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EXPERIMENTALLY GUIDED MONTE CARLO CALCULATIONS OF THE ATMOSPHERIC MUON FLUX FOR INTERDISCIPLINARY APPLICATIONS

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Abstract Atmospheric muons are produced in the interactions of primary cosmic rays particle with Earth's atmosphere, mainly by the decay of pions and kaons generated in hadronic interactions. They decay further on in electrons and positrons and electron and muon neutrinos. Being the penetrating cosmic rays component, the muons manage to pass entirely the atmosphere and can pass even larger absorbers before they interact with the material at the Earth's surface, and due to cosmogenic production of isotopes by atmospheric muons, information of astrophysical, environmental and material research interest can be obtained. Up to now, mainly semi-analytical approximations have been used to calculate the muon flux for estimating the cosmogenic isotope production, necessary for different applications. Our estimation of the atmospheric muon flux is based on a Monte-Carlo simulation program CORSIKA, in which we simulate the development in the atmosphere of the extensive air showers, using different models for the description of the hadronic interaction and taking into account the influence of the Earth's magnetic field. Such simulations are controlled by the experimental results of the muon charge ratio, representing the ratio of positive to negative muon flux, obtained with WILLI detector in IFIN-HH Bucharest.The two advantages in a good estimation of muon flux by our method are due to the fact that CORSIKA code allows a correct description of all secondary interactions in the Earth's atmosphere and of all trajectories of the particles in the geomagnetic field; besides this, such simulations can be checked with experimental data of muon charge ratio measured with WILLI detector.

Key words: muon, flux, CORSIKA

INTRODUCTION

The muon belongs to the family of elementary particles known as leptons. Like the electron it may be positively or negatively charged and has a spin 1/2. However its mass is about 100 MeV, more than two orders of magnitude larger than that of the electron, and about one order of magnitude less than of the proton. It is produced mainly by the decay of pions and kaons generated by high-energy collisions of cosmic rays with the atoms of the Earth atmosphere. Muons are unstable decaying to electrons and positrons and neutrinos (electron (n_e) and muon (n_m) neutrinos) with a half - life of t_m = 2.2 ms\$. Because muons are leptons, they are not affected by hadronic interactions, and hence they interact more weakly with matter than the nucleonic component of cosmic rays. Thus additionally to some few cosmic rays nucleons of high energy the secondarily produced muons manage to pass entirely through the atmosphere and can pass even larger absorbers („penetrating component“) before they interact with the material at surface of the Earth or with rocks deep underground. From these facts a variety of aspects and problems are arising of astrophysical, environmental and material research interests with the question of cosmogenic production of isotopes by atmospheric muons. A rather illustrative field is the application in geochronology, by use of long living isotopes like ^{10}Be ($t = 1.6 \cdot 10^6$ y), ^{26}Al ($t = 7.1 \cdot 10^5$ y), ^{36}Cl ($t = 3.0 \cdot 10^5$ y) and ^{129}I ($t = 1.6 \cdot 10^5$ y). In addition to neutron and a-particle induced reactions muons do contribute by capture of negative muons in target material of elements of nearby Z. The analysis of the ^{36}Cl (produced by muon capture by ^{40}Ca) is used for dating of glacial deposits [1], as correction for estimates of the radiation dose from the neutron flash of the Hiroshima bomb, producing ^{36}Cl in the gravestones (granite from mines of the neighborhood) of the Hiroshima cemetery [2]. Cosmogenic isotope production by muons must be taken into account when dating geomorphic surfaces. Attention to isotope production by muons is crucial for determining surface eroding rates accurately [3].

These examples arising from geophysical applications indicate that there is a variety of cases of quite different aspects, ranging from atmospheric neutrino studies, background estimates for chemical solar neutrino detectors to radio dating, where a sufficient knowledge of the atmospheric (integral and differential) muon flux, in some cases separately for positive and negative muons is required. The information available in literature is incomplete and controversial . A recent compilation is presented in the handbook by Grieder [4]. Recent experiments stem from balloon borne experiments like CAPRICE [5]. A complication originates from the fact that detail features of the atmospheric muon flux depend not only from the altitude of the observation level, but also from the geomagnetic situation of the observation location. The geomagnetic field does not only provide a cutoff for primary cosmic rays, it also influences the propagation of the positive and negative muons in the atmosphere.

In general for application it is hardly technically and economically possible to procede with accurate experimental studies of the atmospheric muon spectrum, before introducing the results into the specific investigations. From these reasons the present studies adopt a different concept, taking profit from the fact that the charge ratio of atmospheric muons is rather sensitive to the ingredients and procedures of Monte Carlo calculations of the atmospheric muon flux. Controlled by experimental results of the charge ratio from detailed measurements with the WILLI apparatus [6,7], which comprise also studies of geomagnetic effects (East-West effect) [7], the Monte Carlo simulation program CORSIKA [8] has been considerably refined and extended by inclusion of a number of sensitivities, primarily focused to reliable and experimentally controlled calculations of the atmospheric neutrino flux [9,10]. The advanced calculations reproduce the measured values of the muon charge ratio also at different geomagnetic cutoff values, so far these values are relevant. Thus the code is considered to deliver also correct results about the integrated and differential muon flux. The present report presents results of flux and charge ratio calculations of atmospheric muons for various different locations. They are compiled for use of applications.First some introduction into the use, the ingredients and specifically adopted calculation procedures is given.

CORSIKA

The simulations discussed in this paper have been made using the CORSIKA program in version 6.000. All bugs found in CORSIKA until version 6.014 have been corrected also in the extended version. The simulation of atmospheric particle fluxes with CORSIKA starts by selecting the type of primary particles and the ranges for the primary energy, zenith and azimuth angles, and by fixing the geographical location on Earth. The primary energies vary for all simulations reported in this paper between the minimum geomagnetic cut-off and 10^{15} eV. The standard CORSIKA version makes use of a planar atmospheric model. This is a good approximation as long the zenith angle q of the particles does not exceed 70°. For the simulation of the East-West-effect of atmospheric muons the zenith angles must bevaried over the complete range. These simulations have been made with the so-called ``curved`` version of CORSIKA. Here the curvature of the Earth's atmosphere is approximated by sliding and tilting plane atmospheres. Each time the horizontal displacement of a particle exceeds a limit of 6 to 20 km (dependent on the altitude), a transition to a new local plane atmosphere is performed [11] .The different primary particles, i.e. protons and helium nuclei are simulated in separate runs and the ratio between them follows the absolute fluxes reported by the AMS prototype mission [12].

The air shower calculation starts by getting a random location on the Earth, a random energy and a random arrival direction. If the particle does not exceed the geomagnetic cut-off for the given location or the solar modulation, a new set of geographic coordinates, energy and arrival angles is used. If the particle fulfills the requirements, the geomagnetic parameters, the altitude, and the atmosphere, are set according to the geographical position. The primary particle is tracked to the first interaction point, given by the cross-section of the particle with air. The nuclear reaction is handled by the selected hadronic interaction model and all secondary particles are tracked up to their decay or further interactions.

CALCULATION OF ATMOSPHERIC MUON FLUX

The calculation of muon flux proceeds by a full 3D-simulation (CORSIKA). The simulations have been done using for the primary particle's spectrum the expresion: $J_P(E) \sim E^{-2.78}$.

The differential particle flux:

$$J_\mu = \frac{dN}{dt \cdot dA \cdot d\Omega \cdot dP}$$

was calculated by dividing the number of particles detected by the surface of the particle collection area (cm^2), solid angle, momentum bin size, and equivalent sampling time of the CR flux [13].

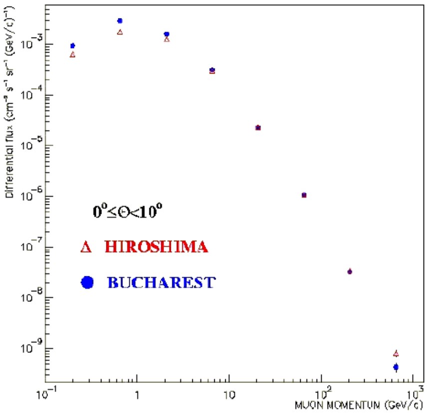

Fig. 1 - Differential flux of the muons for 0° ≤ q<10°

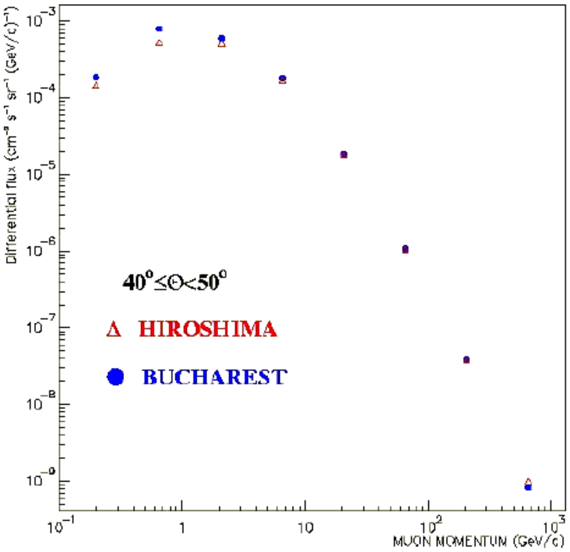

Fig. 2 - Differential flux of the muons for 40° ≤ q<50°

WILLI DETECTOR

The simulation progamm is checked by experimental data of the muon charge ratio measured with the WILLI detector in Bucharest. From this reason a brief account is given about some experimental of these studies. The WILLI detector, built in IFIN-HH Bucharest [6] measures the muon charge ratio by the effective lifetime of stopped muons. Fig.3 presents the rotatable WILLI [1], using 16 scintillator modules for vertical measurements of the muon charge ratio, and 4 scintillators modules in vertical position as anticounters. All counters are made of a 1 cm thick aluminum plate and a plastic scintillator of 90 x 90 x 3 cm^3 closed by an aluminum cover of 2 mm.

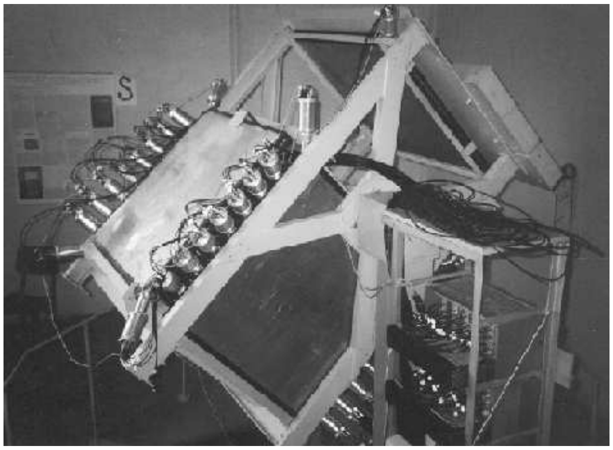

Fig. 3 - The WILLI calorimeter

A good event is induced by a particle triggering the telescope without penetrating to the bottom, together with the appearance of a delayed particle. From the time interval of incoming and decaying particle, the spectrum of the decay times is registered.

The total decay curve of all muons measured in the detector is a superposition of several decay laws, containing 3 detector dependent constants, accounting for the stopping power in the materials and the detection efficiencies, given by the detector geometry, laboratory walls, thresholds and angular acceptance, which have been determined by extensive detector simulations using the code GEANT. The muon charge ratio is obtained by fitting the measured decay spectrum with the theoretical curve.

TEST OF THE SIMULATION PROGRAM BY EXPERIMENTAL RESULTS

The Monte Carlo program outlined in chapt. 2 and to be used for calculations of the muon fluxes at various locations has been ckecked by experimental results of accurate muon charge ratio measurements.

Fig.4 displays the comparison between measured results of the East -West effect performed with WILLI and with CORSIKA simulations. The values are compiled in the following table:

Azimuth	Momentum(GeV/c)	$<q_p>$	R_{WILLI}	$R_{CORSIKA}$
EAST	0.36	35	0.89	0.68
	0.50	35	0.95	0.88
	0.65	35	0.85	0.91
	0.87	35	0.84	0.95
WEST	0.36	35	1.50	1.40
	0.50	35	1.43	1.46
	0.65	35	1.06	1.32
	0.87	35	1.23	1.36

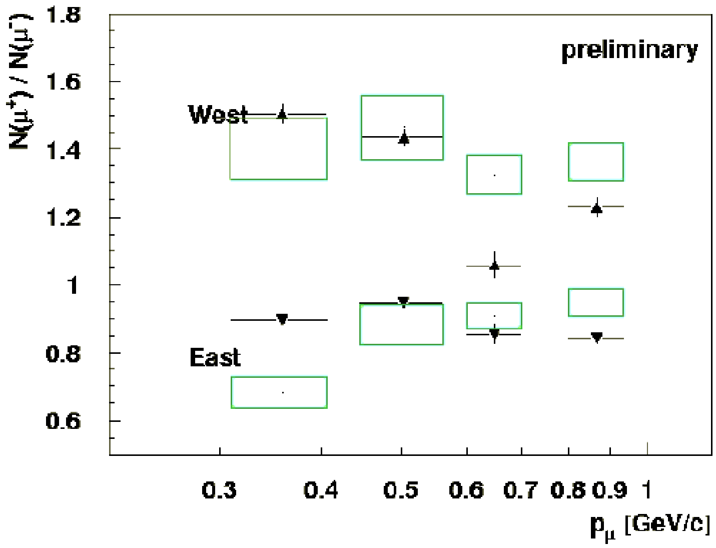

Fig. 4 - Comparison of the muon charge ratio and the EAST-WEST effect with the CORSIKA predictions

CONCLUSIONS

Due to the promising tests on basis of accurate muon charge ratio measurements at low muon energies [10] we adopt the view of a high reliability of the Monte Carlo calculations of the atmospheric muon fluxes at various geomagnetic cutoff values. The present note reports on the differences of the fluxes at low momenta for the two locations: Hiroshima and Bucharest. Such differences may get relevance in special problems of muongenic production of long living nuclei. The present studies are intended to be continued for a third location on the Earth and being compared with results of empirical quasi - analytical formulae.

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