Separation of cosmic-ray components in a single water Cherenkov detector

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Abstract

We describe the use of a water Cherenkov detector to study in detail the signals associated to secondary cosmic rays. In particular we describe a direct way to identify some of the components of secondary cosmic rays. It consists of a polyethylene tank of 1.54 m of diameter filled with water up to a height of 1.2 with one 8" phototube looking downwards in the center of the tank at the level of the water. By collecting data using three different types of triggers, namely, vertical non-central muons, vertical central muons and arbitrary muons, we show the existence of very strong correlations among the voltage amplitudes, charge depositions, and rise times from 10% to 90% for isolated electrons, isolated muons and extended air showers using a single detector. The simple technique described also allows a clear identification of the muon interaction with the PMT glass envelope. We discuss a way in which our results can be used, in conjunction with a classification scheme such as neural networks, to form artificial signals for extensive air showers with the purpose to estimate the muon/EM ratio of air showers measured with large ground arrays of water Cherenkov detectors such as in the case of the Pierre Auger Observatory.

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1. Introduction

The measurement of μ/EM, i.e., the muon contents relative to the electromagnetic component (electrons, positrons and photons), of extensive air showers is one of the requirements to perform a good measurement of the composition of primary cosmic rays by means of giant arrays of water Cherenkov detectors (WCD), such as the Pierre Auger Observatory [1]. Simulations show that extensive air showers (EAS) initiated by Fe nuclei have more muons at ground level than proton-initiated EASs for the same energy of the primary cosmic ray; in turn, gamma primaries produce even less muons. In the case of a hybrid cosmic-ray detector, such as the Pierre Auger Observatory, μ/EM and the EAS’s shower maximum are the main parameters for measuring composition of cosmic rays with energies around...
10^{20}\text{eV}, the first is measured by the fluorescence telescopes and the second with the Cherenkov detector array on the ground.

In this article we describe the existence of very strong correlations among PMT charge deposition, rise-time and amplitude for isolated electrons, isolated muons and extensive air showers in a water Cherenkov detector; we show how these correlations lead to a clean separation of these components by using simple cuts in bi-dimensional parameter spaces. The additional signal due to the interaction of muons with the PMT glass cover can also be easily separated from the other signatures using this technique. Identification of the traces of isolated electrons and muons permits one to form artificial traces for EAS by adding a pre-determined number of true electron and muon traces to form shower traces with known values of $\mu/\text{EM}$. These artificial signatures for EAS can in turn be used to train a neural network with the aim to use it to measure the $\mu/\text{EM}$ value of true showers.

2. Experimental setup

The WCD we used, see Fig. 1, was located in Morelia at 2000 m a.s.l. It consists of a cylindrical polyethylene tank with a diameter of 1.54 m and a height of 1.30 m filled with 2300 l of purified water up to a height of 1.2 m. The tank is optically sealed and has an inner liner bag made of tyvek which reflects light in a highly diffusive way. At the center of the tank there is an 8” PMT, model ETL9354, looking downwards at the top of the water. Fig. 1 also shows the schematics of the basic electronics and data acquisition system used to operate the detector. The events are selected in accordance to three different trigger requirements: (1) vertical non-central muons are selected as the coincidence of the hodoscopes positioned off-axis as shown in Fig. 1; (2) vertical central muons are selected in a similar way but this time the two hodoscopes are positioned along the central axis of the WCD and (3) arbitrary muons are selected by requiring the amplitude of the PMT signal to be above a 30 mV threshold.

The trace of a digital oscilloscope (Tektronix, TDS220) was read out through a GPIB port into a PC running a DAQ program written in LabView. The amplitude of the PMT signal was obtained from the voltage trace, and the current, i.e. voltage/(50\Omega), was integrated on-line to obtain precise measurements of the charge, rise time from 10% to 50%, and rise time from 10% to 90% for each event.

Fig. 1. Schematic diagram of the water Cherenkov detector and the data acquisition system. Inclusive events are selected according to three different trigger requirements: (1) vertical non-central muons are selected by the coincidence of the hodoscopes positioned off-axis as shown; (2) vertical central muons are selected in a similar way but with the two hodoscopes positioned on-axis of the cylindrical water tank; and (3) arbitrary muons are selected by requiring the amplitude of the detector PMT to be above a 30 mV threshold.
3. Results and discussion

Fig. 2 shows the amplitude vs. rise time from 10% to 90% taken with the experimental setup of Fig. 1 using the arbitrary muon trigger. We checked that the data taken with the vertical non-central muon trigger lies at the center of the region labeled as *Muons* in this figure. In order to validate our interpretation, we also checked that the events due to the additional interactions of muons with the PMT glass cover, labeled as *PMT Glass*, also occur in the data taken with the vertical central muon trigger but are absent in the data taken with the vertical non-central muon trigger; these events have a larger amplitude and charge but a shorter rise time due to the localized character of the Cherenkov light produced at the glass cover of the PMT. A dedicated setup to study this effect shows that indeed the Cherenkov signal produced at the PMT may be comparable in integrated PMT charge with the Cherenkov signal from the water [2]. The events labeled as *Electrons*, with rise times around 10 ns, include mostly knock-on and muon-decay electrons produced in the concrete ceiling and walls of our laboratory inside of which the setup was located: we checked that this component is significantly reduced for an identical setup located outside the building. The events labeled as *Muons*, with rise times around 45 ns, include vertical, inclined and corner clipping muons; they occur at a measured rate of around 870 Hz. For comparison, the events labeled as *Electrons* occur at a rate of 80 Hz. The events with charges above 7 vertical equivalent muons (VEM) have a measured rate of 1 Hz; their differential charge spectrum is well fitted by a power law with a spectral index of 3.0, i.e., in agreement with the spectral index of 2.7 for low-energy extensive air showers.

Fig. 3 shows the distribution of the integrated PMT charge for events taken with the setup of Fig. 1 using the arbitrary muon trigger (non-shaded curves) with a superimposed distribution for events taken with the vertical non-central muon trigger (shaded curve). The horizontal axis is in units of VEM, defined so that the peak for vertical non-central muons, measured to correspond to a charge of 107.5 pC, equals 1 VEM. From the previously measured gain of 1.45 pC per photo-electron for the PMT used [3], we know that 1 VEM is equal to 74 photoelectrons. The charge distribution for the curve labeled as *Electrons* in Fig. 3 has a MPV of around 0.14 VEM, i.e., in agreement with the charge distribution we have measured for muon-decay electrons using a similar setup [4]. This charge corresponds to around 10 photoelectrons.

Elsewhere [5] we describe the use of the real electron and muon traces from single WCD to

![Fig. 2. Amplitude vs. rise time from 10% to 90% for arbitrary muon triggers.](image)

![Fig. 3. PMT charge distribution for the arbitrary muon trigger events. The dashed-line data labeled as *Electrons* correspond to events with rise time 10–90% < 20 ns, while the solid-line data labeled as *Muons* correspond to events with rise time 10–90% > 20 ns, see Fig. 2. The shaded curve corresponds to vertical non-central muons. The horizontal scale has been chosen so that the MPV of the latter curve equals 1 VEM: it corresponds to 107.5 pC, or, equivalently, 74 photoelectrons.](image)
form artificial signals for extensive air showers with a known muon/EM ratio. These signals can in turn be used to estimate the muon contents of EAS by using neural networks [6], with the advantage of bypassing the process of a detailed simulation of the detector response to isolated electrons and muons.

4. Conclusions

We have used a single water Cherenkov detector to detect secondary cosmic-ray signals using three different experimental triggers: one for vertical central muons, one for vertical non-central muons and one for arbitrary muons. The signals were read out from a digital oscilloscope into a PC where their charge, amplitude and rise times from 10% to 90% were measured on-line in a precise way. It was shown that by plotting the amplitude vs. rise time, the events separate in a natural way into the following groups of signals associated to secondary cosmic rays: isolated electrons, isolated muons, and extensive air showers. This technique also allows a clear identification of the Cherenkov signal produced by the interaction of muons with the glass envelope of the PMT. Other bi-dimensional parametric spaces that produce good separation are charge vs. amplitude and amplitude vs. charge/amplitude. One application of the present work consists in the use of real muons and electron traces to form artificial EAS traces of known muon/EM ratio to train a neural network, or other classification scheme, in order to estimate the muon/EM ratio of real EAS.

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References