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Atmospheric muon neutrino analysis with IceCube

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Abstract: The heart of the IceCube neutrino observatory is a cubic kilometer Cherenkov detector being constructed in the deep ice under the geographic South Pole. IceCube is sensitive to high-energy muon neutrinos and muon anti-neutrinos by detecting the secondary muon produced when the neutrino interacts in or near the instrumented volume. The principal source of muon neutrinos are neutrinos from the decay of hadrons in cosmic-ray air showers. IceCube operated during 2006 with 9 out of 80 anticipated strings in the ice. I will demonstrate that IceCube can find and reconstruct atmospheric neutrinos with high efficiency.

Introduction

The IceCube neutrino detector [1] is partially deployed at the geographic South Pole. In 2006, the deep-ice detector consisted of 540 light-sensitive Digital Optical Modules (DOMs), arranged 17 meters apart on 9 strings of 60 DOMs each. The detector in this configuration is termed IC-9. The strings are arranged on a hexagonal grid and spaced 125 meters apart. DOMs are deployed in the deep ice between 1.5 and 2.5 kilometers below the surface. Figure 1 shows the location of strings making up the IC-9 array along with the relative position of the AMANDA detector.

IceCube is sensitive to muon neutrinos (and anti-neutrinos) by observing the Cherenkov light from the secondary muon produced when the neutrino interacts near the detector volume. Atmospheric neutrinos, formed in the decay of mesons resulting from a cosmic ray striking the atmosphere, dominate. Since atmospheric neutrinos are relatively well-understood [2], they serve as a verification and calibration tool for the new detector. Muons from neutrino interactions are separated from muons produced in cosmic rays by selecting muons moving upward through the detector. These muons must be the result of a neutrino interaction since neutrinos are the only particle that can traverse the Earth without interacting.

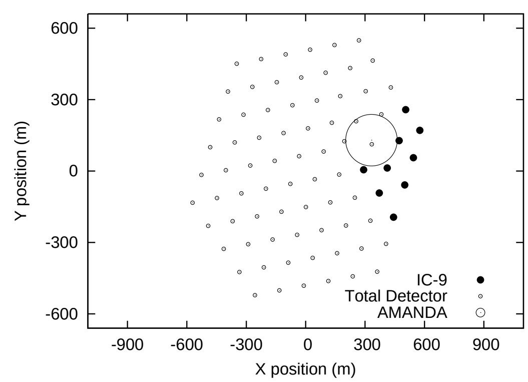

Figure 1: Shown are the locations of strings for the 2006 IC-9 detector, and the location of the strings in the completed detector.

In 2006, we acquired 137.4 days of livetime with IC-9 suitable for analysis. The waveform capture in a DOM was triggered whenever the DOM detected a signal above a threshold of about 0.3 photoelectrons. The DOMs were operated in Local Coincidence (LC) with their neighbors, meaning that a triggered DOM's waveform was only transmitted to the surface if an adjacent DOM on the string also triggered within ± 1000 ns.

Data Acquisition, Filtering and Event Selection

The surface data acquisition system set off a trigger if 8 or more DOMs were read out in 5 μs. When an event is formed, all DOM hits were read out within $\pm 8\mu s$ around the trigger window.

Because of limited bandwidth between the South Pole and the data center in the North, the data is filtered in real time, and only candidates for up-going events are sent North.

Hit cleaning algorithms were applied to the triggered events to remove light from additional suprious muons, and to remove noise hits. The photon arrival times are determined by a fit to the DOM waveform, with a variable number of photon arrivals. The hit cleaning isolated the 4 μs window in which the most hits occur, and remaining DOM hits are kept only if another DOM hit occured within a radius of 100 meters and within a time of 500 ns. At the pole, simple first-guess algorithms were used to reject events that were down-going. Events with fewer than 11 DOMs hit were rejected to limit the data volume. This filter reduced the data rate by approximately 95%. The remaining events were transmitted to the data center via satellite for further study.

In the North, we reconstructed the direction of events using a maximum-likelihood technique similar to the AMANDA muon reconstruction [3]. Only the earliest arrival times were used for reconstruction and no amplitude information was included in this analysis. The likelihood function is based on a parametrization of the photon arrival time distribution. The likelihood function is formed with an analytic approximation to the photon arrival time probability density function, accounting for the short ($\sim$ 20 meter) scattering length of light in IceCube. Events that reconstruct as down-going are discarded. Despite the fact that remaining events appear up-going, they are in fact dominated by mis-reconstructed down-going events. These mis-reconstructed events are removed with quality cuts and the remaining events constitute the neutrino candidate dataset.

The quality cuts are based on direct hits in the detector. Direct hits are those which arrive between $-15ns$ and $+75ns$ from the time expected from unscattered Cherenkov photons radiated from the reconstructed muon. We cut both on the number of recorded direct hits N_{dir} and the largest distance of such hits along the track, L_{dir}. An event with a large N_{dir} and a large L_{dir} is a better quality event because the long lever arm of many unscattered photon arrivals increases confidence in the event reconstruction.

We can fold these two cuts together into one dimensionless number, the cut strength S_{cut} which corresponds to cuts of $N_{dir} \geq S_{cut}$ and $L_{dir} > 25 \cdot S_{cut}$ meters.

Table 1 shows the rates of events passing to the different levels of the analysis, for both experimental data and simulated events. Simulated events fall into three categories. 'Single shower' events are events from single air-shower events in the atmosphere above the detector. 'Double shower' events come from two uncorrelated air showers. Finally 'atmospheric neutrino' events come from π and K decay in the air showers in the Northern hemisphere. The CORSIKA air-shower [4] simulation was used to model down-going air shower events. An extension to high energies [5] for the atmospheric neutrino model of [2] with the cross-section parametrization of [6] was used to determine the expected up-going muon rate. In estimating the systematic error, we have included a 30% uncertainty in the atmospheric neutrino flux modeling [7], and a 20% uncertainty due to uncertainties introduced in the modeling of the depth-dependent ice properties and the DOM detection efficiency.

Results

Figure 2 shows the number of up-going events remaining as we tighten cuts. The contribution of the data is shown together with the expectation for atmospheric neutrinos and the total simulation prediction. Below a cut strength of about $S_{cut} = 10$, the data is dominated by mis-reconstructed down-going cosmic-ray shower muons. For higher cut strengths, we have removed most of these mis-reconstructed events and are dominated by atmospheric neutrinos. The accurate simulation of the mis-reconstructed muon population requires excellent modeling of the depth-dependent ice proper-

Criterion Satisfied	Experimental Data	Single Shower	Double Shower	Atmospheric Neutrinos
Trigger Level	124.5	124.5	1.5	6.6x10^{-4}
Filter Level	6.56	4.96	0.45	3.7x10^{-4}
Up-going ($S_{cut} = 0$)	0.80	0.49	0.21	3.3x10^{-4}
Up-going ($S_{cut} = 10$)	$(1.97 \pm 0.12) \cdot 10^{-5}$	-	-	$(1.77 \cdot \pm 0.63) \cdot 10^{-5}$
Up-going ($S_{cut} = 10$ and $\theta > 120$)	$(1.19 \pm 0.10) \cdot 10^{-5}$	-	-	$(1.42 \cdot 0.51) \cdot 10^{-5}$

Table 1: Event Passing Rates (Hz). Shown are the event passing rates through different processing levels for the simulated event categories and for experimental data. The trigger level comprises the events triggering the detector after hit cleaning and re-triggering. The filter level comprises events which passed the online filtering conditions. Rates are also shown for events which reconstruct as up-going with and without the final quality cuts applied (see the text for cut definition). Note that the rates from air-shower events have been multiplied by 0.90 so that the simulation and data agree at trigger level. This is consistent with an approximately 20% uncertainty in the absolute cosmic-ray flux. For the final sample, statistical errors are given for the data and systematic errors are given for the atmospheric neutrino simulation.

ties and DOM sensitivity. In this initial study, we observe a 60%-80% discrepancy between data and simulation for mis-reconstructed muons. Nevertheless, over four orders of magitude, the background simulation tracks the data, and we see a clear transition to a population dominated by atmospheric neutrinos.

Figure 3 shows the expected energy distribution of simulated atmospheric neutrino events surviving to $S_{cut} = 10$. The lower threshold of about 100 GeV is set by the range of the secondary muons, and the dropoff at high energies is due to the decreasing flux of atmospheric neutrinos.

Figure 4 shows the zenith angle distribution for events which survive at $S_{cut} = 10$. Above 120 degrees, for vertical events, we have good agreement between experimental data and atmospheric neutrino simulation. The excess at the horizon is believed to be residual air-shower muon events. This belief is reinforced by the fact that excess data at the horizon is typically of lower quality (as measured by N_{dir}, L_{dir} and the number of hit DOMs) than expected from atmospheric neutrino simulation. The data above the horizon agrees well in these variables with a pure atmospheric neutrino expectation.

In the recorded 137.4 days of livetime we measure 234 events surviving to $S_{cut} = 10$, compared to an expectation of $211 \pm 76(syst.) \pm 14(stat.)$ events

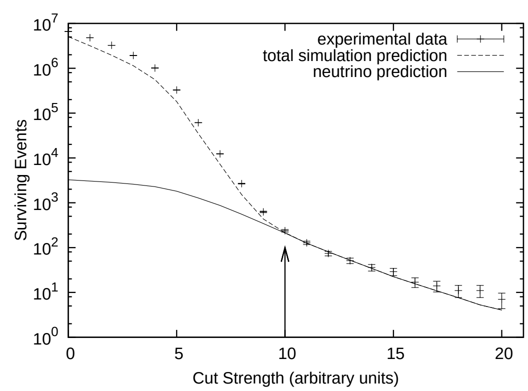

Figure 2: Data vs Cut Strength. Shown is the remaining number of events as the cut strength S_{cut} (defined in the text) is varied. Curves are shown for the data and the total simulation prediction. Also shown is the prediction due to atmospheric neutrinos alone. The selection from the text corresponds to a cuts strength of $S_{cut} = 10$, and is denoted by an arrow. At this point, the data are dominated by atmospheric neutrinos.

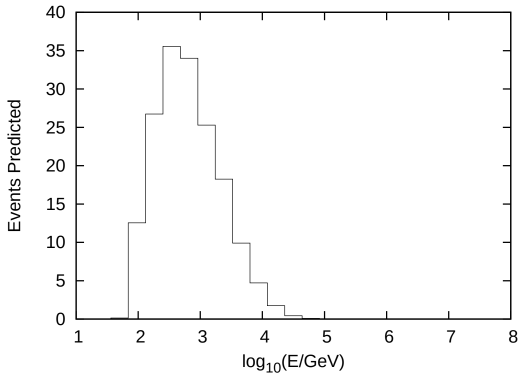

Figure 3: The distribution of neutrino energy for events surviving the analysis cuts, as determined by the atmospheric neutrino simulation.

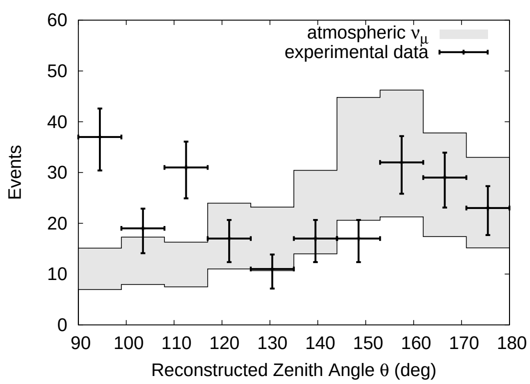

Figure 4: Distribution of the reconstructed zenith angle θ of the final event sample. A zenith angle of 90 degrees indicates a horizontal event, and a zenith of 180 degrees is a directly up-going event. The band shown for the atmospheric neutrino simulation includes the systematic errors; the error bars on the data are statistical only.

from a pure atmospheric neutrino signal. Above a zenith of 120 degrees, where the background contamination is small, we measure 142 events with an expectation of $169 \pm 60(syst.) \pm 13(stat)$ events.

Conclusions

IceCube is partially deployed and acquiring physics-quality data. During the 2006 season, we accumulated 137.4 days of livetime and observe an atmospheric neutrino signal consistent with expectation. We have identified 234 neutrino candidate events. For zenith angles above 120 degrees, the background from misreconstructed muons is small and the sample is dominated by atmospheric neutrinos. The 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.

Acknowledgments

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