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A mobile detector for measurements of the atmospheric muon flux

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Abstract. Measurements of the underground atmospheric muon flux are important in order to determine accurately the overburden in mwe (meter water equivalent) of an underground laboratory for appreciating which kind of experiments are feasible for that location. Slanic- Prohava is one of the 7 possible locations for the European large underground experiment LAGUNA (Large Apparatus studying Grand Unification and Neutrino Astrophysics). A mobile device consisting of 2 scintillator plates ($\approx 0.9\,\mathrm{m}^2$, each) one above the other and measuring in coincidence, was set-up for determining the muon flux. The detector it is installed on a van which facilitates measurements on different positions at the surface or in the underground and it is in operation since autumn 2009. The measurements of muon fluxes presented in this contribution have been performed in the underground salt mine Slanic-Prahova, Romania, where IFIN-HH has built a low radiation level laboratory, and at the surface on different sites of Romania, at different elevations from 0 m a.s.l up to 655 m a.s.l. Based on our measurements we can say that Slanic site is a feasible location for LAGUNA in Unirea salt mine at a water equivalent depth of 600 mwe. The results have been compared with Monte-Carlo simulations performed with the simulation codes CORSIKA and MUSIC.

1 Introduction

A mobile detector for measuring the muon flux was set-up and it is in operation since the autumn of 2009. The detector permits measurements of the muon flux at the surface and in the underground. This feature is important in order to establish accurately the overburden thickness in water equivalent of matter - mwe (up to 10 mwe precision) of any underground site, in a reasonable time scale.

The reason for measuring underground muons from cosmic rays arises from the necessity to know the radioactive background for Slanic-Prahova underground site. This is important in order to establish very accurately the mwe (meter water equivalent) thickness of Unirea site, since IFIN-HH was invited to participate to the consortium of FP7 project 212343 -“Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics”, acronym LAGUNA (Rubbia, 2010). A huge volume detector (min $100.000\,\mathrm{m}^3$) is planned to be installed in an underground site that will be chosen from 7 different locations from Europe. 3 different types of detectors are investigated: LENA (Wurm et al., 2007) (liquid scintillators), MEMPHYS (Tonazzo, 2007) (water) and GLACIER (Rubbia, 2009) (liquid argon). The site for LAGUNA (Rubbia, 2010) experiment will be established taking into account the depth of each site and the possibility to install a large volume detector inside. Slanic site has a huge volume of material already excavated ($2.900.000\,\mathrm{m}^3$), but the shallow depth could be a problem. It seems that the GLACIER experiment is the only one feasible for Slanic, but the exact depth (mwe) of Unirea mine should be measured.

The salt ore from Slanic consists in a lens of 500 m thickness, few kilometers long and wide (see Fig. 1). The salt is extracted from the Slanic mine continuously since ancient times and, due to this fact, many galleries (i.e. shaped caverns) are already excavated. Since the top of the site is not very flat, the theoretical estimation of the m.w.e. depth will be difficult and with high uncertain. From this reason, the measurements of the underground muon flux is necessary.

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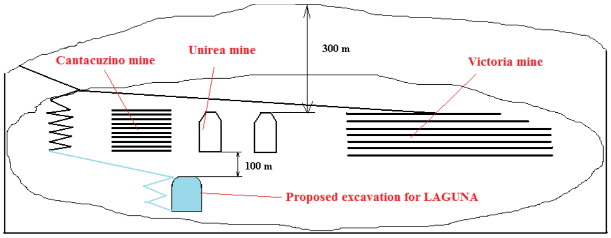

Fig. 1. Artistic view of the salt ore of Slanic

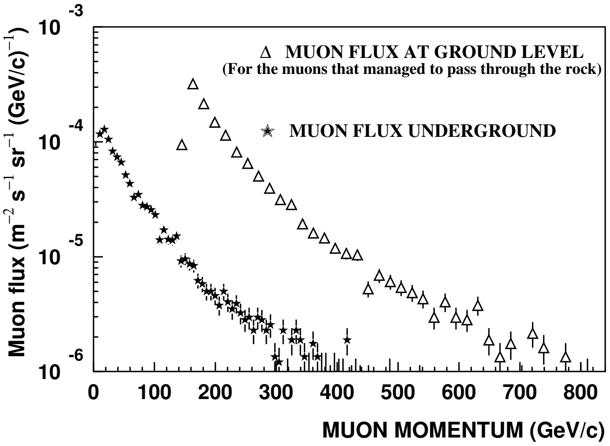

Fig. 2. The simulated muon flux at the surface and in the mine

2 Monte-Carlo simulation of the muon flux in underground

Monte-Carlo simulations have been performed to explore the conditions what can be applied to the experiment. Different simulation codes have been used:

- CORSIKA 6.735 (Heck et al., 1998) (COsmic Ray SImulation for KAscade), a sophisticated Monte-Carlo code for simulations of the development of extensive air showers (EAS) in the atmosphere, has been used to estimate the muon flux at surface.

- MUSIC (Kudryavtsev, 2009) (MUon SImulation Code) is a simulation tool for 3 dimensional simulations of the muon propagation through rock. It takes into account energy losses of muons by pair production, inelastic scattering, bremsstrahlung and ionisation as well as the angular deflection by multiple scattering. The program uses the standard CERN library routines and random number generators.

- GEANT 3.21 (GEANT, 1993), the detector simulation package from CERN has been used to simulate the interaction of the muons with the detector and for a proper calibration of the signal.

The muon flux on surface can also be estimated by semi-analytical formulae of Judge and Nash (Judge and Nash, 1965) (up to 100 GeV) and Gaisser (Gaisser, 2002) (beyond 10 GeV).

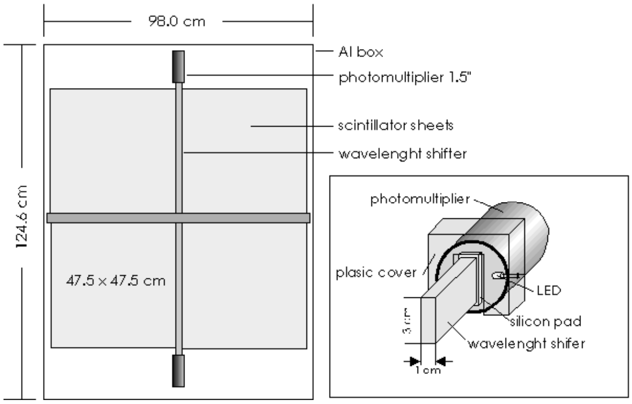

Fig. 3. The detection module. Design of KASCADE (Bozdog et al., 2001)

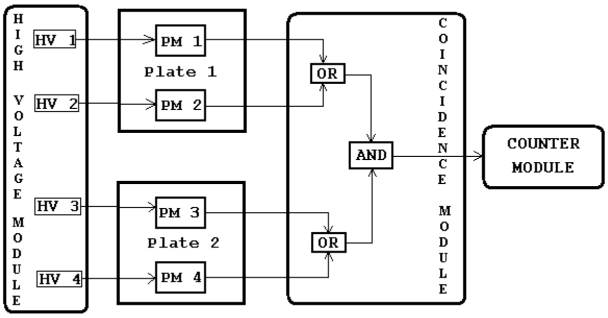

Fig. 4. The electronic detection system

Figure 2 displays the muon fluxes at surface (CORSIKA simulation) and in underground, assuming a simple layer of salt equivalent with 600 mwe. The propagation of the muons through the salt rock is simulated by MUSIC using the muon flux from CORSIKA (only the muons with a zenith angle $< 70°$ have been considerate) as input. The triangles represent only the surface muons that reach the observation level in underground. The energy cut off for the surviving muons is estimated to be around 150 GeV. By these simulation studies we estimate the expected muon rate at 600 mwe to about 10 muons/m^{2}min.

3 The apparatus

The mobile detector was set-up in IFIN-HH and it consists of 2 detection modules. Each module is a scintillator plate of 0.9025 m^2 and 3 cm thickness (see Fig. 3), divided in 4 parts (0.475×0.475 m^2) (Bozdog et al., 2001), readout by two photomultiplier tubes which receives the signal trough a wave length shifter. The modules are arranged one on the top of each other (at 8.5 cm distance), in order to identify the transversing muons as coincidence event.

Table 1. The muon flux data obtained in underground measurements. The m.w.e. depth is estimated by Eq. (1)

Location	Depth (from surface)	Muon flux ($m^{-2}s^{-1}$)	mwe depth
Unirea mine			
Unirea	-208 m	0.18 ± 0.01	610 ± 7
Cantacuzino mine			
Level 8	-188 m	0.19 ± 0.02	601 ± 9
Level 12	-210 m	0.09 ± 0.01	790 ± 13

The signals from the 4 photomultiplier tubes are readout by a coincidence electronic system which is supplied by a high voltage NIM standard module. The signals collected from the 4 PMTs are two by two OR-ed (1 or 2) and (3 or 4) and then are putted in coincidence (see Fig. 4) The resulting pulses are counted by a scaler time module

The detector response is simulated by use of the GEANT 3.21 code. The interaction of the muon with the active detector material and the deposit of the energy in the scintillator plates are analysed.

Considering the fact that not all muons that reach the first layer, do not reach, also, the second one, the angular acceptance of the detector was estimated, using GEANT simulation code. The angular acceptance is defined as the ratio between the number of muons that interact with both layers with the number of muons that reach the first one. Finally, a correction factor of +9% has to be applied on the observed muon rate, in order to include all the muons that reach the detector's surface.

The detector is installed on a van allowing to move quickly the system. The electric power for the entire system is supplied by a mobile electric generator of 1 kW power at 230 V AC or by a $12-230$ V inverter of 1 kW power which transform 12 V CC from the car's battery to 230 V AC.

4 Measurements and results

The measurements of the muon flux in the underground have been performed at the Slanic site at 3 different locations: in Unirea salt mine (in IFIN-HH lab) at 208 m below the entrance and in the active mine Cantacuzino, at 2 different levels, first one at 188 m and the second one at 210 m below surface. All campaigns were performed at approx. the same hour of the day (noon) in order to reduce the influence of the solar activity and atmospheric conditions. The acquisition time for each data set was 1 h. In Cantacuzino mine, where an access road is available, the measurements have been performed using the detector installed on the van. In Unirea mine, the detection modules were removed from the car and transported by an elevator to the observation level. The results of the three measurement campaigns are displayed in Table 1, where the physical depth is referred to the surface (the entrance of the mines).

Table 2. Measured muon flux at different elevations and locations (the altitude was determined with a GPS system).

Latitude (deg)	Longitude (deg)	Altitude (m a.s.l.)	muon flux ($m^{-2}s^{-1}$)
45.29	25.94	655 ± 5	147 ± 2
45.28	25.97	588 ± 5	145 ± 2
45.24	25.94	408 ± 5	143 ± 2
44.32	28.19	70 ± 5	128 ± 2
44.40	26.10	64 ± 5	122 ± 2
44.36	28.05	7 ± 5	119 ± 2

The variation of the muon flux as a function of the water equivalent depth is given by (Formaggio and Martoff, 2004):

$$\phi_\mu(X) = A \cdot (X_0/X)^\eta \cdot e^{-X/X_0} \tag{1}$$

where: $A = 0.03$, $X_o = 1470$ m.w.e. and $\eta = 2.5$.

The difference in the muon flux measured at approximately identical physical depths in Cantacuzino (-210 m) and in Unirea (-208 m) is associated to the different thickness of salt rock above the detection place. Unirea mine is consisting of a huge cavity up to 57 m between the floor and the roof. In contrast, the Cantacuzino mine has a relative homogeneous rock massive above.

Taking advantage of the mobility of the system, the measurements of the cosmic muon flux have been performed for many locations at different geographical positions and different elevations, from sea level up to 655 m. The results are in good agreement with measurements reported previously in Greisen (1942), that estimate a flux of 127 muon/m^2s at 259 m a.s.l. (above sea level). The results are compiled in Table 2 and displayed in Fig. 5. During the campaigns at altitudes 70 m and 408 m the observation conditions were different (wind and low temperature) compared to the others, which led to different values and larger error bars.

5 Conclusions

Suggested by the muon flux measurements reported for other sites (Carmona et al., 2004), the water equivalent depth of different places of the Slanic underground site were determined. The water equivalent depths of the Slanic mine are 610 ± 7 m.w.e. for Unirea mine, 601 ± 9 for Cantacuzino mine (level 8) and 790 ± 13 m.w.e. for Cantacuzino mine (level 12), respectively.

The Slanic site is a feasible location for the GLACIER detector to be located in Unirea mine, with respect to the determined depth of 600 mwe (see Fig. 6).

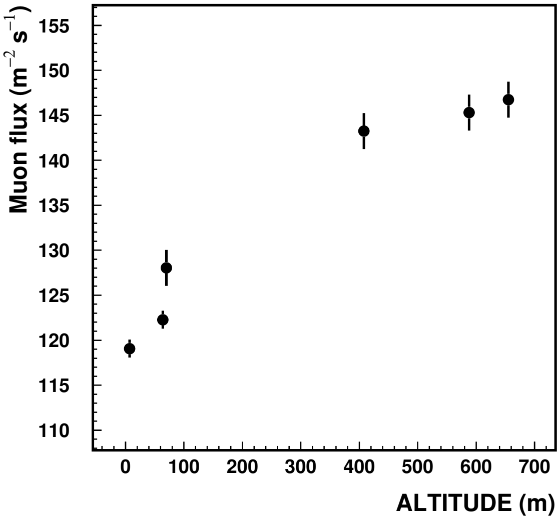

Fig. 5. Measured results of the muon flux variation with altitude in m a.s.l.

In addition, further promising locations for LAGUNA at the Slanic site are under consideration. A new cavern, 100 m below the Cantacuzino mine (see Fig. 1) could be excavated in a reasonable time scale (Arad et al., 2010). In this case a depth of about 1000 mwe would be at disposal for experiments.

In near future, further measurements at different locations in Unirea mine will be performed, in order to get an improved overview on the variation of the Unirea mine's water equivalent depth. We expect that the muon flux varies for different locations of the mine due to the variation of the overburden at the Unirea mine.

Such muon flux measurements could be also used for geological studies, e.g. to explore variations in the rock density above the observation level. The mobility of the detector implies a considerable practical flexibility of using the procedure of measuring muon flux differences for various aspects.

A new detection system for the mobile detector it is in construction and is estimated to start the data acquisition in the autumn of 2011. The system will use a new technology based on optical fiber and MPPC photo-diodes. The new detector will perform precise measurements of the differential moun flux at surface and in underground. The data will be used to test the hadronic interaction models.

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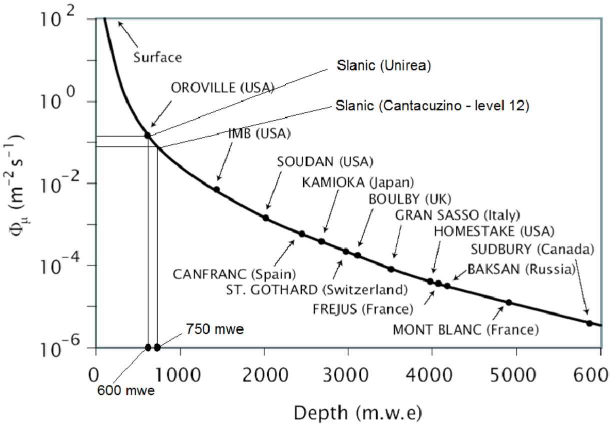

Fig. 6. MWE depths of different underground sites as function of muon flux

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