IceCube – a new window on the Universe

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Abstract. This paper gives an overview of the scientific goals of IceCube with an emphasis on the importance of atmospheric neutrinos. Status and schedule for completing the detector are presented.

Keywords: Neutrinos, Particle astrophysics
PACS: 95.55Vj, 95.85Ry

INTRODUCTION–THE ICECUBE OBSERVATORY

The primary goal of IceCube is to detect high-energy neutrinos of extraterrestrial origin. Its method is to use the Earth as a filter by identifying upward moving events in the intense background of downward, cosmic-ray induced muons. The IceCube design (see Fig. [1]) calls for 4800 digital optical modules (DOMs) in the deep ice. There are 60 DOMs per cable separated from each other by 17 meters and deployed between 1450 and 2450 m into vertical holes melted in the ice. Each down-hole cable (called a "string") is separated by approximately 125 m from the neighboring strings. Each DOM is a glass sphere 33 cm in diameter capable of withstanding the high pressure of more than two km of water when deployed. Inside is a 25 cm Hamamatsu photomultiplier tube (PMT) and an electronics board that digitizes the signals locally using an on-board computer. There is also a local quartz clock that is synchronized to an accuracy of 3 ns to a single IceCube GPS clock on the surface [1].

In addition to its deep neutrino telescope, IceCube also includes a surface air-shower array called IceTop. The surface array consists of stations located near the top of each in-ice string. Each station consists of two tanks separated from each other by 10 meters, and each tank is instrumented with two DOMs embedded in the clear ice that fills the tank. IceTop DOMs are fully integrated into the IceCube data acquisition system. Together the surface array and the deep detectors of IceCube form a three-dimensional cosmic-ray detector.

The principle of particle detection is the same for in-ice and surface detectors; namely, to record the pulse of Cherenkov light from relativistic particles moving faster than the speed of light in ice, which has an index of refraction of 1.3.

1 This paper is based on a talk presented by T. Gaisser on 1 September 2008 at the 3rd Latin American School for Cosmic Rays, Arequipa, Peru in which co-author, Denis Robertson, was a student.
FIGURE 1. Artist’s drawing of the IceCube detector. IceCube currently has three components: the deep neutrino telescope, IceTop, and AMANDA, the smaller forerunner of the IceCube neutrino telescope. On the right is a display of an EeV event recorded by both IceTop and the deep array of IceCube in its present 40-string configuration.

When it is complete IceCube will instrument a cubic kilometer of ice with DOMs, as illustrated in Fig. 1a. The partial detector running with 40 strings already extends a full kilometer in one direction. The kilometer scale of IceCube is set by the requirement that the detector is large enough to measure astrophysical neutrinos if they are produced with an energy density comparable to the energy density of ultra-high-energy cosmic rays [2]. Such a situation would naturally occur if accelerated particles are colliding with photons in the radiation fields of their sources in such a way that there is an equilibrium between production of secondary pions and neutrons. In such a case, the neutral pions decay to produce high-energy gamma rays, charged pions produce neutrinos and neutrons escape to contribute to the pool of ultra-high-energy cosmic rays.

Different neutrino flavors can be distinguished by characteristic patterns of light in the detector. Charged current interactions of muon neutrinos produce a muon which on average carries about 80% of the neutrino energy. Such a muon has a long track so upward-moving muons that start outside the detector can also be detected if the neutrino is headed toward the detector. The IceCube configuration is optimized for high-energy $\nu_\mu$-induced muons for this reason. The characteristic signal of an electron neutrino is a 5 - 10 meter long cascade produced by the high-energy electron from $\nu_e + N \rightarrow e + X$. The
signature of a $\nu_\tau$ is more complex and depends in detail on the energy of the neutrino and where it interacts.

Observation of neutrinos from astrophysical sources will open a new window because neutrinos have very small cross sections and can therefore emerge from deep inside their sources and travel astronomical distances freely. Of special interest are regions of high density, such as microquasars in our galaxy, and extra-galactic Active Galactic Nuclei (AGN) and Gamma-Ray Bursts (GRBs). In such objects high gravitational forces associated with accretion of magnetized plasma generate high energy beams of particles that can interact with the matter and photons in or near the sources and produce pions and other mesons. Neutrinos will be produced from decays like $\pi^\pm \rightarrow \mu^\pm \nu_\mu$ followed by $\mu^\pm \rightarrow e^\pm \nu_\mu \nu_e$. At production there is a relation of 2:1:0 of $\nu_\mu : \nu_e : \nu_\tau$. However, after large distances neutrino oscillations change this ratio to 1:1:1, which means that an astrophysical flux of $\nu_\tau$ is expected. Because $\tau$-neutrinos are rarely produced in the Earth’s atmosphere, their detection would be a strong indication of astrophysical origin.

The paper is organized as follows: We first describe in a general way the expected signals from the different neutrino flavors in the detector and how the energy and direction would be reconstructed from them. Next, we discuss atmospheric muons and neutrinos as background and calibration tool for IceCube. We then discuss the implications for detection of astrophysical neutrinos. Finally, we summarize the other scientific objectives of IceCube and conclude with a description of the status and plans for completion of the detector.

**EVENT RECONSTRUCTION**

Charged particles traveling faster than the speed of light in ice produce Cherenkov light which illuminates the optical modules of IceCube. Cherenkov photons produce signals which are digitized and time stamped in the DOMs. The times and waveforms provide the basic information from which events are reconstructed. Maximum-likelihood fitting techniques are used to reconstruct the direction and energy of each event [3, 4]. In general, the total integrated signal from each event is larger for events that deposit a large amount of energy in the detector and smaller for less energetic events. Corrections for location of the light source relative to the DOMs is essential to obtain an estimate of energy. Corrections include not only the absolute distance of the light source from each DOM but also the properties of absorption and scattering in the ice as a function of depth. In particular, there are several dust layers, the most dense being at a depth of approximately 2100 m.

Flavors can be differentiated by their topologies:

**Electron Neutrino:** A $\nu_e$ interaction in the ice produces an electron which initiates an electromagnetic shower. The rest of the neutrino’s energy goes into fragments of the target that produce a hadronic shower. The size of the showers is of order 10 m, which is small compared to the string spacing. Each electron emits light at the $41^\circ$ Cherenkov angle, and there is a characteristic range of angles of the shower electrons relative to the direction of the event. Because of the small ratio of the region of the light source to the string spacing, it is difficult to reconstruct the direction of electron neutrinos. On the other hand, energy reconstruction is relatively robust because the events are
contained inside the detector. The Cherenkov light generated spreads over a volume which increases with energy (for example a sphere of radius 130 m at 100 TeV [5]).

**Muon Neutrino:** Charged current interactions of $\nu_\mu$ produce secondary muons which can travel long distances in ice (kilometers at TeV), generating showers along their track by bremsstrahlung, pair production and photo-nuclear interactions if their energy is high enough. The energy of the muon decreases as it propagates in the ice, so the energy of the secondary showers diminishes. Therefore the pattern of the light generated by a muon will be a Cherenkov cone along the track characteristic of a minimum ionizing muon on which is superimposed bursts of light from stochastic processes that on average decrease in intensity as the muon loses energy. A minimum ionizing muon can typically be seen by DOMs within 30 to 40 m of its track.

**Tau Neutrino:** $\tau$-neutrinos originate cascades very difficult to distinguish from electron neutrino cascades at low energies. However their flavor can be identified at higher energies. A possible favorable signature is the “double bang” in which two main cascades are produced, the first in the production of the tau lepton and the second in its decay. The tau also generates Cherenkov light during its life. The energy window for double bang events is constrained by the kilometer scale of the detector to $5 < E_{\nu_\tau} < 20$ PeV so that the pathlength of the $\tau$-lepton is between 0.25 and 1 km. Other signatures could be the “lollipop” or the “inverted lollipop”. In the first the tau lepton is produced outside IceCube so the hadronic cascade is not visible but the track of the tau and its decay are detected. The latter is the opposite case, the production of the tau occurs inside IceCube but not its decay. Ref. [6] gives a more detailed description of $\nu_\tau$ signatures in IceCube.

**ATMOSPHERIC NEUTRINOS**

The main event rate in IceCube is from atmospheric muons created by cosmic-ray interactions in the atmosphere. The background events are about 1 million times more numerous than events generated by atmospheric neutrinos. Understanding the downward flux of atmospheric muons and reconstructing the muon directions is a prerequisite for analysis of IceCube data.

To eliminate the very high background of downward muons, IceCube uses upward-going muons to identify and study neutrino interactions. The Earth is used as a filter to select muons produced by charged current interactions of muon neutrinos in the ice or rock below or beside IceCube. After upward moving events are selected, there are still more background events than signal. After the first cut(s) the background consists of misreconstructed downward events and events in which two unrelated muons go through the detector within the same event time window. Further cuts are made to reduce these backgrounds and arrive at the level where most of the upward events are from atmospheric neutrinos.

The intensity of atmospheric neutrinos is fairly well known into the TeV region. It decreases with energy at a higher rate than is expected for astrophysical neutrinos, falling approximately like $E^{-3}$ and steepening to $E^{-3.7}$ for $E \gg 1$ TeV. Figure [2] showing the total atmospheric neutrino spectrum is adapted from figure 25 of Ref. [7]. For energies higher than 100 GeV most of the neutrinos come from decay of kaons until the energy is so high that neutrinos from charm dominate [9]. At high energy the flux is higher
FIGURE 2. Flux of atmospheric neutrinos integrated over all directions from below the horizon. The figure shows the sum of neutrinos and anti-neutrinos (adapted from Figure 25 of Ref. [7]). The prompt component shown here corresponds to the model of charm production in Ref. [8] (see text).

at larger zenith angles and up-down symmetric except for the few GeV range where geomagnetic effects play a role. The uncertainties in the fluxes are around 15% at 1 TeV, and they increase with energy. Uncertainties in flavor ratios and in angular dependence of the neutrino spectra are significantly less than uncertainties in the normalization [10].

The level of charm production becomes a significant uncertainty at high energy. The model for charm [8] shown in Fig. 2 is near the maximum allowed [11] by current observations. A new calculation of charm production [12] is an order of magnitude lower. Because charm contributes an isotropic “prompt” component of neutrinos with a harder spectrum than neutrinos from kaons and pions, it is potentially a significant background in the search for a diffuse flux of astrophysical neutrinos above 100 TeV.

Response of IceCube to atmospheric neutrinos

During construction, IceCube is augmented with new strings each Austral summer (November - February). A new science run begins in April after the new DOMs are frozen in and continues until the following March. From April 2007 to March 2008 IceCube ran with 22 strings in the deep ice and with 26 stations of IceTop on the surface. IceCube has been running in a 40 string configuration since April, 2008. Analysis of data from IceCube-22 (IC22) is currently well advanced. The total exposure of IC22 (km$^2$-sr-years) is already comparable to seven years of AMANDA data, and a discussion serves to illustrate the methods and first results of IceCube.
The neutrino effective area is defined so that the product of neutrino intensity multiplied by the effective area gives the event rate. Its value as a function of angle and energy for IC22 is shown in Fig. 3 from Ref. [13]. The neutrino effective area is given by

$$A_{\text{eff}}(\theta, E_\nu) = \varepsilon(\theta) A(\theta) P(E_\nu, E_{\mu, \text{min}}) e^{-\sigma_\nu(E_\nu) N_A X(\theta)},$$  \hspace{1cm} (1)$$

where $\varepsilon(\theta)$ is the efficiency for a detector of projected area $A(\theta)$ to detect a muon incident at zenith angle $\theta$. The exponential expresses the muon attenuation in the Earth for angle $\theta$ below the horizon, where $X(\theta)$ is the amount of matter (g/cm$^2$) along the chord through the Earth. The factor $P(E_\nu, E_{\mu, \text{min}})$ is the probability that a muon neutrino on a trajectory that will intercept the detector gives a visible muon in the detector. It is

$$P(E_\nu, E_{\mu, \text{min}}) = N_A \int_{E_{\mu, \text{min}}}^{E_\nu} \frac{d\sigma_\nu}{dE_\mu} R(E_\mu, E_{\mu, \text{min}}),$$  \hspace{1cm} (2)$$

where the integrand is the product of the charged current differential cross section and $R$ is the average distance traveled by a muon with energy $E_\mu$ at production before its energy is reduced to $E_{\mu, \text{min}}$, the minimum energy required upon entering the detector for the event to be reconstructed well. The additional contribution from neutrinos that interact within a large detector can be computed in a straightforward way and added as an extra contribution.

The product of the effective area for the lower hemisphere (heavy histogram in Fig. 3) and the atmospheric neutrino flux from below the horizon (Fig. 2) gives the differential response of IC22 to atmospheric $\nu_\mu$. This response is shown in Fig. 4. The dashed line in the logarithmic plot (Fig. 4b) also shows the response of IC22 to a potential diffuse astrophysical flux of muon neutrinos [14] with a spectrum

$$\frac{E_\nu^2 dN_\nu}{d(E_\nu)} = 2 \times 10^{-4} \text{ GeV} m^{-2} \text{s}^{-1} \text{sr}^{-1}.$$  \hspace{1cm} (3)$$
Muons in IceCube

IceCube now has the largest instrumented volume for detecting and reconstructing muons with energies in the TeV range and above. The measurement of muons from all directions is therefore a major benchmark for IceCube. Because of the vast difference in rates of downward atmospheric muons and upward neutrino-induced muons, the measurement requires a dynamic range of sensitivity of more than six orders of magnitude.

FIGURE 4. Response of IC22 to atmospheric muon neutrinos (left: linear scale; right: logarithmic scale). The upper line includes prompt neutrinos from decay of charmed hadrons normalized for the model of Ref. [8]. The broken line shows the response for an $E^2\nu$ differential neutrino spectrum (see text). There are about 6000 well-reconstructed atmospheric neutrinos per year in IC22.

FIGURE 5. Reconstructed direction of muons in IceCube as a function of zenith angle at trigger level [15]. The upward hemisphere is populated mainly by neutrino-induced muons while the downward hemisphere is from muons produced in the atmosphere above the detector. At trigger level the cuts are looser than in Fig. 3.
Figure 5 shows the measured distribution of muons in IC22 as a function of zenith angle for the whole sky-atmospheric muons from above and atmospheric neutrinos from below. The data are compared with simulations that show the components separately (including the contribution from accidentally coincident downward muons).

SCIENTIFIC OBJECTIVES OF ICECUBE

Astrophysical neutrinos

To study astrophysical neutrinos, we first need to discriminate in IceCube which events are caused by atmospheric and which ones by astrophysical neutrinos. One way to differentiate astrophysical neutrinos from atmospheric ones is by means of their energy spectrum, as illustrated in Fig. 4b. This is a challenging quest because the expected intensity is low. Another way would be to see several neutrinos from the same direction, especially if the direction is associated with a known source of high-energy gamma-rays. Even better would be to see two or more neutrinos at the same time and from the same direction as a gamma-ray burst.

Potential sources include AGN and GRBs. Both of these are likely to be cosmic particle accelerators. If so, neutrinos could be produced when accelerated protons (or nuclei) interact with photons or gas near the sources. AGN and GRB are extra-galactic sources. Galactic cosmic-ray accelerators such as supernova remnants and interacting X-ray binaries, or micro-quasars, might also produce neutrinos. Limits from a search with AMANDA for Northern hemisphere point sources of neutrinos in data collected over seven years (3.8 years of live time) are shown in Fig. 6. The blue lines show the sensitivity of IceCube at various stages of construction. IC22 is already more sensitive than AMANDA, and one year of the full IceCube is more sensitive by an order of magnitude.
magnitude. Initial results of searches for point sources with IC22 have been reported at conferences [17, 18].

**Other objectives**

*Indirect detection of dark matter*

IceCube also looks for neutrinos as a signature of dark matter by looking for neutrinos from the Sun or the center of the Earth where weakly interacting massive particles (WIMPs) could accumulate and annihilate each other. The indirect search for WIMPs in the Sun is complementary to direct searches because the capture rate of WIMPs depends on their spin-dependent cross section for interaction with protons in the Sun. In contrast, direct searches with nuclei such as xenon or silicon depend on coherent, spin-independent cross sections. So the two approaches are sensitive to different regions of supersymmetric parameter space [18]. Limits with AMANDA have been published [19], and a search with IC22 is forthcoming.

*Search for exotic particles and processes*

An important signature to look for is any signal that corresponds to propagation of a track through IceCube at less than the speed of light. Possibilities to generate such signals include massive magnetic monopoles, Q-balls and massive nuclearites [20].

Another search looks for non-standard oscillations using the atmospheric neutrino beam. As mentioned above, measurement of atmospheric neutrinos and reconstruction of their energy spectrum is a benchmark measurement for IceCube. In the process of making this measurement it is natural to look for new physics that might show up in the neutrino spectrum at an energy higher than what has previously been explored. In theories that allow violation of the principles of relativity theory, neutrino eigenstates can exist with mixing effects that show up as energy increases (opposite to the case for standard neutrino oscillations). Analysis of the full 7-year AMANDA data sample from this point of view provides new limits on such models while extending the measurement of the atmospheric $\nu_\mu$ spectrum into the multi-TeV energy range [21].

*Geophysics*

Given sufficient statistics that will be accumulated by IceCube on a ten-year time scale, it may be possible to use the known angular dependence of the atmospheric neutrino beam to probe the core-mantle density transition deep in the Earth [23]. The Earth begins to absorb neutrinos from directly below above 10 TeV (see the $150^\circ$-180$^\circ$ line in Fig. 3). Because of the steep decline of the atmospheric neutrino signal above 10 TeV (Fig. 3a), good energy resolution is required to exploit this possibility [9].
Supernovae and Solar physics

Monitoring the event rates in individual IceCube DOMs is the basis for two quite different physics goals: supernova watch and solar and heliospheric physics. By design IceCube is a coarse detector with a threshold of order 100 GeV for muons to have a sufficiently long track to be reconstructed. Therefore, individual events of low energy cannot be reconstructed. However, when a sufficiently nearby supernova occurs the random interactions of anti-neutrinos on protons producing $\approx 20$ MeV positrons near individual DOMs will cause the overall counting rate of the detector to go up $[22]$. Typical counting rates of individual DOMs in the deep, dark ice are in the vicinity of 250 Hz after removing correlated afterpulses. This low rate allows detection of a supernova with good probability out to the Small Magellanic Cloud (62 kpc).

Counting rates in IceTop DOMs on the surface are higher, of order 2 kHz, even though their discriminator thresholds are set higher than in-ice DOMs. The steady, uncorrelated counting rate of the DOMs in IceTop tanks is due to low-energy secondary cosmic ray electrons, photons and muons hitting the tanks. These particles are produced by the continuous flux of galactic cosmic rays with energies of order 10 to 100 GeV interacting in the atmosphere. When an energetic solar flare accelerates particles of several GeV that reach the atmosphere and interact, the event shows up as an abrupt increase in the counting rate of DOMs on the surface followed by a gradual decline as the intensity of the flare particles decreases.

The first extra-terrestrial event seen with IceCube was the solar flare event of December 13, 2006 when there were sixteen IceTop tanks in operation. Using the fact that the increase in counting rate in individual DOMs depends on its discriminator threshold, it was possible to extract some information about the spectrum of the particles in the event $[24]$. The sensitivity provided by the full IceTop with 160 tanks is expected to provide an additional tool for solar and heliospheric physics.

Cosmic-ray physics with IceCube

The main goal of IceCube as a cosmic-ray detector is to measure the energy spectrum and relative composition of protons and heavy nuclei of the primary cosmic rays from 1 PeV to 1 EeV. The goal is to look for a signature of a transition from galactic cosmic rays to a population of particles from extra-galactic sources. Preliminary results from data taken in 2007 with 26 IceTop stations are promising. Using the angular dependence of air showers as a function of shower size on the ground, clear evidence of sensitivity to primary composition is seen $[25]$. The sensitivity arises from the fact that showers generated by protons are more penetrating than showers generated by heavy nuclei, so the proton component contributes relatively more to the event rate at larger zenith angles. This result is from IceTop alone.

Events with trajectories that pass through IceTop and the deep array of IceCube offer another handle on composition. The signal in IceTop is primarily due to the electromagnetic component of the shower. This component is absorbed by the ice leaving only the penetrating high-energy muons in the core of the shower that reach $> 1.5$ kilometer to
produce signals in the deep IceCube DOMs. The ratio of muon component to electromagnetic component depends on composition in a way that is complementary to the measurement of angular dependence on the surface. Requiring a consistent interpretation of the two measurements will be a strong constraint on the analysis, which depends on comparison to Monte Carlo simulations of shower development.

Other shower properties will also provide additional constraints on the interpretation. An example is the relative content of low-energy muons at large distances from the shower core on the surface [26].

The acceptance of full IceCube for coincident events that trigger both IceTop and the deep array is 0.3 km$^2$sr, which is large enough to see a few events in the EeV range. Figure 1b shows one such event observed in 2008 with IC40 when IceCube was half its design size. Such an event contains some 2000 muons with sufficient energy to reach the deep detector. Two important properties of the ice clearly show up in this event display. One is the main dust layer in the middle of the deep strings (around 2100 meters below the surface). The other is the exceptional clarity of the ice below the dust layer, which is apparent from the large amount of light and its extent. This is despite the fact that some of the muons are ranging out inside the detector so the source of light is decreasing with depth in the detector.

**STATUS AND PLANS**

IceCube is currently operating in its 40-string configuration with 40 IceTop stations. This IC40 run began in April 2008 and will continue through the 2008-2009 construction season until the end of March 2009. The current 2008-2009 deployment season saw the addition of 19 IceTop stations and 19 more strings. A new run will begin with the newly deployed strings and tanks in April 2009 after the new DOMs have been commissioned.

One of the new strings installed in the current season is a specially configured “deep core” cable with 50 closely spaced, high quantum efficiency (HQE) DOMs below the dust layer and 10 DOMs above the main dust layer. The concept is to build a densely instrumented, deep subarray within IceCube that will replace AMANDA [27]. Six densely instrumented strings will be placed around a central string of the original plan, equidistant between the central cable and nearest six surrounding cables of the original plan. These 13 strings (six specially configured and seven with standard DOM spacing) will constitute the deep core subarray of IceCube. Its location is such that there are at least three rings of IceCube strings on the standard 125 meter grid between the deep core and the edge of the array. This deep, inner core will be surrounded laterally and above by some 4500 standard IceCube DOMs. The plan is to turn off AMANDA at the end of the current run (end of March 2009) and to install the remaining five special strings of the inner core in the 2009-2010 deployment season.

The deep inner core subarray will increase the sensitivity of IceCube at low energy ($< 100$ GeV) allowing study of neutrino oscillations [29] and increasing the sensitivity for indirect searches for WIMP annihilations in the Sun. Using the outer veto area will enable IceCube to move toward the regime of much more densely instrumented detectors like Super-K. The goal is to use the veto capability to identify a class of partially “contained” events in which the vertex is known with high probability to be
inside the deep core fiducial volume. This would allow the identification of a fraction of the neutrinos from above as well as those from below.

The possibility of increasing the reach of IceCube at higher energy is also under consideration. A straightforward way to accomplish this would be to place some of the last strings of IceCube further out from the center \[13\]. The goal of such an extension would be to increase coverage in the PeV neutrino energy range so the detector would have better sensitivity to weak astrophysical signals with hard spectra above the atmospheric neutrino background. The goal of measuring the intensity of cosmogenic neutrinos (neutrinos produced by interactions of ultra-high-energy cosmic rays with the cosmic microwave background radiation) may be beyond the reach of IceCube itself. New techniques for covering much larger target volumes are being explored with test devices deployed in IceCube holes. These include radio and acoustic techniques as discussed in Ref. [28].

The final deployment season for IceCube is planned for 2010-2011. The plan is to manage resources well enough to be able to deploy the 80 standard IceCube strings of the original plan as well as the 6 special strings of the deep core.

ACKNOWLEDGMENTS

We are grateful to the conference organizers for the opportunity to participate in the 3rd Latin American School for Cosmic Rays. The IceCube Collaboration acknowledges support from the following agencies: U.S. National Science Foundation-Office of Polar Programs, U.S. National Science Foundation-Physics Division, U. of Wisconsin Alumni Research Foundation, U.S. Department of Energy, NERSC, the LONI grid; Swedish Research Council, K. & A. Wallenberg Foundation, Sweden; German Ministry for Education and Research, Deutsche Forschungsgemeinschaft; Fund for Scientific Research, IWT-Flanders, BELSPO, Belgium; the Netherlands Organisation for Scientific Research.

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