THE VATLY CHERENKOV DETECTOR AND ITS RESPONSE TO ELECTRONS AND MUONS

N.T.THAO on behalf of the VATLY team

Institute for Nuclear Science and Technology, 179 Hoang Quoc Viet, Cau Giay, Hanoi
Email: thao@mail.vaec.gov.vn

Abstract. Measurements are presented and commented that describe the response to low signals of the VATLY Cherenkov detector, a replica of one of the 1660 identical detectors used in the ground array of the Pierre Auger Observatory.

Key words: *Cosmic ray*

1. INTRODUCTION

The Pierre Auger Observatory (PAO) is a hybrid detector dedicated to the study of ultra high energy cosmic rays (UHECR). It covers 3'000 km^2 in the Argentinean Pampas where showers are detected from the fluorescence they produce in the atmosphere and by their impact on a ground detector array. It is the largest cosmic ray observatory in the world and has already given two important contributions to UHECR physics: evidence for the GZK cut-off (photoproduction on the cosmic microwave background) and evidence for a positive correlation of the highest energy UHECRs with AGN's in the nearby Universe. Its ground array includes 1660 Cherenkov detectors. The VATLY Cherenkov detector, referred to below as the main tank, is a replica of one of these. It was constructed in Hanoi and assembled on the roof of the VATLY Laboratory (Figure 1), surrounded by three smaller detectors used to provide a biasfree shower trigger [1]. It is a stainless steel cylinder of 3.6 m diameter (about 10 m^2 in area) filled with clean water up to 1.2 m high. The water volume is seen by three down-looking 9" PMTs at 120^o azimuthal intervals on a radius of 1.25 m. Because of the lesser water purity and light reflectivity of the walls, the number of photo-electrons is ~2.3 times less than in the PAO. The front end preamplification of the PMT signals and the HV supplies and dividers use the same electronics as in the PAO but the data acquisition system differs: it is based on the NIM standard for the fast trigger logic and on CAMAC for the data recording, with simple Analogue-to-digital (ADC) and Time-to-digital converters (TDC) rather than Flash ADCs as used in the PAO.

2. RESPONSE TO FEED-THROUGH MUONS: VEM CALIBRATION

The calibration of the response of the VATLY Cherenkov detector uses as reference vertical feed-through muons impacting in the central part of the tank. One speaks of Vertical Equivalent Muons (VEM) which are taken as units in all PAO measurements [2]. As atmospheric muons have momenta ~2 GeV/c, most of them are relativistic and therefore minimum ionizing: they deposit ~2 MeV per centimetre of water irrespective of their momentum. We have designed and constructed a scintillator hodoscope [3] bracketing the VATLY Cherenkov detector from above and below (Figure 1) to provide a trigger on such relativistic feed-through muons. The requirement of a coincidence between the upper and lower scintillators guarantees that the muon has fed through the Cherenkov tank, the laboratory roof and the lower scintillators. The hodoscope is found to provide a very stable trigger with a narrow time of flight distribution and scintillator signals well described by

Landau distributions allowing for an easy selection of relativistic vertical muons [3]. The associated Cherenkov signal is displayed in Figure 2. The value of the relative width of the charge distribution is 22.5%. We obtained this way a calibration of the charge measurement, 1 VEM corresponding to 414±10 raw ADC counts.

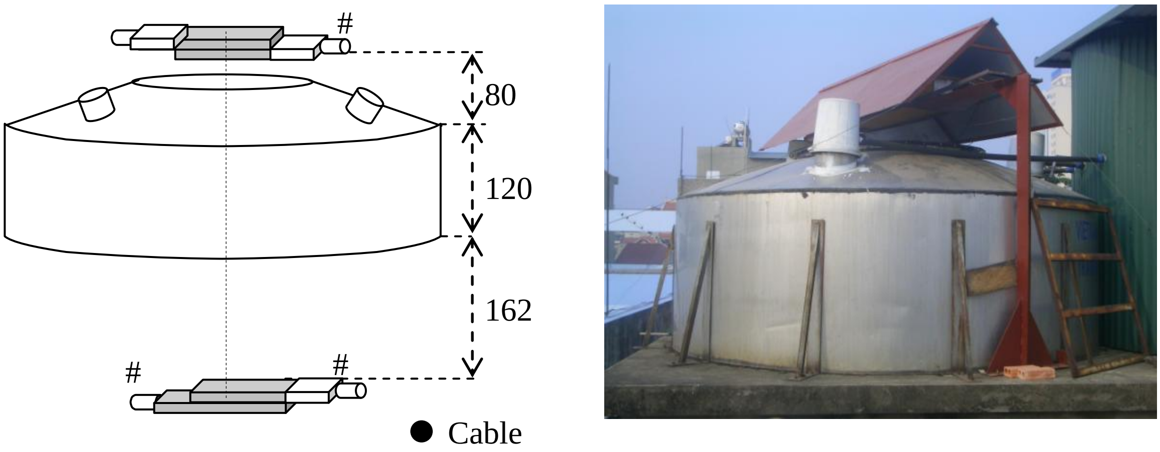

Figure 1. *The VATLY Cherenkov detector and the trigger hodoscope bracketing it from above and below.*

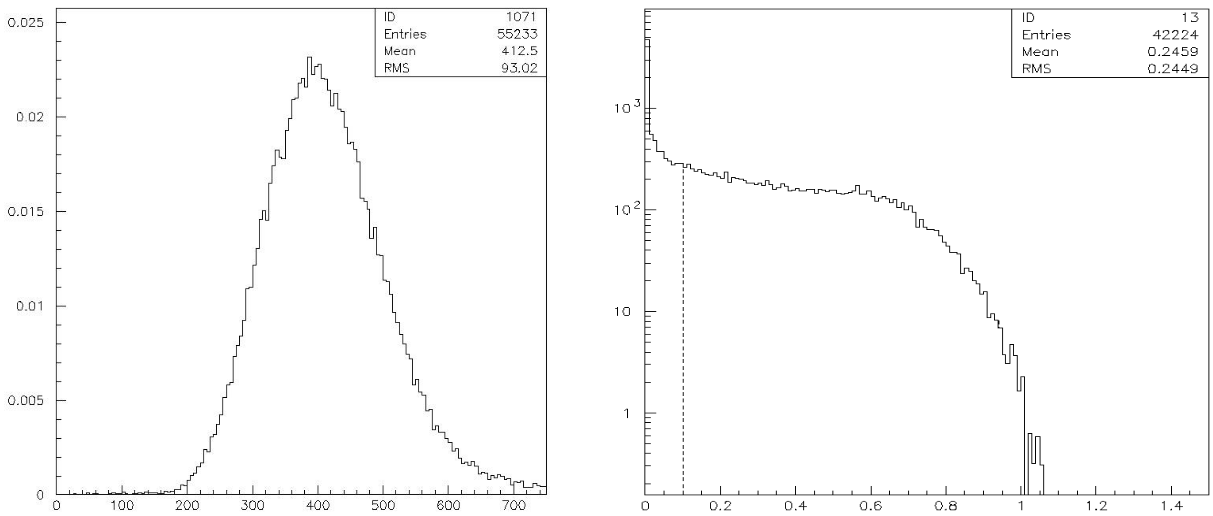

Figure 2. *Right panel: Cherenkov charge distribution associated with relativistic vertical muons (VEM). Left panel: Distribution of the number of Cherenkov photons radiated by muons stopping in the tank as a function of VEM.*

3. MUON DECAYS IN THE VATLY CHERENKOV DETECTOR

A muon having low enough a kinetic energy may stop in the water tank. The number of Cherenkov photons emitted per cm track length before stopping decreases together with the kinetic energy and cancels ~10 cm before stopping. This mechanism is at variance with that at play in a scintillator where ionization losses increase when the energy decreases (Bragg curve), making the Cherenkov detection of stopping muons difficult. We have simulated the process by requiring that the muon stops more than 10 cm away from the tank walls with the bulk of the electron shower covering some 20 cm (half a radiation length). The mean electron signal [4] was taken to be around 0.12 VEM and the cosmic muon flux in Hanoi was taken from earlier measurements of ours [5]. We find that we should expect a maximal rate of detected decay electrons of ~0.46 Hz, of which ~70% should have a detectable muon signal.

In practice, it is reasonable to expect that half of these can be detected. Figure 2 (right) displays the expected distribution of the number of photons radiated by stopping muon. The spike at zero corresponds to stopping muons below Cherenkov threshold. Signals larger than 0.1 VEM make up 33.6% of the stopping muons. Their mean value is 0.4 VEM and their mean track length is 85 cm.

4. AUTOCORRELATION MEASUMENTS: TIME DISTRIBUTIONS

An autocorrelation measures the time delay between two successive pulses produced by a same detector. In the present case we use pulses given by a coincidence of two of the PMTs of the main tank. An autocorrelation may result from three main sources: either a decay electron from a stopping muon having produced the first pulse, or the detection of a second muon from the same shower as that which produced the first pulse, or the detection of a second muon from a different shower than that which produced the first pulse. In practice, the second pulse must occur within 10 μs from the first in order to be detected. As the muon rate is ~1kHz, the probability of having a second pulse in such a narrow window is small, ~1%. To an excellent approximation, we may therefore assume that the first pulse is either followed by zero or one pulse, but never two, in the 10 μs window. The autocorrelation time distribution is therefore expected to be the sum of three terms. Muon decays contribute differently for positive and negative muons because the latter may be captured while the former may not. They are known to be in a 55%/45% ratio [6]. The effective decay rates are 2.2 μs for the former and 1.8 μs for the latter [7]. The contribution of muons from different showers is an exponential with a decay time equal to the reciprocal of the muon rate. The contribution of muons from a same shower depends on the time structure of the shower front. Here we approximate it by an exponential having amplitude g_0 and decay time t_g to be adjusted from the data.

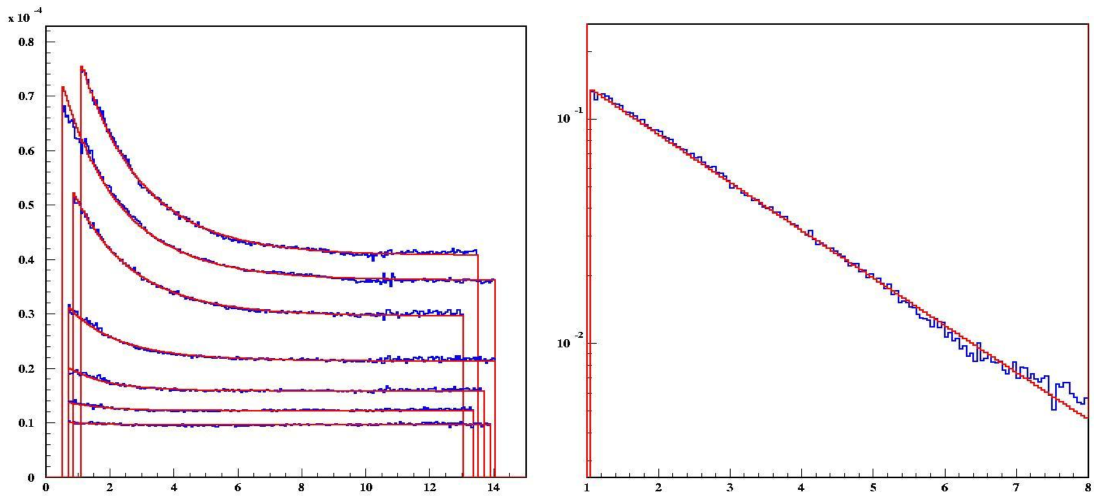

Figure 4. *Right panel:. Autocorrelation time distributions measured for different δ and threshold values (blue) together with the best fit results (red). Left panel: Global fit of the muon decay distribution (data in blue, model in red).*

The measuring electronics [3] was arranged to deal exclusively with events where two successive pulses occur in a same 10 μs window, in order not to overload the system with useless single pulses. An adjustable delay δ defines the sliding time window as [δ, δ+10 μs] after the first pulse. A time to digital converter was used to measure the time delay between the two pulses and a multichannel analyzer to display its distribution. Autocorrelation spectra were collected for different values of δ and of the discriminator threshold used to produce the Cherenkov coincidence pulse.

The results of the best fit to a sum of three exponentials are illustrated in Figure 4. They give a muon detection efficiency of 38±3% at threshold 2.5 and of 13±2% at 3. The χ^2 value is 1.020 per degree of freedom (of which there are 118'185), providing evidence for the quality of the fit and for negligible systematic errors. The ratio between measurements and model has a Gaussian distribution having a σ of 5.3 %. Figure 5 displays the dependence on threshold of the electron detection efficiency, φ. As expected, the sensitivity to electron detection drops to zero when the threshold reaches its higher values. The best fit value of parameter g_0 is $(0.79\pm0.05)\times10^{-5}$ for a decline time t_g of 1.13±0.04 μs in good agreement with an earlier measurement of the lateral distribution function [1]; in practice its effect can be neglected.

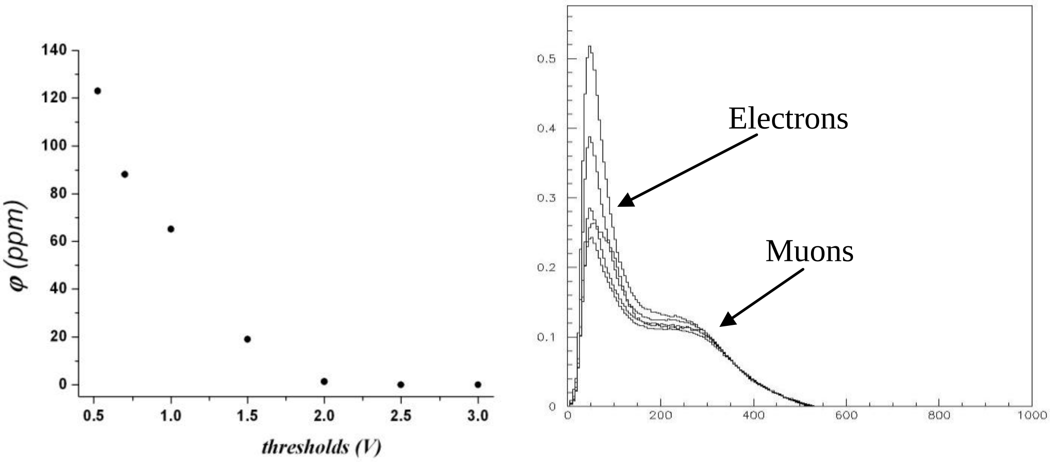

Figure 5. *Left panel: Dependence of φ on threshold. Right panel: a typical set of charge distributions obtained for a same threshold and different values of δ.*

5. AUTOCORRELATION MEASUREMENTS: CHARGE DISTRIBUTIONS

The charge distribution of the second signal of each auto correlated pair was recorded in analog to digital converters. The charge scale was adjusted using the VEM calibration and small threshold variations were corrected for. Consistency with the recorded measuring time was found to be good and taken in due account. A typical set of charge distributions obtained for a same threshold and different values of δ is displayed in Figure 5 (right). Such a set allows for separating the distribution associated with decay electrons from that associated with muons by subtracting from each other two distributions obtained with different values of δ at a same threshold. In particular, at large threshold values, or at large δ values, the electron contribution is negligible and the muon contribution can be readily obtained. The resulting electron and muon charge distributions are displayed in Figure 6.

6. SUMMARY AND CONCLUSION

We have presented measurements of the response of the VATLY Cherenkov tank, a replica of the detectors used in the PAO ground array, to electrons and muons. Relativistic feed-through muons have been used to calibrate the charge scale. Autocorrelation time and charge measurements have allowed for disentangling a number of important informations related to the performance of the detector:

– Excellent agreement has been found with the known decay and capture parameters of muons in water;
– The contribution of muon pairs from a same shower has been measured and found negligible in agreement with the lateral distribution function measured earlier [].
– The dependence on threshold of the electron detection efficiency has been measured with good precision.
– The electron and muon charge distributions have been separately measured.

These results provide a useful contribution to the understanding of the PAO detectors, in particular in the domain of low charges.

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