Azimuth dependence of the charge ratio of the atmospheric muons

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***Abstract*—The WILLI detector, installed in the National Institute of Physics and Nuclear Engineering-Horia Hulubei Bucharest (44^0 26' N, 26^0 04' E, geomagnetic cut-off = 5.6 GV) has been devised for studies of atmospheric muons, in particular of the muon charge ratio. The set up consists of a stack of 16 plastic scintillator modules, with an extension of 90 · 90 cm^2, surrounded by 4 lateral veto counters. The method for measuring the muon charge ratio is based on the observation of the life time of muons stopped in the absorber layers which are placed between the detector modules.**

The apparatus is mounted in a rotatable frame which allows studies of the variation of the charge ratio of atmospheric muons, in particular with the azimuth angle. Such a variation of the charge ratio is a consequence of the influence of the geomagnetic field (East-West effect). We report on the results of studies for various muon energies (in the momentum range p = 0.2-1.0 GeV/c), defined by the cutoff of the absorbers mounted above the detector. The results are compared with Monte-Carlo simulations performed with CORSIKA code.

I. INTRODUCTION

THE charge ratio $R_\mu = (\mu^+ / \mu^-)$ of the atmospheric muons provides sensitive tests of the Monte Carlo simulations of the muon flux. The primary and secondary components of cosmic rays are influenced by the geomagnetic field. This influence leads to the latitude effects of the flux (dependence on the observation site) and to the so-called East West effect, well pronounced for lower muon energies and for large zenith angles of muon incidence. The experimental results control the applied simulation procedures and the invoked hadronic interaction model.

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II. WILLI DETECTOR FOR MEASURING THE MUON CHARGE RATIO

The WILLI detector [1] is a modular system, operating for all azimuth angles and down to 45^0 zenith angle; each module, 1 m^2 area, contains a scintillator layer of 3 cm thickness in an aluminum frame of 1 cm thickness. The active layers are read out by 2 photomultipliers mounted on opposite corners of each plate, using alternate corners. The detector consists in 16 modules for measuring good events and 4 anticoincidence modules, placed vertical on the sides of the detector.

The WILLI detector determines the muon charge ratio by measuring the life time of stopped muons in the detector layers. The life time is different for positive and negative muons: stopped *positive* muons decay with a lifetime of 2.2 μs, while *negative* muons are captured in the atomic orbits, leading to an effectively smaller lifetime depending on the stopping material. The uncertainties in the detector efficiency and the geometry are the same for positive and negative muons.

Figure 1 shows the WILLI device, rotable for measuring muons with different angles of incidence [2];

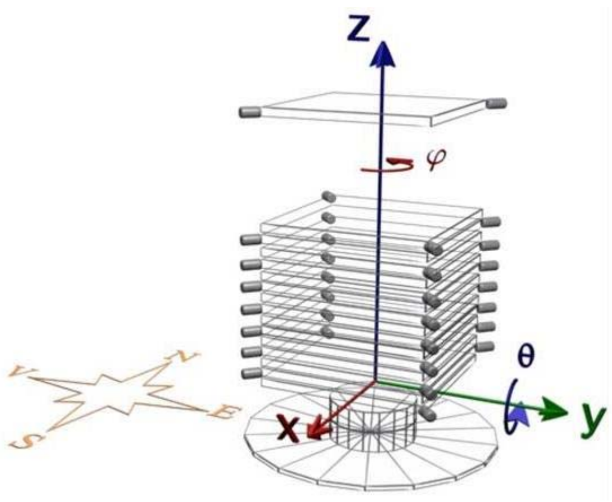

Fig.1 WILLI detector set up

The total decay curve of all muons measured in the detector is a superposition of several decay laws, containing 3 detector-dependent constants, which have been determined by extensive detector simulations using the GEANT [3] simulation tools. The muon charge ratio is obtained by fitting the measured decay spectrum with the simulated curve.

The decay curve of the muons has the expression:

$$dN/dt = [N_0/(R+1)][Rc_0 \cdot 1/\tau_0 \cdot \exp(-t/\tau_0) + + \Sigma c_i \cdot 1/\tau_j \cdot \exp(-t/\tau_j)] \quad (1)$$

where, $R(\mu^+/\mu^-)=N^+/N^-$ represents the muon charge ratio, N^+ and N^- are the numbers of positive and negative muons, respectively, τ_j indicates the lifetime for μ^- with the index j describing the absorber and the index 0 stands for positive muons.

Figure 2 shows the simulations of the exponential decay for different materials and compares the experimental decay curve with the free decay of positive muons.

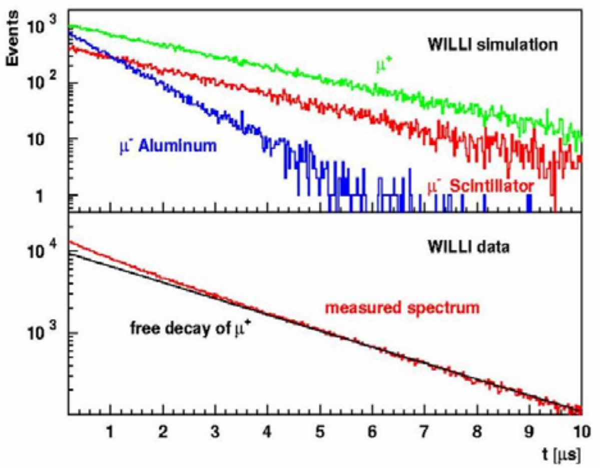

Fig.2. Muon decay curves, simulation and data.

Figure 3 shows the energy and angular acceptance of WILLI detector for measurements of the muon charge ratio performed alternatively in the East and West direction with the detector inclined at 45^0.

Using the GEANT code [3] the energy and angular acceptance of the detector set up has been determined. The results (Fig.3) include the zenith angle distribution of the atmospheric muons. The lower energy cutoff of the registered muons energy can be increased by adding lead absorbers on the top of the device.

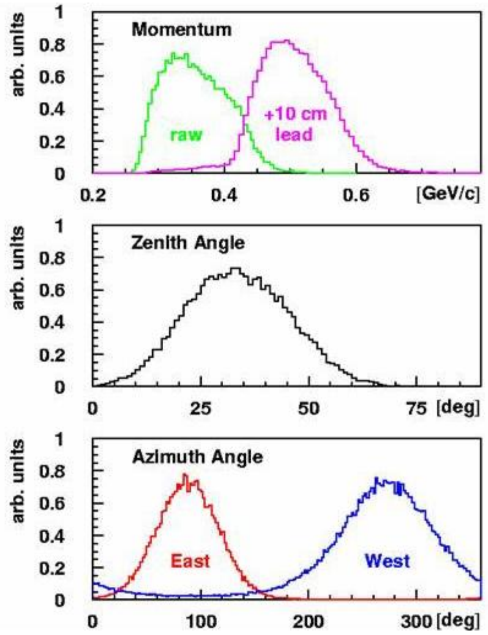

Fig.3. Detector energy and angular acceptance.

III. RESULTS

The azimuth asymmetry A_μ characterizes the East-West effect as:

$$A_\mu = (R_W - R_E)/(R_W + R_E)$$

with R_W and R_E being the value of the muon charge ratio measured in the West and East direction, respectively. For a momentum range of 0.3-0.4 GeV/c, a value of A_μ = 0.26 is obtained.

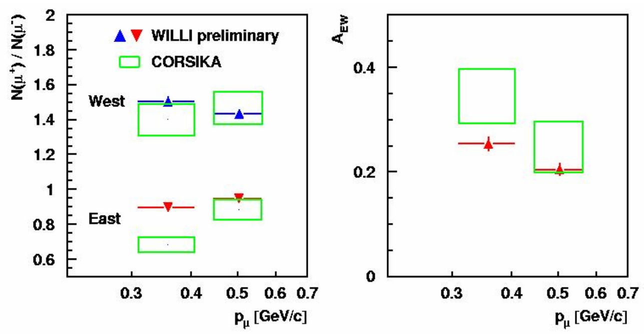

Fig.4. Energy dependence of the muon charge ratio.

Figure 4 displays the measured values of the muon charge ratio and azimuth asymmetry compared with simulations performed with CORSIKA. The green boxes indicate the statistical uncertainties of the simulations. The horizontal bars in the experimental data represent the errors due to energy acceptance.

To investigate the azimuth dependence, muon charge ratio measurements have been performed on 4 azimuth directions: North, East, South, West, (N, E, S, W). In order to get a sufficient statistical accuracy, (by about 10^6 good events on each direction), the measurements lasted many years and the characteristics of the photomultipliers have been changed in time. Unfortunately, due to these instrumental defects it was necessary to introduce a calibration factor for the absolute value by a simulation result, but preserving the information about the shape of the variation.

The data obtained using WILLI (inclined at 45^0) are presented in figure 5 with energies and angles of incidence in the range shown in figure 3.

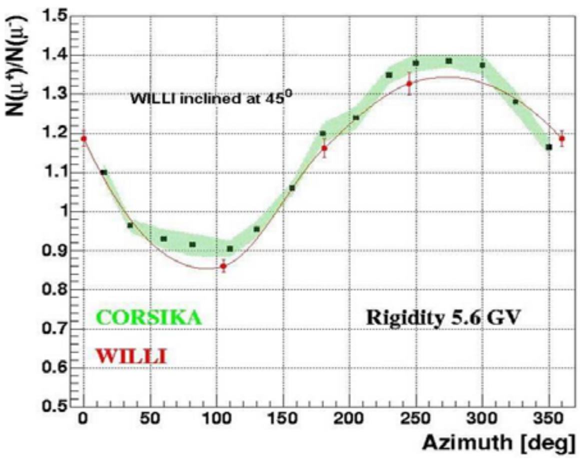

Fig.5. The azimuth dependence of the muon charge ratio compared to simulation expectations obtained with the CORSIKA simulation code [2], [3].

The CORSIKA simulations, based on DPMJET hadronic interaction model [4], reproduce well the pronounced East-West effect observed by WILLI [5]. An azimuth dependence similar to that reported for incident muon energies above 1 GeV [6] was found, but showing that the East-West variation is more pronounced at lower muon energies.

IV. CONCLUSIONS

At low muon energies the muon flux is significantly influenced by the geomagnetic field and dependent on the particular observation site due to the varying geomagnetic cut-off values.

The azimuth variation of the charge ratio for muons of inclined incidence reveals the influence of the geomagnetic field; the procedures handling the geomagnetic field effects in CORSIKA calculations has been verified to be suitable.

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