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Performance of the IceTop Array

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Abstract: We present an overview of the status of IceTop, which now consists of 52 tanks at 26 stations above the 22 deep strings of IceCube. Six months of good data were taken with the previous 16 station-9 string version of IceCube during 2006.

Introduction

During 2006, IceCube ran with sixteen IceTop stations and nine IceCube strings. Ten more stations and thirteen more strings were deployed in the 2006-2007 austral summer, as shown in Fig. 1. When complete, there will be 80 surface stations and a similar number of deep strings in IceCube.

The IceTop air shower array consists of pairs of tanks (A and B) separated from each other by 10 m. Each IceTop station with its pair of tanks is associated with an IceCube string. Each tank is instrumented with two standard IceCube digital optical modules (DOMs) operating at different gains to extend the dynamic range of the tank. This configuration has several advantages:

- Local coincidence between two tanks at a station is used to select potential air shower signals from the high (typically 2 kHz) event rate generated in each tank by uncorrelated photons, electrons and muons.
- Comparison of signals seen by two DOMs within a tank can be used to demonstrate that fluctuations in tank response are much smaller than intrinsic fluctuations in air showers as measured by comparing signals from the same shower in the two tanks at a station [1].
- Two identical sub-arrays (A-tanks and B-tanks) can be used to measure shower front curvature, lateral distribution, timing and density fluctuations, core location accuracy, angular resolution and other properties of showers.

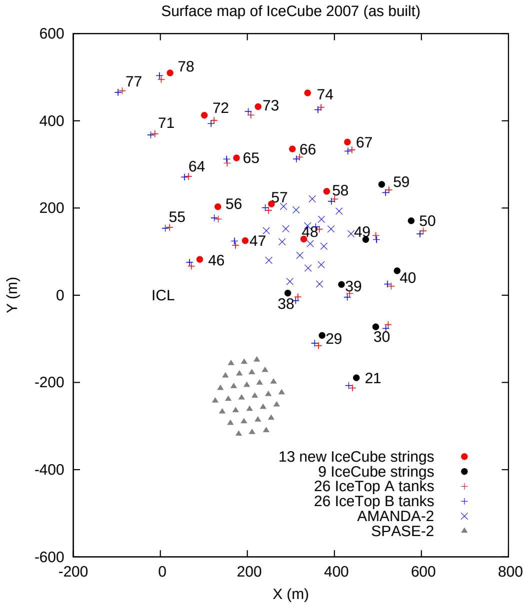

Figure 1: Surface map of IceCube/IceTop in 2007. When completed the array will be symmetric around the IceCube Laboratory (ICL).

- By selecting coincident events in which an event in deep IceCube is accompanied by exactly one hit station in the inner part of IceTop, we can identify and tag a set of events that consist almost entirely of single muons in the deep detector (as compared to the multi-muon events typical of showers big enough to trigger several stations of IceTop). Such events are useful for calibration.

- With 52 tanks we already have a total detector area of 140 m^2, which will grow to over 400 m^2 when the detector is complete. The monitoring stream includes scalar rates of IceTop DOMs that can be used to observe solar and heliospheric cosmic-ray activity.

Calibration of IceTop DOMs

IceTop DOMs are calibrated and monitored with the continuous flux of muons through the tanks [2]. Through-going muons give a broad peak in the distribution of signals from the inclusive flux of all particles that hit the tank. For a vertical muon the signal corresponds to a track length of 90 cm in ice. The peak is calibrated with a muon telescope and with simulations. Air shower signals are then expressed in terms of vertical equivalent muons (VEMs) by comparing the integrated charge of the signal to that of a vertical, through-going muon. Regular calibration runs provide monitoring information and a data base of calibration constants, which is updated weekly. The first 8 tanks deployed in December 2004 provide a 2.5 year timeline for studying stability of the response, which generally varies slowly within a range of ± 5%. In half the cases (8/16) DOMs showed a sudden decrease in response ranging from 10% in two cases to 33% in one. The shifts occurred in mid-winter of 2006, which was the first season that the tanks experienced operation at the ambient winter temperature. (In 2005 winter the freeze-control units were still in operation.)

Air showers in IceTop

With a spacing between stations of approximately 125 m and a surface area per tank of 2.7 m^2, the effective threshold for IceTop is about 500 TeV for a trigger requirement of five or more stations, [3] somewhat higher than the nominal threshold of 300 TeV for showers near the vertical that hit four or more stations. (Here "effective threshold" is defined as the energy above which the previously measured cosmic-ray flux through a defined area-solid angle inside the array equals the observed rate of events.) Figure 2 shows an example of the lateral distribution of signals in a large shower in units of VEMs. The line is the fitted lateral distribution of energy deposition, which has a shape different from the standard NKG function. [3] The NKG function is appropriate for a scintillator array that is relatively insensitive to the photonic part of the signal ($\gamma \rightarrow e^+ + e^-$). Conversion of photons inside the tanks makes an important contribution to signals.

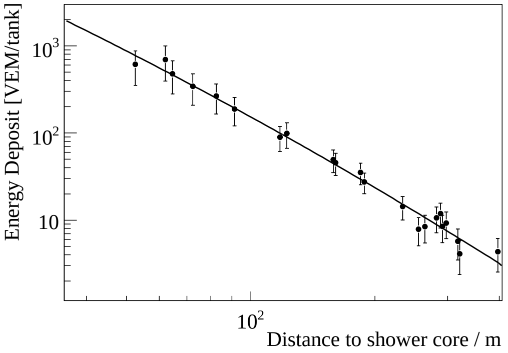

Figure 2: Signal vs distance from shower core with fitted lateral distribution for an event with an estimated energy of 100 PeV.

A convenient measure of primary cosmic-ray energy for showers observed in IceTop is the fitted signal density in VEMs at 100 m from the shower core (S_{100}). The mean energy for $S_{100} = 20$ is approximately 10 PeV for showers with zenith angle less than 30^o and $\sim$ 100 PeV for $S_{100} = 200$. A functional relation for S_{100} as a function of primary cosmic-ray energy and zenith angle for protons is given in Ref. [3], which shows a preliminary energy spectrum extending from 1 to 100 TeV based on this relation. Because of fluctuations on the steep cosmic-ray spectrum, the mean primary energy for a measured S_{100} is smaller than the energy which gives the same average S_{100}. There are also systematic differences in the relation for different primary masses (up to 25 % for Fe). The full energy spectrum analysis will require an unfolding procedure to account for fluctuations.

The same events can be reconstructed independently by the sub-array of A tanks and that of B tanks. From the comparison one can obtain an experimental measure of the accuracy of reconstruction. Such a sub-array analysis indicates that core location can be determined to an accuracy of 13 m and the reconstructed direction to about 2°.

Primary composition from coincident events

An important physics goal is to use the downward moving events observed in coincidence by IceTop and the deep IceCube detectors to study primary composition in the knee region and above. The idea is to measure the distribution of energy deposition by muons in the deep detector as a function of primary cosmic-ray energy and hence to measure the fraction of heavy nuclei, which produce more muons. Previous studies of this type have been done by SPASE2-AMANDA-B10 [4] and by EASTOP-MACRO [5] in the knee region. Status of this analysis with 2006 IceCube data is presented in Ref. [6].

The full IceCube detector can cover the energy range from $< 10^{15}$ eV below the knee to 10^{18} eV. Showers generated by primary cosmic rays in this energy range produce multiple muons with energy sufficient to reach the depth of IceCube. For primary energy of 10^{15} eV, for example, proton-induced showers near the vertical produce on average about 10 muons with $E_\mu > 500$ GeV and iron nuclei about 20. For higher primary energies, the number of muons increases, and the multiplicity in showers generated by nuclei approaches asymptotically a factor of $A^{0.34}$ times the muon multiplicity of a proton shower, or ≈ 2.7 for $A = 56$.

As a consequence of the high altitude of IceTop, showers are observed near maximum so the detector has good energy resolution, which is important when the goal is to measure changes in composition as a function of energy. In some currently favored models [7, 8] the transition from galactic to extra-galactic cosmic rays occurs in the decade between 10^{17} and 10^{18} eV. In the model of Ref. [7] the transition would be characterized by a transition from heavy nuclei at the end of the galactic population to nearly all protons at higher energy as the extra-galactic population dominates. The details of the transition may in principle give information about the cosmology of the extragalactic cosmic ray sources if the change in composition can be measured with sufficient precision and energy resolution [9].

Calibration of IceCube with IceTop

Events reconstructed by IceTop that are also seen in the deep strings can be used in a straightforward way to calibrate event reconstruction in IceCube. One can, for example, compare the directions reconstructed by IceTop with the direction of the muon core reconstructed by one of the algorithms used for muon reconstruction in the neutrino telescope. Examples of verification of timing and direction with IceTop are given in Ref. [1]. As noted above, however, showers that trigger IceTop normally produce bundles of several (at 1 PeV) or many muons in the deep detectors.

In contrast, much of the atmospheric muon background in deep IceCube consists of single muons, as does the target population of neutrino-induced muons. Figure 3 shows the response function for atmospheric muons at the top of the deep IceCube detector, 1.5 km below the surface. About 90% of downward events consist of a single muon entering the deep detector. Most of these events are from cosmic-rays with primary energy $<$10 TeV. The region under the lower curve shows the contribution of events with multiple muons. By selecting a sample of coincident events in which both tanks at one and only one IceTop station are hit, it is possible to discriminate against high-energy events and find a sample enriched in single muons. Coincidences involving only an interior IceTop station provide a sample in which about 75% are single muons in the deep detector. [10] The line from the hit station to the center of gravity of hits in the deep detector can be compared with the direction obtained from the muon reconstruction algorithm in the deep detector alone to check the reconstruction algorithm on single muon tracks. The analysis confirms that the same reconstruction algorithm used for ν_μ-induced upward muons reconstructs most events with an accuracy of better than 2°. [10]

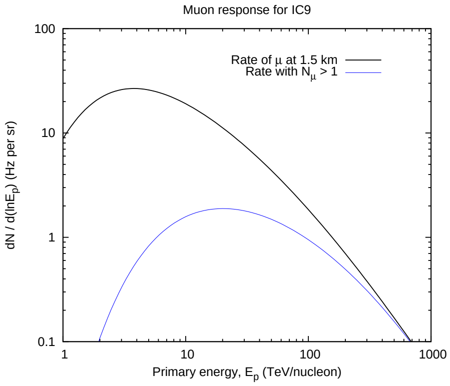

Figure 3: Distribution of primary cosmic-ray nucleons that give rise to muons near the vertical at 1.5 km in IceCube (estimated from Ref. [11]). The lower curve shows the contribution of events with more than one muon entering the deep detector.

Heliospheric physics with IceTop

The monitoring stream of IceCube includes the scalar rates of both discriminators in each DOM. Response of IceTop DOMs to secondary cosmic rays at the surface is discussed in [12]. Signals at the rate of $\sim$2 kHz are produced by a combination of photons converting in the tanks, and electrons and muons that enter the tanks. Most of these particles come from primary cosmic rays with energies in the few GeV range. Large heliospheric events can produce sudden changes in the counting rate. Depending on the nature and orientation of the event (e.g. a coronal mass ejection associated with a large solar flare), one can detect either a decrease in the flux of galactic cosmic rays as the magnetic activity excludes the lower energy cosmic rays from the inner heliosphere or an increase due to solar energetic particles accelerated in the event.

As the setting of the discriminator is increased, the average signal rate decreases as the contribution from the lower energy cosmic-rays falls below threshold. The response of a DOM to the primary cosmic-ray spectrum can therefore be tuned significantly by changing the discriminator threshold– even within the constraint that the threshold must remain below a fraction of the VEM peak. This gives the possibility of studying heliospheric phenomena with unprecedented timing resolution and with significant energy resolution, as discussed in [13].

Acknowledgments

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