Detection of atmospheric muon neutrinos with the IceCube 9-string detector


(IceCube Collaboration)

1III Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany
2Department of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, Alaska 99508, USA
3CTSPS, Clark-Atlanta University, Atlanta, Georgia 30314, USA
4Department of Physics, Southern University, Baton Rouge, Louisiana 70813, USA
5Department of Physics, University of California, Berkeley, California 94720, USA
6Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
7Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
8Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium
9Vrije Universiteit Brussel, Dienst ELEM, B-1050 Brussels, Belgium
10Department of Physics, Chiba University, Chiba 263-8522 Japan
11Department of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
12Department of Physics, University of Maryland, College Park, Maryland 20742, USA
13Department of Physics, Universität Dortmund, D-44221 Dortmund, Germany
14Department of Subatomic and Radiation Physics, University of Gent, B-9000 Gent, Belgium
15Max-Planck-Institut für Kernphysik, D-69177 Heidelberg, Germany
16Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
17Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas 66045, USA
18Blackett Laboratory, Imperial College, London SW7 2BW, United Kingdom
19Department of Astronomy, University of Wisconsin, Madison, Wisconsin 53706, USA
The IceCube neutrino detector is being deployed in the deep ice below the geographic South Pole. The dominant population of neutrinos detected in IceCube is due to meson decay in cosmic-ray air showers. These atmospheric neutrinos are relatively well understood and serve as a calibration and verification tool for the new detector. In 2006, the detector was approximately 10% completed, and we report on data acquired from the detector in this configuration. We observe an atmospheric neutrino signal consistent with expectations, demonstrating that the IceCube detector is capable of identifying neutrino events. In the first 137.4 days of live time, 234 neutrino candidates were selected with an expectation of $21 \pm 7.61 \text{(syst)} \pm 14.5 \text{(stat)}$ events from atmospheric neutrinos.

II. ATMOSPHERIC NEUTRINOS

Neutrinos produced in cosmic-ray air showers at the Earth are known as atmospheric neutrinos and form the chief background to potential astrophysical neutrino observation. The atmospheric neutrino spectrum is relatively well understood [6,7] and has been measured up to $10^5 \text{ GeV}$ by AMANDA [8]. Atmospheric neutrinos from the decay of charged mesons can contribute significantly above $10^4 \text{ GeV}$, depending on the model (see e.g. [9–11]).
This prompt component is not well known due to uncertainties in the charmed meson production, but with the present exposure of IC-9, this prompt component is negligible and it is presently neglected.

III. RESULTS

Data acquired from the IC-9 detector in 2006 between June and November has been searched for up-going neutrino candidates. The search proceeds by a series of cut levels intended to remove down-going events as shown in Table I. Initially, hit cleaning is applied which removes all DOM hits which fall out of a 4 μs time window, and all DOM hits without another DOM hit within a radius of 100 meters and within a time of 500 ns. After hit cleaning, we retrigger, insisting that at least 8 DOM hits survive hit cleaning. Simple first-guess reconstruction algorithms running at the South Pole were used to filter out clearly down-going events. Events with fewer than 11 DOMs hit were also filtered to meet bandwidth constraints from the South Pole. The remaining events were transmitted to the data center in the northern hemisphere via satellite and constitute the filter level of the analysis. At the data center, we reconstructed the direction of events using a maximum-likelihood technique similar to the AMANDA muon reconstruction [12]. Events which were reconstructed as down-going were discarded. Despite the fact that remaining events appear up-going, the data is still dominated by misreconstructed down-going events. These down-going events are removed by additional quality cuts. Events which pass these quality cuts constitute the neutrino candidate data set.

Simulated events fall into the three categories shown in Table I. “Single shower” events arise from single cosmic-ray air showers in the atmosphere above IceCube and result in a single muon or bundle of collinear muons in IC-9. “Double shower” events come from two uncorrelated air showers which happen to occur within the 5 μs event window. The CORSIKA [13] air shower simulation program was used for the simulation of down-going single and double air shower events. Finally, “atmospheric neutrino” events are muon neutrino events from pion and kaon decay in air showers in the northern hemisphere. The atmospheric neutrino model of [14] and its extension up to TeV energies [15] as well as the cross section parametrization of [16] were used to model the up-going muon rates due to atmospheric neutrinos.

The events which are reconstructed as up-going are completely dominated by down-going muons from single and double-shower cosmic-ray events. Misreconstructed events are typically of low quality as measured by two parameters, the number of direct hits \( N_{\text{dir}} \), and the direct length \( L_{\text{dir}} \). A direct hit is a photon arrival in a DOM which is detected between −15 and +75 ns of the time expected from the reconstructed muon with no scattering. \( N_{\text{dir}} \) is the total number of direct hits in an event. The direct length \( L_{\text{dir}} \) represents the length of the reconstructed muon track along which direct hits are observed. An event with a large number of direct hits and a large direct length is a better quality event because the long lever arm of many unscattered photon arrivals increases confidence in the event reconstruction. The strength of the quality cuts can be represented by a dimensionless number \( S_{\text{cut}} \) which corresponds to cuts of \( N_{\text{dir}} \geq S_{\text{cut}} \) and \( L_{\text{dir}} > 25 \cdot S_{\text{cut}} \) meters. In addition to these quality cuts, we impose a cut requiring that events have no more than 46 DOMs hit, which eliminates only about 1% of the final event sample. The purpose of this cut is to leave the high-multiplicity data blinded for an anticipated search for a high-energy diffuse neutrino flux. Figure 1 shows how many events remain as we turn the cut strength up and increase the signal-to-noise ratio. The accurate simulation of misreconstructed down-going events requires excellent modeling of both the depth-dependent ice properties and DOM sensitivity. In this initial study we observe a 60%–80% rate discrepancy for misreconstructed events up to a cut level of about \( S_{\text{cut}} = 8 \) or so. Nevertheless, over more than 4 orders of magnitude, the background simulation tracks the data, the number of wrongly reconstructed tracks is reduced, and for \( S_{\text{cut}} \geq 10 \), the data behaves as expected for atmospheric neutrinos. From simulation, we expect neutrinos with energies be-

<table>
<thead>
<tr>
<th>Criterion satisfied</th>
<th>Data</th>
<th>Single shower</th>
<th>Double shower</th>
<th>Atmospheric neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger level</td>
<td>124.5</td>
<td>124.5</td>
<td>1.5</td>
<td>6.6 \times 10^{-4}</td>
</tr>
<tr>
<td>Filter level</td>
<td>6.56</td>
<td>4.96</td>
<td>0.45</td>
<td>3.7 \times 10^{-4}</td>
</tr>
<tr>
<td>Up-going (( S_{\text{cut}} = 0 ))</td>
<td>0.80</td>
<td>0.49</td>
<td>0.21</td>
<td>3.3 \times 10^{-4}</td>
</tr>
<tr>
<td>Up-going (( S_{\text{cut}} = 10 ))</td>
<td>1.97 \times 10^{-5} ± 0.12 \times 10^{-5}</td>
<td>—</td>
<td>—</td>
<td>1.77 \times 10^{-5} ± 0.63 \times 10^{-5}</td>
</tr>
<tr>
<td>Up-going (( S_{\text{cut}} = 10 ) and ( \theta &gt; 120 ))</td>
<td>1.19 \times 10^{-5} ± 0.10 \times 10^{-5}</td>
<td>—</td>
<td>—</td>
<td>1.42 \times 10^{-5} ± 0.51 \times 10^{-5}</td>
</tr>
</tbody>
</table>
between about $10^2$ and $10^4$ GeV, peaked at 1000 GeV, to survive the analysis cuts.

In 137.4 days of live time we expect 211 ± 76.1(syst) ± 14.5(stat) atmospheric neutrino events to survive at $S_{\text{cut}} = 10$ and 234 events are measured. Above a zenith of 120 degrees, where the background contamination is small, we measure 142 events with an expectation of 169 ± 60.9(syst) ± 13.0(stat) due to atmospheric neutrinos. The principal systematic uncertainty in this atmospheric neutrino expectation is due to the approximately 30% theoretical uncertainty in the atmospheric flux normalization [7]. The other significant systematic error is due to uncertainties introduced by the modeling of light propagation and the detection efficiency of IceCube DOMs. The uncertainty in the atmospheric neutrino rate due to this modeling is estimated at 20% and is obtained in this initial study by examining changes in the neutrino passing rate when varying the cuts to account for the background simulation disagreement in Fig. 1.

Figure 2 shows the measured zenith distribution for the final event sample along with the atmospheric neutrino prediction. The zenith angle distribution agrees well with atmospheric neutrino simulation for vertical events above about 120 degrees. The observed excess is believed to be residual contamination from down-going single and double cosmic-ray muons. This excess disappears if we tighten the cuts beyond $S_{\text{cut}} = 10$, suggesting that the recorded events at the horizon are of typically lower quality than expected from atmospheric neutrino simulation. This reinforces the belief we are seeing residual background at the horizon. Above about $S_{\text{cut}} = 12$, with low statistics, the data at the horizon are consistent with a pure atmospheric neutrino signal. Figure 3 shows the azimuth distribution with the IC-9 geometry in the inset. The azimuth distribution has two strong peaks corresponding to the long horizontal axis of the IC-9 detector. The cut of 250 meters on event length constrains near-horizontal events that can be accepted along the short axis of IC-9 since the string spacing is 125 meters. We expect more uniform azimuthal acceptance in future seasons as the detector grows and becomes more symmetric.

FIG. 1. Data vs cut strength. Shown is the remaining number of events as the cut strength $S_{\text{cut}}$ (defined in the text) is varied. Curves are shown for the data and the total simulation prediction. Also shown is the prediction due to atmospheric neutrinos alone. The selection from the text corresponds to a cut strength of $S_{\text{cut}} = 10$, and is denoted by an arrow. At this point, the data are dominated by atmospheric neutrinos.

FIG. 2. Distribution of the reconstructed zenith angle $\theta$ of the final event sample. A zenith of 90 degrees indicates a horizontal event, and a zenith of 180 degrees is a directly up-going event. The band shown for the atmospheric neutrino simulation includes the systematic errors from the text, and the error bars on the experimental data are statistical. Note that uncertainty due to the atmospheric neutrino flux is an uncertainty in normalization and is nearly independent of a zenith angle.

FIG. 3. Distribution of the reconstructed azimuth angle $\phi$ the final event sample. The band shown for the atmospheric neutrino simulation includes the systematic errors from the text, and the error bars on the experimental data are statistical. The inset shows the horizontal locations of the strings making up IC-9 relative to the center of the future array. Note that uncertainty due to the atmospheric neutrino flux is an uncertainty in normalization and is nearly independent of a zenith angle.
We can characterize the response of the detector to neutrinos with an effective area $A_{\text{eff}}$ which is a function of neutrino energy $E$ and neutrino zenith angle $\theta$. The function $A_{\text{eff}}(E, \theta)$ is defined as the function which satisfies

$$R = \int dE \int d\Omega \cdot \Phi(E, \theta) \cdot A_{\text{eff}}(E, \theta),$$

where $\Phi(E, \theta)$ is an arbitrary diffuse neutrino flux and $R$ is the corresponding rate of events surviving analysis cuts. Figure 4 shows the effective area of IC-9 to neutrinos with the event selection $S_{\text{cut}} = 10$, both for neutrinos near the horizon and for nearly vertical neutrinos. The effective area to neutrinos is much smaller than the geometrical area of the detector, due to the smallness of the neutrino cross section. Above $10^5$ GeV, the Earth starts to become opaque to neutrinos, and the highest energy up-going neutrinos can only be detected at the horizon.

IV. CONCLUSIONS

In 2006, IceCube was approximately 10% deployed and acquiring physics-quality data. Atmospheric neutrinos serve as an irreducible background to astrophysical neutrino observation, as a guaranteed source of neutrinos for calibration and verification of the detector, and may be studied as a probe of hadronic interactions at energies inaccessible to terrestrial labs. In the first 137.4 days of live time we have identified 234 neutrino candidates with the IC-9 detector. For events above 120 degrees, this neutrino sample is consistent with expectations for a pure atmospheric neutrino sample. Selection of events was done within six months of the beginning of data acquisition, demonstrating the viability of the full data acquisition chain, from PMT waveform capture at the DOM with nanosecond timing, to event selection at the South Pole and transmission of that selected data via satellite to the north. During the 2006–2007 season, 13 more strings were deployed, bringing the total number of strings for the InIce detector to 22. The deployment of IceCube will continue during austral summers until 2010–2011, while the integrated exposure of IceCube will reach a km$^3$ · year sometime in 2009.

ACKNOWLEDGMENTS

We acknowledge the support from the following agencies: National Science Foundation–Office of Polar Program, National Science Foundation–Physics Division, University of Wisconsin Alumni Research Foundation, Department of Energy, and National Energy Research Scientific Computing Center (supported by the Office of Energy Research of the Department of Energy), the NSF-supported TeraGrid system at the San Diego Supercomputer Center (SDSC), and the National Center for Supercomputing Applications (NCSA); Swedish Research Council, Swedish Polar Research Secretariat, and Knut and Alice Wallenberg Foundation, Sweden; German Ministry for Education and Research, Deutsche Forschungsgemeinschaft (DFG), Germany; Fund for Scientific Research (FNRS-FWO), Flanders Institute to encourage scientific and technological research in industry (IW1), Belgian Federal Office for Scientific, Technical and Cultural affairs (OSTC); the Netherlands Organization for Scientific Research (NWO); M. Ribordy acknowledges the support of the SNF (Switzerland); A. Kappes and J. D. Zornoza acknowledge support by the EU Marie Curie OIF Program.