Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 56 (2015) 2662–2668

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Altitude profile of atmospheric muons in a location with relatively high cut-off rigidity

Halil Arslan, Mehmet Bektasoglu *

Sakarya University, Department of Physics, 54187 Sakarya, Turkey

Received 5 May 2015; received in revised form 7 September 2015; accepted 9 September 2015
Available online 15 September 2015

Abstract

We have investigated the differential and integrated muon fluxes, muon charge ratios and the zenith angle dependence of the integrated muon intensities at sea level and various depths in the atmosphere of Tsukuba, Japan, for muons with momenta below 400 GeV/c using the Geant4 simulation package. The simulated sea level muon spectrum and charge ratio have been seen to be in good agreement, throughout the momentum interval of the interest, with those from the measurements made by the BESS-TeV spectrometer. Integrated muon intensities have been found to increase as the atmospheric depth decreases up to slightly above 200 g/cm^2, and then they have a trend to decrease at lower atmospheric depths. Muon charge ratios at each of the atmospheric depth of interest have been shown to have a very similar behavior with the one at sea level. Simulation results for the zenith angle dependence of muon intensity have been quite compatible with the existing information in the literature for sea level. It has also been shown that the zenith angular dependence of muon intensity has a tendency to disappear (to obey the secθ distribution) as the atmospheric depth decreases for muons with relatively low (high) momenta.

Keywords: Cosmic rays; Muon; Simulation; Geant4

1. Introduction

Charged mesons, mainly pions and kaons, are produced by the interaction of the primary cosmic rays, mostly protons and alpha particles, with the nuclei of the Earth's atmosphere. Atmospheric neutrinos, as well as muons, are produced from the decay of these unstable particles. Muons are also unstable and decay to produce neutrinos, in addition to electrons or positrons. This close relationship between the neutrinos and muons makes the muon studies in the atmosphere specifically important. Furthermore, the importance of these studies has noticeably risen since the realization of the disagreement between the atmospheric neutrino flux measured by large underground detectors (see, for instance, the observations by Super-Kamiokande (Fukuda et al., 1998)) and that predicted theoretically (e.g., Honda et al., 1995; Barr et al., 1989). The disagreement is that the ratio of the flux of $(\nu_\mu + \bar{\nu}_\mu)$ to that of $(\nu_e + \bar{\nu}_e)$ is expected to be around 2, while the measurements yield a much smaller ratio for the fluxes, a difference that can be attributed to neutrino oscillations.

Many ground-level muon measurements exist at different geomagnetic locations using different detectors (see, for example, Motoki et al. (2003), Kremer et al. (1999) and Tsuji et al. (1998) for measurements by the Balloon-borne Experiment with a Superconducting Spectrometer (BESS), the NMSU/WIZARD/CAPRICE spectrometer and the OKAYAMA telescope, respectively). Furthermore, there are semi-analytical expressions for muon flux at sea level (Judge and Nash, 1965; Gaisser, 2002). Despite

* Corresponding author.
E-mail addresses: harslan@sakarya.edu.tr (H. Arslan), mehmetb@sakarya.edu.tr (M. Bektasoglu).

http://dx.doi.org/10.1016/j.asr.2015.09.012
0273-1177/

the wealth of the measurements at the ground, there are fewer altitude dependent muon measurements mainly made using balloons (see, e. g., Coutu et al. (2000), Boezio et al. (2003) and Bellotti et al. (1996) for measurements by the instruments the High Energy Antimatter Telescope (HEAT), NMSU/WIZARD/CAPRICE98 balloon-borne magnet spectrometer and the Matter Antimatter Spectrometer System (MASS), respectively). Beside these measurements, atmospheric muon flux calculations at different altitudes were made using the Monte Carlo techniques. Computation of the muon fluxes in the atmosphere using the FLUKA Monte Carlo code (Battistoni et al., 2002) and the air shower simulation program AIRES (Hansen et al., 2003) are among the mentioned calculations. The former (the latter) compares the calculated fluxes with the data taken by the CAPRICE94 (CAPRICE98) experiment. In addition, atmospheric muon fluxes have been calculated using other well-known simulation programs including CORSIKA (see, for example, Wentz et al., 2003).

In the present study, we investigate the flux, charge ratio and zenith angle dependence of the atmospheric muons at sea level and various altitudes from the ground of Tsukuba, Japan (36.2°N, 140.1°E, and the vertical cut-off rigidity of 11.4 GV), using the Geant4 simulation package (Agostinelli et al., 2003). Simulation results for the muon flux and charge ratio at sea level have been compared with the experimental data collected in Tsukuba (30 m above sea level) using the BESS-TeV spectrometer (Haino et al., 2004), which is an upgraded version of the BESS spectrometer (Ajima et al., 2000) with newly-developed drift chambers. Simulation results for the altitude dependent profile of the muon flux, charge ratio and zenith angle dependence were given without a comparison with data since no such measurements, to the best of our knowledge, exist at the location.

2. Geant4 simulation

Geant4 (for GEometry ANd Tracking) is a toolkit for the simulation of the passage of particles through matter (Agostinelli et al., 2003). It is extensively being used by different fields of application, among which are high energy, nuclear, accelerator and medical physics.

In this study we have used Geant4 (release 9.6.p03) to model the Earth's atmosphere and to simulate the interactions of the primary particles with the atmospheric nuclei. As an approximation, we have neglected the Earth's curvature and modeled the atmosphere as a rectangular box, consisting of 100 layers each having 1 km of thickness. This approximation is valid for the zenith angles below 70°. Each atmosphere layer has been considered to be made of 75.53% nitrogen, 23.18% oxygen, 1.28% argon and $\sim$0.01% carbon dioxide. The temperature, pressure and density of each layer have been calculated using the standard atmospheric model (NASA, 1976). Details of the atmosphere model used in this work can be found in Arslan (2015).

At fair weather, the Earth's electric field is around 100 V/m at the surface and it drops rapidly with increasing altitude. It is about zero for the altitudes above 10 km. This field, which is produced by the charge distributions due to the radioactive decay of the Earth's surface and ionization by the cosmic rays, has not been included in the simulations since it has been shown (Bektasoglu and Arslan, 2012) that it is not strong enough to make noticeable change in muon fluxes.

When a charged particle approaches the Earth from outer space its trajectory is bent due to the geomagnetic field. The strength and direction of the local magnetic field and the rigidity and direction of propagation of the particle, along with the interactions of the particle with the atmospheric nuclei, are effective for the particle to complete its journey to the Earth's surface. The field components in Tsukuba have been computed by the Magnetic Field Calculator (National Geophysical Data Center, 2015) using the International Geomagnetic Reference Field (IGRF) model (International Geomagnetic Reference Field model, 2015) for the dates when the measurements were made, namely during the first 6 days of October, 2002. For the north, east and vertical components, 29.8 μT, 3.7 μT and 35.4 μT have been used in the simulations, respectively. The total field strength in the location has been calculated to be 46.4 μT.

Simulations have been performed using the standard electromagnetic (EM) package for the electromagnetic interactions and the Bertini Cascade version of the FRITIOF Precompound (FTFP_BERT) model for the hadronic interactions. Geant4 EM package handles basic processes for $e^{\pm}$, photon, $\mu^{\pm}$ and hadrons. The package includes processes such as ionization, bremsstrahlung, multiple scattering, Compton and Rayleigh scattering, and photo-electric effect. The FTFP model is composed of the FRITIOF (FTF) and the Precompound (P) parts. In FTFP, the string fragmentation into hadrons is handled by the Lund fragmentation model. The FTF part in FTFP is capable of calculating hadronic interactions in high energy region. It handles the formation of strings in the initial collision of a hadron with a nucleon in the nucleus. The Precompound (P) part in the model deals with the deexcitation of the remnant nucleus. The Bertini Cascade model generates the final state for hadron inelastic scattering by simulating the intra-nuclear cascade (Geant4 Physics Lists, 2015).

Differential energy spectrum of the primaries needed as the simulation input has been provided of the measurements made using the balloon-borne BESS-TeV experiment (Haino et al., 2004), in which measurements were made in Lynn Lake, Canada, with a cut-off rigidity of 0.5 GV. Since the mentioned primary measurements were made only two months before the muon measurements in Tsukuba, no solar modulation has been needed to be taken into account when comparing the simulation and experimental results. The primaries were isotropically distributed