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COSMIC-RAY MUON FLUX MEASUREMENTS IN BELGRADE LOW-LEVEL LABORATORY

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Abstract: We report results of cosmic-ray muon flux measurements in the Belgrade low-level laboratory (geographic latitude $44^{o}51'$N, vertical geomagnetic rigidity cut-off 5.3GV). Continuous measurements are performed from 2002 to 2006 at ground level (78m a.s.l) and in the underground low-level laboratory (25m.w.e). At the ground level the average muon flux is found to be 1.6(1) x 10^{-2} $s^{-1}cm^{-2}$ and vertical intensity 1.0(1) x 10^{-2} $s^{-1}cm^{-2}sr^{-1}$, while for the underground location the results are 4.5(2) x 10^{-3} $s^{-1}cm^{-2}$ and 2.5(2) x 10^{-3} $s^{-1}cm^{-2}sr^{-1}$, respectively.

Introduction

The knowledge of absolute muon flux of cosmic-ray origin is of interest to many experiments in contemporary nuclear and particle physics. This issue is relevant for neutrino (astro) physics due to close relation between atmospheric muon and neutrino production as well for all experiments that require low background conditions due to muon importance as background source.

Muon flux has been measured in the past at different locations, at different altitudes (sea level, high mountain or balloon born experiments) and at various depths underground. Results of these measurements sometimes differ more than expected from reported experimental errors.

In the present paper, we report the results of muon flux measurements in Belgrade low-level laboratory (geographic latitude $44^{o}51^{'}22^{''}$N, longitude $20^{o}23^{'}21^{''}$E and geomagnetic rigidity cut-off 5.3GV). Measurements are performed at ground level (altitude 78m above sea level) and in the underground laboratory (25m of water equivalent).

When comparing results on sea level or shallow depth muons, one has to have in mind the exact location and period of measurements. For low energy muons the effect of geomagnetic field is significant. Period of measurements is relevant since intensity of cosmic-rays vary with 11-year cycle of solar activity. Solar modulation affects primary protons with energy less than 20 GeV which give contribution to the sea level muon flux. There are other periodic variations of CR flux. The most famous being the one with 27-day period of solar rotation and its correlation with our first results of muon intensity was already analyzed, [1, 2].

Experimental setup

Detector system consists of two identical plastic scintillator detectors. Detectors are produced by the High Energy Physics Laboratory of JINR, Dubna and are similar to NE102. The size of each detector is 50cm x 23cm x 5cm. A single 5cm photomultiplier is mounted on a detector via a correspondingly shaped light guide. When a muon or other charged particle passes through the detector, the scintillator is excited and emits a fluorescent light. The light reaches photomultiplier where it is converted into an electrical signal. After amplification the analog output signal from detector is digitalized by laboratory made A/D converter and then linked to a computer PCI card. The 4k channel spectrum is automatically recorded every 5 minutes, with 270 seconds dedicated to measurements, and 30 seconds being allowed for recording on local hard disc, some quick interventions on the system and data transmission to second local network computer. The setup enables off-line data analysis without interrupting the measurement.

The recorded spectrum for both, ground and underground detectors, is mainly the spectrum of muon energy deposit ΔE. The spectra stretch to about 200 MeV and have a well defined single particle peak corresponding to an energy loss of some 10.5 MeV. The rise in the low energy part of the spectrum is due to ambient radiation. The figure 1 presents, for example, typical ground spectrum as well as performed Monte Carlo simulation of detector response to CR muons based on GEANT4.

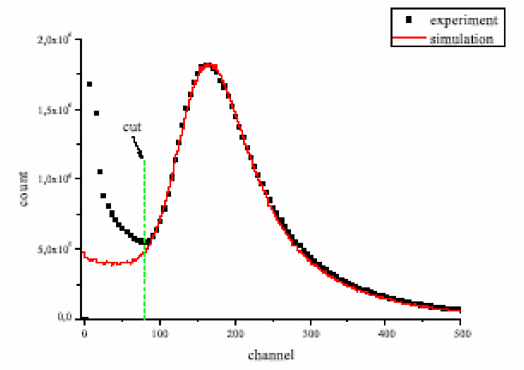

Figure 1: Energy loss spectrum in plastic scintillator detector and GEANT4 based MC simulation of detector response to CR muons for ground detector

Results

All measurements of muon flux are performed at ground level and in the Belgrade low-level underground laboratory simultaneously. The underground laboratory is built under the less loan cliff on the bank of Danube at the depth of 12.0(3) meters corresponding to 25 meters of water. The geological survey revealed that overburden consists of four layers with density ranging from 1.8-2.1gcm^{-3} and with average density 2.0(1) gcm^{-3}. Above the working area of the laboratory there is also a layer of reinforced concrete 30cm thick.

Measurements were performed from 2002 to 2006 entire years, enabling seasonal variations of the flux to be averaged out. The total muon flux is calculated by dividing the number of muon counts by measurement live time and detector area. Detector efficiency is assumed to be 100%. The first step in determination of muon flux is to extract muon events from the recorded spectrum. This is usually done by cutting off the low energy part of the spectrum, originating from background radiation. As an example, the cut is placed in the channel 80 for ground detector, corresponding to some 5MeV of energy deposit. With our experimental setup muon events are well separated from the background as can be seen in fig. 1. However, the exact position of the cut between the two is somewhat arbitrary, and represents a source of systematic error. For better interpretation of recorded spectrum and discrimination of muon events from background, we have performed Monte Carlo simulation of detector response to CR muons, based on GEANT4.

In the simulation it is assumed that muon angular distribution at ground level follows $\cos^n\theta$ law:

$$I(\theta) = I(0)\cdot\cos^n(\theta) \qquad (1)$$

with $n = 1.85 \pm 0.10$ as recommended by Grieder, [3]. Here, $I(\theta)$ is directional intensity of incident muons. Muon energy is sampled from Gaisser distribution, [4]:

$$\frac{dN(E,\theta)}{dE} \propto E^{-\gamma}\left(\frac{1}{1+\frac{1.1E\cos(\theta)}{115}}+\frac{0.054}{1+\frac{1.1E\cos(\theta)}{850}}\right) \qquad (2)$$

with γ=2.7. There is slight disagreement between simulated and experimental spectrum of ground detector in high energy region. This disagreement is removed by including 5% of multimuon events with low multiplicity (N_μ=2 and N_μ=3) into the simulation. This did not alter the low energy region of the spectrum. The difference between simulated and experimental spectrum may be as well caused by deviation of angular distribution from $\cos^{1.85}\theta$ at large angles. This uncertainty is incorporated into estimation of the systematic error.

Underground, only those muons surviving interaction with the rock after energy loss mainly in the ionization processes, are taken into consideration.

The number of muon events embedded in the low energy part of the spectrum, estimated from MC simulation is 10.4% for ground detector data and 6.4% for underground detector data. At the same time, number of low energy background events contributing to muon signal, due to finite resolution of the detector is 0.19% (ground) and 0.27% (underground). These correction factors are taken with 10% uncertainty.

Additional caution must be exercised with respect to detector area which figures in the flux formula. Horizontal area of both our detectors is 1150 cm^2, but muons also pass through the vertical surfaces. At ground level muons with $\cos^{1.85}\theta$ angular distribution have 3.88 times higher probability to pass through horizontal than vertical unit area. Having this in mind, one arrives at 1338 cm^2 effective area of the ground detector. At the same time, with n = 1.55 exponent in angular distribution at 25 m.w.e underground, [3], ratio of horizontal to vertical probabilities is 3.637 (effective area 1350cm^2). These edge effects are relevant for both low and high energy portion of the spectra and should not be neglected.

Total live time of measurements at ground level is about 8 x 10^7 s and number of detected muons is close to 1.7 x 10^9. Consequently, muon flux at ground level is 1.61 x $10^{-2}s^{-1}cm^{-2}$. Due to large number of detected muons, statistical error is by far less than systematic, which we only report here and estimate to be 0.1 x $10^{-2}s^{-1}cm^{-2}$. Finally, result of our ground level measurements of CR muons is:

$$J_{1G} = (1.6 \pm 0.1) \times 10^{-2} s^{-1} cm^{-2}$$

Underground, at depth of 25 m.w.e, 4.6 x 10^8 muons are collected for 7.7 x 10^7s of measurement. Measured muon flux underground is:

$$J_{1U} = (4.5 \pm 0.2) \times 10^{-3} s^{-1} cm^{-2}$$

Attenuation of the muon flux with respect to the surface flux is 3.56.

From these data and known angular distribution of CR muons, one can deduce vertical muon flux:

$I_v = (1.0 \pm 0.1) \times 10^{-2}s^{-1}cm^{-2}sr^{-1}$ for ground level
$I_v = (2.5 \pm 0.2) \times 10^{-3}s^{-1}cm^{-2}sr^{-1}$ for underground.

Discussion and Conclusion

Cosmic-ray muons are continuously monitored in the Belgrade underground laboratory. Results of muon flux and vertical intensity measurements on the ground level (78m a.s.l) and at 25 m.w.e underground are reported here. Additional absorber was not used in our setup other than the thin roof of the laboratory. This should be considred when making comparison of our ground surface result with other data. Only those data on integral vertical intensity with lowest momentum cut-off are directly comparable.

For comparison, we mention here only one result closest to our momentum interval by Allkofer et al, [5]. Their result for integral vertical intensity is $I(p_\mu>0.2GeV/c) = (9.94 \pm 0.05) \times 10^{-3}s^{-1}cm^{-2}sr^{-1}$. It appears that the present intensity masurements at ground level yield somewhat higher result than the reported one, but the diffrerence can be attributed to a wider momentum interval in our case. We should also mention a recent measurement of sea level flux by Enquist et al, [6] with 12.5% higher result than ours. This measurement is performed at higher geomagnetic latitude and since the position of our laboratory is still bellow limiting 50° we can expect the presence of latitude effect.

Underground intensity is in excellent agreement with measurements performed in other laboratories (see compilation Barbouti and Rastin, [7] for details and Figure 2).

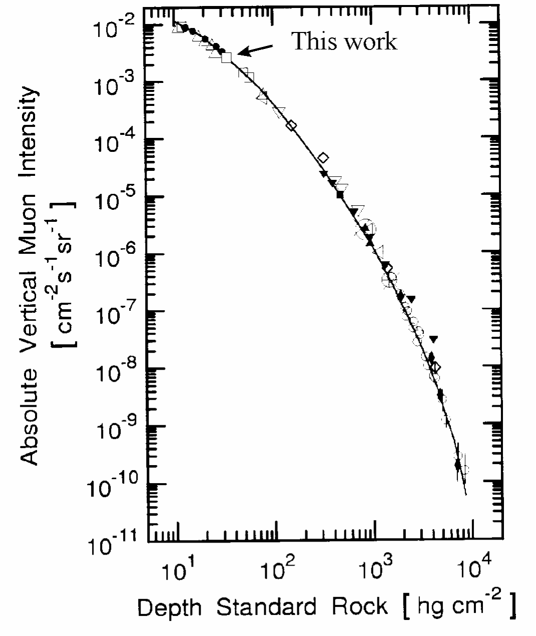

Figure 2: Absolute vertical muon intensity vs. depth, measured from the top of the atmosphere (from [3]). The result of present measurement is indicated.

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