Abstract

IceCube as a three-dimensional air-shower array covers an energy range of the cosmic-ray spectrum from below 1 PeV to approximately 1 EeV. This talk is a brief review of the function and goals of IceTop, the surface component of the IceCube neutrino telescope. An overview of different and complementary ways that IceCube is sensitive to the primary cosmic-ray composition up to the EeV range is presented. Plans to obtain composition information in the threshold region of the detector in order to overlap with direct measurements of the primary composition in the 100 – 300 TeV range are also described.

Key words: cosmic rays, air showers, composition

1. Introduction

The principal goal of IceCube is to identify and measure high-energy neutrinos from extra-terrestrial sources, thus opening a new view into acceleration of protons and nuclei in energetic cosmic sources. The recently completed IceCube neutrino telescope was described in a separate talk in this session by DeYoung (2011), which gives a status report on searches for astrophysical neutrinos with the partially completed detector.

This paper presents IceCube as a cosmic-ray detector with an emphasis on its potential contributions to improving knowledge of the spectrum and composition of the primary cosmic radiation. There are several different and

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complementary cosmic-ray measurements that IceCube can make. First, consider IceCube as a 3-dimensional air shower detector, consisting of an array of 1 km$^2$ on the surface and a 1 km$^3$ array between 1.45 and 2.45 kilometers in the ice directly below the surface array. (See Fig. 1). There are several classes of events that such a detector can measure. Events with trajectories that pass through both parts of the detector can be reconstructed independently by the surface array and by the in-ice array. The ratio of the shower size on the surface to the energy deposited by the muon bundle in the deep ice is sensitive to composition because heavy primaries put a larger fraction of their cascade energy into muons than protons of the same shower size. An example of such an event is shown in Fig. 2 (left). Its energy can be estimated from the IceTop reconstruction as $\approx 5$ PeV. Depending on the mass of the primary particle, this event would have 30 to 80 muons with sufficient energy to reach 1500 m and would deposit 5 to 15 TeV from muon energy loss in the deep detector.

Because the string spacing of 125 m in the in-ice array is larger than the lateral extent of such a group of high-energy muons, it is not possible to count the tracks. However, the number of muons is closely related to the amount of energy deposited in the detector, which is proportional to the

Figure 1: Configuration of IceCube.
amount of Cherenkov light generated. It is therefore possible to reconstruct the energy deposited from the observed light in the detector and hence to obtain a measure of the primary composition given the energy of the primary cosmic ray as determined by the surface array (Feusels et al., 2009).

The geometrical acceptance of IceCube for trajectories that pass inside both the surface and the deep arrays is $A\Omega \approx 0.3 \text{ km}^2\text{sr}$, the exact value depending on how far inside the two sub-arrays the trajectories are required to lie. This corresponds to typical zenith angles of 20°. With this acceptance, the maximum energy above which the intensity is too low to obtain enough events for analysis is $\sim 1 \text{ EeV}$. The acceptance can be increased by approximately a factor of ten by using all events with zenith angles $< 60^\circ$. Given the steep spectrum, this would increase the maximum useful energy
to $\sim 3$ EeV. There are two ways to do this. One is to use only the IceTop information. The other is to use muon bundles that are well reconstructed in the deep array, including those that pass outside of IceTop, as illustrated in Fig. 2 (right).

Preliminary results show a sensitivity to primary composition through the angular dependence of the events reconstructed with IceTop only (Klepser, 2008). At a given total energy per particle, proton showers are more penetrating so they contribute relatively more to showers of a given size at large zenith angle than heavy primaries. A consistent interpretation of the spectra measured at different zenith angles requires a mixed composition. This analysis is at a preliminary stage, using events from an early phase of construction when there were only 26 IceTop stations, and limited to zenith angles of $\leq 46^\circ$ (Kislat, 2011). It is promising because it will be complementary to results obtained from the ratio of high-energy muons to shower size in coincident events.

Another complementary approach to composition using only IceTop is possible if information about the fraction of muons in the shower front at the surface can be obtained. Accomplishing this is non-trivial because the IceTop detectors do not identify particles on an event by event basis, but only give a measure of the energy deposited in the tank. Efforts to measure the muon component at the surface are underway using energy deposition in the tank to identify muons at large core distances (Kolanoski, 2008). This measurement will provide complementary information because low-energy muons at the surface reflect later stages of shower development as compared to high-energy muons that penetrate to the deep detector.

The angular resolution for reconstruction of muons bundles in the deep part of IceCube is at the level of 1–2 degrees. This is sufficient to determine the location of the shower core at the surface. For events of sufficiently high energy (depending on how far outside of IceTop the core is) it will then be possible to reconstruct surface shower size and extend the geometrical acceptance for coincidence measurements with both the IceTop and in-ice components of IceCube.

Yet another complementary approach is to measure the atmospheric muon flux as a function of energy deposition and angle with the deep component of IceCube only. Preliminary results (Berghaus, 2009) with the 22 strings of IceCube operating in 2007-08 show that the atmospheric muon spectrum can be measured with the full IceCube up to several hundred TeV, which probes the primary spectrum well into the knee region of the spectrum. One pos-
sibility is to identify single energetic muons by measuring the characteristic large bursts of light due to bremsstrahlung and hadronic interactions along their trajectories.

IceCube is sufficiently large to measure the spectrum of atmospheric neutrinos into the region above 100 TeV (IceCube Collaboration, 2011). This gives a very clean sample of events, the interpretation of which depends on assumptions about the shape and composition of the primary spectrum in the knee region. In the case of both muons and neutrinos, the contribution of the prompt component from charm decay is also of interest. For neutrinos there is also the expected contribution of astrophysical neutrinos from unresolved point sources, which is after all the main goal of IceCube.

Effects of composition and charm have to be separated by their different characteristic energy and angular dependence. Kaons and pions in the TeV energy range and above have decay lengths longer than their interaction lengths, so the intensity of neutrinos and muons from their decays is suppressed by one power of energy relative to the primary spectrum. In addition the intensity is proportional to $1/\cos\theta$ because the interaction length is longer in the low-density upper atmosphere. Charmed hadrons decay promptly because of their short lifetimes, so above the threshold region, neutrinos and muons from charm decay have the same spectral index as the primary spectrum, and they are isotropic. The astrophysical component is present only in the neutrinos and is therefore in principle distinguishable by comparisons between muons and neutrinos.

The power of IceCube as a cosmic-ray detector is that it can make several different and complementary measurements that relate to the energy-dependence of the primary composition in different ways. They must all give a consistent result. The energy region from PeV to EeV is of particular interest in connection with the transition from galactic to extra-galactic cosmic rays.

### 2. IceTop

IceTop in its final configuration consists of 81 stations on the surface above the deep part of IceCube at an average pressure depth of approximately 680 g/cm$^2$. The layout is shown in Fig. 3. Each station has two tanks separated from each other by 10 meters. Each pair of tanks is located 25 meters from the point on the surface directly above one of the deep IceCube strings. Thus the average spacing between neighboring IceTop stations is 125 meters, the
Figure 3: Surface map of IceCube. Numbered circles indicate location of IceCube strings. Pairs of blue dots mark IceTop tanks.

same as for the in-ice strings. There are, however, significant deviations from the regular triangular grid for the surface array caused in some cases by nearby buildings and in others by the contingencies of the deep drilling process which sometimes required tanks at adjacent stations to be oriented differently with respect to their associated strings. There are several more closely spaced stations in the center of the array that can be used to select a low-energy subset of events, as described in the next section.

Tanks are 2 m in diameter filled with water to a depth of 90 cm. The tanks are insulated and instrumented during a 50 day freeze-in period with freeze-control units (FCUs) to manage the expansion as the water freezes from the top down. Tank tops are open while the water freezes. The FCUs are mounted in insulated compartments on the outside of each tank. In addition to managing the expansion water, the FCUs also control a vacuum system connected to a filter on the bottom of the tank that removes dissolved gas from the water to prevent formation of bubbles. When the freeze is complete, the FCUs are removed, the space above the ice is filled with insulation and the tanks closed.

Each tank is equipped with two standard IceCube digital optical modules
Figure 4: Diagram of an IceTop ice Cherenkov tank. The diffusely reflecting liner illuminates the photomultipliers in a way that is well correlated with the total track length of charged particles in the tank. The fluctuations in the response of a single tank to a given event are small compared to the intrinsic fluctuations in the shower front as measured by comparing signals from tanks at the same station in each event (IceCube Collaboration, 2006).

(DOMs) with 10 inch photomultipliers (IceCube Collaboration, 2010a), each enclosed in a pressure sphere along with the electronics for digitization and time keeping. The IceTop DOMs are fully integrated into the IceCube data acquisition system (IceCube Collaboration, 2009). Fig. 4 illustrates how the IceTop detector is illuminated by Cherenkov light diffusely reflected from the white, inner lining of the tank. One DOM runs at low gain and the other at high gain to give a dynamic range for each tank of more than 4 orders of magnitude. The DOMs are mounted facing down with the photocathode half of the pressure sphere in the water. Basic calibration is provided by the spectrum of low energy cosmic-ray hits in the tanks, which occur at a rate of approximately 2 kHz per tank. The tank spectrum consists of a low-energy electromagnetic component and a muon peak at higher energy. The peak is used to define a signal equivalent to a vertical muon (VEM). As for Auger (Etchegoyen et al., 2005), Cherenkov light generated by air shower signals is measured in units of VEM. For IceTop tanks, one VEM corresponds to approximately 150 to 250 photoelectrons in the photomultiplier, depending on which of two types of liner the tank has (Demirörs, et al., 2007). Thus signals in IceTop tanks are significantly larger than the signals in the deep
ice, which are typically at the level of one or a few photoelectrons.

In addition to their utility for calibration, the counting rates produced in the tanks by low energy cosmic radiation are available for heliospheric studies of solar modulation and solar energetic particle events. The ground-level solar particle event of December 13, 2006 was studied with data taken with the 32 tanks then in operation (IceCube Collaboration, 2008).

The basic air shower trigger of IceTop requires 6 DOMs to report signals within a 5µs time window. For purposes of triggering, a DOM only reports if its neighbor is also hit, a condition called “local coincidence”. For IceTop, the local coincidence is configured so that the neighbor of a given DOM is always in the other tank at the same station. Thus, even if only high-gain DOMs are above threshold, this trigger includes all 3-station events. In presentations so far, however, only events involving both tanks at 5 or more stations have been used for reconstruction and analysis. The 5-station software trigger corresponds to an energy threshold for full efficiency of 1 PeV for vertical showers. The energy threshold can be lowered by using the three (and four) station events, as discussed in the next section.

3. Overlap with direct measurements

As is the case with all air shower detectors, IceCube does not measure the primary cosmic rays directly but only samples their cascades deep in the atmosphere. Information about primary composition must be inferred from measurements of the properties of the secondary air showers. In this situation it is important to extend the indirect measurements to sufficiently low energy to overlap as much as possible the energy range probed by direct measurements. Recent measurements with ATIC (Panov et al., 2009) and CREAM (Ahn et al., 2010) balloon-borne calorimeters are providing increased statistics and a new view of the region around 100 TeV/nucleus and above, thereby stimulating a renewed interest in an energy region previously studied primarily with balloon-borne emulsion chambers, JACEE (Asakimori et al., 1998) and RUNJOB (Apanasenko et al., 2001). By selecting a subset of small events in IceTop it is possible to obtain an overlap in energy with direct measurements down to < 300 TeV (Ruzybayev et al., 2009).

Fig. 5 shows the effective area obtained from simulations separately for protons and for iron primaries for 3- and 4-station events compared to the

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1See also Kopenkin & Sinzi (2009) for a more recent analysis of RUNJOB data.
Figure 5: Effective area as a function of energy for various classes of events. Left panel is for primary protons, the right panel for primary iron. The black line is for the standard IceTop analysis which requires 5 or more stations to have hits in both tanks, which becomes fully efficient for vertical events above a PeV. For IceTop 40 shown here, the cores were required to be located in the interior portion of the array with an area of 0.11 km$^2$. Each plot has two sets of colored histograms: the green histograms are for 3-station events in the main IceTop array, while the pink histograms at slightly higher energy are for 4-station events. The histograms at lower energy were made for planning the locations of more closely spaced stations in the center of the array.

acceptance for IceTop when it was running with 40 stations. The acceptance curves for 3- and 4-station events at first rise as energy increases and then decrease as more stations are hit. Thus, for example, the sum of all 3-station events in the interior of IceTop-40 peaks at 300 TeV for primary protons and at just below a PeV for primary iron. The three station trigger therefore preferentially selects light primaries. Selecting a particular group of stations with smaller spacing, it is possible to shift the response to somewhat lower energy. Studies of the final array configuration with the goal of overlapping direct measurements are currently underway.

4. Muons in IceCube

The amount of data on TeV muons being accumulated by IceCube is enormous. At a rate of more than 2 kHz, the deep IceCube detector collects almost 100 billion events per year. In addition to the potential for con-
straining the energy dependence of the cosmic-ray composition in the knee region, the high rate of muons in IceCube also supports detailed studies of cosmic-ray anisotropy (IceCube Collaboration, 2010b). The IceCube map extending cosmic-ray anisotropy studies into the Southern hemisphere is shown by DeYoung (2011) in this volume.

Another aspect of the high rate of cosmic-ray muons in IceCube is that the characteristic correlation of atmospheric muons at high energy with the temperature in the stratosphere can be used as an additional probe of the relative contributions of pions, kaons and charmed hadrons to the flux of leptons in the atmosphere (Desiati & Gaisser, 2010). The variation observed with the 40-string version of IceCube is reported by Tilav et al. (2009).

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