Measurements of the atmospheric muon flux using a mobile detector based on plastic scintillators read-out by optical fibers and PMTs

D I Stanca¹, B Mitrica¹, M Petcu¹, I M Brancus¹, A Jipa², A Haungs³, H Rebel³, A Saftoiu¹, G Toma¹

¹ Horia Hulubei National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania
² Department of Physics, University of Bucharest, Romania
³ Institut fur Kernphysik, Karlsruhe Institute of Technology, Karlsruhe, Germany

E-mail: denis.stanca@gmail.com

Abstract. Precise measurements of the muon flux are important for different practical applications, in environmental studies and for the estimation of the water equivalent depths of underground sites. A first configuration of the mobile detector was composed of two 1 m² scintillator plates, each viewed by wave length shifters and read out by two PMTs (Photomultiplier Tubes). A more recent configuration of the mobile muon detectors, set up in IFIN-HH, Romania, consists of two 1 m² detection layers, each one including four 1×0.25 m² large scintillator plates. The light output in each plate is collected by twelve optical fibers and then read out by one PMT. The calibration has been made by comparing the energy deposit spectrum of minimum ionizing particles with the spectra simulated with the GEANT4 code. The device is used to measure the muon flux on different locations at the surface and underground.

1. Introduction

The cosmic ray muon flux, defined as the number of muons traversing a horizontal element of area per unit of time [1], is of interest for various branches of science, in elementary particle physics, as a messenger of astrophysical processes, in environmental and material research, studying radiation damages, and with a role for cosmogenic production of long-lived isotopes.

A particular important motivation for measuring the flux of atmospheric muons at different locations at the surface and in underground sites arises from the need for information on the cosmic radiation background. This background consists not only of muons which have survived the passage through the rock above, but also of contributions from natural radioactivity and muon-induced radiation products like neutrons, which can play a decisive role in low background experiments [2]. Another application of importance is the estimation of the water equivalent depth of any underground site, by the flux of atmospheric muons.

Two different versions of a mobile muon detector have been set up in a van at IFIN-HH, Romania, with different configurations of the active layers as described in the next chapter. Comparative studies are performed for both cases. A method of collecting light using optical fiber readout of the plastic...
scintillator sheet was tested, and the results are compared with the results of the classical method in which light guides are used for the light collection.

2. The apparatus

The construction principle of the mobile muon detector is to overlay two 1 m$^2$ active layers of scintillator material, in order to identify traversing muons by coincidence events. Thanks to its mobility, the device can be used to measure the muon flux at different locations at the surface and underground.

A former configuration of the mobile detector was composed of two detection modules, each module being a scintillator plate (NE114 type) of 0.9025 m$^2$ and 3 cm thickness. It was divided, as we can observe in figure 1a, in four parts (0.475·0.475 m$^2$) [3,4] and readout by two photomultiplier tubes (EMI 9902 type) which receive the signal through a wavelength shifter (NE174A type).

![Figure 1](image1.png)

Figure 1. The detection module of a) the first detector setup. Design of KASCADE [3]; b) the new detector setup [5].

The present configuration, presented in figure 1b, consists of two detection modules, each composed of 4 plastic scintillator sheets (Polystyrol 80%, Methylmetacrylate 20%) having the sizes of 100·25·1 cm$^3$. Every sheet is crossed by 13 longitudinal strips, 12 of them being filled with an optical fiber. The light signal of each sheet is readout by a PMT. The modules are arranged on top of each other (at 30 cm distance). The signals from the eight photomultiplier tubes are OR-ed four by four (1 or 2 or 3 or 4) and (5 or 6 or 7 or 8) and then are AND-ed in coincidence using a gate of 50 ns, so no correction due to the dead time of the detector is necessary. A counter module registers the coincidence events.

The calibration has been made by comparing the measured energy deposit spectrum of the minimum ionizing particles with GEANT simulated responses. The comparison of the measured and simulated spectra, of both configurations, is shown in figure 2. The difference in the most probable energy deposit between the two configurations comes from the different thicknesses of the plates (3 cm versus 1 cm). For the first configuration, with the most probable energy deposit at 6.3 MeV, the signal threshold was set to 2.1 MeV [4]. For the new configuration, with the most probable energy deposit of 2.4 MeV, a signal threshold of 1.8 MeV is set.

Considering the fact that not all muons that interact with the first layer manage to pass to the second one, due to scattering losses in between, the acceptance of the detector was also investigated using GEANT4 code. The muon flux at the surface of the ground was estimated using CORSIKA code [8], using the primary cosmic ray spectrum of proton and helium, obtained from AMS results during a space shuttle mission [9].
Figure 2. a) The energy calibration for one scintillator plate of the previous configuration, made by comparing the measured energy deposit spectrum of the minimum ionizing particles with GEANT 3.21 [6] simulated one; b) The energy calibration for one scintillator sheet of the recent detector setup, made by comparison of the measured energy deposit spectrum of the minimum ionizing particles with GEANT 4.94 [7] simulated one.

A correction factor $a=1.56$ has to be applied to the observed muon rate at ground level. The distance between the centers of the two active layers of the detector is 30 cm. For a distance of 8 cm, obtained if the two active layers are overlapping, a correction factor $a'=1.11$ is obtained. No correction factor due to the geometry of the detector’s surface is required. The corrected muon flux is given by the $\Phi_\mu = a R$ formula, with $R$ the counting rate of the detector and $\Phi_\mu$ the real flux.

3. Measurements

Using the mobility of the detector, measurements of cosmic muon flux have been performed for both configurations of the active layers at different locations on the surface with different elevations. The results, presented in table 1, are compared with those previously reported in [10] and displayed in figure 3. The acquisition time for each data set was 1 h, all runs being performed at approximately the same time of the day (noon) in order to reduce the eventual influence of the solar activity and of atmospheric conditions [11].

Table 1. Cosmic muon flux measured at different geographic locations with different elevations, using both configurations of the active layers.

|                  | Latitude (°) | Longitude (°) | Altitude (m a.s.l.) | Muon flux (m$^{-2}$ s$^{-1}$) |
|------------------|--------------|---------------|---------------------|-------------------------------|
| Former configuration | 44.36        | 28.05         | 7±5                 | 119.07±3.57                    |
|                  | 44.40        | 26.10         | 64±5                | 122.28±3.67                    |
|                  | 44.32        | 28.19         | 70±5                | 128.05±3.84                    |
|                  | 45.24        | 25.94         | 408±5               | 143.24±4.30                    |
|                  | 45.28        | 25.97         | 588±5               | 145.30±4.36                    |
|                  | 45.29        | 25.94         | 655±5               | 146.74±4.40                    |
| Recent configuration | 44.97        | 26.02         | 219±5               | 129.10±4.45                    |
|                  | 45.07        | 26.03         | 266±5               | 136.65±4.7                     |
|                  | 45.24        | 25.94         | 438±5               | 142.73±4.89                    |
|                  | 45.26        | 25.96         | 603±5               | 143.39±4.91                    |
|                  | 45.26        | 25.97         | 693±5               | 144.57±4.94                    |
Measurements have been performed also underground for both configurations in the Unirea Mine (-208 m depth from surface). The responses are similar, $0.18 \pm 0.01 \text{ m}^2 \text{s}^{-1}$ for the first configuration and $0.191 \pm 0.002 \text{ m}^2 \text{s}^{-1}$ for the second one.

**Figure 3.** Measured results of the muon flux variation with altitude, obtained with both detector configurations of the active layers of the detector. The circles represent the data obtained with the former configuration. The data obtained with the new configuration is presented with triangles. The cross point represents the results from the reference [10].

4. **Concluding remarks**

We have set up and studied a versatile detector for cosmic muon flux which can be used for different purposes where the information about the flux of atmospheric muons is of interest. An application has been demonstrated by the determination of water equivalent depths in Unirea mine of Slanic [11].

**Acknowledgements**

The present work has been enabled by the support of the Romanian Authority for Scientific Research by the projects PN II – IDEI grant 271/2011 and grant POSDRU/88/1.5/S/56668. We thank the KASCADE-Grande group of the Karlsruhe Institute of Technology for essential contributions. We thank Prof. M. Teshima for various useful communications.

**References**

[1] Grieder P 2001 *Cosmic Rays at Earth: Researcher’s Reference Manual and Data Book* (Amsterdam: Elsevier) p 133
[2] Schreiner P and Goodman M 2005 *Proc. 30th ICRC* (Pune, India) vol 9 p 97
[3] Bozdog H et al 2001 *Nucl. Instr. and Meth.* A 465 455
[4] Antoni T et al 2003 *Nucl. Instr. and Meth.* A 513 490
[5] Stanca D 2012 *Rom. Rep. Phys.* 64 831
[6] Application Software Group 1993 *GEANT-Detector Description and Simulation Tool, Program Library Long Writeup W5013* (Geneva: CERN)
[7] GEANT4 Collaboration 2003 *Nucl. Instr. and Meth.* A 506 250
[8] Heck D et al 1998 Report FZKA 6019 Forschungszentrum Karlsruhe
[9] Wiebel-Sooth B, Biermann P L and Meyer H 1998 *Astron. Astrophys.* 330 389
[10] Greisen K et al 1942 *Phys. Rev.* 61 212
[11] Mitrica B et al 2011 *Nucl. Instr. and Meth.* A 654 176-183