector stations situated at the shallow depth of 75 m. This overburden of about 210 m.w.e. provides about 45 GeV cut-off energy for atmospheric muons. The three central stations are capable of performing muon tracking with the angular resolution of up to 1 degree and with density resolution of up to 60 muons per m$^2$. The remaining stations (Fig. 2) are intended to sample the lateral density distribution of muons over the fiducial area of about 300 m$^2$.

Our simulations indicate that the lateral density distributions of muons with energy over 45 GeV are model-independent and contain the information both on the mass and on the energy of the primary cosmic ray [9]. The energy can be deduced from the muon density at the core while the mass – from the slope of the lateral distribution.
Figure 2: Layout of detector stations of the EMMA experiment. The three central stations provide high-resolution tracking to determine the direction of the muon shower around the core. The remaining stations have adequate resolution to sample the density at the edges of the distribution.

If completed and operated for three years in the full configuration, EMMA would make a significant contribution towards solving the long-standing puzzle of the presence of the knee in the energy spectrum of cosmic rays. This, in turn, may reveal further information on the cosmic-ray sources and acceleration mechanisms. The current understanding is that the acceleration can take place up to the knee energies in supernova shock fronts that could propagate thousands of years after the explosion. However, there should be also other mechanisms since the supernova shock front mechanism does not produce energies above the knee. Addressing these questions is relevant and important as they are among the major topics in the present-day astrophysics.

The second important task for EMMA is to verify the alleged muon excess [10] in the extensive air showers (EAS). This problem is extremely important because, if confirmed, it would force substantial revision of the existing particle interaction models with serious repercussions in multiple fields of science relaying on these models.
5 C14 experiment

The beta decay of the long-lived radioactive $^{14}\text{C}$ is the main source of background for low-energy ($E \approx 300 \text{ keV}$) neutrino measurements using high-purity liquid scintillation detectors [11]. The lowest $^{14}\text{C}$ concentration has been reported by the Borexino Collaboration for Pseudocumene (PC) amounting to $\sim 2 \times 10^{-18}$ [12]. There are three other published results for the concentration (for PXE and PC+Dodecane) with the highest being $(12.6 \pm 0.4) \times 10^{-18}$ [13][14][15]. Currently the preferred solvent for the new generation of large neutrino detectors is LAB (Linear alkylbenzene). LAB, just like the other petrochemical products, is synthesized from the crude gas or oil extracted from deep geological deposits where the expected remanences of the cosmogenic $^{14}\text{C}$ are very low. It should therefore be possible [16], by a careful selection of the gas field that is free of recent contaminants, to reach low concentration of the radiocarbon. The concentration of $^{14}\text{C}$ in LAB has not yet been measured with sufficient sensitivity. Lab2 in the Pyhasalmi mine is one of the sites where a dedicated setup for such measurements is being constructed (Fig. 1). It is intended to make systematic analysis of the samples of different origin and composition with the aim of finding concentrations smaller than $10^{18}$ for the use, for instance, by the SNO+ [17] and the JUNO Collaboration [18]. Such low concentrations are currently below the sensitivity of the Atomic Mass Spectrometry [19].

6 Future plans and possibilities

6.1 Giant liquid-based neutrino detectors

Considering the modern infrastructure and safety, the quality of the surrounding rock, the small footprint of the ore deposit, the low maintenance costs, and the depth of the main level (4100 m.w.e.), the Pyhasalmi mine has ideal conditions to host underground experiments of the next generation [20]. In fact, Pyhasalmi was already selected as the prime site for the far detector of the LAGUNA-LBNO project. The plan was to produce neutrino beam at CERN and send it over the distance of 2288 km to Finland [21]. However, following new strategy and cooperation agreements, CERN has ceded to Fermilab all accelerator-based neutrino physics research and LAGUNA was replaced by the DUNE experiment [22]. Nevertheless, the feasibility for the construction of giant caverns, capable of containing 50 kton detectors together with the needed equipment in a single cave has been confirmed [23].

The second of the LAGUNA detectors that has chosen the Pyhasalmi mine as its preferred location is LENA (Low Energy Neutrino Astronomy) [11] – a 50 kton liquid scintillator, multi-purpose neutrino observatory. Unfortunately, the LENA Collaboration failed to obtain adequate support from the funding agencies to realize the project. Instead, the majority of the neutrino scientists involved with the liquid
scintillator technology have joined the reactor neutrino experiment – JUNO [18]. Nevertheless, the bulk of the astroparticle goals of LENA cannot be covered by JUNO as it is located at a relatively shallow depth of 600 meters and at the distance of 53 km from 10 high-power nuclear reactors. It is therefore conceivable that, in a few years and benefiting from the technological developments of JUNO, LENA or a similar project will be reconsidered.

6.2 Acoustic detection of neutrinos in the rock

One of the requirements of the extended site investigation for LAGUNA-LBNO was to drill a network of boreholes reaching far out and deep down from the vicinity of the main level into the surrounding area. These boreholes have very well documented geological profile and are now available for scientific research. As illustrated in the Fig. 3, the explored area covers the volume of about 1 km$^3$ reaching from the depth of around 1300 m down to 2500 m. The total length of the new boreholes is 3.5 km. It has been proposed [24] to deposit strings of microphones into the boreholes in a similar fashion it has been done or is going to be done by the ANTARES/AMADEUS [25] and the KM3NeT [26] collaborations for the purpose of acoustic detection of particle showers following interactions of ultra-high energy neutrinos. This type of measurement in the rock have never been tried or even proposed before. Nevertheless, since the density of rock is three-times larger and the speed of sound is four-times larger, the amplitude of the generated bipolar pressure pulse in rock should be by an order of magnitude larger than in water. In addition, a higher density of rock also guarantees higher interaction rate for neutrinos while a longer attenuation length in rock reduces signal dissipation.

7 Conclusions

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Figure 3: A network of 3.5 km of boreholes covering the volume of about 1 km$^3$ extending from the depth of around 1300 m down to 2500 m. It has been proposed to use the boreholes for the deployment of microphones for acoustic detection of high-energy neutrinos.

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