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# A mobile detector for measurements of the atmospheric muon flux in underground sites

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ABSTRACT

Muons comprise an important contribution of the natural radiation dose in air (approx. 30 nSv/h of a total dose rate of 65–130 nSv/h), as well as in underground sites even when the flux and relative contribution are significantly reduced. The flux of muons observed underground can be used as an estimator for the depth in mwe (meter water equivalent) of the underground site. The water equivalent depth is important information to devise physics experiments feasible for a specific site. A mobile detector for performing measurements of the muon flux was developed in IFIN-HH, Bucharest. Consisting of two scintillator plates (approx. 0.9 m$^2$) which measure in coincidence, the detector is installed on a van which facilitates measurements at different locations at the surface or underground. The detector was used to determine muon fluxes at different sites in Romania. In particular, data were taken and the values of meter water equivalents were assessed for several locations at the salt mine in Slanic-Prahova, Romania. The measurements have been performed in two different galleries of the Slanic mine at different depths. In order to test the stability of the method, also measurements of the muon flux at the surface at different elevations were performed. The results were compared with predictions of Monte–Carlo simulations using the CORSIKA and MUSIC codes.


## 1. Introduction

The muons in the atmosphere originate from leptonic decays of pions and kaons generated by the high-energy collisions which cosmic rays experience with the atoms of the Earth's atmosphere. Muons are unstable particles which decay into electrons and positrons, respectively, with two corresponding neutrinos (electron ($\nu_e$) and muon ($\nu_\mu$) neutrinos) with a life time (in their own reference system) of $\tau_\mu = 2.2\ \mu$s. As leptons, muons are less affected by hadronic interactions and interact weakly with matter. They penetrate large thicknesses of matter before they are stopped and subsequently decay. Hence they are historically known as the "penetrating component" of secondary cosmic rays, even detectable in deep underground sites. The cosmic ray muon flux, defined as the number of muons transversing a horizontal element of area per unit of time [1], is of interest for various branches of science, in elementary particle physics as a "heavy electron", as a messenger of astrophysical processes, in environmental and material research inducing natural radiation damages, and with a role for cosmogenic production of long-lived isotopes. The focus of this paper is on studies of the atmospheric muon flux in the Slanic-Prahova underground site. This site is actually under discussion as the location of a large detector of the LAGUNA project [2–4]. This paper intends to provide some basic information characterizing the site, in particular on the underground depth of the salt mine.

A different reason for measuring the flux of atmospheric muons underground arises from the need for information on the cosmic radiation background for different sites. This background consists not only of muons which have survived the passage through the rock above, but also of contributions of natural radioactivity and of muon-induced radiation like neutrons, which can play a decisive role for low background experiments [5].

For a simple and efficient procedure for measuring the muon flux at different places a mobile device was set-up and operated since autumn 2009, registering the muon flux at the surface and in the underground. Determinations of the water equivalent depth of any underground site could be done in a reasonable

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time scale. This feature is important in order to establish very accurately the overburden thickness in water equivalent of matter (mwe). First measurements have been performed on the underground site of the Slanic-Prahova mine where IFIN-HH operates a low-radiation level laboratory [6].

## 2. The LAGUNA project

LAGUNA [2] (Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics) is a research project, supported by the European Union. The goal of the project is to set up the infrastructure for a large underground laboratory. The first step is to explore adequate locations for looking for extremely rare events like proton decay or for the experimental research on Dark Matter.

Seven underground laboratories of Great Britain, France, Spain, Finland, Italy, Poland and Romania are involved. For LAGUNA, three detector types are considered based on different active detection media: MEMPHYS with water [7], LENA, a liquid scintillator detector [8] and GLACIER using liquid argon [9]. The site for LAGUNA experiments will be chosen using the following criteria: the depth of the site, i.e. the ability to absorb and shield against high-energy muons, the available space and possibility to install a large volume detector inside (larger than 100 000 m$^3$), and the natural radiation background. The site proposed in Romania is located in the salt mine Slanic- Prahova, geographically situated at 45.23°N latitude and 25.94°E longitude. The elevation of the Slanic site is 408 m above the sea level at the entrance of the mine. The muon contribution to the natural radiation dose in air has been determined [11] to be $31.3 \pm 0.6$ nSv/h at the same elevation and latitude as Slanic site.

The salt ore at Slanic consists of a lens of 500 m thickness, a few kilometers long and wide (see Fig. 1). Salt has been extracted from the Slanic mine continuously since ancient times and, due to this fact, many galleries (i.e. shaped caverns) are already excavated.

The largest one is the "tourist" mine "Unirea" (see Fig. 2) characterized by:

- depth: 208 m below ground level,
- temperature: 12.0–13.0 °C,
- humidity: 65–70%,
- excavated volume: 2.9 million m$^3$,
- floor area: 70 000 m$^2$,
- average hight: 52–57 m,
- distance between walls: 32–36 m,
- existing infrastructure: electricity, elevator, phone, Internet, GSM networks.

The humidity of the underground atmosphere is caused by a very low water infiltration correlated with a temperature of only 12–13 °C.

Besides the "tourist" mine UNIREA, muon flux measurements have been performed also in the "active" mine CANTACUZINO (see Fig. 1) at two different levels with physical depths of 188 and 210 m from the entrances.

During the last 5 years a new laboratory [6] for low background measurements was installed by IFIN-HH in the UNIREA salt mine of Slanic-Prahova. From the Slanic site a huge volume of material has been already excavated, but the shallow depth could induce a problem. Following [10] for the GLACIER experiment the Slanic mine could be a feasible location as for this technique a depth of only 600 mwe is necessary. The main goal of this work was to determine the water equivalent depth (mwe) of the Unirea mine.

## 3. Monte–Carlo simulation of the muon flux

Monte–Carlo simulations were used to perform some preliminary explorations regarding the expected results of the experimental studies. Different simulation codes have been used:

- CORSIKA 6.735 [12] (COsmic Ray SImulation for KAscade), a sophisticated Monte–Carlo code for simulations of the development of extensive air showers (EAS) in the atmosphere, has

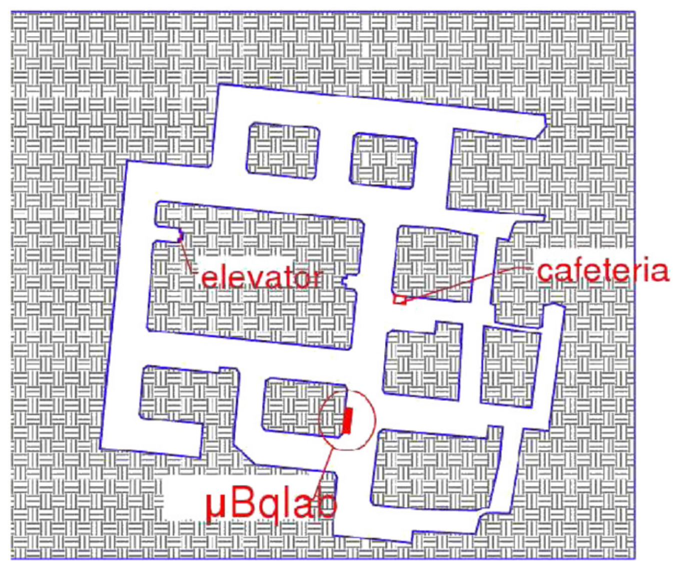


**Fig. 2.** Map of Unirea mine, with the $\mu Bq$ laboratory of IFIN-HH.

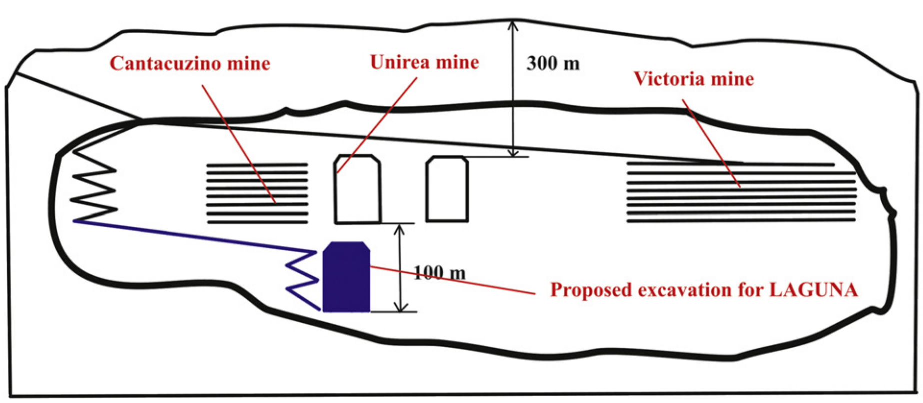


**Fig. 1.** Artistic view of the salt ore of Slanic.