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IceTop tank response to muons

L. DEMIRÖRS[3], M. BEIMFORDE[1], J. EISCH[2], J. MADSEN[4], P. NIESSEN[3], G. M. SPICZAK[4], S. STOYANOV[3], S. TILAV[3] FOR THE ICECUBE COLLABORATION[5]

[1]*Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany*
[2]*Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA*
[3]*Bartol Research Inst., Dept. of Physics & Astronomy, University of Delaware, Newark, DE 19716, USA*
[4]*Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA*
[5]*see special section of these proceedings*
levent@udel.edu

Abstract: Each digital optical module (DOM) of the IceTop air shower array is calibrated by identifying and understanding its muon response, which is measured in vertical equivalent muon (VEM). Special calibration runs and austral season measurements with a tagging telescope provide the basis for determining the VEM and monitoring its variation with time and temperature. We also study muons that stop and decay in the tank. The energy spectrum of the electrons from muon decay is well known (Michel spectrum) and can also be used as a calibration tool. Both spectra are compared to a GEANT4 based Monte Carlo simulation to gain a better understanding of the tank properties.

Introduction

IceTop is an air shower array of ice–Cherenkov counters [1, 2]. Each of its current 26 stations is made up of two IceTop tanks. The tank shell is black, cross–linked polyethelyne, 6 mm thick, 1.1 m high, and 1.9 m in diameter. A second layer of 4 mm thickness, made out of zirconium fused polyethylene, is molded on the inner surface to act as a diffusely reflective liner (eight tanks deployed in 2005 have Tyvek linings). Each tank is filled with 90 cm of frozen water and then covered with 47 g/cm^2 of perlite to provide insulation and a barrier to light leaks around the fitted wooden tank cover.

The tank ice is viewed by two standard IceCube digital optical modules (DOMs). They consist of a 10" Hamamatsu R7081–02 photo multiplier tube (PMT) and processing and readout electronics. Two different types of digitizers are used to process the PMT signal: a fast pipelined ADC (FADC) with 255 samples of 25 ns each, and two Analog Transient Wave Digitizer (ATWD) chips, with three channels of up to 128 samples of about 3.6 ns each. The three channels are configured with different pre–amplification factors to extend the DOM's dynamic range (for details, cf. [3]).

IceTop setup for calibration runs

Periodic special IceTop calibration runs are carried out to serve two purposes: one, to calibrate the conversion from integrated waveform to vertical equivalent muon (VEM) for each DOM in a tank, and two, to monitor the DOMs response's time dependence.

The calibration run configuration differs from the regular one used for air shower data runs. In this so–called singles mode, the local coincidence between DOMs and the simple majority trigger are disabled. All DOMs are set to the same nominal gain of $5 \cdot 10^6$, while in the air shower mode, the two DOMs in the same tank are set to different gains (in 2006, $5 \cdot 10^6$ and $5 \cdot 10^4$, resp.) to extend the dynamic range of a tank. For the DOMs that are operated at the lower gain, the VEM might differ due to changes in the collection efficiency of the PMT. Currently, that effect is not taken into account.

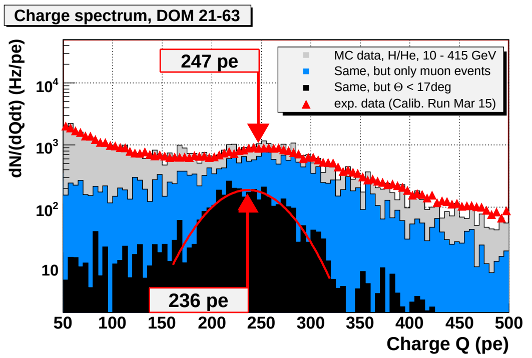

Figure 1: MC simulated charge spectrum for DOM 21–63. See text for further explanations.

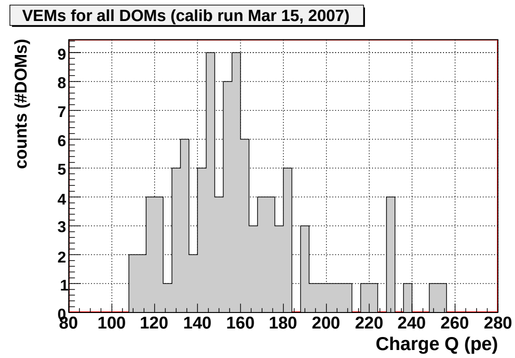

Figure 2: Distribution of VEMs for all DOMs.

The data files are analyzed with an IceTop specific waveform processing module written for the official offline software suite. Each raw waveform, given in ATWD channel counts, is corrected for the specific, ATWD chip–dependent pedestal pattern, and calibrated to give charge. Further corrections include the (optional) adjustment of any residual baseline offset and a droop correction. Finally, the charge, given in units of photo electrons (pe), is calculated by summing up all the waveform bins.

Calibration using through-going muons

A DOM's response to a vertical muon passing an IceTop tank is defined to be one VEM. The energy deposit of such a muon is around 200 MeV in the tank [4]. By finding the vertical muon signal in the measured total charge spectrum, the DOM–dependent charge–to–VEM conversion factor is determined. However, single IceTop tanks cannot discriminate between different particles or incident angles. Therefore, the relation between the measured peak position of the total charge spectrum and the VEM must be determined with simulations and the tagging telescope.

This is illustrated in Fig. 1. The measured total charge spectrum is shown in triangles. The simulated total charge spectrum (light grey) is obtained with GEANT4 based simulations. Using Corsika [5] generated hydrogen and helium air showers with primary energies between 10 and 415 GeV and angles up to 70 deg as input, the DOM response is simulated by generating and tracking the Cherenkov light in a tank. Several tank and DOM properties, e.g. the reflectivities of the sides and top, ice quality, PMT quantum efficiency, are taken into account [6].

Superimposed on the simulated total charge spectrum is the contribution from only muons. Choosing a cut on the muons' incident zenith angle that correponds to the angular acceptance of the tagging telescope (< 17 deg), the black histogram is obtained. It gives the best estimate for the VEM, which is determined as the mean of a Gaussian fit, 236 pe for this particular DOM.

Comparing this to the peak position of the simulated total charge spectrum, 247 pe, gives a correction factor of about five percent. This is the amount by which the measured total charge spectra's peak positions have to be corrected to determine the VEM. Currently, it is assumed that this correction factor is the same for all IceTop tanks.

The spread in VEM is shown in Fig. 2 for a run taken on March 15, 2007. The fluctuations in the response, even between DOMs in the same tank, are the main reason to introduce the VEM as a uniform, array–wide unit.

The VEM response per DOM is tracked with regular calibration runs. In Fig. 3, the VEM response over time is shown for both DOMs in Tank 21b. Both DOMs exhibit a rather stable VEM response, except for a sharp drop in DOM 21-64 around July 2006. In total, about half of all DOMs of the oldest tanks, deployed in 2005, show a significant drop in their VEM response in mid–2006. Though the specific cause of these changes in the DOM response is unknown, evidence points to seasonal effects,

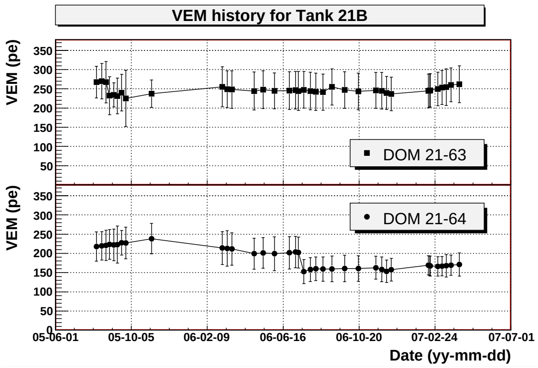

Figure 3: History of charge to VEM conversion for DOMs 21-63/64

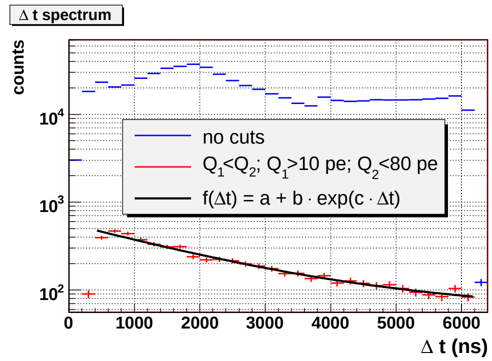

Figure 5: Time difference distributions between the two signals in a FADC trace. The exponential fit yields a lifetime of τ =2.06±0.16 μs.

i.e. the change in temperature during the Antarctic winter.

Muon Telescope Measurements

A portable, solar–powered muon telescope was developed to tag muons that have angles close to vertical ($<$ 17 deg) and pass through the center of the tank. With this device the VEM charge can be determined independently from simulation.

The muon telescope is a completely autonomous device, having its own data acquisition system and power supply. It measures signals in coincidence between two scintillator slabs 70 cm apart and records the GPS clock time stamp on a Flash Media drive.

Measurements were taken during the polar season 2005/2006 on tanks deployed one year earlier. Configuring the DOMs in a tank to singles mode, data were taken for six hours. Matching the GPS time stamps from both the muon telescope and the DOMs was done using a $[-2, 2]\,\mu$s time window. Thus, a tagged quasi–vertical muon data set is obtained. Figure 4 shows the charge spectra for DOMs 63 and 64 in Tank 39b and superimposed the tagged muon charge spectra. If compared to Fig. 1, the tagged spectra show some differences. This is mainly due to the fact that in the simulation muons over the whole tank surface are accepted, while the tagging telescope is positioned in the tank center. When the statistics in simulation are improved, more realistic cuts can be applied. Still, the qualitative difference between the tagged and the full spectrum is well reproduced in the simulated spectrum.

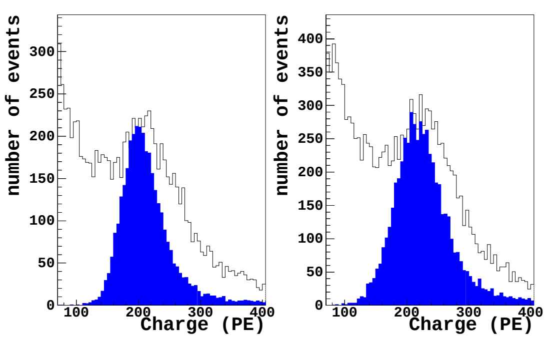

Figure 4: Total charge spectra (black) for tank 39b with tagged muon spectrum (blue) superimposed. See text for further explanation.

Calibration using stopping muons

An IceTop tank stops muons of kinetic energies up to 210 MeV (vertical muons) and 430 MeV (muon crossing through the tank diagonally from an upper to a lower corner). After stopping, the muon decays with its characteristic mean lifetime of 2.19703 μs into an electron and an antineutrino–neutrino pair (neglecting muon capture). The resulting energy distribution of the electron is the well–known Michel spectrum. The maximum electron energy is 53 MeV, which corresponds to a range of less than 25 cm in the tank ice. Thus, most of the decay electrons are well contained within the

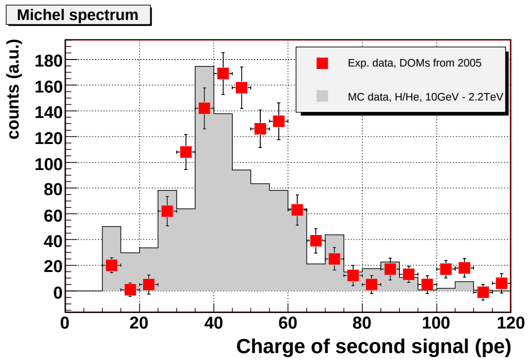

Figure 6: Measured Michel spectrum (symbols) in comparison with a simulated one.

tank volume, making them a suitable calibration sample.

A feasibility study was carried out by applying the method outlined in [7] to the IceTop configuration. First, calibration data from 2005 were analyzed to find FADC traces with two distinct signals. The time difference of those two signals is shown in Fig. 5 as the upper histogram. To suppress background, stringent cuts were applied on the integrated charges Q_1 and Q_2 of the primary and secondary signal, respectively. The cuts were adjusted by using the GEANT4 based simulation from [6].

Fitting the remaining time difference spectrum yields a lifetime of $\tau\ =2.06{\pm}0.16\,\mu$s, which is comparable to the muon mean lifetime of 2.2 μs.

To extract the Michel spectrum from the background, a difference method is chosen that does not require the cuts imposed above. First, two time windows are chosen, a "decay" window between 1 and 2 μs, and a "crossing" window between 5 and 6 μs. For both time windows, the integrated charge of the second signal is calculated. By subtracting them from each other, the Michel spectrum is obtained, which is compared to a simulated spectrum in Fig. 6. Though the simulation lacks statistics, it qualitatively describes the measured spectrum rather well.

Conclusion

The VEM calibration of the IceTop air shower array with through–going muons is a well established and well understood procedure. The VEM is measured and calibrated on a weekly to monthly basis and provides, in conjunction with the single DOM rate and temperature, a basic set of observables for monitoring the detector hardware. GEANT4 based simulations agree well with the measured charge spectra and the muon telescope data, showing that the input parameters describe the actual tank properties rather well.

The stopping muon analysis has shown the feasibility of using the muon decay signal as a supplementary calibration source. Already at this stage, the GEANT4 based simulation shows a promising agreement with the measured spectra. However, further improvements in both the analysis and the simulation are needed to establish it as a standard calibration method.

Acknowledgments

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