Spectrum of energy depositions in the Auger Water Cherenkoov Detector

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Abstract

The measured spectrum of energy depositions in a Water Cherenkov Detector (WCD) prototype for the Pierre Auger Observatory is presented. A WCD (area 10 m^2)is located in the Puebla University campus at a depth of 800 g/cm^2 (2200 m above sea level). Differential and integral spectra in a wide energy deposition range (0.5 - 150 of vertical equivalent muons) are presented. The problem of the WCD "self calibration" procedure (by rate of the muon events) is discussed. The characteristic change of the slopes of the differential spectrum at the transition from single muon signals to EAS signals is also discussed. The measured energy deposition spectrum at extreme signals is used to estimate the linearity of the response of the WCD PMTs.

Key words: Auger array, water Cherenkov detector, extensive air showers

1 Introduction:

In the Pierre Auger Observatory array for the study of the Extreme Energy Cosmic Rays, the water Cherenkov detector (WCD) is the basic extensive air shower (EAS) particle detector. The basic component of the WCD is a circular tank of diameter 3.6 m, filled with water to the height of 1.2 m. Three photomultiplier tubes (PMT's) each of diameter 20 cm observe the Cherenkov light generated in water by the fast EAS charged particles. The detailed description of WCD and the expected EAS signals in the WCD can be found in [1] (see Figure 1).

Given the large number of WCD's that will be deployed at the observatory site and the expected long time operation, the monitoring of all the WCD's is a serious problem. In previous large EAS arrays (Haverah Park, Yakutsk, AGASA) the monitoring of the particle detectors was performed in the analysis of the detector signal in its response to the commands from the registration center and in the analysis of the events selected by the detector "local" trigger (the EAS selecting system works in two stages: in the first stage every detector selects the signal not associated with EAS and in the second stage by comparison of signals from several detectors and the true EAS events are selected). The local trigger rate was used as an estimator of the detector operation in the Haverah Park and Yakutsk arrays. Modern technology of the detector controllers allows us to access more detailed information on the detector response to the local trigger. One may, for example, analyze the spectrum of energy depositions in the WCD and the distribution of widths of the signal. In principle, having

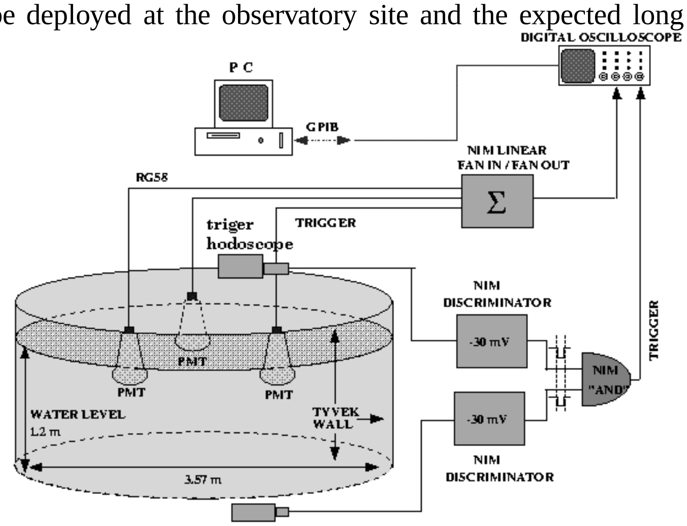

Figure 1: Schematical view of the WCD Prototype at Puebla operating to obtain VM.

this information for every PMT of the detector make it possible the full calibration of the detector signals in standard units for all array detectors. This "self-calibration" method demands that the full information on the performance of WCD in the events selected by the local trigger should be collected and analyzed.

With this aim, the Puebla University full size prototype WCD is being tested since several months ago. The results of measurements of the WCD energy deposition spectrum are presented here. The experimental results are discussed having in mind the expected spectrum caused by cosmic rays at the Puebla observation elevation of 2.2 km (the average atmospheric depth 800 g/cm^2). Notice that the Puebla elevation is close to the Northern Auger site elevation (870 g/cm^2). For an extrapolation aplicable to the Southern Auger site (950 g/cm^2), the Puebla average data should be corrected for the difference in elevation and the temporal variation of the atmospheric pressure.

2 Experimental results

The WCD is a radiator system which measures the energy deposition by the fast charge particles by the Cherenkov light generated in water.

The Cherenkov light signal is measured by the PMT either in number n of photoelectrons (p.e.) generated at the tube cathode or in charge C collected at the tube anode C = e n K (K is the PMT gain, e is the electron charge). Although the anode peak amplitude A (in volts) is a useful parameter related with the energy deposition by the particles, it is also sensitive to the temporal signal shape and in not the best measure of the energy deposition .

The single relativistic cosmic ray particles produce signals of duration of about 60 ns (FWHM $\sim 25ns$) determined by the time of photons collection in the tank and the cable extension (1 p.e. signal duration of the Hamamatsu tube R-5912 is 8 ns FWHM).

Spread in time of EAS signals varies with the core distance R and could be as long as 5 μs at R $>$ 2 km. In the Auger array, the footprint is about 10-20 μs ,and the time bin is 20 ns, therefore the time dynamic range is wide. The amplitude of the signal could change in a dynamic range of 17 bits [1].

In this WCD prototype, the signals are recorded by the Tektronix digital oscilloscope connected to the computer. The recording of the oscilloscope traces by the computer is a relatively slow proccess (two per second).

At signal threshold corresponding to the rate of less than 2.0 kHz the signals were selected by the peak amplitudes in the oscilloscope. The signal traces were integrated in the computer (the noise level was taken from the part of the oscilloscope trace before the signal) and the integrated charge of the signal was recorded in order to build the energy deposition distribution. The Figure 2 shows the differential and integral spectra of the WCD energy depositions started from 0.5 Vertical Equivalent Muon (VEM). We compare both spectra with the produced by the heigth signal spectrum, (Figure 3) In the spectrum, several characteristic regions could be clearly identified [5] ,[6].

1. The first one is the region of the single cosmic ray particle rate. It is dominated by passages of relativistic muons. As geometry of the muon passages varies, the muon signals are spread in a wide range of charges. The smallest signals are from "clipping" muons crossing only part of the available water. Muons with the longest "diagonal" passages produce the largest signals. The standard path of a "vertical muon" is selected by the scintillation detector telescope (two scintillation pads above and under the water tank). The signal in units of VEM's, indicated in the Fig. 2 and 3 by an arrow, is the reference signal. It will be used as the unit of the energy deposition in every WCD of the Auger array (it shows that WCD produced around 100 pe) .

2. The second one is the region of the rate associated for some authors with secondary showers produced in water by cosmic ray muons and hadrons. As a large amount of matter in the water tank (to compare with the thin matter layers in the scintillation detectors of the Yakutsk and AGASA arrays) it makes the

2nd region in WCD more pronounced than in the scintillation detectors. Secondary shower region takes the intermediate position between pure muon signals and the EAS signals region.

3. The 3th region of the spectrum correspond to the rate of EAS energy depositions. The EAS energy deposition is a sum of energy depositions from all EAS components: electromagnetic component (in water photons are converted to electrons), hadrons (producing secondary showers in water) and muons. The expected spectrum of EAS energy deposition and the probability to find the EAS core at distances ¿ R to a given deposition, could be calculated using the experimentally known lateral distribution function (LDF) of the EAS energy depositions (in VEM per m2 , Haverah Park data, [2]). For all particle primary spectrum [3] the expected yield of EAS events with core distances $R >$(normalized to unity) is presented in Fig 4. In those calculations the approximation formula [2] for the LDF was extrapolated from R $>$50 m down to small distances R=3 m. It should be noted that LDF's of energy depositions in scintillation detectors (Yakutsk, AGASA) and in WCD are similar at distances R $>$ 100 m. They differ in absolute values (due to the different amount of matter in the detectors). At distances R $<$ 100 m the WCD LDF is steeper due to larger depositions from the hadron component. Due to this difference the effective core distances for a given WCD energy deposition are smaller (R=3- 30 m) to compare with distances R=10-100 m for the given scintillation detector energy deposition.

   The expected percentage of events with large core distances R $>$1km- to be selected by the Auger final trigger (coincidence of signals in the several WCD separated by distance L=1.5 km)- in events with a given energy deposition is extremely small. In EAS events it is of about 0.001 (Fig 4) and even less for all WCD events. In the 1st stage of the WCD triggering a high rate of useless signals should be recorded to select the useful Auger array events ($>$ 1-3 VEM per 10 m^2). For 1 VEM threshold, this rate is 1.37 kHz, for 3 VEM threshold, it is 100 Hz and for 5.3 VEM threshold, it is 20Hz. In analysis of the signal duration (see our second paper [4]) a strong cut off of the useless signals could be achieved [6].

The dependence of signal rate on the array altitude (average depth in atmosphere) and on the atmospheric pressure is different in various energy deposition spectrum regions. In the region of signals from single muons and hadrons the rate changes with atmospheric pressure by 2% per cmHg. In the EAS signal region it changes by 10% per cmHg. Using the appropriate dependence on the atmospheric pressure the corrections of the WCD rate at various array elevations and for various atmospheric pressure were calculated. It was found that the energy deposition spectrum in the range of C=1-5 VEM at elevations of 800-1000 g/cm2 does not varies much.

The shape of energy deposition spectrum in the range of C $>$10 VEM is determined by the expected EAS "energy deposition density spectrum" that could be approximated by the power law with the exponent η close to the exponent γ of the primary energy spectrum ($\eta = \gamma/b$) where b~ 0.9 is the exponent in the dependence C $\propto E^b$ of the effective energy deposition C on the primary energy E). The exponent of the "density spectrum" slowly increases with the WCD energy deposition (much slower than the primary energy spectrum exponent changes in the "knee" region). In the WCD range of C = 10 - 150 VEM the exponent η is expected to be equal to 2.0. The fit of the energy deposition spectrum to the power law at the largest possible energy depositions is a good "self-experimental" test of the linearity of the PMT response to the largest WCD light signals. In the longest run of the Puebla WCD (200 hours) with the threshold 20 VEM the differential spectrum agrees with the power law of the exponent $\eta + 1 = 3.0$ at signals as large as 150 VEM.

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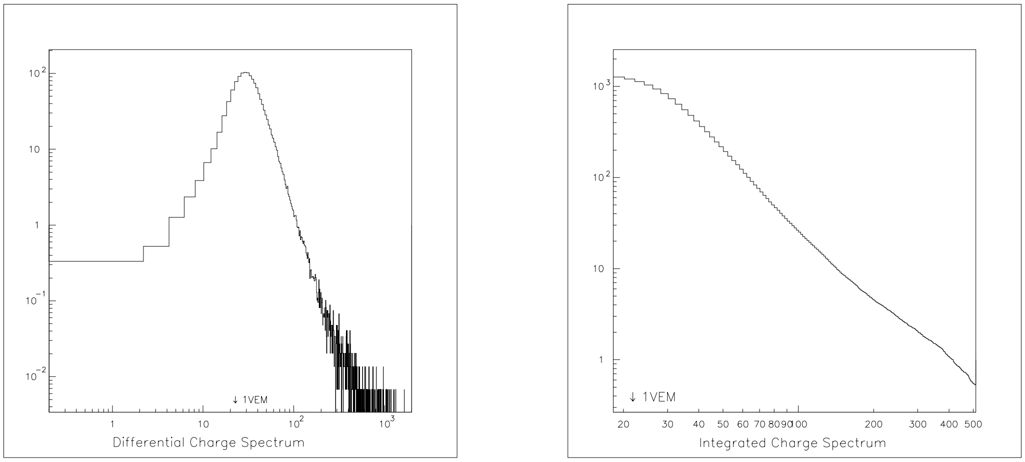

Figure 2: Differential Charge spectrum (rigth), Integrated charge spectrum (left)

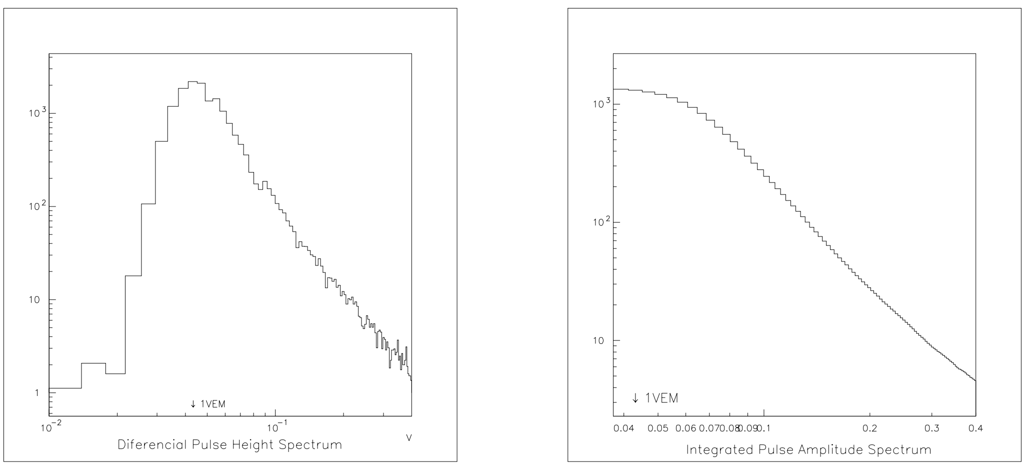

Figure 3: Differential (left) and integral (rigth) pulse amplitude spectrum

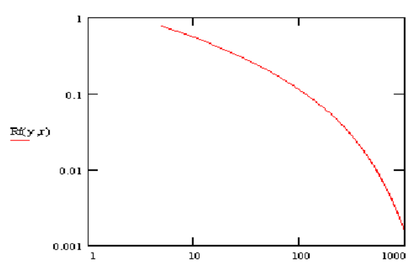

Figure 4: Probability to find the EAS at core distances larger than r