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Response of the Pierre Auger Observatory Water Cherenkov Detectors to Muons

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Two test detectors similar to the Pierre Auger Observatory Water Cherenkov Detectors have been installed at the Observatory site and at the Institut de Physique Nucléaire d'Orsay. The signals from the tanks are read out using three 9" photomultipliers and analyzed by both a digital oscilloscope with high sampling frequency and the Auger surface detector electronics. Additionally, the detectors are equipped with plastic scintillators serving as muon telescopes. The trigger is provided either by the muon telescope or by the coincidence of the three PMTs. The scintillators are movable allowing the study of the detector response to atmospheric muons arriving with different incident angles. In this paper, the results of measurements for vertical and inclined background muons are presented. These results are compared to simulations and important calibration parameters are extracted. The influence of the direct light detected by the PMTs, particularly important for inclined showers, is discussed.

1. Introduction

The Pierre Auger Observatory Surface array samples the shower particles at the ground level by Water Cherenkov Detectors (WCDs) having a 1.5 km spacing between each other and covering an area of 3000 km^2 [1]. The shower particles at the ground level are mainly gammas, electrons and muons with mean energies below 10 MeV for gammas and electrons and about 1 GeV for muons. When impinging the WCD, electrons and muons emit Cherenkov radiation which is propagated in the purified water and uniformly reflected by the Tyvek® liner. The gamma rays are converted by Compton scattering and pair production into relativistic electrons emitting similarly Cherenkov radiation. This Cherenkov light is detected by three 9" XP1805 Photonis photomultiplier tubes (PMTs) viewing the WCD from the top. The PMTs are equipped with a resistive base having two outputs: anode and amplified last dynode. This allows a large dynamic range, total of 15 bits, extending from a few to about 10^5 photoelectrons. The high voltage is provided locally by a custom made ETL low power consumption module. The nominal operating gain of the PMTs is 2×10^5. The signals from anode and dynode are filtered with a 5 pole anti-aliasing filter with a cut-off at 20 MHz, and digitized at 40 MHz using 10 bit Flash Analog-to-Digital Converters (FADC) [2].

The WCD response to single muons is an important feature of the Surface Detector array (SD array). Several test detectors to study this response have been installed. The current paper reports on recent results obtained by the IPN-Orsay (IPNO) test detector at the Institut de Physique Nucléaire - Orsay (France) and a test detector called CAPISA at the Pierre Auger Observatory Campus (Malargüe - Argentine). Both test detectors are Water Cherenkov Detectors with the same design and similar equipment used for the Auger Surface Array. In addition, they are equipped with two movable scintillators, one above and the other under the water tank allowing to trigger on passing muons. The CAPISA detector is equipped with the Pierre Auger SD electronics while a digital oscilloscope with high sampling frequency (1 GHz) is used for the IPNO data acquisition. The trigger for both test setups is provided either by a coincidence between the two scintillators or by a three fold

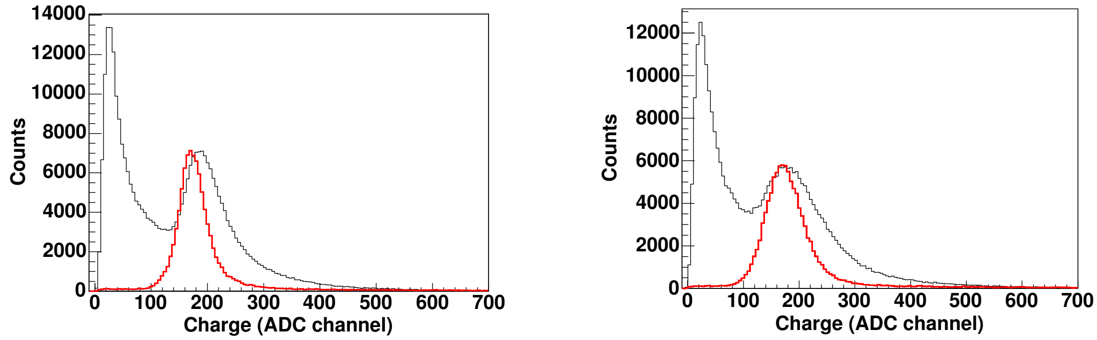

Figure 1. The muon charge histogram triggered by the scintillators for the Q_{VEM} and by the coincidence of the 3 PMTs for the Q^{peak}_{VEM}. In the left for the sum of the 3 PMTs, and in the right for a single PMT.

coincidence between the three PMTs. For both test detectors an absolute calibration was performed by using the single photoelectron response. The results of the measurements are compared to simulations performed by GEANT4.

2. Response to Vertical Muons

In the WCD, the electrons and gammas are completely converted while vertical muons deposit approximately 240 MeV of energy. For the detector calibration, the chosen unit is the total charge deposited by the vertical muons crossing the center of the tank (VEM) [3]. In the calibration process the determination of the VEM unit is done by using background muons acquired in the 3-fold coincidence between the PMTs, which produce a peak in the charge histogram (Q^{peak}_{VEM}). The conversion between the Q^{peak}_{VEM} and the charge corresponding to vertical muons Q_{VEM}, triggered with the muon telescope, is crucial.

The number of detected photoelectrons (pe) depends on several parameters: water quality and transparency, liner diffusion coefficient, PMT response, optical coupling of the PMTs to the liner window, etc. The mean value obtained for the SD array PMTs is about 90 pe with RMS of about 20 pe corresponding to the charge deposited by muons in 3-fold coincidence (Q^{peak}_{VEM}). The measured photoelectron value for the IPNO detector is about 70 while for CAPISA it is about 95. The IPNO test tank has a slightly poorer water quality which can explain the difference. Although the number of photoelectrons measured for the IPNO detector is relatively low, the detector still is representative of the Auger WCDs. The decay time of the muon average pulse shape is about 50 ns for the IPNO detector and about 64 ns for CAPISA. Typical values for Auger WCDs varies from 60 to 80 ns. The decay times of the CAPISA and IPNO test detectors correspond to decay lengths of about 25 m and 17 m, respectively. The ratio between the total charge (Q^{peak}) and the maximum amplitude value (I^{peak}) of the muon signals is directly proportional to the signal decay time and is therefore a useful parameter for the detector quality monitoring [4]. This ratio is about 3.5 for the SD array detectors. For the CAPISA and IPNO test detectors the value is about 3.4 and 2.8, respectively.

An important parameter entering directly into the calibration is the difference between the detector response to vertical muons (Q_{VEM}) and to the muons triggered by a coincidence between the three PMTs (Q^{peak}_{VEM}) and thus entering the tank from arbitrary directions. In figure 1 the histograms of the total charge for the Q_{VEM} and the Q^{peak}_{VEM} are plotted for the sum of the 3 PMTs in the left and for a single PMT in the right for the CAPISA detector. The Q^{peak}_{VEM} is systematically $\sim 9\%$ higher than the vertical muon response Q_{VEM} for the sum of the

Table 1. Comparison between experimental data and GEANT4 simulations.

	Experiment	Simulation
IPNO Q_{VEM}/I_{VEM}	2.8	2.8
CAPISA Q_{VEM}/I_{VEM}	3.4	3.5
IPNO $Q_{VEM}^{peak}/I_{VEM}^{peak}$	2.6	2.6
CAPISA $Q_{VEM}^{peak}/I_{VEM}^{peak}$	3.5	3.2
IPNO Q_{VEM}^{peak}/Q_{VEM}	1.09	1.08
CAPISA Q_{VEM}^{peak}/Q_{VEM}	1.09	1.08
IPNO Q_{VEM} photoelectrons	70	40
CAPISA Q_{VEM} photoelectrons	95	60

3 PMTs. Similarly, the individual PMT response to muons is $\sim 5\%$, lower than the sum of the three PMTs. This simply reflects the fact that the sensitivity to crossing muons impinging on the tank in different position is greater with the three PMTs than with only one which can only collect a portion of the total Cherenkov light deposited.

Simulations were performed by using the GEANT4 package. A quantum efficiency of about 25 percent maximum and a collection efficiency of 60% are used for the PMTs. The decay length of the muon signal is adjusted to the experimental decay time of the average pulse shape to take into account the detector water quality. Table 1 summarizes the different results. The ratios obtained between the Q_{VEM} and Q_{VEM}^{peak} are well reproduced by the simulations. However, the number of photoelectrons obtained by the simulation is smaller than the number measured experimentally. This can be due to several effects such as the quantum efficiency and the collection efficiency of the PMTs and the optical coupling of the PMTs to the liner window. Further measurements of the PMT response have been undertaken to understand the differences in the photoelectron yield.

3. Response to inclined muons

The Pierre Auger Surface Detector is capable of detecting shower particles also from very inclined showers. This is an important feature increasing the geometrical aperture and yielding sensitivity to detect neutrino induced showers [5]. In the case of inclined muons the probability that the PMTs detect direct Cherenkov light increases. Furthermore, the photocathode efficiency can be different as a function of arrival angle of the induced light. The response of the WCD to inclined muons have been studied at the IPNO test detector. Two scintillators were placed on the side of the tank triggering on muons arriving with different angles and with different vertical positions into the water tank. Measurements were performed for different angles varying from 20° to 70° zenith angles. The charge deposited by the muons was calculated for each PMTs and the muon track length was estimated from the position of the scintillators. In the case of direct light, the measured charge versus track length would deviate from linear correlation. Figure 2 shows the results of the measurements.

As a function of the increasing zenith angle large differences are observed between the PMTs. The PMT close to the arrival direction will collect more light than those further away. Individual PMTs will therefore significantly deviate from the linear behavior charge versus muon track length. However, the sum of the charge measured by the 3 PMTs has a linear behavior up to 60°. Similar results has been obtained by using a prototype detector placed at Tandar Laboratory in Buenos Aires [6]. For inclined showers it is therefore crucial to sum the light measured by all 3 PMTs to ensure a correct response of the detector. At 70° a clear deviation of the linear behaviour is observed also for the sum of the three PMTs. This can indicate the presence of direct light

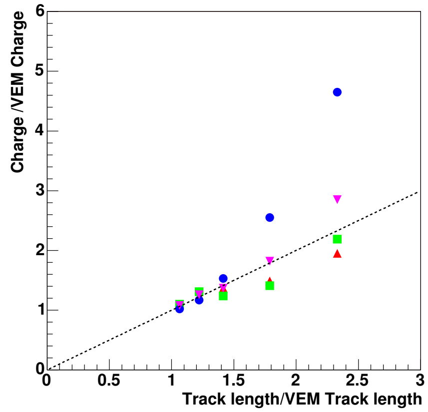

Figure 2. The points show for 5 different angles (20°, 35°, 45°, 56° and 70°) the charge measured in the 3 PMTs (triangle up, square, circle) as well as the total charge on the sum of the PMTs (triangle down), with respect to the track length in the tank. All quantities are normalize to the VEM corresponding values for comparison.

yielding a different response of the PMTs and the associated electronics. Further measurements at even larges zenith angles are currently being performed.

4. Conclusions

The response of the Pierre Auger Observatory Water Cherenkov Detectors to muons has been studied by using test detectors installed at the Observatory site and at the Institut de Physique Nucléaire d'Orsay. The results obtained on the charge deposited by vertical muons and by 3-fold coincident muons are in agreement with detector simulations performed by GEANT4. It is shown that in the case of inclined showers the detector response is linear up to 60° if the sum of the three PMTs is used. At angles larger than 60° direct light induces a deviation from the linear response that needs to be taken into account in the reconstruction of horizontal showers. Further measurements and simulations are in progress to model the detector response at large angles.

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