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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}C concentration is determined from several liquid scintillator samples. A dedicated setup has been designed and constructed with the aim of measuring the ^{14}C/^{12}C ratio smaller than 10^{-18}.

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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 high ways 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 ven 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.

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/m^3. Radioactive background of surrounding rock is the following:

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

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

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

The new laboratory operation started with measurements of concentration of ^{14}C isotope in liquid scintillators.

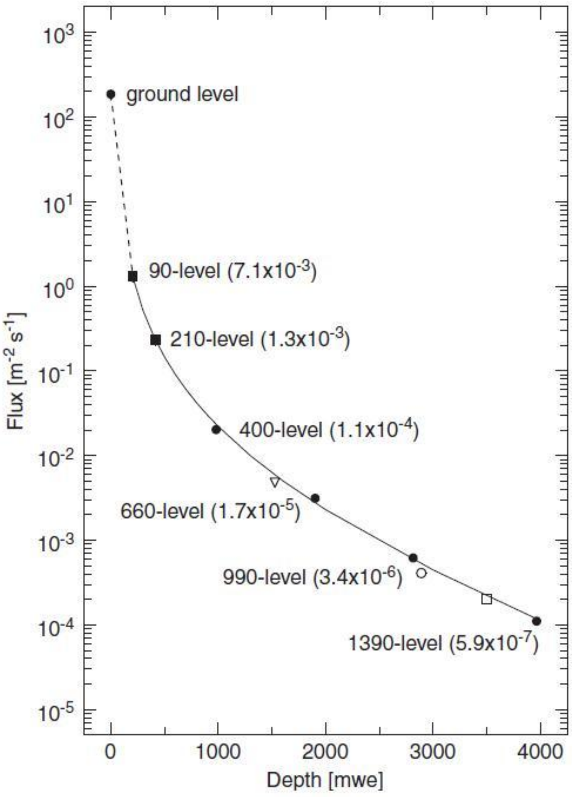

Figure 3. Depth-intensity curve measured in the Pyhasalmi mine [3]

3. Measurements of ^{14}C/^{12}C ratio in liquid scintillators

The intrinsic ^{14}C content in liquid solvents is the main source of background at very low energies in high-purity liquid scintillation detectors. ^{14}C concentration values measured in a number of liquid organic solvents are presented in Tab. 1 for scintillators based on PC (Pseudocumene; C9H12), PXE (Phenylxylylethane; C16H18) and Dodecane (C12H26). So far there are no published data for the ^{14}C concentration measurements in LAB (Linear alkylbenzene; C6H5CnH2n+1, n=10÷16) which is presently the most actively used solvent for liquid scintillator being under development for large-scale detectors of low energy neutrinos like SNO+ and JUNO.

Table 1

^{14}C concentration (×10^{-18})	Liquid scintillator & fluor	Experiment	Reference
1.94±0.09	PC+PPO	Borexino CTF	4
9.1±0.4	PXE+p-Tp+β-MSB	Borexino CTF	5
3.98±0.94	PC-Dodecane+PPO	KamLAND	6
12.6±0.4	PXE+PPO	Dedicated set-up	7

The end-point energy (Q_β) of the ^{14}C β-decay spectrum is relatively low, Q_β=156 keV. Therefore, the detector counting rate due to ^{14}C β-decay could be simply lowered by setting the appropriate threshold energy. Nevertheless, unfortunately, too high concentration of ^{14}C in the liquid scintillator may results in the effect of pile-ups of pulses. For instance, in the Borexino detector at Gran Sasso, Italy, the trigger rate is largely dominated by the ^{14}C isotope [8] (with the ^{14}C/^{12}C ratio of $\sim 2 \times 10^{-18}$).

Based on the analysis of the ^{14}C/^{12}C ratio in liquid scintillators produced using derivatives from old deep oil and gas fields [9], it is believed that values of ^{14}C content 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 in this case neutron flux is produced by U and Th decay chains. A dedicated 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 goal to find samples with ^{14}C concentrations smaller than 10^{-18}. Careful measurements of ^{14}C concentrations are presently ongoing simultaneously with essentially similar set-ups and rock overburden, in two deep underground laboratories: in the Baksan Neutrino Observatory, Russia [10] and in the new low background laboratory in the Pyhäsalmi Mine [11].

The Accelerator Mass Spectroscopy (AMS) method [12] is capable to measure isotopes concentrations at the level of 10^{-15}. To study the ^{14}C concentration in liquid scintillators at the level lower than 10^{-15} a dedicated experimental set-up has been developed, Fig. 4a. The central part of the detector set-up of the present work consists of two low background PMTs (3" ET 9302B), Fig. 4c, two acrylic light guides and a quartz vessel of 1.6 litres, Fig. 4c. The vessel and light guides are wrapped by VM2000 high reflective foil.

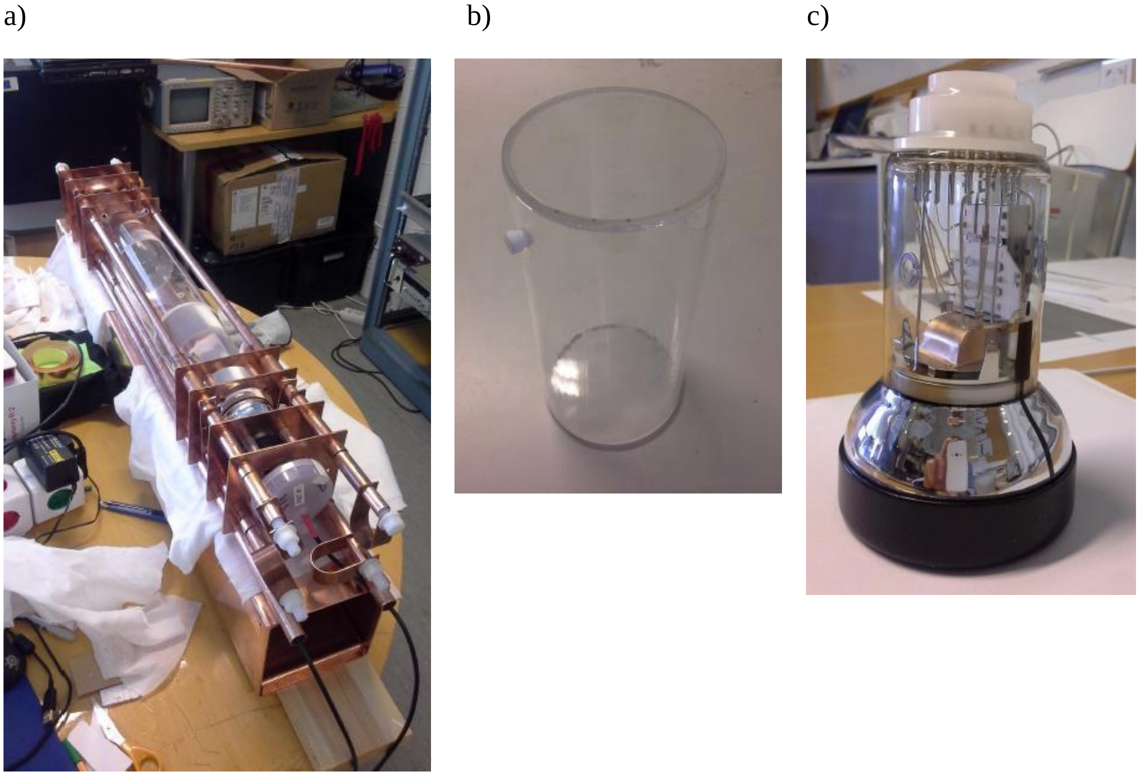

Figure 4. A dedicated set-up for measurements of 14C concentration in the Pyhäsalmi mine.

The shielding against γ and neutron background is implemented using thick layers (10÷15 cm) of copper and lead around the central part. Paraffin layer (approximately 10 cm, as the outer

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layer) may also be used to thermalize neutrons from the surrounding rock. The central part of the set-up is flushed with nitrogen to reduce the background from radon. The DAQ is developed using the DRS4 evaluation board (V5) [13] which is based on the DRS4 Switched Capacitor Array chip designed at the Paul Scherrer Institute, Villigen, Switzerland. Output signals of the two PMTs are fed directly to the inputs of the DRS4 board, which is connected to the DAQ Laptop via an USB connector. The DRS4 digitizes the pulse waveform in 10-bits range with 0.2 ns step and with the maximum sampling rate of 5 GS/s. 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:

^{238}U ≤ 220 mBq/PMT
^{232}Th ≤ 24 mBq/PMT
^{40}K ≤ 400 mBq/PMT

Solvents of the liquid scintillator samples are purified by standard means using Al_2O_3 column and they are mixed with ~3 g/l of PPO and bubbled with nitrogen to remove oxygen. The purification process is currently performed at the room atmosphere. A special purification system where the full process could be performed in a nitrogen atmosphere is presently under development. The energy calibration of the whole set-up is carried out using a number of γ-ray radioactive sources and finding the position of their Compton edges or the full absorption peak at low energies (~100 keV). ^{57}Co, ^{109}Cd, ^{133}Ba, ^{137}Cs and ^{241}Am sources are currently used in calibration measurements.

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 the laboratory with a fast blue LED light source. In the data processing, the digitized waveforms of the PMT signals are analyzed and the signal waveforms are used to suppress α-particles and neutron

induced backgrounds.
Measurements of ^{14}C content in different samples of liquid scintillators are being intensely done and as long as there are no final experimental results available yet from the new low background laboratory in the Pyhäsalmi mine.

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.

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