Expected angular distribution of atmospheric muons at Super-Kamiokande detector

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Abstract

The angular distribution of atmospheric muons at the site of Super-Kamiokande (SuperK) detector was calculated using a set of three-dimensional Monte-Carlo codes for muon propagation. These codes include recent treatment of multiple Coulomb scattering of muons and new consideration of cross section of inelastic muon interaction in matter. Results of simulation are compared with SuperK data near the horizontal direction.

1. Introduction

The flux and angular distribution of upward-going muons, measured by SuperK neutrino detector [1] apparently show that they are affected by neutrino oscillation. To estimate oscillation parameters, the expected and observed shape of the zenith angular distribution of upward-going muon fluxes are compared. An additional contribution of the atmospheric muons to the flux of upward-going muons near horizon could change shape of angular distribution in the same way as neutrino oscillations make. Therefore additional uncertainties in values of oscillation parameters could arise.

The main goal of this work is the calculation of angular distribution of atmospheric muons at SuperK and the estimation of background due to downward-going muons, using three-dimensional Monte-Carlo codes for muon propagation. These codes include recent treatment of multiple Coulomb scattering of muons and new consideration of cross section of inelastic muon interaction in matter. The experimental cuts and the angular detector resolution are also taken into account.

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2. Input data and MC code for calculation of downward-going muon flux at SuperK site

The downward-going muon flux at SuperK detector is determined mainly by the muon flux at the surface, the relief of mountains, the orientation and location of the detector coordinate system with respect to the survey map system, and the average density and chemical composition of the rock.

The SuperK is located at the altitude of 340 m, i.e. practically at sea level. The atmospheric muon differential spectra and angular distribution from Ref.[2] have been used for calculation of underground muon flux. These spectra are in agreement with data [3,4] within experimental uncertainties.

The standard reference map, as well as standard values of parameters: rock density (ρ=2.70$\pm$0.06g/cm^3), the orientation and location of the SuperK coordinate system with respect to the survey map's system, average values of $\langle Z\rangle$=10.08,$\langle A\rangle$=20.334, $\langle Z/A\rangle$=0.511, and $\langle Z^2/A\rangle$=5.003 have been used [5].

Three-dimensional MC codes for simulation of muon propagation through rock have been applied. Muon transport is performed with variable optimized steps. The program allows us either to consider the average ionization energy loss calculation along tracking step, or to account for fluctuations. It performs the discrete sampling of bremsstrahlung [6] and pair production [7] processes. A special feature of this program is the 3-dimensional simulation of the muon tracks. The recent treatment of multiple Coulomb scattering of muons [8] is used. In this approach the muon angular distribution is similar to the Moliere distribution after passing through the small thickness of material and moderate deflection angles. However, at large thickness of scatterer, the angular distribution is drastically changed by influence of the nuclear form factor. Multiple scattering and lateral displacement are regarded as continuous processes occurring along muon track. The muon scattering angle in inelastic muon-nuclear interactions is also being sampled. The program uses a new cross-section of this process [9], that was calculated based on the modern nucleon structure functions and on the present knowledge of nuclear effects. These new features allow us to describe in right way muon scattering in a wide range of angles.

3. Experimental cuts and angular detector resolution

For calculation of the downward-going muons angular distribution at SuperK near the horizontal direction, the experimental cuts and the angular resolution of the installation have been taken into account. A minimal track length cut of 7m is applied. The through going muon events satisfying $\cos\theta \leq 0.10$ and stopping muons with $\cos\theta \leq 0.12$ are selected, where θ is the zenith angle of muon track and $\cos\theta \leq 0$ corresponds to upward-going events. The angular resolution of detector, i.e. the distribution of deviations between the reconstructed track direction and the real muon direction $\Delta\theta_{rec}$ can be fitted to a Gaussian function with $\sigma = 0.9 \pm 0.06^{\circ}$. The trigger efficiency for a muon with track length more than 7m is $\sim 100\%$ which is almost isotropic for $-1 \leq \cos\theta \leq 0$. Details of such muon fitter are described elsewhere [10,11].

4. Result

The calculated angular distribution of the downward-going muons events near the horizontal direction has been compared with data. Statistic of the through going (stopping) muons corresponds to a period of 537 (451) live days. Fig.1 show the expected and measured zenith angle distribution of the through going and stopping muons. The two histograms there correspond to the maximal and minimal expected number of events and have been calculated by varying the angular resolution in the region within uncertainties. The number of cosmic ray muons in bin $-0.05 \leq \cos\theta \leq 0$ is estimated to be $0.4 \leq N_{th} \leq 3.5$ for the through going muons in a period of 537 live days and $4 \leq N_{st} \leq 5$ for stopping muons in a period of 451 days.

To compare MC prediction and SK data, neutrino induced muons have to be subtracted. Atmospheric muon contribution to bin $-0.05 \leq \cos\theta \leq 0.025$ ($-0.025 \leq \cos\theta \leq 0$) is expected to be 0(4)events. Therefore, number of neutrino induced events are 27 in each bin. Using this result for symmetric bins above horizon we found 17 (0÷0.025) and 199 (0.025÷0.05) events. Those numbers should be compared with expected numbers 10÷18 and 149÷223 respectively. The same procedure ha been applied to stopping muons and the results are DATA/MC=12/(5÷30) and 65/(50÷62) for the same angular bins. In Fig.1 the data after subtraction of the neutrino produced muon events are shown also by open circles. So the angular distribution of atmospheric muons below horizon shows a Gaussian behavior with σ approximately equal to the detector angular resolution.

5. Conclusions

The expected angular distribution of the downward-going muon events at SuperK near the horizontal direction has been calculated. The number of atmospheric muons in the zenith angular bin with -0.05÷0 has been estimated for the through-going muons to be 0.4÷3.5 in 537 live days and for the stopping muons to be 4÷5 in 451 live days.

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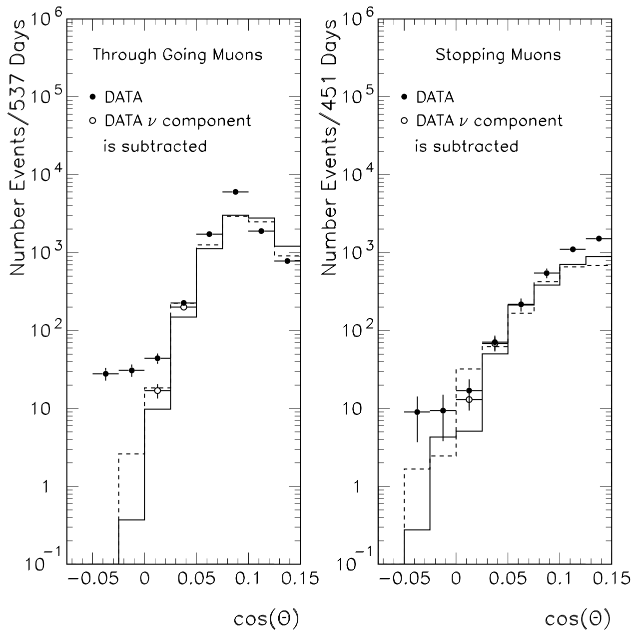

Fig. 1. Zenith angle distribution of muons near the horizon. Open circles indicate events after substraction of the neutrino produced muons. The histograms correspond to the maximal and minimal expected number of events.

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