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Measurement of cosmic ray muon flux in the Belgrade ground level and underground laboratories

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Abstract

The cosmic-ray muon count rate and energy loss spectra in plastic scintillator detectors are recorded in the Institute of Physics, Belgrade. Measurements are performed at two different levels: at the surface level (78 m a.s.l.) and in the Belgrade underground laboratory at the depth of 25 m.w.e. From experimental data and with the use of GEANT4 computer simulation the flux and vertical intensities have been determined. At ground level the muon flux is determined to be $J_{1G} = (1.37 \pm 0.06) \times 10^{-2}\,\mathrm{s^{-1}\,cm^{-2}}$ and vertical intensity $I_{vG} = (8.4 \pm 0.4) \times 10^{-3}\,\mathrm{s^{-1}\,cm^{-2}\,sr^{-1}}$ while the same quantities underground are $J_{1U} = (4.5 \pm 0.2) \times 10^{-3}\,\mathrm{s^{-1}\,cm^{-2}}$ and $I_{vU} = (2.5 \pm 0.2) \times 10^{-3}\,\mathrm{s^{-1}\,cm^{-2}\,sr^{-1}}$. Their relation to the results of similar measurements worldwide is discussed.

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Keywords: Muon flux; Cosmic rays; Underground laboratory

1. Introduction

Measurements of the atmospheric muon flux have been carried out many times in the past, including some very recent experiments. Except for being an important problem *per se* in cosmic-ray physics, knowledge of the absolute muon flux is of interest for many experiments in contemporary nuclear and particle physics. The issue is relevant for neutrino (astro)physics, because of the close relation between atmospheric muon and neutrino production. In the experiments requiring very low background (dark matter search, proton decay, double beta decay) muons represent an important source of background. If not directly, since the muon flux is effectively suppressed at large depths underground, then by generating high-energy neutrons in the interactions in the rock or detector itself. The muon flux is also important because of the claims of long term cosmic-ray intensity variations, which may have relevance to global warming (e.g. Ref. [1]).

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

In the present paper, we report the results of muon flux measurements in the Belgrade laboratory (geographic latitude 44°51′N, vertical geomagnetic rigidity cut-off 5.3 GV). Measurements are performed at ground level (altitude 78 m a.s.l.) and in the Belgrade underground laboratory (at the depth of 25 m of water equivalent).

When comparing the results on sea level or shallow-depth muons, one has to bear in mind the exact location and period of measurements. For low energy muons the effect of the geomagnetic field is significant. At different geomagnetic latitudes the geomagnetic field prevents the arrival of cosmic-ray (CR) particles with rigidity (momentum per unit charge) lower than some cut-off value. Influence on the CR flux is expected from the Equator to geomagnetic latitude ~45°.

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The period of measurements is relevant since the intensity of cosmic-rays varies with the 11-year cycle of solar activity. Solar modulation affects primary protons with energies less than 20 GeV which give contribution to the sea level muon flux. Braun et al. [2] recorded 1.5% variation in the flux of muons with $E > 0.7$ GeV over the solar activity cycle. There are other periodic variations of CR flux, the most famous being the one with 27-day period of solar rotation, which can influence the results of short-lasting measurements. This effect can vary from a fraction of a percent to several percent, with larger amplitudes expected in the period of solar activity rise [2]. There is also the important possibility of a long term variation mentioned earlier [1].

The same objection holds for the variation of the CR flux with atmospheric conditions. The most important parameters for CR muons are atmospheric pressure and temperature profile from the ground to the layer of the atmosphere where most of the pions (muon progenitors) are produced. Simulations with CORSICA imply a flux change of $\pm 1\%$ over the year, due to atmospheric temperature variations [3].

2. Description of the experiment

Our detector system consists of two identical plastic scintillation detectors. The detectors were produced by the High Energy Physics Laboratory of JINR, Dubna, and are similar to NE102. Both detectors are in the shape of a cuboid with dimensions 50 cm × 23 cm × 5 cm. The largest detector surface is placed horizontally. One detector is situated in the underground laboratory, and the other at ground level. The detectors operate independently. A single 5 cm photomultiplier is mounted on each detector via a correspondingly shaped light guide. When a muon (or other charged particle) passes through the detector, the scintillator is excited and emits fluorescent light. The light reaches the photomultiplier where it is converted into the proportional electric signal.

After amplification, the analog output signal from detector is digitized by the home-made A/D converter and then linked to a computer PCI card. The 4000 channel spectrum is automatically recorded every 5 min, with 270 s dedicated to measurements, and 30 s being allowed for recording on a local hard disc, some quick interventions on the system, and data transmission to the second local network computer. The setup enables off-line data analysis without interrupting the measurements.

The spectra, recorded during the calendar year 2002, for both ground and underground detectors, and shown in Fig. 1, are mainly the spectra 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 ~10.6 MeV. The rise in the low energy part of the spectrum is due to environmental radiation.

3. Data treatment and results

Measurements of the muon flux are performed at ground level and in the Belgrade underground laboratory. The laboratory is built under the loamy loess cliff on the bank of the Danube at a depth of 12.0 ± 0.3 m. The geological survey revealed that the overburden consists of four layers with density ranging from 1.8 to 2.1 g/cm^3 and with an average density of 2.0 ± 0.1 g/cm^3. Above the working area of the laboratory there is also a layer of reinforced concrete of 30 cm thick.

Both ground and underground measurements were performed during the entire year 2002, enabling seasonal variations of the flux to be averaged out. Additional measurements at the ground level were taken in the period October–December 2006 using various thickness of the lead absorber, with the purpose of discriminating between muons and other CR components. The ground level detector was covered with 5, 10, and 15 cm of lead, and each measurement lasted for about a week. Measurements without absorber were repeated with approximately the same duration.

A small additional absorber comes from the detector housing and the thin roof of the laboratory which combine to give 3.7 g/cm^2 of the absorber layer.

The total muon flux is determined by dividing the total number of muon counts by measurement live time and detector area. The detection efficiency is assumed to be

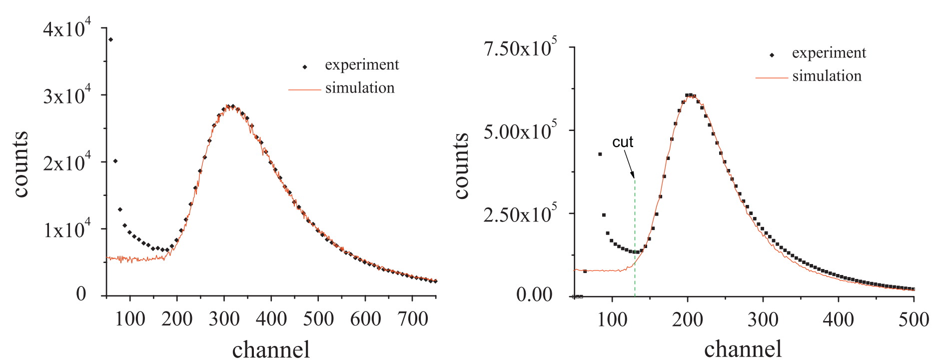

Fig. 1. The energy loss spectrum in the plastic scintillation detector (dots) and GEANT4-based Monte Carlo simulation (line) of detector response to CR muons: ground detector (left); and underground detector (right).

100%, which is a plausible assumption for this type of detector (see discussion on the subject in Refs. [4,5]). This is justified only after MC simulation of the detector response to CR muons is performed, which makes the fiducial volume equal to the real volume of the detector.

The first step in the determination of the muon flux is to extract muon events from the recorded spectrum (Fig. 1). 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 channel 178 for the ground detector (corresponding to about $\sim$6 MeV of energy deposit) and channel 130 for the underground detector (corresponding to $\Delta E \approx 6.5$ MeV) in the plateau separating the low and high energy parts of the spectrum. 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 the recorded spectrum and discrimination of the muon events from the background, we have performed the Monte Carlo simulation of detector response to muons, based on GEANT4.

In the ground level measurements, one must also consider the problem of electron contamination. The classical approach to the problem is to apply absorber capable of stoping the soft CR component and to report the result for the flux of muons above the corresponding momentum cutoff. The absorber layer of 15 cm of lead (the practical definition of the separation between the soft and the hard component of the cosmic radiation) is frequently used. With the typical muon energy loss of $\sim$2 MeV/(g/cm^2), as often assumed in the literature, after passing through the 15 cm of lead, only muons with $p > 0.32$ GeV/c remain. Many historic results are given in this form. We point out that actual energy loss in lead differs significantly from the above value, as calculated precisely in Ref. [6]. The stochastic nature of the energy loss process is another reason why this procedure is not quite correct.

Here we adopt a different strategy. First, the experimental energy deposit spectra are compared with GEANT4-based Monte Carlo simulation for the purpose of the estimation of the signal-background mixing. In the simulation it is assumed that the muon angular distribution at the ground level follows the $\cos^n \theta$ law:

$$I(\theta) = I(0) \cdot \cos^n(\theta) \tag{1}$$

with $n = 1.85 \pm 0.10$ as recommended by Grieder [7]. Here, $I(\theta)$ is the directional intensity of the incident muons. The muon energy is sampled from the Gaisser distribution [8]:

$$\frac{\mathrm{d}N(E,\theta)}{\mathrm{d}E} \sim E^{-\gamma} \left(\frac{1}{1 + \frac{1.1E\cos(\theta)}{115}} + \frac{0.054}{1 + \frac{1.1E\cos(\theta)}{850}} \right) \tag{2}$$

with the exponent $\gamma = 2.7$.

Results of measurements with the lead absorber, together with the simulation, are plotted in Fig. 2.

As far as the measurements with the 15 cm of lead are concerned, the number of muon events embedded in the low-energy part of the spectrum, estimated from the MC simulation, is 6.57%. At the same time, the number of low-energy background events contributing to the muon signal, due to the finite resolution of the detector, is 0.57%. These correction factors are taken with 10% uncertainty, which is a conservative estimate.

The total live time of the measurement is 504 360 s and the total number of detected muons (after above described corrections) is 8 260 379.

Additional caution must be exercised with respect to the detector area which figures in the flux formula. The horizontal area of both our detectors is 1150 cm^2, but muons also pass through the vertical surfaces. At ground level, muons with the $\cos^{1.85}\theta$ angular distribution (Eq. (1)) contribute to the flux through the horizontal detector surface:

$$\begin{aligned} J_{1H} &= \int_{\Omega_1} I(\theta) \cdot \cos\theta \cdot \sin\theta \cdot \mathrm{d}\theta\,\mathrm{d}\varphi \\ &= 2\pi \cdot I(0) \cdot \int_0^{\pi/2} \cos^{(n+1)}\theta \cdot \sin\theta \cdot \mathrm{d}\theta \\ &= 2\pi \cdot I(0) \cdot \frac{1}{n+2} \end{aligned} \tag{3}$$

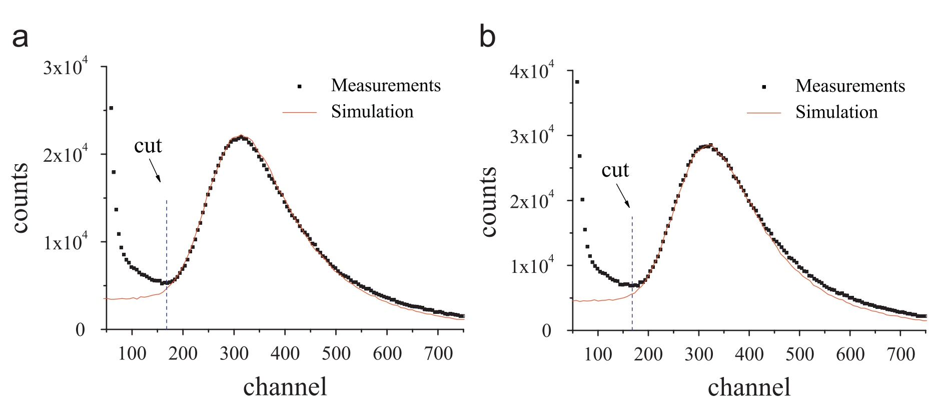

Fig. 2. Energy deposit spectrum in the plastic scintillator detector (dots) and GEANT4-based Monte Carlo simulation (line) of detector response to CR muons after passing: 10 cm of lead (a); and 15 cm of lead (b).

where Ω_1 is the upper hemisphere, and also to the flux through the vertical surfaces:

$$J_{1V} = \int_{\Omega_2} I(\theta)\cdot\sin^2\theta\cdot\cos\varphi\cdot\,\mathrm{d}\theta\,\mathrm{d}\varphi = \int_{\Omega_2} I(0)\cos^n\theta\cdot\sin^2\theta\cdot\cos\varphi\cdot\,\mathrm{d}\theta\,\mathrm{d}\varphi \quad (4)$$

where Ω_2 is a quarter of the sphere.

From the ratio of the above two equations, one can conclude that ground level muons have a 3.88 times higher probability to pass through the horizontal than the vertical unit area. Having this in mind, one arrives at 1338 cm^2 fiducial surface area of the ground detector. At the same time, with $n = 1.55$ exponent in angular distribution at 25 m.w.e. underground [7], the ratio of horizontal to vertical probabilities is 3.637 (effective area 1350 cm^2). These edge effects are relevant for both low- and high-energy portion of the spectra and should not be neglected.

Consequently, the flux of muons at ground level after passing through 15 cm of lead is $1.22\times10^{-2}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$. The statistical error is much smaller than the systematic one, which is the only one that we report here and is estimated to be $0.05\times10^{-2}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$. The largest contribution to the uncertainty of the result comes from the uncertainty in the signal-background mixing and from the uncertainty in the angular distribution exponent, which contribute to the uncertainty of the fiducial surface area of the detector. In order to evaluate the flux correction and the associated uncertainty, it was necessary to rely on simulation. Any uncertainty resulting from the theoretical input into simulation was not encountered for when the flux uncertainty was evaluated. One such possible source of uncertainty is deviation of muon spectra from Gaisser distribution (Eq. (2)) at low energies. For this reason, our flux uncertainty might be slightly underestimated.

The same procedure, applied to measurements with 10 cm of lead (+6.00% − 1.00% correction to signal-background mixing; 360 180 s of measurement live time; 6 140 379 detected muons), yields a flux of $1.27\times10^{-2}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$ with the uncertainty of $0.05\times10^{-2}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$.

Assuming 10 cm layer of lead to be sufficient to stop the electron component, the 4.09% difference between the two fluxes could be attributed to those muons passing through the thinner absorber and reaching the detector, but not passing through the thicker one.

From the MC simulation of the interaction of muons with an angular distribution given by Eq. (1) with the lead shield in our geometry, the form of survival probability vs. energy is deduced, and the results are presented in Fig. 3.

From the survival probability distribution, it is possible to arrive at the flux ratio of 1.0409, if only muons with energy higher than ~500 MeV contribute to the detector signal. Since lower energy muons are expected to pass the lead shield, one concludes that only muons with $E \geqslant 500$ MeV are present at the ground. As a last step, the survival probability distribution is used to correct the flux result for muons lost in the shield. This correction amounts to 11.9% of the result for the 15 cm of lead. The procedure is equivalent to extrapolating to zero momentum cutoff.

The values of the quantities estimated (energy threshold, flux difference after passing 10 and 15 cm of lead, etc.) depend strongly on the details of the applied procedure. The amount of the lost-in-the-shield muon correction relies on Gaisser energy distribution (Eq. (2)) at low muon energy. The difference between Gaisser (theoretical) and the actual energy distribution represents a source of additional systematic error. By applying different cuts to the data, it is possible to arrive at different intermediate results (for quoted quantities), but the final flux estimate appears to be stable with respect to these changes.

Not all of these muons are absorbed by the shield. Some of them did not reach the detector due to multiple scattering in the lead absorber. The number of muons scattered out is estimated with MC simulation of the multiple scattering process in the present geometry. In the simulation it is assumed that the angular deviation from incident muon direction follows the Gaussian distribution [9]:

$$f(\Delta\theta) = \frac{1}{2\pi\sigma_\theta}\cdot\exp\left(-\frac{(\Delta\theta)^2}{2\sigma_\theta^2}\right) \quad (5)$$

with variance $\sigma_\theta = 13.5/(p\beta)\sqrt{L/\lambda}$, where p is the muon momentum (in MeV/c), $\beta = v/c$, L-depth of the absorber,

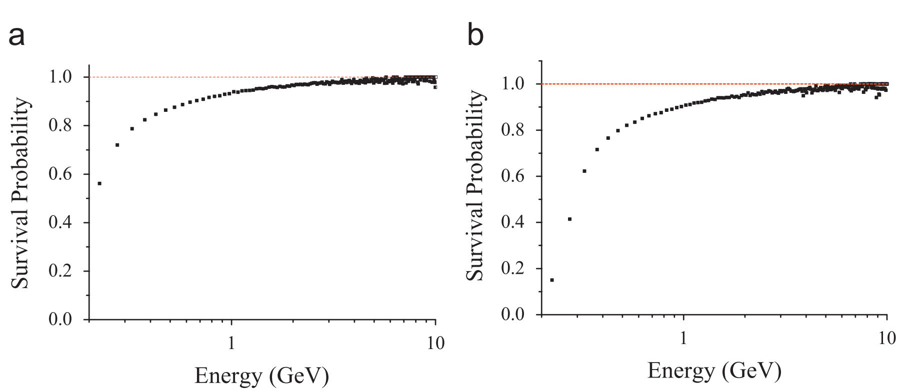

Fig. 3. Survival probability vs. energy for muons with angular distribution (1) after passing: 10 cm of lead (a); and 15 cm of lead (b).

and λ-radiation length (0.56 cm for lead). Estimated flux loss due to multiple scattering is 1.8%.

Finally, the result of our ground level measurements of CR muon flux is

$$J_{1G} = (1.37 \pm 0.06) \times 10^{-2}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}. \tag{6}$$

When the identical spectrum analysis procedure is applied to measurements with an unshielded detector (+13.17% − 0.07% correction to signal-background mixing; 459 270 s of measurement live time; 10 436 564 events), the calculated flux is 23.9% higher. This difference is actually our estimation of the electron contamination. This result from October 2006 is some 4% higher than the result of unshielded measurements during the entire year 2002 (+10.4%−0.19% correction to signal-background mixing; 1.49×10^7 s of measurement live time; 3.23×10^8 events) and can serve as a crude estimate of the solar modulation effect.

Underground, only those muons surviving interaction with the rock, mainly in the ionization processes, are taken into consideration. The result of the MC simulation is shown in Fig. 1b.

Underground, at a depth of 25 m.w.e., 8.8×10^7 muons are collected for 1.45×10^7 s of measurement. The measured muon flux underground is

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

From this value and the known angular distribution of CR muons, one can deduce the vertical muon intensity:

$$J_1 = 2\pi I_v \int_0^{\pi/2} \cos^{(n+1)}\theta \sin\theta\,\mathrm{d}\theta = k^{-1} I_v. \tag{7}$$

The conversion factor is found to be $k = 0.6127$ for ground level and $k = 0.5650$ underground. The resulting vertical intensity is

$$I_{vG} = (8.4 \pm 0.4) \times 10^{-3}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\text{—ground level}$$
$$I_{vU} = (2.5 \pm 0.2) \times 10^{-3}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\text{—underground.}$$

We mention again that ground level results refers to all detectable muons at the ground.

Uncertainty originating from uncertainty in the exponent n in the angular distribution is incorporated into the error estimate.

4. Conclusion and comparison with other data

Cosmic-ray muons are continuously monitored in the Belgrade underground laboratory. Results of the muon flux and vertical intensity measurements at ground level (78 m a.s.l.) and at 25 m.w.e. underground are reported here.

Our result for the ground-level muon flux is generally in line with previous high-latitude measurements. However, the earliest measurements of the sea-level CR muon flux and the vertical intensity have significantly lower values than the later ones (mostly conducted in the seventies). Our result seems situated between the two, but slightly in favor of the older data. It is essentially identical to the result of Greisen [10], after Rossi correction [11] and to the result of Allkofer [12]. It is 2.4% higher than result of Pomerantz [13] (measurement at latitude 52°N; altitude 90 m a.s.l.), but 4.8% lower than Flint et al. [14] (after altitude correction) and 5.3% lower than Kraushaar [15] results.

In bigger disagreement with our data are the results of Crookes and Rastin [16] (8.7% higher than ours); Karmakar et al. [17] at 16°N geomagnetic latitude and 122 m a.s.l. (7% higher); and especially Allkofer et al. [18]. (9.3% higher) and Hayman and Wolfendale [19] (10.5% lower).

We also mention a recent measurement of the muon flux by Enqvist et al. [4] with $1.8 \times 10^{-2}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This result is significantly higher than ours, but direct comparison is difficult to make since authors did not provide the altitude data.

On the other hand, some recent experiments of the differential muon intensity reported lower values than previous: BESS [22] (20% lower) and CAPRICE94 [21] (10–15% lower). Possible reason for discrepancies between differential spectrum measurements is in systematic error associated with normalization procedure, converting relative measurements into absolute ones.

The underground intensity is in excellent agreement with measurements performed at shallow depth in other laboratories. Our result together with the compilation of other results is plotted in Fig. 4. References used for this purpose are indicated in the figure, and could be found within Ref. [7]. Results are presented in the form $I_v \cdot d^3$ vs. d so that discrepancies are more clearly visible. The solid line in the figure is the empirical depth-intensity expression obtained by Barbouti and Rastin [20] that should be valid for depths from 10 to 10^4 hg cm^{-2}:

$$I_v(X) = \left(\frac{K}{(X^\alpha + a)(X + H)}\right)\exp(-\beta H) \tag{8}$$

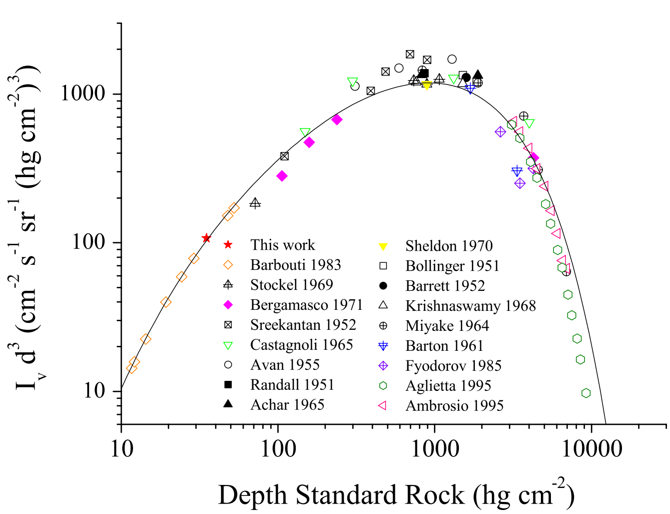

Fig. 4. Absolute vertical muon intensity vs. depth measured from the top of the atmosphere. The result of present measurement is indicated.

with the values of the parameters: $a = 75$, $H = 200\,\mathrm{hg\,cm^{-2}}$, $K = 270.72\,\mathrm{hg\,cm^{-2}}$, $\alpha = 1.68$ and $\beta = 5.5 \times 10^{-4}\,\mathrm{hg^{-1}\,cm^2}$. Depth X is given in $\mathrm{hg\,cm^{-2}}$ of standard rock, and vertical intensity $I_v(X)$ is in units of $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$.

Assuming that there is no trend in time variation of the muon flux over the last 50 years, we attempted to estimate the most probable muon flux that could be derived from the available experimental data. Majority of references used for compilation could be found in Ref. [7]. The others are listed in Refs. [21–24]. Present result is also included in the analysis. Data, taken at different experimental conditions, are put on equal footing by applying three type of corrections: altitude correction, geomagnetic correction and correction with respect to momentum threshold.

Altitude correction to the sea level is made with the use of the Rossi curve intensity vs. atmospheric depth [11]. When necessary, atmospheric depth X (measured in $\mathrm{g/cm^2}$) is converted in the height above sea level h (in meters) with the expression: $h = c \cdot \ln(b/(X - a))$ with the parameters $a = -135.3657$, $b = 1173.5795$ and $c = 9644.8107$ [25].

Measurements at low geomagnetic latitudes are corrected to expected values at approximately 50°N, above which very little flux variation with rigidity cut-off is expected. Correction factors are determined from Ref. [26].

Finally, all measured fluxes are corrected to momentum threshold $p > 0.32\,\mathrm{GeV}/c$, since this is the most frequently used threshold value.

Therefore, the result is reported in the form: vertical intensity $I_v(p > 0.32\,\mathrm{GeV}/c)$ at sea level and above 50° of geomagnetic latitude.

Thus obtained the most probable vertical intensity is found to be $(8.6 \pm 0.3) \times 10^{-3}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ by adopting equal weights to the data, or $(9.10 \pm 0.13) \times 10^{-3}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ weighting according to the quoted errors.

The evidence for or against a linear slow time dependence will be considered elsewhere.

Acknowledgement

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