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# Investigation of the zenith angle dependence of cosmic-ray muons at sea level

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**Abstract.** Angular distribution of cosmic-ray muons at sea level has been investigated using the Geant4 simulation package. The model used in the simulations was tested by comparing the simulation results with the measurements made using the Berkeley Lab cosmic ray detector. Primary particles' energy and fluxes were obtained from the experimental measurements. Simulations were run at each zenith angle starting from $\theta = 0°$ up to $\theta = 70°$ with 5° increment. The angular distribution of muons at sea level has been estimated to be in the form $I(\theta) = I(0°)\cos^n(\theta)$, where $I(0°)$ is the muon intensity at 0° and $n$ is a function of the muon momentum. The exponent $n = 1.95 \pm 0.08$ for muons with energies above 1 GeV is in good agreement, within error, with the values reported in the literature.

**Keywords.** Cosmic muon; angular dependence; Geant4.

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## 1. Introduction

High-energy charged particles originating in outer space and travelling at nearly the speed of light, bombard the Earth's atmosphere from all directions. These particles, called primary cosmic rays, are mostly protons and $\alpha$-particles. Their collisions with the nuclei in the atmosphere produce showers of secondary particles, such as charged pions, which are unstable mesons decaying into muons and neutrinos (more detailed information can be found, for instance, in [1]). This relationship makes muon measurements an important tool for calculating neutrino flux [2]. Muons do not interact strongly with the atmospheric nuclei and experience relativistic time dilation in the Earth's reference frame. As a result, many of the muons are able to reach the Earth's surface and they are the most abundant charged particle at sea level, where the integral intensity of vertical muons above 1 GeV/c is around 70 $m^{-2}\ s^{-1}\ sr^{-1}$ [3].

Measurements of the angular dependence, together with the absolute flux and charge ratio, of the muon spectrum at sea level over a broad energy range are important to get

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information on the propagation of cosmic rays in the atmosphere. The azimuthal angle dependence of the atmospheric muon charge ratio at sea level has recently been studied experimentally by different groups [4–6]. Measurements of the charge ratio obtained using the WILLI detector [6] have also been successfully reproduced using Geant4 simulation package [7]. The zenith angle ($\theta$) dependence of the cosmic muon intensity at sea level has been investigated for different zenith angle ranges [8,9], as well. For $\theta \leq 75°$, it is given by the expression

$$I(\theta) = I(0°)\cos^n(\theta),$$

where $I(0°)$ is the intensity at 0° and $n$ is a function of the muon momentum. The value of $n$ around 1 GeV is $1.85 \pm 0.10$ [10].

Since they are charged, muons can be detected by different types of particle detectors and there have been many muon measurements using rather sophisticated detectors at the ground, in the atmosphere and underground [11–13], in addition to the measurements with the large area tracking detector of the GRAPES-3 experiment [14], the large area coordinate detector DECOR [15] and the KASCADE extensive air shower detector [16]. Recently, muon measurements have also been made using the Berkeley Lab detector [10], which is one of the relatively simple muon detection systems. In this study, the Geant4 simulation package [17,18] has been used to estimate the angular distribution of the cosmic muons at sea level. For this purpose, first of all, reliability of the simulations was tested by comparing the zenith angle dependence of muon flux obtained using the simulations with the one measured using a Berkeley Lab cosmic ray detector [19]. Since the detector has a large acceptance, the fluxes belonging to neighbouring zenith angles overlap. These overlaps prevent one from making the measurements at a specific zenith angle. After reproducing the experimental angular dependence of muon flux with Geant4, simulations were performed at each zenith angle from $\theta = 0°$ up to $\theta = 70°$ with 5° increment.

## 2. Experimental set-up and measurements

Angular dependence of cosmic-ray muons was measured using the Berkeley Lab cosmic ray detector. It is a compact and portable apparatus that requires a 12 V power source to operate and it mainly consists of a pair of scintillation paddles, a circuit board and a casing. The paddles are placed parallel to each other with a separation distance of ~11 cm. Each paddle has an area of ~200 cm$^2$ and a thickness of 0.635 cm. The pulses for muon candidates are distinguished from the noise by employing a coincidence circuit that compares the signals from each photomultiplier tube. A muon count is registered when hits from each paddle occur within 800 ns. The detector components are held together using a wooden casing. Further details of the detector can be found in the Berkeley Lab cosmic ray detector assembly manual [19] and a schematic drawing of the detector is given in [20].

The detector's response as a function of the position of muons was tested using a pencil-type radioactive source. The source was held perpendicular to the upper scintillator plate and measurements were made for 10 min at each of the several positions along the plate.

The response was concluded to be uniform since no significant change was observed among the counts obtained from the measurements made at each location.

Angular dependence of the muon intensity was measured at the top floor of the Physics Department (40°N, 30°E) at an altitude of ∼230 m from sea level. The coincidence rates were measured every 10° from the zenith between 0° and 90°. The rotation has been made in the northern direction, along the magnetic field lines of the Earth, in order to avoid the effect of geomagnetic field, the so-called East–West effect [21]. Data at each angle were taken for ∼6 h in 1 min intervals.

Electrons, positrons and photons are the soft components of the secondary cosmic radiation. They are almost completely absorbed in a 15 cm thick lead shield. However, their flux at sea level amounts to about 35–40% of that of the muons and they are not as energetic. Even though their energy extend to around 10 GeV, the intensity for energies <80 MeV amounts to ∼70% of the total flux [10]. Hence, it can be concluded that relatively low-energy (up to a couple of 100 MeV) soft components, due to higher intensity at lower energies, contribute to the measurements. These low-energy soft components cannot penetrate lead easily. For instance, the range of a 100 MeV electron in Pb is only 1.67 cm [22].

In order to minimize the contribution of other charged particles, mostly electrons and positrons, a slab of lead with a thickness of 2.2 cm was inserted between the paddles as an absorber and the measurements were repeated for each zenith angle. Geant4 simulations using electrons with different energies incident upon a 2.2 cm lead have shown that no electron with $E < 250$ MeV passes the absorber, while some electrons with greater energies are able to penetrate it (for instance, ∼10% for 0.4 GeV electrons). Muons also lose energy when passing through the lead absorber, in addition to the energy loss in the roof material (concrete). A simple estimate of the energy loss $\Delta E$ by a muon as it travels a vertical distance $\Delta H$ is $\Delta E = (2\,\mathrm{MeV/g/cm^2})\ \Delta H\rho$, where $\rho$ is the density of the material. Muon energy loss in the roof material ($\Delta H_{\mathrm{Concrete}} = 30$ cm) and in the absorber

**Table 1.** Counting rates measured at each zenith angle for cases without and with absorber between the scintillation paddles.

| Zenith angle (°) | Counting rate (counts/min) | |
|---|---|---|
| | Without absorber | With absorber |
| 0 | $91.0 \pm 0.3$ | $77.2 \pm 1.3$ |
| 10 | $86.9 \pm 0.5$ | $75.3 \pm 1.0$ |
| 20 | $80.0 \pm 0.5$ | $67.8 \pm 1.3$ |
| 30 | $71.4 \pm 0.4$ | $57.3 \pm 1.3$ |
| 40 | $57.6 \pm 0.4$ | $49.4 \pm 1.2$ |
| 50 | $43.4 \pm 0.3$ | $36.6 \pm 0.9$ |
| 60 | $35.6 \pm 0.3$ | $25.4 \pm 0.8$ |
| 70 | $28.8 \pm 0.3$ | $17.4 \pm 0.7$ |
| 80 | $22.3 \pm 0.2$ | $11.5 \pm 0.4$ |
| 90 | $19.8 \pm 0.2$ | $10.8 \pm 0.4$ |

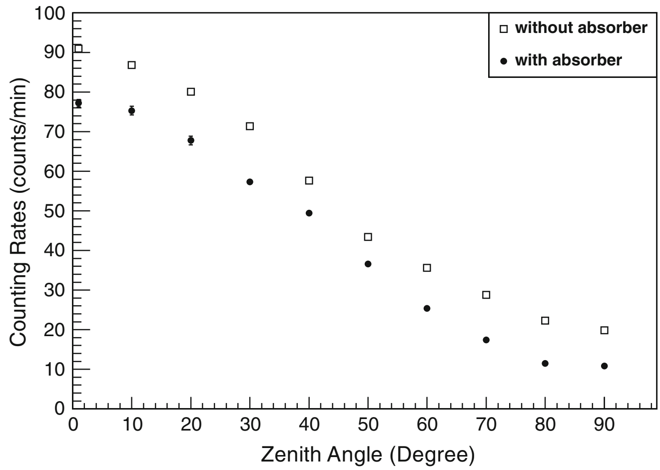


**Figure 1.** Angular distributions of cosmic muons at sea level measured using a Berkeley Lab cosmic ray detector (■) with and (□) without absorber material between the scintillation paddles.

($\Delta H_{\text{Lead}} = 2.2$ cm) have been calculated to yield 150 and 50 MeV for concrete and lead, respectively.

Results are given in table 1 and plotted in figure 1. As seen in the figure, the count rates decrease and shape of the distribution changes, especially at 40° and 50° zenith angles, when the absorber is inserted between the plates.

Fitting the distribution obtained with no absorber (with absorber) plotted in figure 1 with the function $m \cos^n \theta$ gives $m = 87.2 \pm 1.0$ counts/min and $n = 1.27 \pm 0.03$ ($m = 74.8 \pm 1.0$ counts/min and $n = 1.51 \pm 0.04$). One can notice that muon angular measurements made with the absorber in the detector paddles give bigger $n$ value, which indicates a difference between shapes of the two distributions. This difference could mainly be due to the elimination of the coincidence events by the electrons and positrons at sea level since these soft components experience greater deviations [23] than the penetrating rays. In the past, a similar study was made by measuring the angular distribution of the radiation stopped by 3.8 cm of lead in order to determine the scattering effects on the angular distribution [24].

Due to the geometry of the detector, the coincidence counts at each zenith angle are overlapped with the ones at neighbouring angles, which makes counting of the particles at certain zenith angle impossible. One way of decreasing the overlapping effect is to increase separation of the scintillation plates [8], where the separation distance of the scintillator plates is 1 m. Deconvolution of the data can be considered as another method. However, we have used simulation utilizing the Geant4 simulation package instead.

## 3. Simulation

Geometry and tracking (Geant4) is a toolkit for the simulation of the passage of particles through matter [17,18]. We have used Geant4, release 4.9.3.p01, for simulating the atmosphere and the interactions of the primary particles with the atmospheric nuclei. The atmosphere was modelled as a rectangular box with 600 km $\times$ 600 km base and 50 km height consisting of 50 layers, each with 1 km of thickness. It was considered to be made of 75.53% nitrogen, 23.18% oxygen, 1.28% argon and ∼0.01% carbon. For each layer, the temperature $T$, the pressure $P$ and the density $\rho$ were calculated using the standard atmospheric model [25]. The model consists of three zones, the troposphere, the lower stratosphere and the upper stratosphere. The troposphere runs from the surface of the Earth to 11 km, the lower stratosphere runs from 11 km to 25 km and the upper stratosphere runs from 25 km to higher altitudes. The metric unit curve fits at the three zones for temperature and pressure, together with the density $\rho$ derived from the equation of state, are given elsewhere [25].

The geomagnetic cut-off rigidity, which depends on the geomagnetic position, is a quantitative measure of the shielding provided by the Earth's magnetic field against the charged cosmic ray particles, among which are muons. The trajectories of these particles are bent when they cross the Earth's magnetic field. The lower-energy ones are affected more by the geomagnetic field, whose main source is the electric current in the fluid outer core of the Earth. Its magnitude over the surface of the Earth varies from 30 $\mu$T to 60 $\mu$T. In the simulations, we have used the magnetic field values as 25.2 $\mu$T, 2.1 $\mu$T and 39.7 $\mu$T for the north, east and vertical components, respectively. These field components, which yield 47.1 $\mu$T for the total field, have been calculated using [26] for Sakarya, Turkey (40°N, 30°E) where the measurements were made.

At fair weather, the electric field on the surface of the Earth is around 100 V/m directed towards the Earth's centre. This field is formed mostly by the charge distributions due to the radioactive decay of the Earth's surface and ionization by the cosmic rays. It drops rapidly with increasing altitude falling below 5 V/m at altitudes above 10 km due to the increasing atmospheric conductivity. However, this relatively low electric field does not have a significant effect on the muons above 0.1 GeV energy [27], and so the electric field was not taken into account in order to speed up the simulations.

For the physics processes, the quark-gluon string precompound (QGSP) together with the Bertini cascade (BERT) and high precision (HP) neutron model, the so-called QGSP_BERT_HP, and standard electromagnetic (EM) models were used for hadronic and electromagnetic interactions, respectively. The emstandard package handles basic processes such as ionization, bremsstrahlung, multiple scattering, Compton and Rayleigh scattering, photoelectric effect, pair conversion and annihilation for electron, positron, photon and hadron interactions up to 100 TeV. QGSP is the basic list applying the quark-gluon string model for high-energy interactions for pions, kaons, protons, neutrons and nuclei. It is built from the component model, quark-gluon string (QGS), which handles the formation and excitations of strings in the initial collision of a hadron with a nucleon in the nucleus in the range ∼10 GeV–∼100 TeV and precompound (PreCo), which takes the excited nucleus formed by the high-energy interactions from its highly excited state down to equilibrium and is valid for protons and neutrons in the energy range 0–170 MeV. The BERT part is used for primary protons, neutrons, pions and kaons below ∼10 GeV. Finally the HP part transports neutrons with kinetic energies below 20 MeV down to thermal energies. Further information on the Geant4 physics processes can be found in the Geant4 web site [17].

## 4. Results and discussion

Before studying the angular dependence of muons, the simulation was tested by comparing the results with the measurements made using the Berkeley Lab cosmic ray detector with absorber in the scintillation paddles. In order to simulate the measurements, the detector acceptance has to be known. The acceptance of the Berkeley Lab detector at each measurement orientation has been calculated using Geant4 by recording particles passing through both detector paddles, regardless of the particles' energy. Results, which are very similar to those obtained by another group [8] are shown in figure 2.

The default Cartesian coordinate system in Geant4 has its origin at the centre of the modelled atmosphere. The system is such that its $x$- and $y$-axes are perpendicular and parallel to the atmosphere layers, respectively. In order to select the muon events remained in the detector acceptance, we have first considered a virtual detector at the bottom layer of the modelled atmosphere. We have further assumed that the longer sides of the detector plates are parallel to the $y$-axis, the normal of the plates coincides with the $x$-axis at $\theta = 0°$ and the $z$-axis is in the north–south direction, parallel to the magnetic field lines of the Earth. At $\theta = 0$, the theta dependence of the muons coming from the left and right sides of the $x$–$y$ plane is symmetric with a peak around $\theta = 0$, and the muons are accepted if the angle they make with the $x$-axis is $\leq 56°$ (see figure 2). When the detector is assumed to be rotated, for instance clockwise around the $y$-axis by 10°, the symmetry is broken in such a way that muons coming from the left (right) side of the $x$–$y$ plane are accepted up to 40° (60°), with a peak at 10°. For simplicity and as a fairly close approximation, only two-dimensional configuration has been considered and decision of the theta ranges has been made based on the fact that muon events coming from left and right sides of the plane made by the detector's normal and the $y$-axis is symmetric up to $\theta = 50°$. Acceptance coverage for all orientations is given in table 2. In the simulation, a

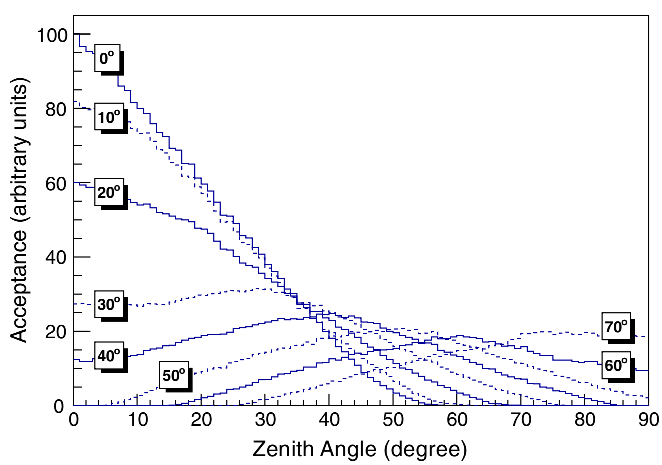


**Figure 2.** Acceptance of the Berkeley Lab cosmic ray detector at each measurement orientation.

**Table 2.** Cosmic ray detector's zenith angle coverage for all the detector orientations.

| Zenith angle (°) | Allowed zenith angle ranges (°) for muons | |
|---|---|---|
| | Coming from the left | Coming from the right |
| 0 | 56–0 | 0–56 |
| 10 | 40–0 | 0–60 |
| 20 | 28–0 | 0–68 |
| 30 | 16–0 | 0–76 |
| 40 | 6–0 | 0–86 |
| 50 | – | 5–90 |
| 60 | – | 15–90 |
| 70 | – | 25–90 |

total of two million primary protons were randomly distributed on the top the fiftieth layer, assumed to be the top of the atmosphere, towards the Earth's surface. The absolute fluxes of primary protons obtained in a balloon-flight measurement at an altitude of 37 km [28] have been used for kinetic energies above 4 GeV. The relatively low-energy protons with $\bar{E}_{\rm kin} < 4\,\rm GeV$ were not included in the incident particles since simulations using them had produced no muons at sea level. Muon events reaching the bottom of the modelled atmosphere, which is also the bottom of the first layer and considered to be the sea level, with the energy cut of $E > 200\,\rm MeV$ for the energy loss of muons in the roof material and lead absorber were recorded for each zenith angle taking into account the detector's acceptance.

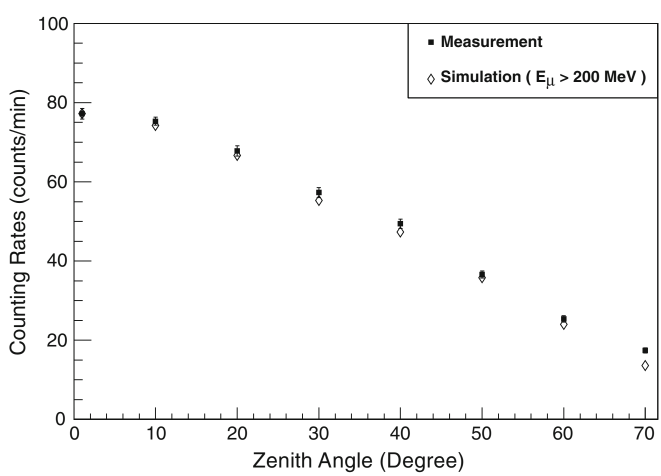


**Figure 3.** Zenith angle dependence measurements at sea level using a Berkeley Lab cosmic ray detector with (■) absorber between the scintillation plates and (◇) normalized simulation counts. Normalization was made at $\theta = 0°$.

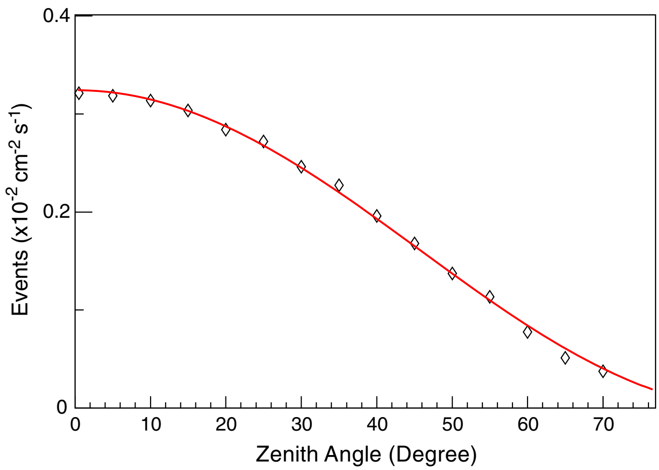


**Figure 4.** Zenith angle dependence of cosmic muons at sea level using Geant4 simulation package.

The detector gives ~77 counts/min when the detector plates are horizontal ($\theta = 0°$). On the other hand, the simulation yields ~73 counts/min for the same orientation. There could be several reasons such as the weather conditions at the time the data were taken, dependence of the simulation results on the physics and atmospheric models, etc. for the discrepancy between these results. On the other hand, since the primary purpose of this investigation is to study the angular dependence of the cosmic muons, the simulation events were normalized to the measurements made using the Berkeley Lab cosmic ray detector at $\theta = 0°$. Results of the simulation, together with those from the measurements, are illustrated in figure 3. Very good agreement is observed between our simulation result and measurement made using Berkeley Lab cosmic ray detector for $\theta < 70°$ where the Earth's curvature can be neglected.

Having confirmed the consistency of the simulation with the experiment, we have studied the angular dependence of the cosmic muons by shooting the primaries on the top of the atmosphere with 5° increment starting from the zenith angle 0° up to 70° (two hundred thousand particles at each zenith angle with $0 < \phi < 2\pi$, where $\phi$ is the azimuth angle). Since the secondary particles produced by the interaction of the primary cosmic rays with the Earth's atmosphere travel in almost the same direction as the parent primaries [29], it can be assumed that one can take direction of the primaries as that of the secondary muons. With this assumption, numbers of the muon events at sea level ($E_\mu > 1$ GeV) are plotted as a function of $\theta$ ($\leq 70°$) as shown in figure 4. Also shown in the figure is the $m \cos^n \theta$ fit yielding $m = (3.3 \pm 0.05) \times 10^{-3}$ cm$^2$ s$^{-1}$ and $n = 1.95 \pm 0.08$.

## 5. Conclusion

Geant4 simulation package has been used to estimate the angular distribution of the cosmic muons at sea level. Reliability of the model used in the simulation was tested by comparing the simulation results with the measurements made using a Berkeley Lab cosmic ray detector. Primary particles were shot at the top of the modelled atmosphere. Simulations were run at each angle from the zenith starting from $\theta = 0°$ up to $\theta = 70°$ with 5° increment. The exponent $n$ in the equation $I(\theta) = I(0°)\cos^n(\theta)$ was obtained as 1.95±0.08 for muons with energies above 1 GeV. It is in good agreement with the values reported in [10] and references therein. Based on the previous azimuthal angle simulations [7] and the results of this study, one can conclude that Geant4 is a reasonable simulation toolkit for investigating the angular dependence of cosmic muons at sea level. Consistency of the simulations with the experimental results make one think that the simulations can be extended for cases where experimental measurements are difficult to make, if not impossible. It also indicates that the physics and atmospheric models used in the simulations are successful in reflecting the interaction of cosmic rays in the atmosphere.

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