A New Low Background Laboratory in the Pyhäsalmi Mine: Towards 14C free liquid scintillator for low energy neutrino experiments

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A new low background laboratory in Pyhäsalmi mine in the Central Finland has been put into operation in the beginning of 2017. The laboratory operates at the depth of 1436 m (~4100 meters of water equivalent). In this paper we present description of the laboratory’s existing facility and background conditions. In the laboratory a series of measurements has been started where the \(^{14}\text{C}/^{12}\text{C}\) ratio is determined from several liquid scintillator samples. A dedicated setup has been designed and constructed with the aim of measuring the \(^{14}\text{C}/^{12}\text{C}\) ratio smaller than \(10^{-18}\).
1. Introduction

The Pyhäsalmi mine is located in the Central Finland. The maximum depth of the mine is ~1440 m corresponding to ~4100 meters of water equivalent (m.w.e.). There is well developed infrastructure in and around the mine. High quality highways and railroads connect the site with international airports in Helsinki and Oulu. The geographical location and transverse section of the mine are shown in Fig. 1a and b respectively. It takes half an hour to reach the deepest point from the surface by very heavy trucks using 11 km long decline or just 3 minutes by a hoist capable transporting ~21 tons of ore or 20 persons. At the deepest point there is also high quality communication system (fiber optics, mobile phone network).

The foregoing put the mine into excellent position to host large scale astroparticle experiments. Indeed, the site has been under intense discussions connected with a number of astroparticle physics experiments - LAGUNA long base line experiment and LENA multi-purpose low energy neutrino project.

a) b)

Figure 1. Pyhasalmi mine – a) geographical location; b) transverse section/

Presently a collaboration of several Finnish and Russian universities and institutions are running the EMMA experiment [1, 2], which is located in the mine at relatively shallow depth of 85 m (~240 m.w.e.). The experiment measures muon multiplicities of extensive air showers trying to study mass composition of primary cosmic rays around the “knee” region (~5×10^{15} eV).
2. Facility of a new low background laboratory in the Pyhasalmi mine.

In parallel to the EMMA experiment several years ago we started to develop a low background laboratory in the big cavity at the depth of 1436 m (~4100 m.w.e.). The laboratory is provided with air ventilation, electricity and connected with the surface laboratory via optical fibre. A photograph of the new low background laboratory is shown in Fig. 2.

Figure 2. Pyhasalmi mine

The radon content in the laboratory is at the level of less than 20 Bq/m³. Radioactive background of surrounding rock is the following:

\[ ^{238}\text{U} \leq (7.8\pm0.3)\times10^{-8} \text{ g/g} \]
\[ ^{232}\text{Th} \leq (7.6\pm1.5)\times10^{-8} \text{ g/g} \]
\[ ^{40}\text{K} \leq (1.69\pm0.02)\times10^{-7} \]

The rock activity measurements were done at the Baksan low background laboratory. The depth intensity curve measured at different depths in the mine is presented in Fig. 3 [3]. The muon flux at the depth of 1390 m, slightly above the low background laboratory is

\[ F=(1.1 \pm0.1)\times10^{-4} \text{ m}^{-2} \text{ s}^{-1} [3]. \]

The new laboratory operation started with measurements of concentration of \(^{14}\text{C}\) isotope in liquid scintillators.
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Figure 3. Depth-intensity curve measured in the Pyhasalmi mine [3]

3. Measurements of $^{14}$C concentration in liquid scintillators

The intrinsic $^{14}$C concentration in a liquid is the main source of background at very low energies in high-purity liquid scintillation detectors. Previously measured concentration values are shown Tab. 1 for scintillators based on PC (Pseudocumene; C9H12), PXE (Phenylxylylethane; C16H18) and Dodecane (C12H26). There are no published data for the $^{14}$C concentration in the LAB (Linear alkylbenzene; C6H5CnH2n+1, n=10−16) being currently the most favorable liquid scintillator in large-volume detectors (e.g. SNO+ and JUNO).

<table>
<thead>
<tr>
<th>$^{14}$C concentration ($\times 10^{-18}$)</th>
<th>Liquid scintillator &amp; fluor</th>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.94±0.09</td>
<td>PC+PPO</td>
<td>Borexino CTF</td>
<td>4</td>
</tr>
<tr>
<td>9.1±0.4</td>
<td>PXE+p-Tp+β-MSB</td>
<td>Borexino CTF</td>
<td>5</td>
</tr>
<tr>
<td>3.98±0.94</td>
<td>PC-Dodecane+PPO</td>
<td>KamLAND</td>
<td>6</td>
</tr>
<tr>
<td>12.6±0.4</td>
<td>PXE+PPO</td>
<td>Dedicated set-up</td>
<td>7</td>
</tr>
</tbody>
</table>

The β-decay end-point energy of $^{14}$C is quite low, $Q_\beta$=156 keV, and the counting rate may be often lowered by setting the appropriate threshold energy. However, too high concentration of $^{14}$C in the liquid may result in pile-ups of pulses. For example, in the Borexino detector at Gran Sasso, Italy, the trigger rate is largely dominated by the $^{14}$C isotope [8] (with the concentration
of $2 \times 10^{-18}$).

Based on the analysis of the $^{14}$C concentration in liquid scintillators derived from deep oil and gas fields \cite{9}, values lower than $10^{-18}$ should be achievable if the source is carefully chosen. The contamination from the reaction $^{14}$N(n; p)$^{14}$C is expected to be the main source of $^{14}$C also deep underground but now neutrons are emitted by the decay chains of U and Th isotopes. A campaign has been started to measure the $^{14}$C concentration in several liquid scintillator samples (based on oil, gas and coal derivatives of different locations) with the aim of finding out concentrations smaller than $10^{-18}$. Measurements are being carried out simultaneously, with essentially similar instruments and rock overburden, in two deep underground laboratories: in the Baksan Neutrino Observatory, Russia \cite{10} and in the new low background laboratory in the Pyhäsalmi Mine \cite{11}.

In order to study the $^{14}$C concentration in liquid scintillators at the level lower than approximately $10^{-15}$, being currently the lower limit achieved by Accelerator Mass Spectrometry (AMS) method \cite{12}, a dedicated experimental setup has been developed, Fig. 4a. The central part of the detector setup of the present work consists of two low-activity PMTs (3" ET 9302B), Fig. 4c, two acrylic light guides and a quartz (or acrylic) vessel of 1.6 litres, Fig. 4c. The vessel and light guides are wrapped by VM2000 reflecting foil.

The shielding against $\gamma$ and neutron background is complemented using thick layers (10-15 cm) of copper and lead around the central part. Paraffin layer (approximately 10 cm, as the outer layer) may also be used to thermalize neutrons from the rock. The central part of the setup is planned to be flushed with nitrogen to reduce the background from radon. The DAQ is realized with the DRS4 evaluation board (V5) \cite{13} based on the DRS4 Switched Capacitor Array chip designed at the Paul Scherrer Institute, Villigen, Switzerland. The two PMTs are directly
connected to the inputs of the DRS4 board which is connected to the DAQ Laptop via an USB connector. The DRS4 samples the pulse in 1024 bins of the width of 0.2 ns with the maximum sampling speed of 5 GS per second. Two channel high voltage power supply module NHQ 203M HV produced by iseg, Germany, is used to power the PMTs. The PMTs radioactive background levels were measured also at the Baksan low background laboratory and their values are the following:

\[
\begin{align*}
^{238}U & \leq 220 \text{ mBq/PMT} \\
^{232}Th & \leq 24 \text{ mBq/PMT} \\
^{40}K & \leq 400 \text{ mBq/PMT}
\end{align*}
\]

The liquid scintillator samples are purified using Al₂O₃ column and then mixed with ~3 g/l of PPO and bubbled with nitrogen to remove oxygen. The purification is currently performed in the room atmosphere. A special purification system where the full process could be performed in a nitrogen atmosphere is in the design phase. The energy calibration is performed with several γ-ray sources using the position of their Compton edges or the full absorption peak at low energies (around 100 keV). Sources currently in use include \(^{57}Co, ^{109}Cd, ^{133}Ba, ^{137}Cs\) and \(^{241}Am\). Essentially linear calibration curves are expected.

Figure 5. Shielding of the set-up for measurements of 14C concentration.

The calibration of 3-inch ET9302B photomultiplier tubes has been carried out in a black box with a LED light source. In the data processing the digitized waveforms are analyzed and the signal shapes are used to reduce α and neutron induced backgrounds. So far there are no final experimental results available yet from Baksan or Pyhäsalmi measurements for any sample. However, as a preliminary result, a concentration value close to \(10^{-17}\) has been obtained in the first measurement of a LAB samples of Russian origin (KINEF Company, S.-Petersburg region, Russia).
4. Conclusion

The new low background laboratory in Pyhäsalmi mine in the Central Finland started to operate. The laboratory is located at the depth of 1436 m (~4100 meters of water equivalent). In the laboratory a series of measurements began to study $^{14}$C concentration in a number of liquid scintillators produced by several manufacturers and from different oil and coal derivatives. A dedicated setup has been developed and built with the aim of measuring the $^{14}$C/$^{12}$C ratio smaller than $10^{-18}$. The laboratory’s deep location, low radioactivity background of surrounding rock and very good infrastructure allows to hope that the laboratory will start to attract many large-scale astroparticle physics experiments. This work was supported by the Russian Foundation for Basic Research, grant #16-52-53120.

References