MEASUREMENTS OF THE CHARGE RATIO OF ATMOSPHERIC MUONS *

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(*Received January 7, 2000*)

The measurements of the muon charge ratio representing the ratio of positive to negative atmospheric muons are performed using a small compact device, WILLI, by detecting the life time of the muonic atoms. Avoiding the difficulties of measurements with magnetic spectrometers, this method gives precise results on muon charge ratio especially in the low energy range relevant for the atmospheric neutrino anomaly. The detector, the method and the results on muon charge ratio for five energy ranges below 1 GeV are presented. The results can be used to improve hadronic interaction models.

PACS numbers: 14.60.Ef, 13.35.Bv, 23.40.–s, 95.55.Vj

1. Introduction

During the propagation of cosmic rays in the atmosphere by the interactions with atmospheric nuclei pions and kaons are produced, which subsequently decay in muons and neutrinos:

$$\begin{aligned} A_{\rm cr} + A_{\rm air} &\rightarrow \pi^{\pm},\ K^{\pm},\ K^{0}\ldots\,, \\ \pi^{+} &\rightarrow \mu^{+} + \nu_{\mu}; \quad \mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu_{\mu}}\,, \\ \pi^{-} &\rightarrow \mu^{-} + \overline{\nu_{\mu}}; \quad \mu^{-} \rightarrow e^{-} + \overline{\nu_{e}} + \nu_{\mu}\,. \end{aligned}$$

* Presented at the XXVI Mazurian Lakes School of Physics, Krzyże, Poland September 1–11, 1999.

A similar decay chain is for the charged kaons. At high energies, the study of muons provides signatures on the chemical composition of cosmic rays and of the interaction characteristics relevant to the air shower development in the atmosphere. At low energies the studies imply interesting aspects in view of the investigation of the so-called atmospheric neutrino problem and in examining the effects of the Earth's magnetic field on the propagation of secondary cosmic rays. Thus, the measurements of the muon charge ratio, *i.e.* the ratio of the positive to negative muons in the atmospheric flux is of interest for testing the hadronic interactions models and for clarifying the atmospheric neutrino anomaly. Many experimental studies carried out above a few GeV muon energy have used magnetic spectrographs, in which the charge particle trajectories are determined before and after traversing the magnetic field [1]. The Coulomb scattering plays an important role in restricting the momentum resolution at low energies. In studies of the charge ratio of the muon flux, the instrumental acceptance, scattering effects and the detection efficiency for particles of different charges need careful consideration and are sources of uncertainties. This paper reports measurements of muon charge ratio at muon energy smaller than 1 GeV with a method avoiding the difficulties of a magnetic spectrometer by use of a relative compact detector based on the observation of the muon capture and the subsequent decay.

2. Method of observing decay electrons from muon capture in the matter

The principle of our measurements of muon charge ratio is based on different behaviour of positive and negative muons in matter: stopped positive muons decay by the life time of free muons, the negative muons are captured in atomic orbits, where they may either decay or are absorbed by the atomic nucleus [2]. This leads to a reduced life time of stopped negative muons depending on the stopping material. The total decay curve of all muons which decay in the detector is a superposition of several decay laws:

$$\frac{dN}{dt} = \left[\frac{N_0}{(R+1)}\right] \left[R\frac{c_0}{\tau_0}\exp\left(-\frac{t}{\tau_0}\right) + \sum_{j=1}^{3} \frac{c_j}{\tau_j}\exp\left(-\frac{t}{\tau_j}\right)\right] , \qquad (1)$$

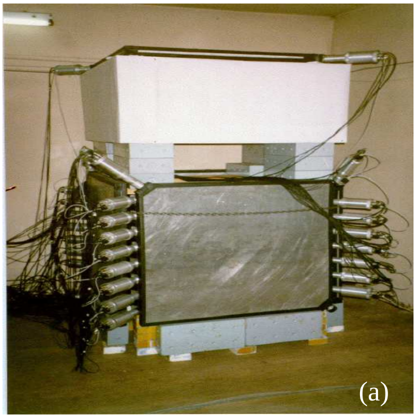
where $R(\mu^+/\mu^-) = N_+/N_-$ represents the muon charge ratio, N_+, N_- being the number of positive and negative muons, respectively, $N_0 = N_+ + N_-$, and the index j indicates the different absorber materials. There are precise experimental results available about the lifetime in various materials.

3. The measurements of the muon charge ratio with WILLI detector

In the frame of some prototype studies for the air-shower experiment KASCADE [3], in IFIN-HH, Bucharest, the WILLI (Weakly Ionising Lepton Lead Interactions) detector has been built up for studies of the interaction of high energy muons with matter.

The previous setup [2] used for muon charge ratio measurements [4] has been modified. It consists of 15 detector and absorber modules. The absorbers are the 1.2 cm thick aluminium supports. The active detectors are plastic scintillators (NE114, 3.0 cm thickness), whose light is collected by two photo-multipliers. The energy signals taken from the anode and the third dynode are conducted to an ADC. A timing signal, taken from a dynode is analysed by Multiple Time Digital Converter. One scintillator detector positioned 87 cm above the detector stack is used as trigger and defines the acceptance geometry. Four modules placed around the stack serve as anticounters (Fig. 1(a)).

The signature of a stopped and decaying muon is a particle triggering the telescope, but not penetrating till the bottom of the scintillator stack, together with the appearance of a delayed particle, disappearing in the surrounding of the stopping locus, see Fig. 1(b). From the time interval of incoming and decaying particle the spectrum of the decay times is registered. The background is less than a permille of the active signal.



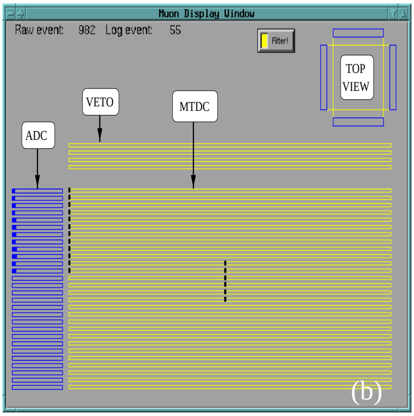


Fig. 1. (a) The modified configuration of the WILLI detector (with anti-counters); (b) Event display: ADC and MTDC image of a muon decay event; the ADC scale corresponds to the 0–4095 channel range and the MTDC comprises 256 bins of 20 ns width; the muon stops after penetrating 6 active layers and the electron appears in the following 3 layers [5].

As explained previously, the measured time spectrum is a superposition of different decay curves. For three different materials forming the modules, four constants appear in the expression (1) accounting for the stopping power in the materials, the decay probability of muons bound in muonic atoms, detection efficiencies. Thresholds and angular acceptance have been determined by extensive detector simulations using the code GEANT [6].

The Fig. 2(a) shows the comparison between the simulated results and the experimental decay curve, being obvious the effect of the material dependent decay time, aluminium providing the best discriminating effect.

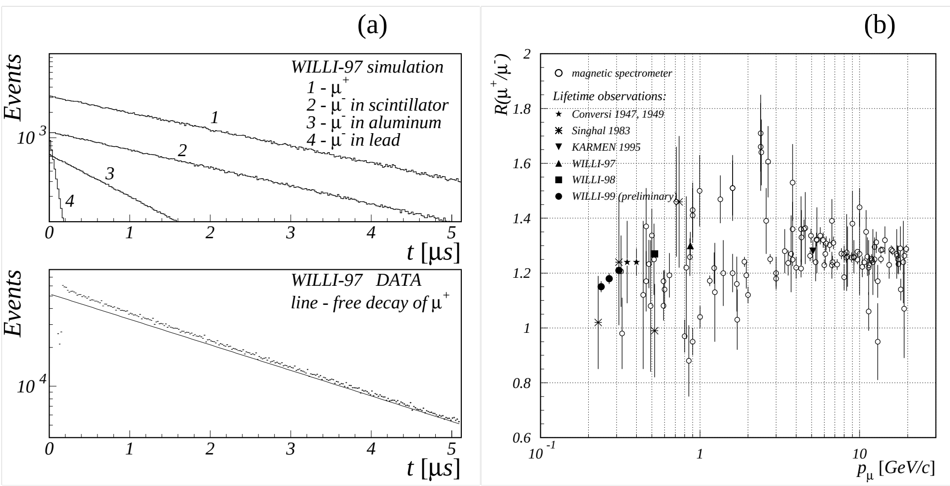


Fig. 2. (a) Monte Carlo simulations results of the contribution of different materials to the total decay curve and the experimental decay curve compared with the decay curve expected for positive muons [7]. (b) The present experimental knowledge of muon charge ratio.

One can notice that aluminium provides the best discriminating effect, reducing significantly the effective mean life time of negative mean life time as compared to that of positive muons; the decay probability for Al is 39.05% while for Pb only 2.75%.

In a next configuration the detector has been optimised for muon charge ratio measurements by removing the Pb layers and improving the geometry and the background rejection by use of anti counters [7] (see Fig. 1(a)).

The Fig. 2(b) displays the present knowledge of muon charge ratio for energies less than 20 GeV. Our results concern the lower energy end:

- WILLI97 experiment $R(\mu^+/\mu^-) = 1.30 \pm 0.05$ for a mean muon momentum of 0.86 GeV/c,

- WILLI98 experiment $R(\mu^+/\mu^-) = 1.27 \pm 0.01$ for a mean muon momentum of 0.53 GeV/c,

- WILLI99 experiment $R(\mu^+/\mu^-) = 1.15 \pm 0.02$ for a mean muon momentum of 0.24 GeV/c,
  $R(\mu^+/\mu^-) = 1.18 \pm 0.02$ for a mean muon momentum of 0.27 GeV/c,
  $R(\mu^+/\mu^-) = 1.21 \pm 0.02$ for a mean muon momentum of 0.31 GeV/c.

4. Concluding remarks

Under instrumental-methodical aspects our studies demonstrate a simple and efficient procedure to measure the muon charge ratio with a small compact detector reaching accuracies in the order of few percent and excluding systematic errors of magnetic spectrometers. The method has been already used by large-volume detectors, the KAMIOKANDE detector [8] and the KARMEN detector [9]. In contrast to these setups, our device is small, compact and easily transportable, suitable for balloon flights for measuring profiles in altitudes.

The modulation of muon fluxes, known as the east–west effect due to the geomagnetic field, gains importance for the low-momentum region and for larger zenith angle [10]. It is expected to be more pronounced in the momentum range below 1GeV, where our measurements are performed. In the future the WILLI device will be modified into a rotatory configuration for the observation of muons arriving with different angles of incidence in zenithal and azimuthal plane.

The set up of the calorimeter in NIPNE Bucharest was realized with the support of Romanian Ministery of Research and Technology, the International Bureau Bonn and Forschungszentrum Karlsruhe, Germany. The studies have been supported by a grant of the Volkswagen Stiftung.

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