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The charge ratio of atmospheric muons below 1.0 GeV/c: Status and Perspective

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Abstract. The compact WILLI device, built in IFIN-HH Bucharest (44°26'N latitude, 26°04'E longitude and 85 m a.s.l.) at a vertical cut-off rigidity of 5.6 GV, has been used for measurements of the charge ratio in the vertical atmospheric flux at momenta below 1 GeV/c. In this low energy range the studies of muon charge ratio provide information useful for the discussion of the so-called atmospheric neutrino anomaly and for studies of atmospheric neutrino and antineutrino fluxes. The experimental method is based on the observation of the reduced effective lifetime of negative muons, stopped in matter, as compared to the lifetime of positive muons. Avoiding the difficulties and the systematic errors of magnetic spectrometers, results with high accuracy are obtained, indicating a decrease of the muon charge ratio from 1.30 (at 0.87 GeV/c) to 1.15 (at 0.24 GeV/c). The detector WILLI has been recently transformed in a rotatable device for measuring the muon charge ratio for different angles of incidence in azimuthal and zenithal range. With such perspective a systematic "muon charge ratio spectroscopy" may provide interesting geophysical observations.

1 Introduction

At low energies the actual interest in studies of the muon charge ratio arises from the aspects related to the so-called atmospheric neutrino anomaly and from examining the effects of the Earth's magnetic field on the propagation of secondary cosmic rays (Ryazhskaya, 1996). When the primary cosmic radiation interacts with the Earth's atmosphere, baryons and mesons are produced. Atmospheric muons originate mainly from the decay of charged pions and kaons in muons and the subsequent decay of the muons:

$$\begin{array}{llll} \pi^{\pm} & \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}}) & 99.99\,\% & \tau = 26\,ns \\ K^{\pm} & \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}}) & 63.51\,\% & \tau = 12\,ns \end{array}$$

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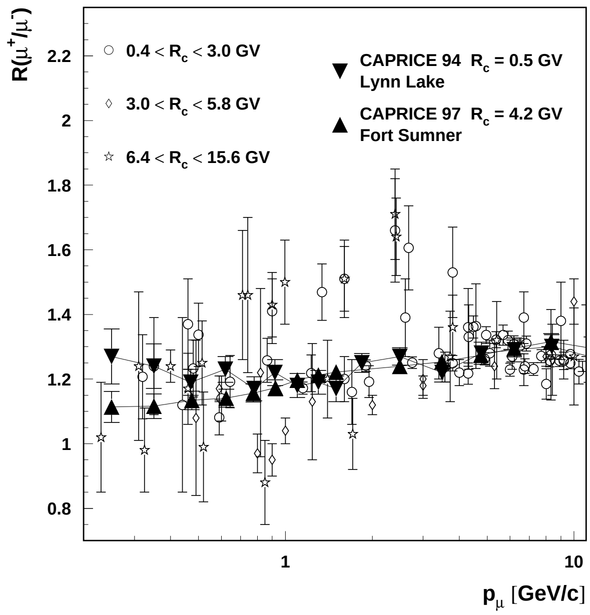

Fig. 1. Compilation of measurements on the charge ratio of vertical muons at low muon momenta. The different symbols stand for different intervals of the geomagnetic cut-off R_c at the location of the experiment (Vulpescu et al., 1998; Kremer et al., 1999).

Muons have a relative large lifetime $\tau_0 = 2.2\,\mu$s, thus only part of them decay:

$$\begin{array}{l} \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu} \\ \mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu . \end{array}$$

Considering the decay chains, it is obvious that the ratio of positive to negative atmospheric muons, called the muon charge ratio:

$$R_\nu = \frac{\mu^+}{\mu^-}$$

maps the neutrino production and carries information on the hadronic interactions, used in the calculations of atmospheric

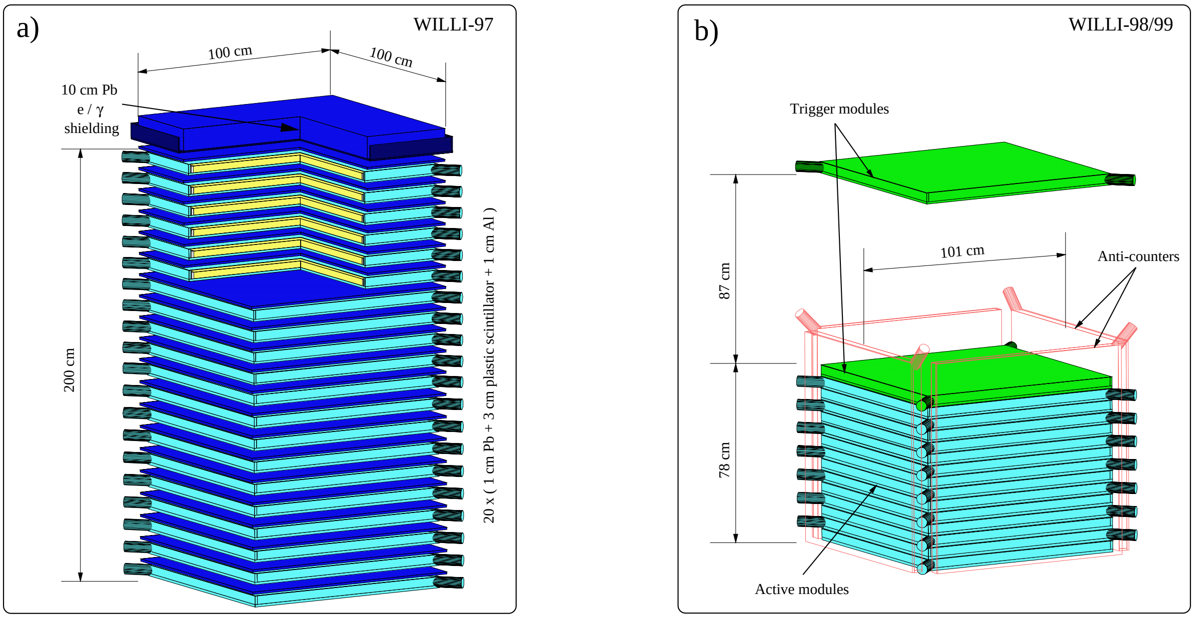

Fig. 2. a) The original sampling calorimeter configuration of the WILLI detector used in WILLI-97 runs. b) The second configuration, improved for the measurements on the muon charge ratio used in WILLI-98 and WILLI-99 runs.

neutrino fluxes. Super-Kamiokande (Fukuda et al., 1998) and other experiments find that the ratio of muonic to electronic neutrinos is much smaller than the theoretical predictions. In addition, the effect is depending on the angle of incidence of the neutrinos. A possibility to verify the invoked models, which are used for the neutrino flux calculations, is to compare the theoretical results for the muon flux, with the experimental data (Wentz et al., 2001).

The compilation of muon charge ratio values measured in the last decades shows that at higher energies all experiments are consistent with a value $\frac{\mu^+}{\mu^-} \approx 1.3$ (Fig. 1). At energies lower than 1.0 GeV, the experimental uncertainties appear to be larger and the data disagree with each other. This finding led us to perform measurements in this energy range.

2 The method and the apparatus

An experiment have been developed for studying the charge ratio of atmospheric muons with an electromagnetic calorimeter WILLI (Weakly Ionizing Lepton Lead Interactions) set-up in IFIN-HH Bucharest, related to studies of the KASCADE experiment. Differently from other experiments, using magnetic spectrographs, in which the charged particle trajectories are measured before and after traversing a magnetic field, our method (Vulpescu et al., 1998) to determine the muon charge ratio is based on the different behavior of positive and negative muons stopped in matter. While positive muons decay with their natural life time, the negative muons are captured in atomic orbits and form muonic atoms, leading to a shorter lifetime of negative muons in matter. The WILLI device measures the effective life-time of the stopped muons for both charge states by observing the appearance of decay electrons and positrons after the muon stopped.

The initial configuration, WILLI-97 (Fig. 2a), consisted of 20 modules, each made of a lead plate of 1 m^2 area, 1 cm thick and a plastic scintillator of 90 x 90 x 3 cm^3, contained in an aluminum box (1 cm thick lateral walls and bottom and 1 mm cover) (Vulpescu et al., 1998).

In a further step (Fig. 2b), the detector has been optimized for the measurement of the muon charge ratio by removing the lead plates and improving the geometry in order to have a background rejection using four scintillator modules in vertical position as anti-counters to cover the sides of the detector (Vulpescu, 1999). With this configuration two sets of measurements have been performed with the detector placed at the basement of the Nuclear Physics Department under 60 cm reinforced concrete (WILLI-98) and in another building with less shielding material above, where data have been taken for muons at lower energy, WILLI-99 (Vulpescu et al., 2001).

The detector is equipped with 40 photomultipliers providing energy deposit (amplitude, by 40 anodes and 40 dynodes) and time information (by 40 dynodes, from which 32 are analyzed, 28 signals of 14 layers and 4 signals of anti-counters). The trigger is made out of four separate signals corresponding to two of the detector layers which define the accepted solid angle of the device. The light of the scintillator is collected by two photomultipliers with wavelength shifters. The energy signals taken from the anode and the third dynode are conducted to an ADC. The timing signals, taken from the dynodes are analyzed by a Multiple Time Digital Converter. The signature of a stopped and decaying muon is a particle triggering the telescope, but not penetrating till the bottom of

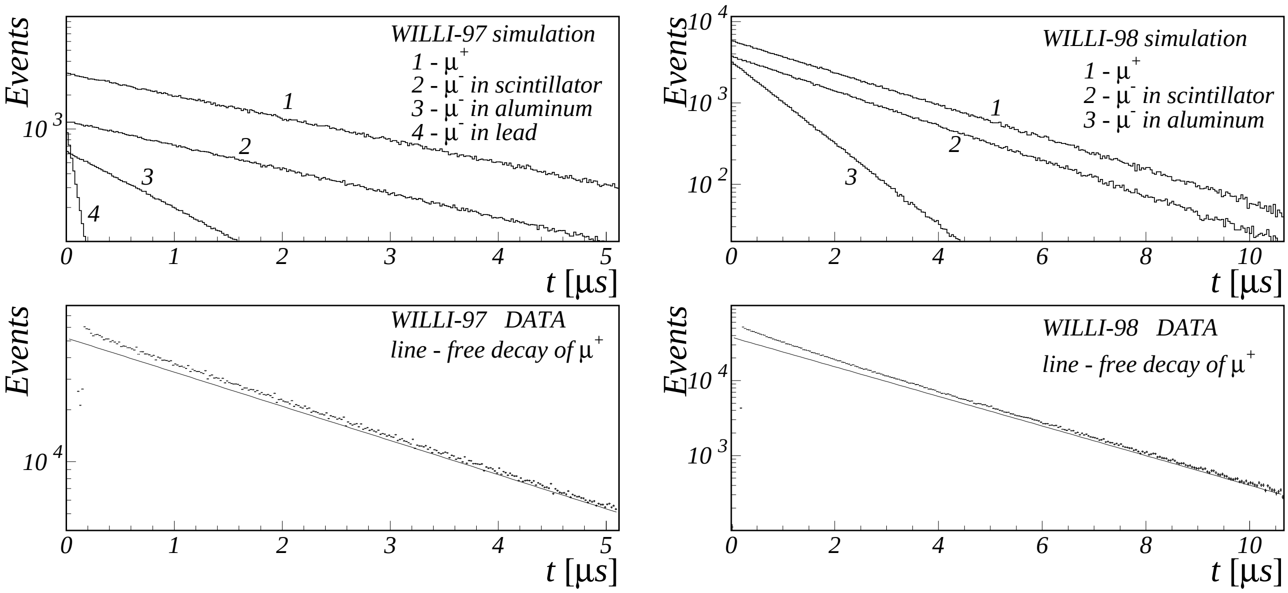

Fig. 3. Upper figures: Monte Carlo simulation results on the contribution of different absorber materials to the total decay curve, assuming $N(\mu^+)/N(\mu^-) = 1$. Lower figures: The experimental decay curves compared with the free decay of positive muons.

the scintillator stack, together with the appearance of a delayed particle in the surrounding of the stopping locus. From the time difference between the incoming muon and the decay electron, the spectrum of the decay times is registered.

3 Monte Carlo simulations and results

The total decay curve of all muons measured in the detector is a superposition of several decay laws :

$$\frac{dN}{dt} = \frac{N_0}{(R+1)}[Rc_0\frac{1}{\tau_0}exp(\frac{-t}{\tau_0}) + (\Sigma c_j\rho_j\frac{1}{\tau_j}exp(\frac{-t}{\tau_j}))]$$

where $R(\frac{\mu^+}{\mu^-}) = \frac{N^+}{N^-}$ represents the muon charge ratio, N^+, N^- being the number of positive and negative muons, respectively, $N_0 = N^+ + N^-$, ρ_j gives the decay probability, and τ_j indicating the mean lifetime of μ^- with index j for different absorber materials, index 0 standing for positive muons.

The expression contains four detector dependent constants c_j, for WILLI-97 and three constants for WILLI-98/99, 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 (CERN, 1993). The charge ratio of the muons is estimated by fitting the decay law above to the experimental data.

Fig. 3 shows the results of the simulations indicating the decay exponentials for different materials and the comparison of the experimental decay curve with the free decay of positive muons. One notices that aluminum provides the best discriminating effect, reducing significantly the effective mean life time of negative muons as compared to that of positive muons, and the decay probability for Al is 39.05 % while for Pb only 2.75 %. It is seen also the improvement by removing the lead absorbers in the new configuration, resulting in an increase of the number of the detected muons which are stopped in aluminum.

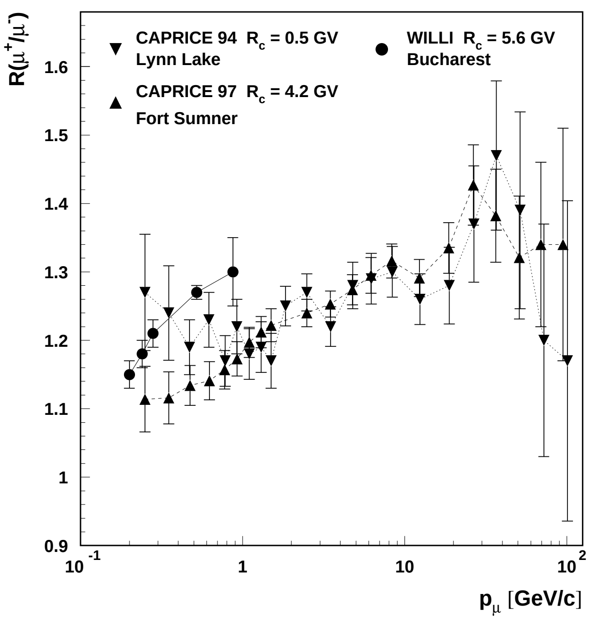

Fig. 4. The WILLI results for the muon charge ratio at sea-level together with recent results from CAPRICE experiment for two locations with different geomagnetic cut-off rigidities (Kremer et al., 1999).

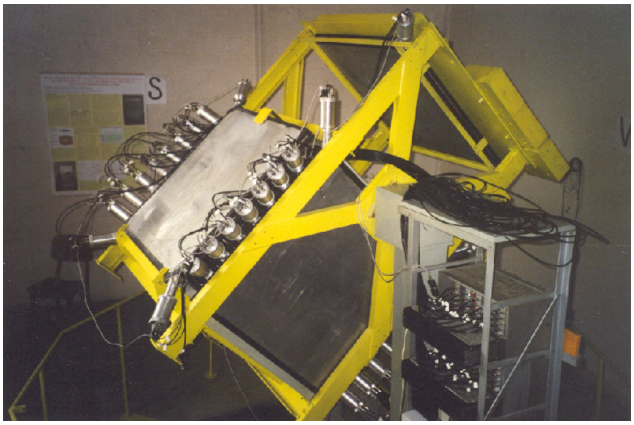

Fig. 5. A photograph of the modified WILLI detector for measuring muons with different angles-of-incidence.

The Tab. 1 presents the results of all three experiments with different detector configurations. In the WILLI-99 experiment the upper and the bottom sections of the detector have been analyzed separately.

$< p_\mu >$	$< \theta_\mu >$	$R(\frac{\mu^+}{\mu^-})$	ΔR	WILLI
0.87 GeV/c	26°	1.30	0.05	1997
0.52 GeV/c	19°	1.27	0.01	1998
0.28 GeV/c	16°	1.21	0.02	1999-lower half
0.24 GeV/c	17°	1.18	0.02	1999-full
0.20 GeV/c	19°	1.15	0.02	1999-upper part

Table 1. The results of the muon charge ratio measurements WILLI-97, WILLI-98 and WILLI-99 at sea level, p_μ and θ_μ stand for the momentum and zenith angle of the muons.

Fig. 4 shows the results of WILLI compared to other recent experiments (Kremer et al., 1999). The WILLI results indicate a smooth decrease of the charge ratio towards lower energy, which could be expected due to geomagnetic cut-off. The CAPRICE experiment reported a similar decrease, but with lower values, for New Mexico, at nearly the same geomagnetic cut-off as in Bucharest. The CAPRICE results for Lynn Lake (where actually no cut-off effect is expected) show higher values for lower energy, but with a strange modulation around $p_\mu = 0.8$ GeV/c.

4 Concluding remarks

The measurements of the muon charge ratio by means of magnetic spectrometers are affected by systematic effects at low muon energies due to problems in the particle and trajectory identification, leading to quite different results. Our method overcomes such difficulties by measuring the lifetime of muons stopped in matter. The measurements indicate a muon charge ratio value of 1.3 at a momentum of 0.8 GeV/c, decreasing to 1.15 at 0.2 GeV/c, what can be attributed to the geomagnetic cut-off. Our results are different from the CAPRICE results for Fort Summer in New Mexico where the geomagnetic cut-off is similar to that in Bucharest.

The WILLI detector is a suitable instrument for the further investigation of the modulation of the muon charge ratio and therefore of the neutrino fluxes by the geomagnetic cut-off. The details about the geomagnetic influence have not been systematically explored using the observation of muons with different arrival directions. The WILLI detector is now modified in a rotatable set-up (Fig. 5), which will allow precise measurements of the East-West effect, caused by the anisotropy of the primary proton flux and the local magnetic field, bending charged particles on their way through the atmosphere.

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