IceTop: the Surface Component of IceCube

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Abstract

A km^2 air shower array consisting of 80 pairs of ice Cherenkov tanks is an integral part of the design of the IceCube neutrino telescope at the South Pole. In this paper we describe the plans for construction and operation of this surface array. We outline its capabilities for veto and calibration of the neutrino telescope, and we discuss the opportunities for related cosmic-ray physics with the combined instrument.

1. Introduction: Design of IceTop

The solid surface above a neutrino telescope in deep ice makes possible the construction of a surface array for veto and calibration purposes. In addition, the resulting three-dimensional array is available for studies of cosmic-ray cascades up to the EeV range. The IceCube neutrino telescope [1,2] consists of 80 strings on a 125 m grid. The strings are instrumented with digital optical modules (DOMs) between depths of 1.4 and 2.4 km. The surface component of IceCube will consist of two tanks near the top of each hole, forming a km^2 array of 80 stations on a 125 m triangular grid. Each tank will be 2 m in diameter filled with ice to a depth of one meter. This choice of detector follows the design used at Haverah Park [3] and Auger [4], which gives a large sampling area for horizontal as well as vertical showers. Each tank will be instrumented with two DOMs, one operating at low gain and the other at high gain to achieve dynamic range $> 10^5$, with some overlap for calibration. Design of IceCube electronics [1,2] allows for exchange of hit information between neighboring DOMs. This capability will be used to define two types of local coincidences at a station:

- coincidence between tanks = potential air shower
- activity in one tank only = potential atmospheric muon.

All signals will be time-stamped in the same way as signals from in-ice DOMs [1], and complex signals will be digitized.

The composite spectrum of signals due to single muons from all directions incident on the tank will be used for calibrating and monitoring the tanks. We

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have measured the spectrum and angular distribution of muons at the South Pole [5]. Based on these measurements, the overall rate in a cylindrical tank of the stated dimensions is estimated as 1000 Hz. This method of calibration is used for the Auger tanks [4]. Because the IceTop tanks are smaller, there will be a greater proportion of corner-clippers, and the calibration technique will be modified accordingly. The successful use of GEANT 4 for simulation of signals generated by muons in IceTop test tanks [6] is the first step in this process.

Tank DOMs will be connected to DOM hub processors in the IceCube counting house over the same surface cables [1] that carry power and data for the in-ice DOMs. The IceTop trigger processor will search for two types of signals. Coincidence among several (e.g. $N \geq 4$) stations with potential air-shower signals constitutes an air shower. The array will be tuned for a threshold of 300 TeV for showers near the vertical, well below the knee of the spectrum. In addition, a coincidence of single muon signals within an appropriate time window from a sufficient number of stations to reduce background (e.g. 10 hits in 10 μs) is a potential horizontal (zenith angle $\theta > 60°$) air shower. IceTop triggers will feed into the IceCube global trigger processor in parallel with triggers from in-ice string processors.

2. Veto and Calibration

All data are buffered long enough so that the surface array can be queried for activity whenever there is a trigger for a potential neutrino signal from the in-ice detectors. Backgrounds associated with all showers above threshold for the surface array can be vetoed directly in this way, including a fraction of showers with cores outside the physical boundary of the surface array if they are sufficiently large to trigger the array. The most common background in the deep detector is from atmospheric muons with sufficient energy at production ($>$ 300 GeV) to penetrate down to the vicinity of the neutrino telescope. Such muons will typically be accompanied by small ($\sim$ 10 TeV) air showers, some fraction of which will hit close enough to a surface station to be recognized as a coincidence between the two tanks at that station. We estimate the coverage for such small showers to be about 5%. The total muon rate in the deep detector is $\sim 1 - 2$ kHz [2], so this small fraction still gives a large sample of tagged events for studying this source of background.

Other possible backgrounds accessible to study include showers above threshold that pass through the surface array (so their direction is well-determined) but with a direction such that they pass outside the deep array. Composite backgrounds consisting of accidental coincidences between two or more downward events can also be studied.

Because the earth is largely opaque to neutrinos with energy above a PeV, searches for ultra-high energy neutrinos will be made near and above the horizon.

The signal would be a sequence of bursts of radiation from an extremely energetic neutrino-induced muon, a single large cascade from a ν_e or a double or single large cascade from a ν_τ. One potential background for such events would be the muon core of a large, nearly horizontal air shower. Showers of sufficient energy to produce 5 or more muon hits in the surface tanks at a perpendicular distance of 2 km from the shower axis can be vetoed by the surface array. Given the spacing and size of the surface tanks, we estimate the threshold for recognizing such peripheral horizontal showers is about 10^{17} eV.

Showers with directions and energies reconstructed by the surface array provide a sample of tagged muon bundles that can be used for calibrating reconstruction algorithms used for the deep neutrino telescope. Figure 1a shows the characteristics of muon bundles for proton-induced showers of various energies. Such muon bundles associated with small showers tagged by the present South Pole Air Shower Experiment (SPASE-2) [7] have been used to provide an independent measure of pointing resolution of AMANDA [7,8].

3. Primary Composition

The combined acceptance for contained trajectories of the three-dimensional array formed by the surface and in-ice components of IceCube is approximately 1 km^{2}sr, which is large enough to study coincident events into the EeV range. Expected coincidence rates are indicated for the various primary energies in Fig 1a.

The method for carrying out a measurement of primary composition by measuring the ratio of deep muon signal to surface shower size has been developed for the SPASE/AMANDA experiment [9]. Measurement of the density of Cherenkov light at a nominal position relative to the muon bundle is proportional to the Cherenkov light generated by the muons in the deep ice, and hence to the number of muons with sufficient energy at production to penetrate through the deep detector ($E_\mu > 500$ GeV). Since the number of such muons for showers of a given size is different for primaries of different mass, the relation between N_μ and shower size (N_e) depends on primary mass. Figure 1b (Ralph Engel, private communication) shows the separation between protons and iron in the N_μ-N_e plane for showers of various primary energies. The simulations were done with hybrid-CASC [10] with the threshold set low enough so that all plotted muons are directly simulated. The excellent energy resolution above 3×10^{15} eV implied by the figure is a consequence of the high altitude of the South Pole (equivalent to a vertical atmospheric depth of 700 g/cm^2).

The composition analysis currently under way with SPASE and AMANDA extends to 5×10^{15} eV, just above the knee of the spectrum and shows a transition toward a larger fraction of heavy nuclei above the knee. The large acceptance for surface-underground coincidences with IceCube will allow the same technique to

be used from below the knee to 10^{18} eV. At the high end of this energy region there are indications from fluorescence experiments [11] of the beginning of a trend back to a larger fraction of light nuclei, which makes this topic of particular interest for further study.
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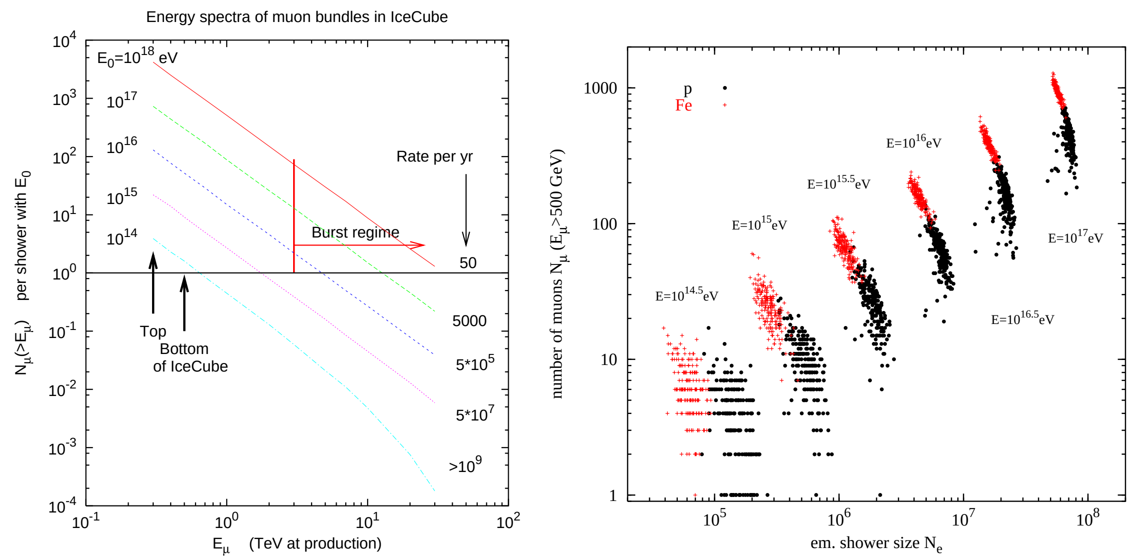

Fig. 1. Left panel: Integral energy spectra of muons in showers of primary energies from 0.1 to 1000 PeV for IceTop-IceCube coincidences. Right panel (Ralph Engel, private communication): Muons in deep detector as function of shower size at surface. Black points for protons; grey (red) points for iron primaries.

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