Detection of Cascades induced by Atmospheric Neutrinos in the 79-string IceCube Detector

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Abstract. Neutrino production and oscillation physics can be studied by utilizing the very high flux of atmospheric neutrinos observed with IceCube. In a Cherenkov medium such as ice, atmospheric muon neutrino interactions create tracks while cascades (showers) are produced by atmospheric electron neutrinos and by neutral current interactions of all flavors. We present the first detection of atmospheric neutrino-induced cascades at energies between 30 GeV and 10 TeV using the DeepCore array of the IceCube detector. Using 281 days of data, 1029 events are observed with 59% predicted to be cascades.

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High energy neutrino telescopes, like the IceCube neutrino observatory are sensitive to all active flavors of neutrinos. The detector, using the deep Antarctic ice sheet as a Cherenkov medium, observes many atmospheric ν_μ-induced muons through charged current (CC) interactions in the ice at energies as high as 400 TeV [1]. However, searches for atmospheric ν_e CC, ν_τ CC, and all-flavor neutral current (NC) interactions have so far only resulted in upper limits for the flux [2, 3]. The main signature for these interactions is a compact shower, producing a roughly spherical light distribution, called a "cascade." We report the observation of atmospheric cascades in IceCube, using the first data with the DeepCore low-energy extension at energies between 30 GeV and 10 TeV. At these energies, the cascade detection channel is well suited for studying kaon production in air showers and detecting neutrino oscillation signatures such as $\nu_\mu \to \nu_\tau$.

DeepCore takes advantage of compact sensor spacing, high quantum efficiency photomultiplier tubes, deployment in the clearest ice, and a lower trigger threshold than the surrounding IceCube detector to observe neutrinos as low as 10 GeV [4]. In this analysis, we consider the data collected between May 31, 2010 and May 13, 2011. The IceCube detector consisted of 79 strings where the DeepCore subarray was defined as six densely instrumented strings optimized for low energies [4] and the seven adjacent standard strings. This fiducial volume contains 454 digital optical modules (DOMs) deployed at depths below 2100 m. The raw data, after applying quality criteria (90% of data retained), is composed of light signals ("hits") in the DOMs. The hits are collected in two modes - with and without a local coincidence (LC) requirement on signals in neighboring DOMs. Details of the LC logic can be found in Ref. [5]. With cuts designed to remove noise hits, the extra non-LC hits enhance reconstruction, background rejection,

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and particle identification especially for the lowest energy events.

A low threshold trigger, requiring minimum three LC hits within a time window of 2500 ns, is applied in the fiducial region. A special filter is run on the triggered event sample at the South Pole to reject cosmic-ray muons which penetrate the fiducial region, resulting in a passing rate of 17.5 Hz. A factor of 10 reduction in data compared to the triggered events is achieved by this algorithm while maintaining 99% of the atmospheric neutrinos that interact in the fiducial volume. The filtered data are sent north for further processing. The details of the trigger and filter algorithms are in Ref. [4].

Atmospheric neutrinos are the decay products of charged pions, kaons, and muons created in cosmic-ray interactions with nucleons in the atmosphere. At high energies, above $\sim$100 GeV, atmospheric ν_e are produced mainly by semileptonic kaon decays like $K^+ \rightarrow \pi^0 e^+ \nu_e$ mode. The muons from meson decays with higher energies are more likely to interact before they decay, not producing ν_e in the atmosphere. Thus, ν_e production is highly suppressed compared to ν_μ [6]. The theoretical uncertainties associated with the ν_e flux are large due to the model uncertainties in the kaon production and the lack of ν_e measurements at these energies [7, 8].

The backgrounds for the atmospheric ν-induced cascades consist of cosmic-ray muons that mimic signal events and ν_μ CC events with low energy muons. The cascade analysis identifies the topology of the light pattern and enforces containment of the signal to reject those backgrounds. Veto techniques in the DeepCore fiducial volume remove more than six orders of magnitude of the background events while retaining reasonable efficiency for atmospheric ν-induced cascades [9]. Following the veto step, the background rejection is performed in three stages, each with a Boosted Decision Tree (BDT) [10]. The first stage is formed from five variables that characterize cascade signals in the detector and are built from the spherical hit pattern, localized time structure, and quick charge deposition. This selection reduces the data rate to 0.1 Hz, a factor of $\sim$1800 with respect to the trigger. The simulation predicts the atmospheric ν_e rate at this stage to be 6.2×10^{-4} Hz, corresponding to 63% efficiency with respect to the trigger. In the next stage, we carry out more sophisticated likelihood reconstructions on the reduced dataset, utilizing the scattering and absorption of Cherenkov photons in the ice [11]. From these reconstruction results, a seven variable BDT is formed and its selection reduces the atmospheric muon background to 5.0×10^{-4} Hz, rejecting an additional factor of 200 (3.6×10^5 cumulatively) and retaining $\sim$40% of the ν_e signal (2.6×10^{-4} Hz) compared to the first stage. At the final stage, tight cuts are made on the previous sample which contains a large fraction of atmospheric neutrinos. The cuts aim for high purity cascade detection by rejecting ν_μ CC events where possible. The background rejection techniques are discussed in more detail in Refs. [9, 12].

We observe in total 1029 events in 281 days of data and expect 651 (550) cascades and 455 (415) tracks from simulations using the Bartol (Honda) atmospheric neutrino model [13, 14]. The observation is consistent with either model, as shown in Fig. 1. Approximately half of the cascades are predicted to be ν_e events and the other half ν_μ NC events. The residual ν_μ CC background events have short outgoing muons with simulations indicating a median track length of 80 m where the tracks are not easily detected. In the currently available 28 hours of atmospheric muon simulation, no events remain. The 90% upper limit on this prediction is 554 events in 281 days. The simulated statistics are being increased. Note that neutrino oscillations of $\nu_\mu \rightarrow \nu_x$ have a small

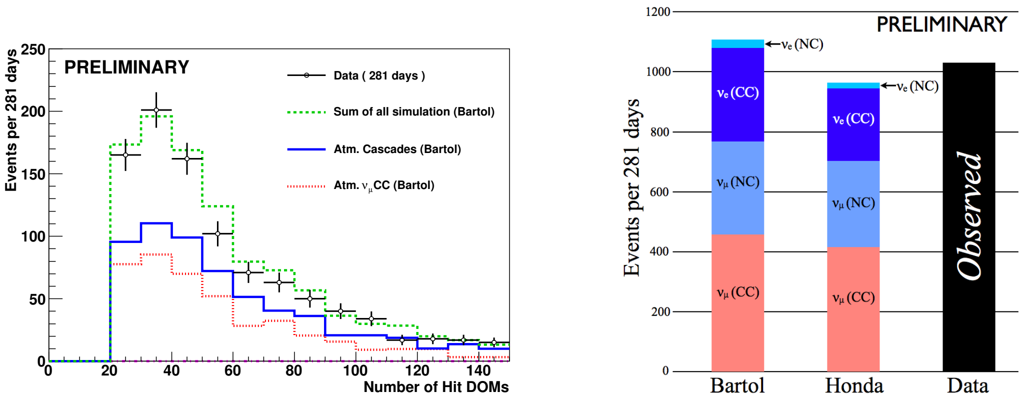

FIGURE 1. The event rate as a function of the number of hit DOMs (left). The total simulated rate is consistent with the measurement from 281 days of data. Errors are statistical only. The bar histogram (right) shows simulation predictions for different interactions with two atmospheric flux models (Bartol [13] and Honda [14]) and the observed data rate.

(<3%) effect due to relatively high energy of the cascades ($< E_\nu > \sim 180$ GeV). The rate predicted by the Honda model is lower than that from the Bartol model because the two models treat the normalization of the cosmic-ray spectrum and the kaon production in the atmosphere differently [6, 8]. Systematic uncertainties are not included.

We have reported on the observation of atmospheric neutrino-induced cascade events in IceCube. The observations are consistent with models of atmospheric neutrinos between approximately 30 GeV and 10 TeV. Systematic errors arise from light sensitivity of DOMs, ice modeling, cosmic-ray composition, neutrino-nucleon cross section, and atmospheric neutrino flux model. The background contamination from atmospheric muons and systematic uncertaities are currently under evalution. We expect results using a similar veto technique, aiming at neutrino oscillation measurements and WIMP dark matter searches in near future.

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