WILLI, a Detector for Measuring the Charge Ratio of Cosmic Muons

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Abstract

The WILLI (Weakly Ionising Lepton Lead Interactions) detector is a small compact device for performing measurements of the charge ratio of cosmic muons by detecting the life time of the muonic atoms. This method gives precise results on the charge ratio in the energy range relevant for the atmospheric neutrino anomaly, avoiding usual difficulties of measurements with magnetic spectrometers. The results can be used to check and to improve interaction models for calculating neutrino fluxes. The technique of the instrument, its performance and the results on the charge ratio measurements are presented.

1 The relevance of the charge ratio of atmospheric muons for hadronic interaction models and the atmospheric neutrino anomaly:

With the propagation of cosmic rays (CR) in the atmosphere, pions and kaons are produced by the interactions with air nuclei. Muons and neutrinos are resulting from their decay:

$$\begin{aligned} A_{CR} + A_{Air} \rightarrow \quad & \pi^{\pm},\ K^{\pm},\ K^{0}\ \ldots \\ & \pi^{+} \rightarrow \quad \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu} \\ & \pi^{-} \rightarrow \quad \mu^{-} + \overline{\nu}_{\mu} \rightarrow e^{-} + \overline{\nu}_{e} + \nu_{\mu} \end{aligned} \tag{1}$$

(and with a similar decay chain for the charged kaons). The ratio of the numbers of positive to negative muons, called muon charge ratio, provides important information on the interactions of the primary cosmic particles with the atmosphere nuclei, since it reveals detailed features of the multiplicity distributions and production cross sections of the parent particles and is a sensitive test quantity of hadronic interaction models. Hence at low energies (GeV range) studies of the muon charge ratio are related to predictions of the atmospheric neutrino fluxes and with the so-called atmospheric neutrino anomaly (Wentz 1999). This anomaly is the observation that the measured ratio of the neutrino fluxes $F(\nu_\mu + \overline{\nu}_\mu)/F(\nu_e + \overline{\nu}_e)$ appears to be significantly lower than the expected value ≈ 2 (Gaisser and Stanev 1988, Honda 1995). The experimental deficit of muonic neutrinos (KAMIOKANDE: Fukuda 1998) has been interpreted to be due to flavour oscillations of $\nu_\mu \rightarrow \nu_\tau$. As the muon charge ratio, observed in the range 0.1 – 2 GeV, directly reflects the ratio of the numbers of electronic neutrinos and

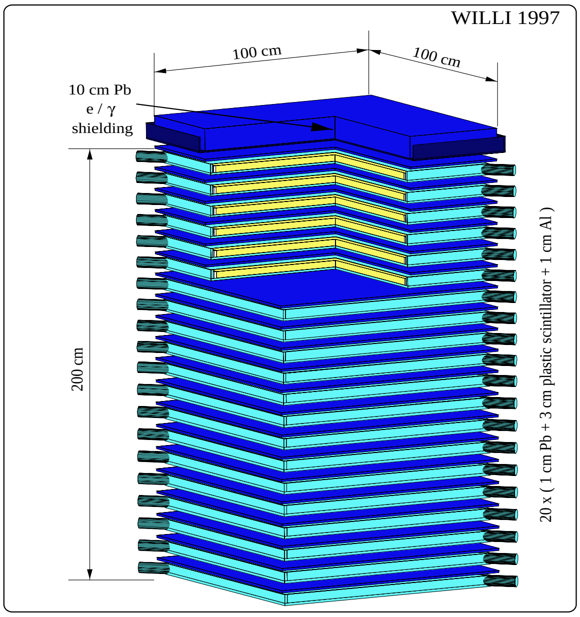

Figure 1: The sampling calorimeter configuration of the WILLI detector.

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antineutrinos: $\nu_e/\overline{\nu}_e \approx \mu^+/\mu^-$ (Honda 1995), and since neutrinos and antineutrinos do interact with matter in a different way, the charge ratio is also an important information for evaluating neutrino detector responses. The observed muon charge ratio originates from the interaction of primary particles mainly of the GeV range. Consequently the propagation of the primaries and of the secondaries is noticeably influenced by the Earth's magnetic field and eventually by solar modulations. Thus additionally to the particle physics aspects there are further perspectives of muon charge ratio studies which establish a general interest in this observable of our environment.

2 Observation of the decay electrons for measuring the muon charge ratio with the WILLI detector:

Many experiments for the muon charge ratio have used magnetic spectrographs. Instrumental effects of different acceptance, scattering and detection efficiency for particles of different charges need careful consideration and are sources of uncertainties. This paper reports measurements of the muon charge ratio at low energies, avoiding the difficulties of a magnetic spectrometer with a relatively compact, small, flexible and mobile apparatus based on the observation of the decay electrons by delayed coincidence.

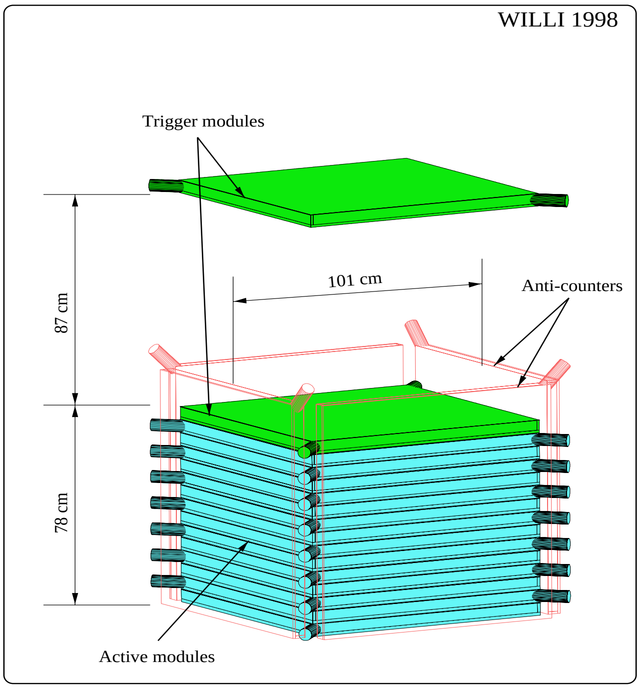

Figure 2: The modified configuration of the WILLI detector.

This instrument, a small sampling calorimeter (90×90 cm^2 area), has been built up in NIPNE Bucharest, ($44^o 26'$ N latitude, $26^o 04'$ E longitude and sea level) for some prototype studies of cosmic muon interactions with the matter (Vulpescu 98) in context with the air shower experiment KASCADE. In the first stage of realisation (Fig. 1), the detector consisted of 20 layers of lead (1 cm thickness), separated by 20 active layers of NE114 scintillators (3 cm thickness) placed in between aluminum layers (1.2 cm thickness), being used for both exploratory studies of muon energy spectroscopy (Brancus 1998) and for muon charge ratio measurements (Vulpescu 1998). In a subsequent configuration (Fig. 2) the detector has been optimized for muon charge ratio measurements, by removing the Pb layers and improving the geometrical set-up and background rejection by use of anticounters (Vulpescu 1999).

The principle of the measurement is based on the different behaviour of positive and negative muons in matter. Stopped positive muons decay by the lifetime of free muons. Negative muons are captured in atomic orbits, where they may decay or are absorbed by the atomic nucleus. This leads to a reduced life time of stopped negative muons, depending on the stopping material. The total decay curve of all muon decays in the detector is a superposition of several decay laws:

$$dN/dt = [N_0/(R+1)][R\, c_0\, 1/\tau_0\, \exp(-t/\tau_0) + \sum c_j\, 1/\tau_j\, \exp(-t/\tau_j)], \quad (2)$$

where $j = 1,2,3$, indicates the different absorber materials, $R(\mu^+/\mu^-) = N^+/N^-$, represents the muon charge ratio, N^+, N^- being the number of positive and negative muons, respectively and $N_0 = N^+ + N^-$.

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

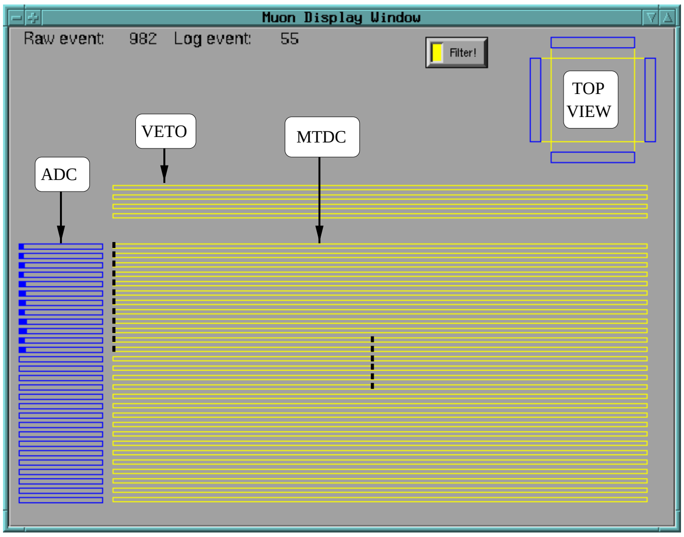

Figure 3: The offline display of a single event.

The light of the scintillators is collected by two photomultipliers via wavelength shifters. The mean energy loss of the minimal ionising muons (vertical incidence) of 6 MeV is used for the energy calibration of the detector (Vulpescu 1998). The energy signals taken from the anode and the third dynode are conducted to an ADC. A timing signal, given by the first dynode is analysed by a Multiple Time Digital Converter. A first trigger from the first layers starts the time measurement when the muon enters and the delayed signal from the decay electron is recorded in the remaining layers.

The signature of a stopped and decaying muon is a particle triggering the telescope, but not penetrating till the bottom of the detector, together with the appearance of a delayed particle, produced in the surrounding where the muon stopped (Fig. 3). With registrating the time interval of the incoming and decaying particle, the spectrum of the decay times is measured. The background of the decay curve is in the order of less than a per mille of the used signal.

The measured time spectrum is a superposition of four decay curves, the parameters c_0, c_i $(i = 1, 2, 3)$ which take into account the stopping power of the materials, the decay probability of muons bound in muonic atoms, detection efficiencies, detector geometry, laboratory walls, thresholds and angular acceptance, have been determined by extensive detector simulations using the GEANT code (Fig. 4). The dependence of the decay time on the absorber material is obvious. Aluminium reduces significantly the effective mean life time of negative muons as compared to that of the free decay of positive muons. Though the effective life time get even shorter for higher Z materials, the absorption is correspondingly larger and implies low rates of decay electrons. The decay probability for Al is 39.05% while for Pb only 2.75%. Hence aluminum proves to be the optimum choice under all practical aspects. Fig. 5 displays a compilation of world- wide measured results at different energies. The average value

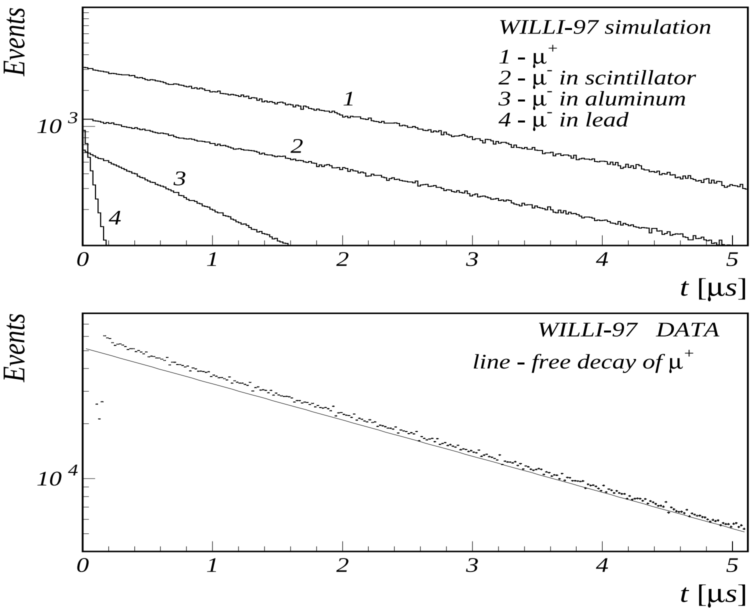

Figure 4: Monte Carlo simulation results of the contributions of different materials to the total decay curve, and the experimental decay curve compared with the decay curve expected for positive muons ($\tau = 2.2\mu$s).

of about 1.20 at energies < 20 GeV slightly increases with the energy. Our results:

WILLI 1997 experiment: $R(\mu^+/\mu^-) = 1.30 \pm 0.05$ for a mean muon momentum of 0.86 GeV/c
WILLI 1998 experiment: $R(\mu^+/\mu^-) = 1.27 \pm 0.01$ for a mean muon momentum of 0.53 GeV/c

concern the low energy part relevant for the atmospheric neutrino anomaly.

4 Concluding remarks:

The present study demonstrates a simple and efficient procedure to measure muon charge ratio with a small and compact detector, reaching accuracies in the order of few percent and excluding systematic errors of magnetic spectrometers. The reported results are obtained with two different geometrical configurations permitting two different muon energy ranges. It has been shown (Tsuji 1998) that the variation of muon fluxes, known as the east-west effect of the geomagnetic field, is more important for the low-momentum region and for larger zenith angle. In the future our device will be modified into a rotatable configuration for the observation of muons with different angles of incidence in zenithal and azimuthal plane.

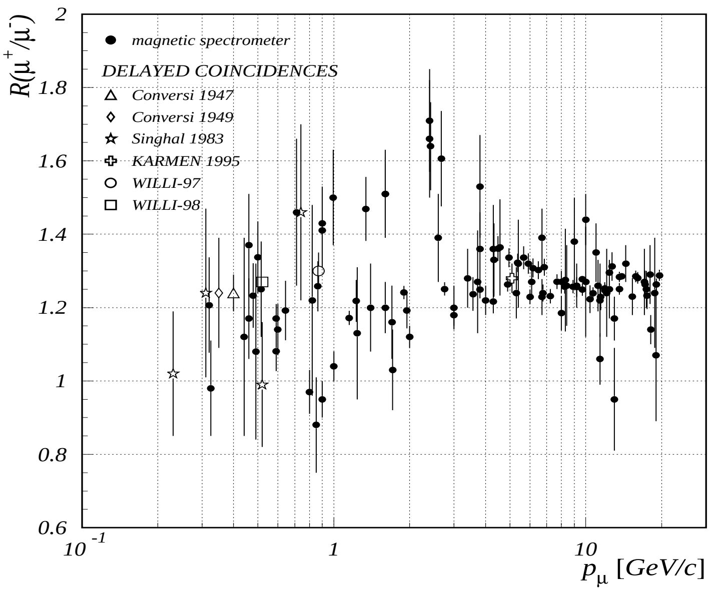

Figure 5: The present experimental knowledge on muon charge ratio.

Acknowledgements

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