COSMIC RAY MEASUREMENTS USING WILLI-AIR SETUP

A. BĂLĂCEANU[1,2], N.V. ZAMFIR[1], A. GHERGHEL-LASCU[1,2], B. MITRICĂ[1], M. NICULESCU-OGLINZANU[1], A. SĂFTOIU[1], D. STANCA[1*], T. MOSU[1], D. DUMITRIU[1], C. VANCEA[1], M. DOBRE[2]

[1]Department of Nuclear Physics,
National Institute for Physics and Nuclear Engineering "Horia Hulubei",
Atomistilor 407, RO-077125, POB-MG6, Măgurele-Bucharest, Romania
[2]University of Bucharest, Faculty of Physics, RO-077125, Măgurele-Bucharest, Romania
[*]Corresponding author email: *denis.stanca@nipne.ro*

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The Weak Ionization Lead Lepton Interaction for Air-shower Investigations in Romania (WILLI-AIR) experiment aims to investigate the secondary charged particles produced in the interactions of cosmic rays with atmosphere nuclei, focusing on the low energy region of the primary incident particles spectrum, up to 10^{15} eV.

With 24 field detector stations, forming the AIR array, and a 20 layers electromagnetic calorimeter, named WILLI, the experiment is focusing on determinations of the muon flux and the muon charge ratio measured only in Extensive Air Showers. Each field station uses two pieces of plastic scintillator as sensitive volume, read-out individually by one photo-multiplier. The experiment covers a 1600 m^2 area, being correlated with the energy range of the investigated primary particles. Combining the information from the AIR array and the WILLI determinations, the muon charge ratio in Extensive Air Showers is determined.

Key words: Muon flux, muon charge ratio.

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1. INTRODUCTION

The primary cosmic rays are important not only for the investigating of the interstellar and extragalactic medium, but also provide the possibility to investigate and test the hadronic interactions models at energies with several orders of magnitude greater than any existent on ground particle experiment.

The Earth's atmosphere is constantly bombarded by protons, helium and heavier nuclei, up to iron, with an integral intensity of around 1000 particles per square meter per second, the energy spectrum spreading over 11 orders of magnitude, scaling up to 10^{20} eV [1]. When the primary interaction occurs, the cosmic particles initiate the production of particles in cascading interactions, the phenomena being called Extensive Air Shower (EAS), with the resulted particles moving in the towards direction of the primary particle.

The backbone of the EAS is given by hadrons, most of them pions and K-ons, that disintegrates, feeding the muonic and the electromagnetic components.

When the secondary particles reach ground, the footprint of the EAS can be sampled and measured with different types of detectors, resulting several parameters of interest, like the number of charged particles, the number of muons, the center of the cascade, the arrival direction, the height where the number of particles was maximum, etc., from which we can deduct information regarding the primary cosmic ray, like mass or energy. Hybrid experiments were developed, like KASCADE - Grande, or Pierre Auger Observatory, measuring cosmic particles with energies up to 10^{20} eV.

Due to a small cross section interaction with matter and a long lifetime, the muons can penetrate the Earth, the most energetic ones being found in deep underground locations. This is the reason why knowing the muon flux is of extreme importance for deep underground facilities or for ultra low background experiments, like the experiments located in the ultra low background measurements laboratory from Slanic Prahova salt mine [2–6]. An important safety feature to be taken into consideration by the researchers working for underground experiments is the radon concentration [7], which tends to accumulate in non vented underground places, one important characteristic for Slanic Prahova salt mine being a very low value, smaller than 10 Bq/m^3.

Our experiment is aiming to measure the muon charge ratio using WILLI calorimeter, from individual Extensive Air Showers identified by AIR array, for primary cosmic rays with energies up to 10^{15} eV [8].

In order to distinguish between negative muons (μ^-) and positive muons (μ^+), the WILLI calorimeter is used, the detection principle being based on their different behavior when interacting with matter.

The positive and negative muons disintegrate according to Eq. (1) and Eq. (2):

$$\mu^- \rightarrow e^- + \bar{\nu_e} + \nu_\mu \tag{1}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu_\mu} \tag{2}$$

The negative muons can be captured by the atoms of the traversed matter and form a muonic atom. This bounding influences the μ^- lifetime. With a mass about 200 times larger than the electron, the corresponding Bohr radius is smaller and it will overlap with the nucleus wave functions. The lifetime is correlated to the atomic number of the host atom (see Table 1 for the lifetimes of μ^- and μ^+ when traversing different materials utilised in WILLI detector structures). One can observe that the mean lifetime for the μ^- after the atomic capture decreases, while for the μ^+ is constant.

Element	Atomic Number Z	Lifetime of μ^+ (μs)	Lifetime of μ^- (μs)
Free Decay	0	2.2	2.2
Carbon	6	2.2	2.0
Aluminium	13	2.2	0.88
Iron	26	2.2	0.22
Lead	82	2.2	0.08

Table 1.

The mean lifetimes for μ^+ and μ^- traversing different materials [9].

2. THE METHOD OF DELAYED COINCIDENCES

The negative muons are captured inside atoms by replacing one electron and thus forming muonic atoms. By comparing the different lifetimes of these excited atoms with the lifetime of positive muons it is possible to obtain the ratio between the positive and the negative muons. The mixed atmospheric flux contains both positive and negative muons. In the interaction with different materials inside the detector, the decay law contains a superposition of several decay laws [10]

$$\frac{dN}{dt} = N_+ c_0 \frac{1}{\tau_0} exp\left(-\frac{t}{\tau_0}\right) + N_+ \sum_{j=1}^{m} c_j \frac{1}{\tau_j} exp\left(-\frac{t}{\tau_j}\right) \tag{3}$$

where:

N_+, N_-	number of μ^+, μ^- interacting inside the detector.
m	number of materials in the detector.
c_0	detection efficiency for μ^+ in all materials.
c_j	detection efficiency for μ^- in material j.
τ_0	mean lifetime of μ^+ (2.197 μs).
τ_j	mean lifetime of μ^- in material j.

The mean lifetime τ_j is known from experimental measurements [9]. Another parameter of interest is c_0 and c_j and can be determined by Monte-Carlo simulations. These constants express the stopping power of different materials. The remain parameters N_+ and N_- are of interest. These two are expressed in the total muon number(Equation 4) and muon charge ratio(Equation 5).

$$N_0 = N_+ + N_- \tag{4}$$

$$N_0 = N_+ + N_- \tag{5}$$

By replacing Equation 4 and Equation 5 in Equation 6, we find:

$$\frac{dN}{dt} = \frac{N_0}{R+1}\left[Rc_0\frac{1}{\tau_0}exp\left(-\frac{t}{\tau_0}\right)+\sum_{j=1}^{m}c_j\frac{1}{\tau_j}exp\left(-\frac{t}{\tau_j}\right)\right] \tag{6}$$

This function is utilised for the data analysis. The results of the fit strongly depends on the calculus of the efficiencies c_0 and c_j.

3. THE APPARATUS

Weak Ionization Lead Lepton Interaction for Air-shower Investigations in Romania (WILLI-AIR) is a development of a previously implemented WILLI-EAS facility [11–14], the area covered by the experiment being doubled to 1600 m^2 by the addition of another 12 field stations.

Composed of WILLI calorimeter, previously operated in IFIN-HH, and the AIR array, the experiment aims to measure the muon charge ratio in Extensive Air Showers, an observable of great importance for hadronic interaction models. The WILLI-AIR geometry is schematically represented in the left part of Figure 1 [10]. 16 detection modules are stacked, one on top of each other, the first two, represented in green, being also used for triggering the data acquisition. An absorber (not represented in the Figure) made of 100 mm lead and 12 mm steel is placed on top of the detector. All the muons coming from the top, and that are not stopped by the absorber, will be measured. Each active layer contains a plastic scintillator of 900x900 mm^2, mounted inside an Aluminium box. The size of the walls thickness for this coverage is 10 mm, except the lid which is only 1 mm. The signal from the light is collected by four wave length shifter, two for each photomultiplier(EMI 9902 type) [10].

In the Figure 1 right side, the layout of the AIR array is outlined, as well as its placement relative to the WILLI detector. Each field station uses two pieces of plastic scintillator as sensitive volume, read-out individually by one photo-multiplier, placed inside an aluminium box for optical screening.

Due to the upgrade of the front-end electronics (FEE) [15] and of the digital acquisition system (DAQ) [16], all the particles that are interacting in the calorimeter can be recorded. The DAQ and the Front End Electronics (FEE) can easily go up to a trigger rate of 6 kHz.

Another characteristic of the DAQ is the adjustable time window for triggering that offers the possibility to record multiple signals in the same trigger window for each detection channel. This features of the DAQ is of great importance because muons that decay or are captured inside the detector's materials will generate a signal for the resulted electron, delayed with respect to the minimum ionizing phenomena corresponding to the triggering muon, but appearing in the same time window. This sequence of signals, a trigger signal followed by a delayed signal is refereed as a

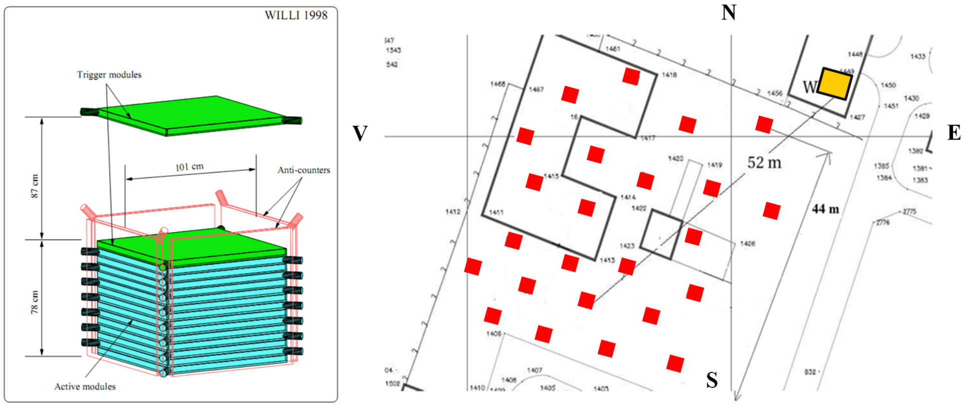

Fig. 1 – Left: the WILLI simplified geometry and right: the placement of the scintillator array relative to the WILLI detector.

multi-hit event, being referred to in the following chapter. A dead time of 5 ns between hits is estimated.

The final experiment, described initially as a theoretical approach in [8] and presented with the last development in [15], is focused on measuring the muon charge ratio of a single EAS. The experiment can emphasize the radial and azimuthal variation of the ratio between negative and positive muons inside the extended air shower. This study is possible using a spectrometer situated nearby a detector array to determinate the incident EAS. For this experiment in coincidence with the electromagnetic calorimeter, at a distance of proximately 50 m to the center of the mini-array is positioned. The mini-array consists of 24 detection stations. Each box contains two pieces of plastic scintillator of 0.5 m^2 surface and 40 mm thickness, each of them read-out by two photomultipliers. These detectors are re-utilised form the Kascade Grande experiment [17, 18].

4. MEASUREMENTS AND RESULTS

This paper presents preliminary measurements using the WILLI detector in coincidence with a scintillator array. The presented plots are obtained using the Root [19] and Go4 [20] software for data analysis.

The presented measurement is obtained for a mean zenith angle of 20° and a azimuth angle of 45°. By recording data using first two layers from the top in coincidence, a rate of about 75 muons per second per square meter is obtained. Also these plates are utilized to configure the trigger signal for the DAQ. The detector geometry utilized for measuring the muon flux can be seen in Figure 1 - left side.

The position of the a hit in one layer is reconstructed by subtracting the time

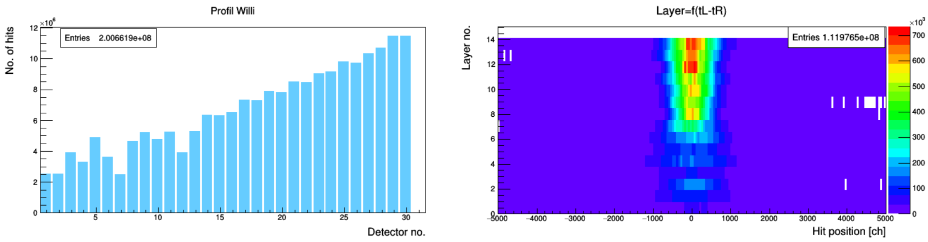

Fig. 2 – Left: the detector profile; Right: the hit position on each detection layer.

from the opposite corners($t_{(Left)} - t_{(Right)}$). There are 14 layers which are labeled from the bottom towards the top of the detector. The hit position on all detection channels is represented in Figure 2 - right side.

The profile of cosmic muons arrived in WILLI detector is represented in Figure 2 - left side.

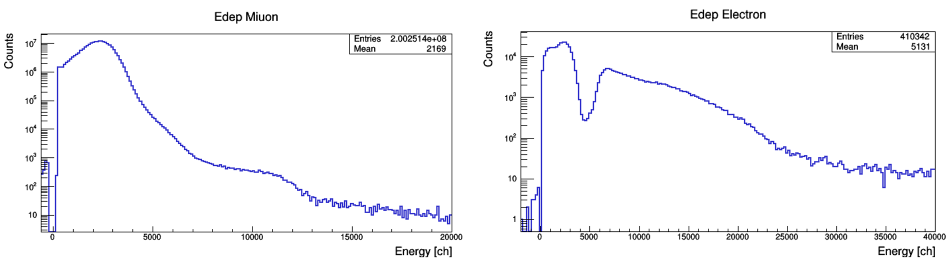

Fig. 3 – Energy deposited in all active channels of the detector by: left - muons and right - electrons resulted from muon decay inside the detector.

The energy deposited by muons in the detector can be seen in the left plot of Figure 3 and the energy deposited by the electrons is shown in the right plot.

The energy deposited by the muons in the WILLI detector is presented in the left part of Figure 3. The right plot of the figure shows the energy deposited in the detector by the electrons resulted from the muon decays that take place inside the layers of the detector. One can observe that the energy distribution of the electrons is no as clean as the one from the muons. The contamination is due to the selection done in the arrival time of the electrons, which in this case overlaps over a small interval with the arrival time of muons.

Figure 4 shows the arrival time of the charged particle in each detector channel for one hit per channel per event (left side) and two hits per channel per event (right side). The trigger window is set to 10 μs and the distance between the trigger and the start of the time window is 850 ns. We observe a peak followed by a tail after the main peak comes from the signal given by the electron that appears after the muon disintegration inside the detector material.

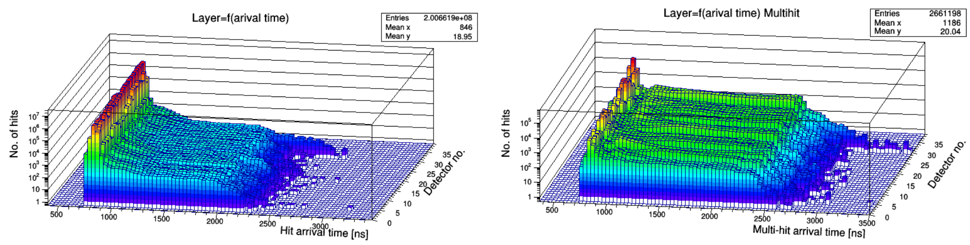

Fig. 4 – Arrival time in each detection channel for: left - one hit per channel per event and right - two hits per channel per event when WILLI is self triggered.

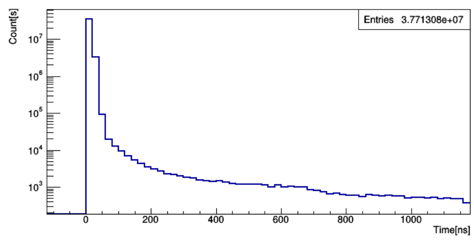

Fig. 5 – Arrival time in all the detector layers obtained by summing the one hit and two hits case.

The profile of the sum between the two histograms presented in Figure 4 depicting the arrival time of the charged particles in the case of one hit and two hits per channel per event, respectively, is plotted in Figure 5. From this type of histogram the muon charge ratio can be obtained.

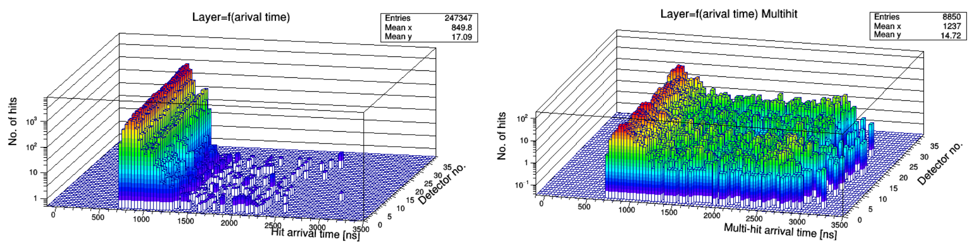

Fig. 6 – Arrival time in each detection channel obtained when WILLI is in coincidence with the scintillator array for: left - one hit per channel per event; right - two hits per channel per event.

The WILLI detector can be used in coincidence with the scintillator array mentioned above. The measured data from this coincidence has been analysed in a simmilar way at the data measured only with the WILLI detector. The results are presented in Figures 6 and 7. One can observe that the statistics is lower in this case due to the coincidence between the detector and the array.

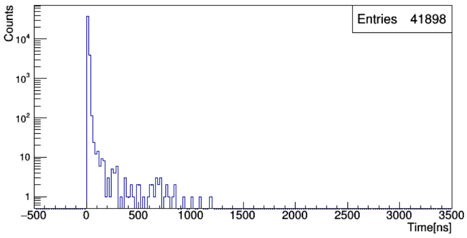

Fig. 7 – The total arrival time as a sum of one hit and two hits per channel per event cases given by the coincidence between WILLI and the scintillator array.

5. CONCLUSIONS

The WILLI-AIR experiment is developed to investigate charged particle resulted in the interaction in the external layers of the atmosphere of primary cosmic particles with nuclei. The experiment is focused on the charged particles that arrive at the ground level and produced by primary particles with initial energy up to the 10^{15}eV.

There are two main aspects regarding this work. The first one is providing measurements on low energy cosmic muons, in a certain region of the cosmic rays spectrum, where there is still more to be solved. Any kind of data are important for the scientific community and in our case it is a measurement waited for a long time. The muon charge ratio has been measured in the past decades by many experiments, but the correlation between the number of muons (positive and negative ones) inside an air shower, in the low energy range of the cosmic ray spectrum is still to be determined.

Second aspect of this work is focused on the hardware development. The process of testing many different scenarios and different schematics is time consuming but in the end delivers real solutions and real understanding of the detectors, front-end and DAQ systems. Further, this hardware can be extended to different experiments and measurements.

Using the set-up presented above we obtain a muon charge ratio of 1.35 ± 0.2 for a measurement using WILLI calorimeter in coincidence with scintillator array, utilising a multiplicity of two detectors. The current measurement is preliminary due to the low statistics. In a future publication we will have more events available and provide a better estimate.

Using the WILLI calorimeter in coincidence with any two detector stations of the scintillator array, muon measurements were performed. A value for the charge ratio is not possible at this point due to the low statistics. This can be improved by long time measurements, a minimum period of a few months being required for acceptable statistics.

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