Applications of Cosmic Muon Tracking at Shallow Depth Underground

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A portable cosmic muon telescope has been developed for environmental and geophysical applications, as well as cosmic background measurements for nuclear research in underground labs by the REGARD group (Wigner RCP of the HAS and Eötvös Loránd University collaboration on gaseous detector R&D). The modular, low power consuming (5 W) Close Cathode Chamber-based tracking system has 10 mrad angular resolution with its sensitive area of 0.1 m^2. The angular distribution of cosmic muons has been measured at shallow depth underground ($<$ 70 meter-rock-equivalent) in four different remote locations. Application of cosmic muon detection for the reconstruction of underground caverns and building structures are demonstrated by the measurements.

Keywords: tracking detector, muon flux, muon tomography

1. Introduction

High energy muons are generated at the altitude of 20-30 km in the atmosphere. These particles can reach the surface of the Earth by the relativistic time dilatation and penetrate to underground. The muon flux decreases by the traversed material (slant depth). These particles have approximately $f(\theta) = f_0 cos^n(\theta)$ zenith angular distribution, where θ is the zenith-angle, f_0 is the vertical flux and $n \approx 2$ is the exponent.

The aim of our research is the tomographic mapping of rock thickness by measuring the angular distribution of cosmic muons from an observation point well below the structures to be investigated.

The present paper focuses on muon flux measurements which have been performed at shallow depth underground with the aim to investigate the possibility of the reconstruction of underground tunnels and building structures by measuring the angular distribution of cosmic muons.

2. Portable tracking detector for cosmic muons

A portable tracking detector has been developed by the REGARD group. The Close Cathode Chamber-based detector[1,2] is optimized for geophysical applications[3,4] with its weight of 15 kg, size of $51 \times 46 \times 32$ cm^3, sensitive area of 0.1 m^2 and angular resolution of 10 mrad. Our muon telescope is housed in a plexiglass box, which besides giving mechanical support, provides environmental isolation as well. The CCC-chambers require continuous 1–2 l/h gas flow during data taking. In our case the gas is a standard, non-flammable mixture of Ar and CO_2 in 82:18 proportion. A 10 l gas bottle is enough for about a month of data taking.

A PIC32 microcontroller based data acquisition (DAQ) system was developed and its small size units fit well between the middle tracking layers. All functions (high voltage unit generating 1 kV, trigger system, data handling, environmental control, human-machine interface, etc.) are integrated into the DAQ. The total power consumption of the complete detector system is less than 5 W, thus the Muontomograph can operate for a week supplied by a standard 50 Ah battery.

The portable tracking detector is capable of performing 2-dimensional angular distribution measurement for cosmic muons, which allows a tomographic mapping of the soil density above the measurement points.

3. Muon flux measurements at shallow depth underground

Muon flux measurements have been performed at four different remote tunnels in the Jánossy Pit Budapest Hungary as well as in Felsenkeller, Dresden, Germany. The parameters of the measurements are summarized in Table 1: the site of measurement, the depth from the top of the atmosphere, the time of the measurement, number of detected muon tracks and the results (f_0 and n).

The measured angular distributions with the corresponding statistical errors (3–8 %) are shown in Fig. 1. The angular distributions have been fitted with $f_0 \, cos^n(\theta)$ functions (see the parameters in Tab. 1). Our results (both of vertical flux and n exponent) are in good agreement with the earlier measurements.

Table 1. The summary of the measurements at shallow depths underground with measurement time, detected muon tracks and the results.

place	depth (m)	density-length^{a,b} ($\mathrm{hg\,cm^{-2}}$)	time (day)	muon tracks ($\times$ 10^3)	f_0 ($\mathrm{m^{-2}\,sr^{-1}\,s^{-1}}$)	n
Jánossy Pit	10	27.8 $\pm$ 1.5	5	1,200	28.72 $\pm$ 0.74	2.19 $\pm$ 0.17
Jánossy Pit	20	48.7 $\pm$ 3.2	7	550	12.45 $\pm$ 0.29	2.11 $\pm$ 0.16
Jánossy Pit	30	75.1 $\pm$ 5.4	11.5	472	5.85 $\pm$ 0.22	2.00 $\pm$ 0.24
Felsenkeller	50	130.3 $\pm$ 10	20	217	1.77 $\pm$ 0.07	2.21 $\pm$ 0.27

Note: ^{a} 1 $\mathrm{hg\,cm^{-2}}$ = 1 meter-water-equivalent depth. ^{b} The density-length of the atmosphere is 10.3 $\mathrm{hg\,cm^{-2}}$.

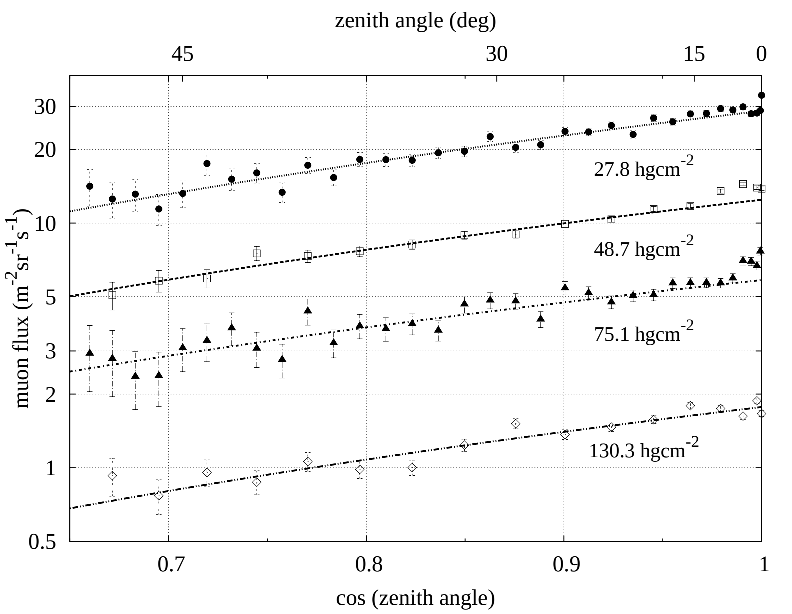

Fig. 1. The measured muon flux have been measured at four different depth (*dots*) up to 55 degree.

4. Muon tomography experiments in the Jánossy Pit

The Jánossy Pit is an excellent place to test the capabilities of our detector on muon tomography at shallow depth. There are three parallel tunnels under each other at 10 m, 20 m and 30 m depth with the size of $11 \times 2.5 \times 2.6\,\mathrm{m^3}$, $9.5 \times 2.5 \times 2.6\,\mathrm{m^3}$ and $23 \times 2.5 \times 2.6\,\mathrm{m^3}$ respectively. The soil density is $2.2 \pm 0.2\,\mathrm{g\,cm^3}$ and tunnels are built from concrete with the density of $2.4\,\mathrm{g\,cm^3}$.

The geometry of the Jánossy Pit has been implemented into GEANT 4 [5] simulation program with the above parameters. The expected muon flux have been calculated bin by bin from the empirical formulae of vertical muon flux versus depth[6] and the combination of 2-dimensional angular distribution of cosmic muons.

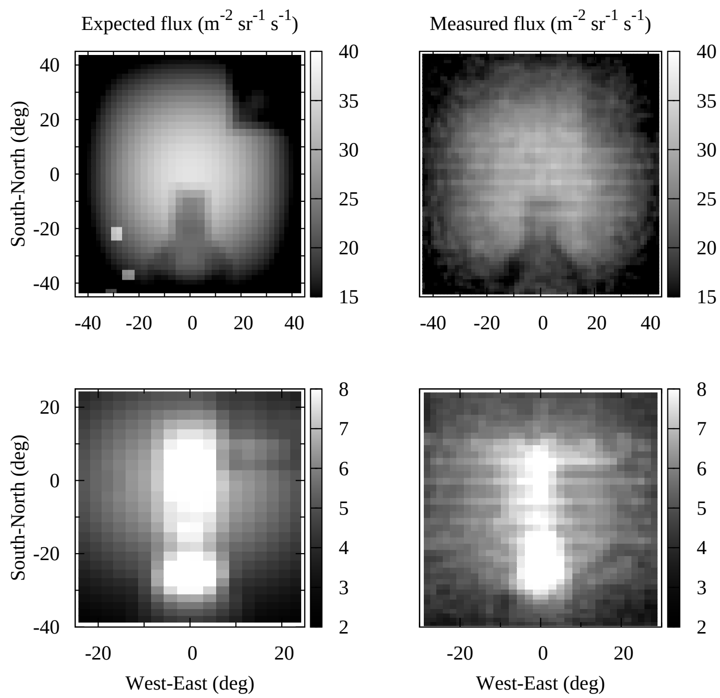

Fig. 2. Cosmic muon measurements (*right panels*) have been compared with GEANT 4 simulation (*left panels*): the tunnels and the building structures are reproduced by our measurements.

Figure 2 shows the expected muon flux (*left panels*) and our measurements (*right panels*) at the depth of 27.8 $\mathrm{hg\,cm^{-2}}$ (*upper panels*) and at the depth of 75.1 $\mathrm{hg\,cm^{-2}}$ (*lower panels*). Our measurements are in agreement with the expected flux, and reproduce well the actual underground structures. Specifically, the *upper panels* show the pit entrance of the tunnel system towards South and the building edge at the North-East corner from 10 meter depth. In the *lower panels*, two parallel tunnels are observed in the North-South orientation from 30 meter depth.

5. Summary, conclusion

A portable tracking detector based on Close Cathode Chamber technology has been developed for 2-dimensional angular distribution measurements of cosmic muons by the REGARD Group. Our muon flux measurements have been performed in four different underground tunnels ($<$ 70 meter-rock-equivalent) by the Muontomograph. Our measurements are in good agreement with the expected muon flux. The results demonstrate the applicability of our portable tracking detector to perform muon tomography measurements.

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