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Angular and energy distribution for parent primaries of cosmic muons at the sea level using Geant4

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ABSTRACT

The angular and energy distributions of the primary cosmic rays that are responsible for the muons reaching the sea level have been estimated using the Geant4 simulation package. The models used in the simulations were tested by comparing the simulation results for the differential muon flux with the BESS measurements performed in Lynn Lake, Canada. Then, direct relationship between the propagation directions of the muons and those of the responsible primary particles has been investigated. The median energies for the parent primaries of vertical muons reaching the sea level with the threshold energies (E_μ) in the range 0.5–300 GeV were obtained. Simulation results for the median primary energies, 15.5 E_μ and 11.2 E_μ for $E_\mu = 14$ GeV and $E_\mu = 100$ GeV, have been found to be in good agreement with the literature. Furthermore, median primary energies for the low energy muons with large zenith angle have been seen to be relatively higher than the ones for the muons with narrower angles.

1. Introduction

Protons are the most abundant charged particles of the primary cosmic rays which bombard the Earth's atmosphere from all directions. The study of the primary cosmic rays provides information on their origins and acceleration mechanisms in addition to their propagation through the interplanetary and interstellar media. The primary cosmic ray data have been obtained by direct measurements using the satellite based [1,2] or balloon-borne [3,4] detectors for energies below $\sim 10^{14}$ eV. Since the flux of the primaries with higher energies gets extremely low and the direct measurement is no longer practical, indirect measurements via extensive air showers [5–9] are made to get information on the abovementioned primaries.

The primary cosmic rays that enter the Earth's atmosphere interact with the nuclei present in the air and produce secondary particles, mostly unstable mesons like pions and kaons. Muons, which are the decay products of such mesons, could generate signals in the detectors located not only at the ground level [10] but also in underground laboratories [11]. Because of the close relation between muon and neutrino production, precise measurement of the atmospheric muon flux is important for cross checks on the atmospheric neutrino flux (see, for instance, [12]). In addition, cosmic muon measurements are valuable to obtain the information on the propagation of the cosmic rays in the atmosphere.

Knowledge of the interrelation between the energies of the cosmic muons at the sea level or underground and those of the parent primaries is important to study the variations in the intensities of primary radiations. Such knowledge could be acquired from the response (or coupling) functions, which are the energy distributions of primaries responsible for the muons with certain energies. Response functions of the sea level muons with different threshold energies, which correspond to specific underground depths, have been derived by different groups using different methods. For the information on both the methods and the studies based on such methods, see [13,14] and references therein.

Various simulation programs, such as CORSIKA [15], FLUKA [16,17] and Geant4 [18], are being extensively used in cosmic ray studies. In this study, Geant4 simulation package has been utilized to estimate the angular and energy distributions for parent primaries of cosmic muons with different energies. In order to accomplish this, firstly, we have tested the models (atmosphere, physics etc.) used in the simulations by reproducing the flux of cosmic muons at the sea level obtained from the cosmic ray experiment [19] performed in Lynn Lake (56.5°N, 101°W) with the cut-off rigidity of 0.4 GV. Secondly, we have investigated the relationship between the propagation directions of the muons and those of the responsible primary particles by comparing their zenith angles. Finally, we have obtained the energy distributions and the median energies for the parent primaries of the vertical and non-vertical muons reaching the sea level with several threshold energies. Results for the vertical ones have been compared with those of the previously made calculations.

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2. Simulation

Monte Carlo simulations for interactions of the primary cosmic rays with the modelled atmosphere have been performed using Geant4, release 9.3.p01. Since the curvature of the Earth can be neglected for zenith angles $\theta < 70^\circ$ [20] and the primary cosmic ray measurements in Lynn Lake were made at an altitude of ~ 37 km [21], the atmosphere has been modeled as a rectangular box with 500 km $\times$ 500 km base and 37 km height consisting of 37 layers with a thicknesses of 1 km. The size of the base area has been chosen slightly larger than the required one in order to evaluate the muon flux correctly. The temperature, pressure and density of each layer have been calculated using the standard atmospheric model [22]. A similar atmosphere model was recently utilized successfully in order to investigate the atmospheric muon distributions at the ground level [23–25].

The magnetic field components of the Earth in Lynn Lake, where the experiment was performed, were calculated as 10.2 μT, 1.7 μT and 59.4 μT for the northern, eastern and vertical components, respectively, using the magnetic field calculator of National Geophysical Data Center [26]. Since the atmospheric electric field does not have a significant effect on the cosmic muons above 0.1 GeV energy [27], the electric field was not taken into account in the simulations. The FTFP_BERT model from the standard physics models available in Geant4 was used for the physics processes. The FTFP_BERT model was formed by combining two different models, which are the FRITIOF Precompound (FTFP) model and the Bertini Cascade (BERT) model. The FTFP model has also several sub-component models that are responsible for various parts of the high energy interactions from a few GeV to 100 TeV. While the FRITIOF part handles the formation of strings in the initial collision of a hadron with a nucleus, string fragmentation into hadrons and de-excitation of the remnant nucleus are handled by the Lund fragmentation and the precompound models. In addition, the BERT model describes the hadronic interactions and generates the final state for hadron inelastic collisions below 10 GeV. Further information on the Geant4 physics processes could be found in the Geant4 web site [28].

The energy distribution of the primary protons used in the simulations was adapted to the Balloon-borne Experiment with Superconducting Spectrometer (BESS) results obtained in 1998 below the energy of 120 GeV [21]. For the protons with higher energies, the distribution was extrapolated up to 10 TeV according to the power law with a spectral index of 2.7 (see Fig. 1). Primaries were isotropically distributed on the top of the 37th layer with zenith angle cut $\theta \leq 70^\circ$. Momenta and zenith angles of both negative and positive muons reaching bottom of the first level (sea level), together with those of their parent protons, were recorded.

3. Results and discussion

Before studying the angular and energy distributions for parent primaries of cosmic muons, the simulation output for the vertical flux of muons at the sea level was tested against the flux measurements made by the BESS spectrometer in Lynn Lake. Given in Fig. 2 are the vertical differential momentum spectra of sea level muons in Lynn Lake up to ~ 400 GeV/c obtained from the simulations compared with the spectra obtained from the experiment. A good agreement between the Geant4 simulation results and the experimental ones is seen, especially in the high momentum region. However, there exists

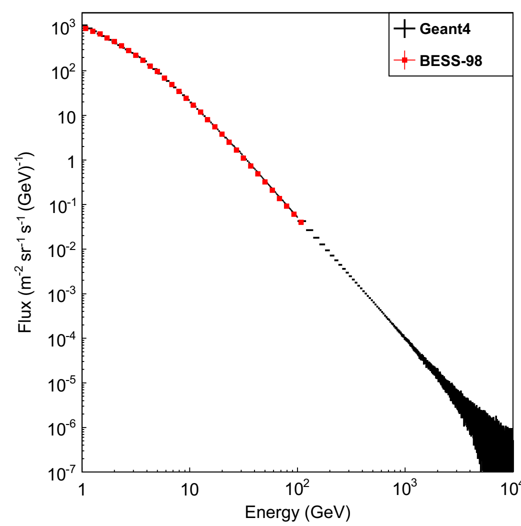

Fig. 1. Energy spectrum of the primary protons used as an input for the Geant4 simulation and results of the BESS measurements [21].

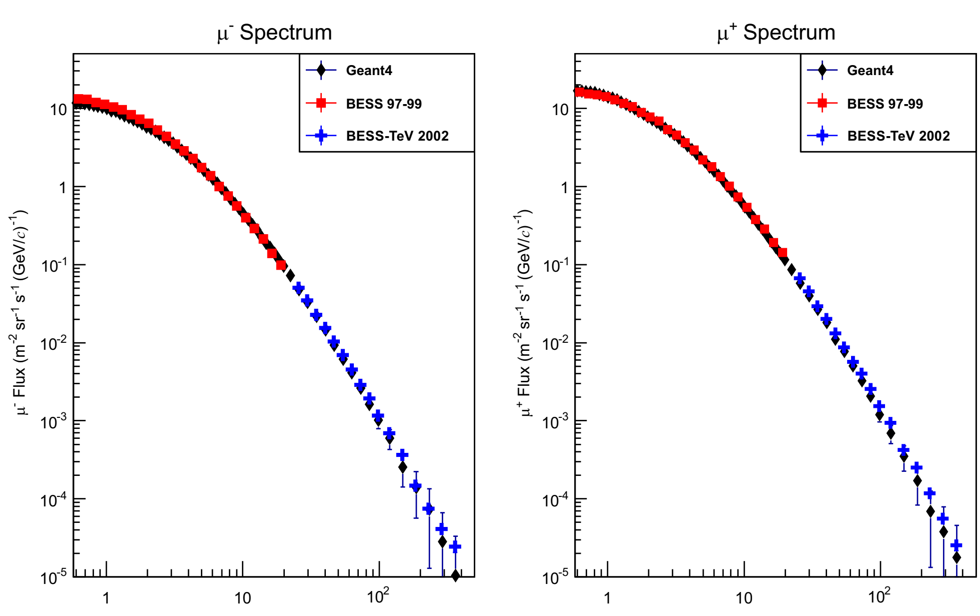

Fig. 2. Geant4 simulation result for vertical differential momentum spectrum of muons in Lynn Lake together with the experimental values [4,19].