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ELEMENTARY PARTICLES AND FIELDS
Experiment

Study of Single Muons with the Large Volume Detector at the Gran Sasso Laboratory*

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Abstract—The present study is based on the sample of 2.9×10^6 single muons observed by the Large Volume Detector (LVD) at the underground Gran Sasso Laboratory during 36 500 live hours from June 1992 to February 1998. We have measured the muon intensity at slant depths from 3 to 20 km w.e. Most events are high-energy downward muons produced by meson decay in the atmosphere. The analysis of these muons has revealed the power index γ of the π and K spectrum: $\gamma = 2.76 \pm 0.05$. The remainders are horizontal muons produced by the neutrino interactions in the rock surrounding the LVD. The value of this flux near 90° is $(6.1 \pm 2.7) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The results are compared with the Monte Carlo simulations and the world data. *© 2003 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

The study of atmospheric muons at large underground depths is the subject of experimental investigations because of the following reasons. First, muons and muon-produced secondary particles are the background for underground detectors designed to search for rare events, including the tasks of neutrino and gamma-ray astronomy. Second, the calculations of atmospheric muon and neutrino fluxes are based on a hypothesis about the primary cosmic-ray spectrum and hadron–hadron interactions. The existing deep underground detectors are not able to measure muon energy for the direct deduction of energy spectrum. But they are able to measure the muon "depth–intensity" curve. This curve shows the vertical–muon flux as a function of the rock (water, ice) depth and is related to the muon propagation through the rock, the muon energy spectrum at sea level, and then, to the primary cosmic-ray spectrum.

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The connection to the muon propagation allows the tests of the cross sections of the muon interactions with the rock which have been used in the program for the muon transport.

The measurements of muon intensity are made using the single detector and technique from a relatively small depth to a large depth, where neutrino-induced muons dominate and are of special interest. Such an experiment observes muons at zenith angles from the vertical to the horizontal direction. The statistics for the measurement of neutrino-induced flux in the horizontal direction are small enough, but the uncertainties in detecting the muon direction are absent. There is no need to suppress the flux of atmospheric muons by a factor of about 10^6 using accurate time measurements.

The Large Volume Detector (LVD) structure and the complicated profile of the Gran Sasso mountains provide an opportunity to measure the muon depth–intensity curve for slant depths from 3 to 20 km w.e. and the neutrino-induced muon flux in the horizontal direction, where the atmospheric muon flux is suppressed due to the large slant depth. The expected number of horizontal events caused by neutrino-induced muons is small (about one—two events per one LVD tower per year), therefore we cannot at the moment make any conclusions about neutrino oscillations.

In our previous paper [1] we have presented our first results on the measurement of the muon depth–intensity curve for the depth range of 3–20 km w.e. Since that time we have improved the criteria for event selection and increased the statistics. The analysis of [2] was based on the events with all multiplicities. Multiple muon events, especially for large depths, are more difficult to reconstruct than single muons. To avoid this problem, we have also performed the analysis of single muons using stronger criteria for the run and event selection. This analysis is based on increased statistics, compared with our previous publications.

In Section 2, the detector and the procedure of data analysis and conversion of the muon intensity to the vertical are briefly described. In Section 3, the results of the analysis of the depth–vertical muon intensity relation ($I_\mu(x)$) are shown. In Section 4 we present the analysis of neutrino-induced events. Section 5 contains our conclusions.

2. DETECTOR AND DATA SELECTION

The LVD has been extensively described elsewhere [1, 3, 4]. The detector is located at the Gran Sasso Laboratory, Italy. The minimal rock overburden is 3 km w.e. The LVD consists of three towers. Each tower is made of 38 modules with dimensions of $2.1 \times 6.2 \times 1.0$ m^3. Data were obtained using the first LVD tower from June 1992, when it was put into operation, until February 1998. The total live time was 36 500 h. The tower is $13 \times 6.6 \times 12$ m^3. Each module contains eight scintillator counters with the active volume of $1.0 \times 1.5 \times 1.0$ m^3 and the mass of liquid scintillator of 1.2 tons, and a tracking detector is attached to the bottom and one vertical side of the supporting structure. Each tracking detector is made up of four layers of tubes operating in limited streamer mode. Each layer has independent x and y readout strips. These established the x and y coordinates of the hits. The tracking system allows the measurements of particle direction to be taken with an accuracy better than 0.5°.

The mountain structure above the Gran Sasso Laboratory allows the measurements of muons which traversed a slant depth from 3 to more than 12 km w.e. The depths correspond to the median muon energies at sea level from 1.5 to 40 TeV at zenith angles from 0° to 90°. In this analysis we have used the sample of events containing only single muons. Events with all multiplicities are usually studied in the experiments with cosmic-ray muons. Such an analysis supposes the accurate reconstruction of each event. The study of depth–intensity curve with all muon events observed by the LVD has been presented in [2]. The multiple muons have been considered as independent muons and the acceptance both single and multiple muons has been assumed the same. This is a good and well-proven approximation for the derivation of the all-particle primary spectrum. The task requires, however, the reconstruction of muon events with all multiplicities and the measurements of the direction and slant depths with good accuracy. This is a more difficult task for multiple muon events than for single ones. Most muons traverse small rock thicknesses. If the slant depth for a small fraction of these events is incorrectly defined, then the intensity in this direction will not change much. However, these erroneously reconstructed events can significantly contribute to the muon intensity at large depths. To be sure of the precise event reconstruction, in this analysis we have dealt with single muons only. The size of one LVD tower is small enough, and more than 90% of muon events are single muons. The number of muons in bundles is about 10–12% of the total number of muons. Possible uncertainties from neglecting multiple muons are less than or comparable to the errors from including multiple-muon events with erroneous reconstruction. In the case of single-muon analysis we need to correct the absolute intensity for the number of unreconstructed events (multiple muons and muon-induced cascades).

The trigger for muon events has been defined as follows: (i) the energy deposition is greater than

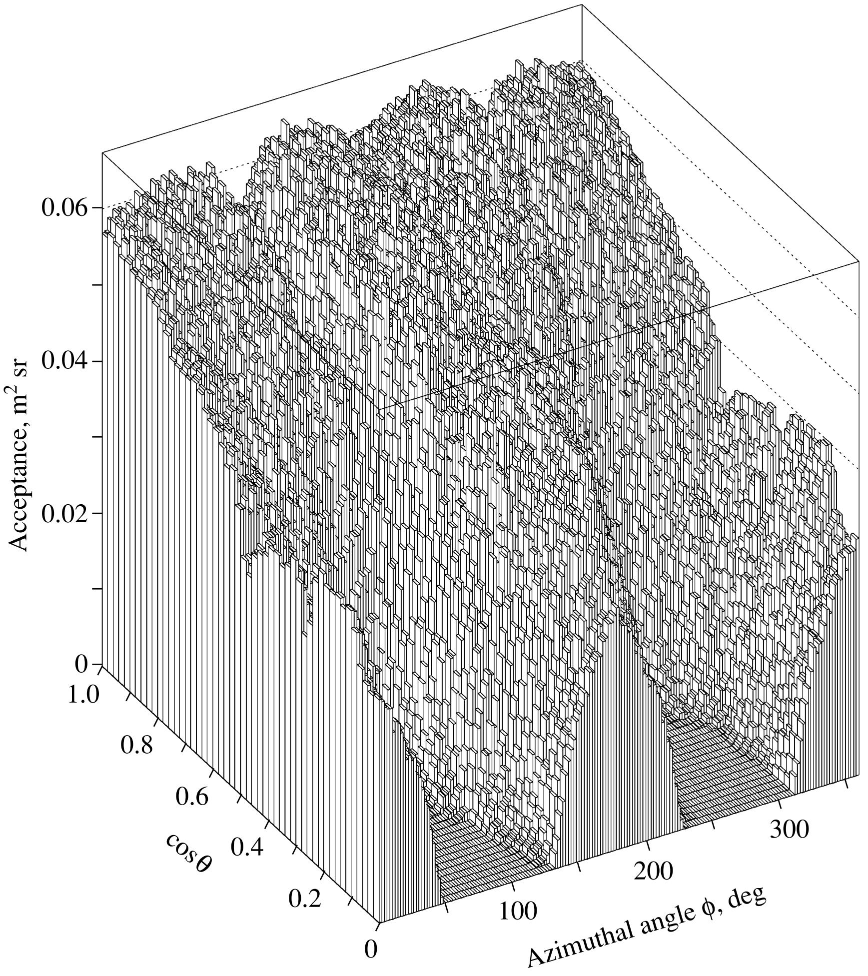

Fig. 1. The LVD acceptance for single muons as a function of the cosine of the zenith angle θ and azimuthal angle ϕ. The angular cell for this plot was chosen as 0.02 ($\cos\theta$) × 2° (ϕ).

30 MeV in at least two scintillator counters in two different modules and (ii) hits in at least three layers in any three tracking detectors (hits in at least one layer per detector). The data runs have been selected as follows: runs have been accepted if they lasted longer than an hour and the counting rate is within a 15% range around the mean value for the set of runs. Moreover, we have required at least 36 of 38 tracking modules and 240 of 304 scintillator counters of the first tower to be operated during any particular run. These criteria ensured the full and uniform acceptance of the detector. The final muon sample after these cuts consisted of 3 151 580 events. 2 877 659 (91%) events have been reconstructed as single muons. Multiple muons and muons accompanied by cascades constituted 9%. All reconstructed single muons were binned in a two-dimensional array with a cell size of 1° at azimuthal angle ϕ and 0.01 at $\cos\theta$, where θ is the zenith angle. The accuracy of the reconstruction has been checked by observation of the Moon shadowing effect with single-muon data [5]. It is better than 0.65°.

The acceptance for each angular bin has been calculated using the simulation of muons traversing the LVD, taking into account the detector response. The thickness of the rock crossed by the muon was determined from the mountain map.

The angular distribution $N_\mu(\phi, \cos\theta)$ obtained in the experiment has been converted to the depth–intensity relation using the formula

$$I_\mu(x_m) = \frac{\sum_{ij} N_\mu(x_m(\phi_j, \cos\theta_i))}{\sum_{ij}(S(x_m(\phi_j, \cos\theta_i))\epsilon(x_m(\phi_j, \cos\theta_i))\Omega_{ij}T)}, \quad (1)$$

where the summing up has been done over all angular bins $(\phi_j, \cos\theta_i)$ contributing to the depth x_m, $S(x_m(\phi_j, \cos\theta_i))$ is the cross section of the detector in the plane perpendicular to the muon track at the angle $(\phi_j, \cos\theta_i)$, $\epsilon(x_m(\phi_j, \cos\theta_i))$ is the efficiency of

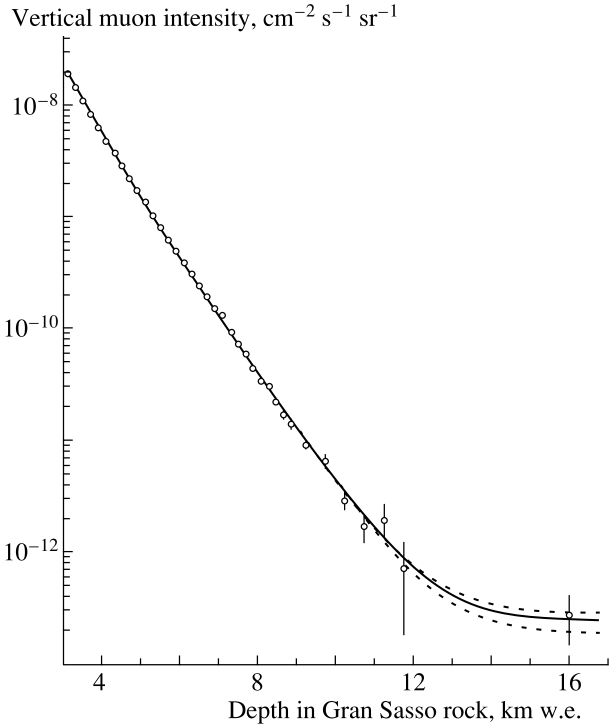

Fig. 2. Depth–vertical muon intensity relation in Gran Sasso rock. The LVD data are presented together with the best fit (solid curve). Dashed curves show the calculated intensities for the maximal and minimal contributions from neutrino-induced muons (see text for details).

muon detection and reconstruction, Ω_{ij} is the solid angle for the angular bin, and T is the live time. Angular bins with ϵ less than 0.03 were excluded from the analysis. The acceptance A is defined as

$$A(\cos\theta, \phi) = \epsilon(\cos\theta, \phi)\Omega(\cos\theta, \phi)S(\cos\theta, \phi) \quad (2)$$

and is shown in Fig. 1.

The intensity of muons at zenith angle θ was assumed to be related to the vertical intensity I_0 through the relation

$$I(x_m, \theta) = I_0(x_m, \theta = 0°)/\cos\theta_i^*, \quad (3)$$

where

$$\cos\theta_i^* = \frac{I_\mu^c(x_m, \cos\theta = 1)}{I_\mu^c(x_m, \cos\theta_i)} \quad (4)$$

is the ratio of the calculated muon intensity at $\cos\theta = 1$ to that at $\cos\theta_i$. This relation is valid for muons of atmospheric origin if we neglect the contribution of the prompt muons from charmed particles. According to the LVD data, the ratio of prompt muons to pions does not exceed 2×10^{-3} at a 95% confidence level [6].

For the depth–intensity relation, the bin width of 200 m w.e. has been chosen. For a depth more than 9 km w.e., we have chosen bins with the width of 500 km w.e. to increase the statistics for each bin. The conversion of muon intensity to the middle points of each depth bin has been done using formula

$$I_\mu^m(x_i) = I_\mu^m(x_m)\frac{I_\mu^c(x_i)}{I_\mu^c(x_m)}, \quad (5)$$

where $I_\mu^m(x_m)$ and $I_\mu^c(x_m)$ are the measured and calculated muon intensities at the weighted average depth x_m, which corresponds to the depth bin with the middle value of x_i; and $I_\mu^m(x_i)$ and $I_\mu^c(x_i)$ are the derived and calculated muon intensities at the depth x_i, which is the middle point of the depth bin. The values of x_m have been obtained by averaging the depths for all angular bins contributing to the given depth bin with a weight equal to the detected number of muons. To calculate the muon intensities at x_m and x_i, we have used the muon spectrum at sea level with previously estimated parameters [1, 2] (see also Eq. (7)) and the simulated muon survival probabilities. Since the width of depth bins is quite small (200 m w.e. for depth bins with high statistics) and the number of angular bins contributing to each depth bin is quite large (several hundreds), the conversion factor does not exceed 10%.

3. DEPTH–VERTICAL INTENSITY RELATION IN GRAN SASSO ROCK

To calculate the intensity of muons underground requires the intensity of muons at the surface as a function of energy and zenith angle, and the survival probability as a function of slant depth of rock traversed:

$$I_\mu(x, \cos\theta) = \int\limits_0^\infty P(E_{\mu0}, x)\,\frac{dI_{\mu0}(E_{\mu0}, \cos\theta)}{dE_{\mu0}}\,dE_{\mu0}, \quad (6)$$

where $P(E_{\mu0}, x)$ is the probability of a muon with an initial energy $E_{\mu0}$ at sea level to reach the depth x and $dI_{\mu0}(E_{\mu0}, \cos\theta)/dE_{\mu0}$ is the muon spectrum at sea level at zenith angle θ. The intensity at the surface in the units of (cm^2 s sr GeV)$^{-1}$ can be approximated by [7]

$$\frac{dI_{\mu0}(E_{\mu0}, \cos\theta)}{dE_{\mu0}} = A \cdot 0.14 \cdot E_{\mu0}^{-\gamma} \quad (7)$$
$$\times \left(1\bigg/\left(1 + \frac{1.1E_{\mu0}\cos\theta^*}{115\ \text{GeV}}\right)\right.$$
$$\left. + \; 0.054\bigg/\left(1 + \frac{1.1E_{\mu0}\cos\theta^*}{850\ \text{GeV}}\right)\right),$$

where the values of $\cos\theta$ have been substituted by $\cos\theta^*$, which have been taken from [8]. According to [8], $\cos\theta^* = E_{\pi,K}^{\text{cr}}(\cos\theta = 1)/E_{\pi,K}^{\text{cr}}(\cos\theta)$,

Table 1. The value of power index of meson spectrum for various depth ranges (the errors are statistical only)

Depth interval, km w.e.	γ	χ^2/d.o.f.
3–12	2.76 ± 0.02	25.8/34
4–12	2.78 ± 0.03	19.0/29
5–12	2.79 ± 0.04	16.8/24
6–12	2.82 ± 0.06	14.8/19
7–12	2.94 ± 0.14	11.4/14
8–12	2.76 ± 0.22	6.7/9
9–12	2.60 ± 0.50	3.3/4

where $E^{\rm cr}_{\pi,K}$ are the critical energies of pions and kaons. Equation (7) has been obtained under a simple assumption of scaling in the high-energy hadron–nucleus interactions. Under this assumption, the power index of the primary spectrum, γ, is expected to be equal to that of the meson (pion + kaon) spectrum, $\gamma_{\pi,K}$.

The muons were tracked through the rock using the propagation code MUSIC [9] to calculate the muon survival probabilities $P(E_{\mu 0}, x)$. The randomness of all processes of muon interaction with matter (nuclear interaction, pair production, bremsstrahlung, and ionization) has been taken into account. The cross sections were taken from [10–12]. The muon intensities calculated with a bremsstrahlung cross section from [12] are lower than those with a bremsstrahlung cross section from [13], which was used in our previous paper [1]. Using the cross section from [13] will result in a higher power index (softer muon spectrum) compared to the cross section from [12]. The difference in power index is of the order of 0.01.

The measured depth–intensity curve is shown in Fig. 2 together with the best fit. The underground muon flux observed at a slant depth x and zenith angle θ has a two-component nature and can be presented as:

$$I_\mu(x,\theta) = I_\mu^{(\mu)}(x,\theta) + I_\mu^{(\nu)}(\theta), \tag{8}$$

where $I_\mu^{(\mu)}(x,\theta)$ is the contribution of atmospheric muons and $I_\mu^{(\nu)}(\theta)$ denotes the contribution of muons from neutrino interactions in the rock surrounding the detector. For slant depths of 13–20 km w.e. the muons seen in the LVD are of later origin. The last experimental point in Fig. 2 corresponds to the neutrino-induced muon flux. This flux was measured at the depth of 13–20 km w.e. To convert the flux of neutrino-induced muons to vertical intensity, we used the calculated ratio of horizontal and vertical fluxes of neutrino-induced muons, which is equal to 2.1 at an energy threshold of 1 GeV for most models of atmospheric neutrino production:

Table 2. The number of muons at large depths h observed by LVD ($N_{\rm obs}$) and the calculated values ($N_\mu^{\rm atm}$ are atmospheric muons, N_μ^ν are neutrino-induced muons, and $N_\mu^{\rm tot} = N_\mu^{\rm atm} + N_\mu^\nu$)

h, km w.e.	$N_\mu^{\rm atm}$	N_μ^ν	$N_\mu^{\rm tot}$	$N_{\rm obs}$
$h > 13$	0.45	3.75	4.20	5
$h > 14$	0.31	2.92	3.23	4
$h > 15$	0.03	1.50	1.53	2

$$I_\mu^\nu(x,\theta=0^\circ) = I_\mu^\nu(x,\theta=90^\circ)/2.1. \tag{9}$$

The depth–intensity curve has been fitted to the calculated function with two free parameters: the additional normalization constant, A, and the power index of the atmospheric pion and kaon spectrum, γ. As a result of the fitting procedure, the following values of the free parameters have been obtained: $A = 1.59 \pm 0.50$ and $\gamma = 2.76 \pm 0.05$ for muon energies at sea level from 1.5 to 40 TeV. The errors of the parameters include both statistical and systematic uncertainties. The latter takes into account possible uncertainties in the depth, rock composition, and density and the uncertainty in the cross sections used to simulate muon transport through the rock. These values are in good agreement with the results of a similar analysis performed for the muon events with all multiplicities observed by the first LVD tower during 21 804 h of live time: $A = 1.95 \pm 0.50$ and $\gamma = 2.78 \pm 0.05$. Note that the estimates of the parameters A and γ are strongly correlated. The larger the value of γ is, the larger the normalization factor A should be.

We have repeated the fitting procedure for restricted depth ranges. The results of this test are presented in Table 1. The results show that the power index is the same within errors for all depth ranges.

Neutrino-induced muon flux has not been included in the fit procedure but has been added to the best fit at the 2.5×10^{-13} cm^{-2} s^{-1} sr^{-1} level. Dashed curves in Fig. 2 show the possible values of the muon intensities if we take into account the uncertainties in the calculation of atmospheric neutrino spectrum at sea level and structure functions and the corrections for quasielastic scattering, and the energy threshold of the detector. The experimental value $(2.9 \pm 1.3) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1} is in agreement with the calculated one $(2.5 \pm 0.5) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. It also agrees with the compiled world results on underground muon intensities presented by Crouch in [14], where the flux of neutrino-induced muons is equal to $(2.17 \pm 0.21) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}.

If the formula from [15] is used for the muon spectrum at sea level instead of Eq. (7), the best-fit value of γ will be decreased by 0.04–0.05.

The value of γ obtained with the LVD data is in reasonable agreement with the results of other surface and underground experiments: DEIS [16], MUTRON [17], MIPhI [18] (the energies of these experiments correspond to first few points of our depth–intensity curve), ASD [19], NUSEX [20], MACRO [21], and MSU [22] (if we consider the muon spectrum from [15] in the latter case). The LVD data disagree with the results of the Baksan Scintillator Telescope and the KGF [23, 24]. The difference here is likely due to the different measurement methods, the applied analysis procedure in each experiment, and uncertainties in the knowledge of overburden composition.

4. NEUTRINO-INDUCED MUONS

Let us describe the evaluation of the horizontal neutrino-induced muon flux in more details. High-energy neutrinos will produce high-energy muons in the rock. These muons will have enough energy to traverse the entire detector. The reconstructed muons that traversed rock thickness greater than 12 km w.e. have been considered as candidates for neutrino-induced muons. These depths correspond to zenith angles of more than 85°. We have recorded 95 such candidates during 36 500 h of the LVD lifetime. A careful visual scan of all of these tracks eliminated five candidates from the sample because of confusion in the pattern recognition.

Since the timing of the LVD experiment (12.5 ns) is not sufficient to determine the direction of a track crossing one tower, there is a twofold ambiguity in the direction for each measured track. In other words, the LVD cannot discriminate between muon direction (θ, ϕ) and $(180^\circ - \theta, 180^\circ + \phi)$. For $\theta < 90^\circ$, it is reasonable to assume that muons come from above, since the rock thickness is smaller above the horizon. Gran Sasso mountain has a very complicated profile, and for many bins at $\theta \approx 90^\circ$ with $x > 12$ km w.e. the slant depth for inverse direction x_1 appears to be less than 8 km w.e. The muon intensity for 8 km w.e. is 80 times greater than the intensity for 12 km w.e. In this case we assume that the muon came from the direction with the smaller slant depth. Near-horizontal muons with reconstructed slant depths greater than 12 km w.e. and slant depth less than 8 km w.e. in the opposite direction were excluded as neutrino-induced candidates and considered as bins $(\theta, 180^\circ + \phi)$. Totally, we had 67 such events.

Some angular bins with slant depths greater than 12 km w.e. are surrounded by bins with smaller slant depths. According to the calculations of [9], the average angular deviation of muons is 0.45° at 10 km w.e. and it is mainly caused by multiple Coulomb scattering. The probability of muon coming from the direction with smaller slant depth is greater. We have considered such a muon as coming from the direction with smaller depth, assuming that it had been recorded into the bin with greater depth due to the reconstruction error or scattering.

Five muons produced in neutrino interactions with surrounding rock have survived all cuts for slant depths $x > 13$ km w.e.; for $x > 14$ km w.e., we have found four such events; and for $x > 15$ km w.e., there are two neutrino-induced muons.

A Monte Carlo has been used to estimate the expected number of neutrino-induced muons. The spectrum of neutrino-induced muons has been calculated following the formula

$$\frac{dN_\mu}{dE_\mu} = \int\limits_{E_\mu}^{\infty} \frac{dN_\nu}{dE_\nu} \frac{P(E_\nu, E_\mu)}{dE_\mu} dE_\nu. \qquad (10)$$

dN_ν/dE_ν represents the neutrino spectrum and $P(E_\nu, E_\mu)/dE_\mu$ is the probability that a neutrino produces a muon in the interval $(E_\mu, E_\mu + dE_\mu)$. We have used the Bartol neutrino flux [25], which has a systematic uncertainty ±14%, and the Morfin and Tang [26], as well as Duke and Owens [27] parton distribution functions, which result in a less than 1% difference in muon spectra. The major sources of uncertainties in the neutrino-induced muon flux are the uncertainty in the neutrino fluxes and neutrino cross sections because of required extrapolations of the structure functions to small $x \ll 10^{-4}$. For neutrino-induced muons, the calculations of atmospheric neutrino flux by various authors differ by as much as 17%. Different standard parametrizations of charged current cross sections also differ by as much as 13% [28]).

Table 2 shows the number of muons observed by the LVD during 36 500 h, as well as calculated values (the uncertainty of calculations is 20%).

The observed number of muons at large slant depths agrees with the predictions within errors. The measured neutrino-induced horizontal muon flux is $(6.1 \pm 2.7) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}, while the calculated one is $(5.2 \pm 1.1) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. Our measured value agrees with the results of other experiments: Soudan-2, $(5.00 \pm 0.55 \pm 0.51) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1} [29]; Frejus (the flux recalculated for our energy threshold), $(4.77 \pm 0.86) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1} [30]; and in a South African mine, $(4.59 \pm 0.42) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1} [31].

5. CONCLUSIONS

We have measured the underground muon intensity as a function of the slant depth in the range of 3–20 km w.e. The analysis of depth–intensity relation in the depth range of 3–12 km w.e. has been done to obtain the power index of the differential energy spectrum of the pions and kaons in the atmosphere, $\gamma = 2.76 \pm 0.05$ in the energy range of 1–40 TeV. The errors include both statistical and systematic uncertainties with the systematic error due to the dominating uncertainty of the muon interaction cross sections. Our results are in good agreement with other experiments. Muons that traversed a slant depth more than 13 km w.e. were analyzed to obtain the horizontal flux of neutrino-induced muons. This flux is equal to $(6.1 \pm 2.7) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1} and is consistent with our calculations and the reported results of other experiments. Our fit of the depth–intensity curve to this data is in good agreement with the fit of Crouch, which is a summary of various experiments.

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