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Recent Results from IceCube

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The IceCube Neutrino Observatory is a cubic kilometer detector located at the geographic South Pole. IceCube was designed to detect high-energy neutrinos from cosmic sources, and the DeepCore extension of IceCube enables the study of atmospheric neutrino interactions down to energies of a few GeV. IceCube has detected a diffuse flux of neutrinos in the energy range from 100 TeV to several PeV, the properties of which are inconsistent with an atmospheric origin, and has also published competitive limits on atmospheric neutrino oscillation parameters and other neutrino properties. This paper presents the latest results from IceCube and prospects for future upgrades and expansions of the detector.

1. Neutrino Signals and Backgrounds in IceCube

The sources of the highest energy cosmic rays are as yet unknown. It is expected that these cosmic rays are accelerated to high energy in extreme astrophysical environments such as gamma ray bursts (GRBs), active galactic nuclei (AGNs) and supernova remnants, where strong magnetic fields and shock waves accelerate charged particles. The interaction of the accelerated particles with matter and photons would produce pions: the charged pions would decay to muons and then electrons, with an accompanying flux of neutrinos with a flavor ratio of 1:2:0 ν_e:ν_μ:ν_τ, and the neutral pions would decay to gamma rays. Although the bending of charged cosmic rays in magnetic fields makes them difficult to trace to their sources, gamma rays and neutrinos should point back to their sources. The very low flux of high energy neutrinos from distant sources requires a large detector.

The IceCube Neutrino Observatory[1] was constructed in order to detect astrophysical neutrinos from cosmic ray acceleration sites. IceCube is located at the geographic South Pole near the Amundsen-Scott research station. IceCube instruments

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*See http://icecube.wisc.edu/collaboration/authors/current for full author list and acknowledgments.

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one cubic kilometer of ice with 86 cables, called "strings", each of which contains 60 Digital Optical Modules (DOMs), deployed between 1450 m and 2450 m deep in the ice. Most of the strings are horizontally separated by 120 m. In the central DeepCore region of the detector,[2] strings are spaced horizontally at 40 − 70 m. The DOM is a glass pressure vessel containing a 10-inch photomultiplier tube (PMT), digitizing electronics, and LED flashers for calibration. Most DeepCore DOMs are equipped with high quantum efficiency (HQE) PMTs, 35% more efficient than standard IceCube PMTs. IceCube also includes a surface array, IceTop,[3] for cosmic ray air shower measurements. IceCube has been fully operational since 2011.

DOMs record light from particle interactions in the ice. The time and amplitude of signals recorded by the PMTs are used to reconstruct the direction and energy of the particles. Neutrino interactions at TeV energies are primarily Deep Inelastic Scattering (DIS), which create a hadronic cascade at the neutrino interaction vertex with an outgoing lepton. Due to scattering of photons off of dust particles in the ice, cascades look nearly spherical, but are observed by DOMs on multiple strings. In neutral current (NC) interactions, the outgoing lepton is a neutrino and the only observed signal is the hadronic cascade. Electron neutrino charged current (CC) interactions result in an electromagnetic cascade, which in IceCube is not separated from the hadronic cascade, so the energy of the two cascades is summed in analysis. Muon neutrino CC interactions result in an outgoing muon which generates light along its path, a linear signature called a "track". Most tau neutrino CC interactions result in either an electromagnetic or hadronic cascade, except in 18% of cases where the tau decays to a muon. If the tau is above about 100 TeV in energy, the cascade from the tau decay may be resolved from the initial hadronic cascade as a double cascade. At 100 TeV energies, the deposited energy resolution of cascades is 10%, but the direction resolution is only 15°. For tracks, the direction resolution is better than 1°, but the deposited energy only gives a lower limit on the energy of the muon, since the muon usually exits the detector.

The primary background for astrophysical neutrino searches in IceCube is the high rate of muons from cosmic ray air showers (about 3 kHz at trigger level). The remaining background is atmospheric neutrinos, of which a few hundred per day are observed in IceCube. The "conventional" atmospheric neutrino flux results from the decay of charged pions and kaons in air showers. Since these particles interact before decaying, the conventional atmospheric neutrino spectrum is more steeply falling than the primary cosmic ray spectrum and the expected astrophysical neutrino spectrum. An additional "prompt" neutrino flux is expected at energies above 100 TeV,[4] arising from charmed mesons. These particles decay before interacting, producing a harder spectrum. The prompt flux has yet to be observed.

2. Astrophysical Neutrinos in IceCube

Upward-going tracks in IceCube comprise a pure neutrino sample, consisting of astrophysical neutrinos and an irreducible background of atmospheric neutrinos.

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However, downgoing signals must also be considered to view the Southern Hemisphere neutrino sky. In order to select downgoing neutrinos and reject the cosmic ray muon background, the outer layers of the detector are used as a veto. Muons will deposit first light in the outermost strings or uppermost DOMs of the detector, whereas a neutrino interacting in the IceCube instrumented volume will deposit first light in an interior string. Furthermore, at least 6000 photoelectrons are required to be deposited in the detector, in order to select high energy events. These selection criteria define the High Energy Starting Event (HESE) sample. This search includes both tracks and cascades, which is advantageous since the expected neutrino flavor ratio at Earth is 1:1:1 ν_e:ν_μ:ν_τ based on a flavor ratio of 1:2:0 at the source and the standard oscillation mixing matrix, so the majority of expected signal is in the cascade channel. The first observation of astrophysical neutrinos by IceCube[5] used the HESE selection in 3 years of IceCube data. The observed events, with energies ranging from 30 TeV to 2 PeV, reject atmospheric origin at 5.7 σ. An independent search using high energy upgoing muon neutrinos (tracks only) between 191 TeV and 8.3 PeV[6] excludes atmospheric origin at 5.6 σ. Since then, IceCube has continued to update the HESE sample, results are reported here for 6 years.

82 events pass the HESE selection in 6 years (2078 days) of IceCube data.[7] Two of these events are clearly due to coincident atmospheric muons and are excluded from analysis. In this time period we expect 25.2±7.3 events from atmospheric muons, and $15.6\pm^{11.4}_{3.9}$ events from atmospheric neutrinos. The energy and zenith angle distributions of the HESE events are shown in Fig. 1. The zenith angle distribution does not show the suppression of downgoing events expected from the veto acting on cosmic ray-induced background events, so these events are consistent with astrophysical origin.

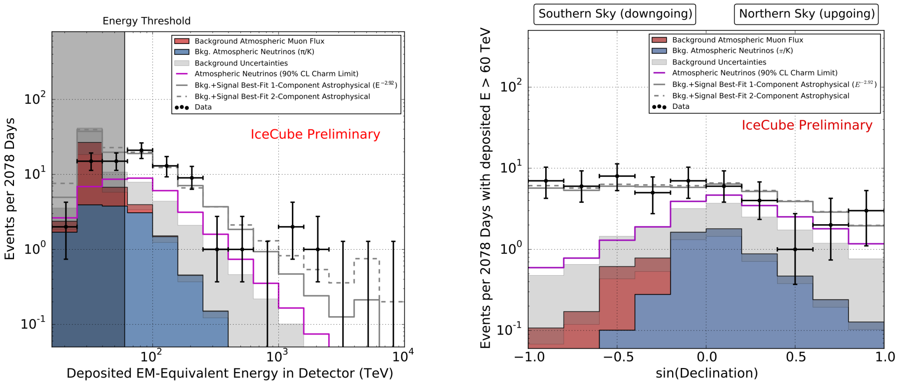

Fig. 1. The deposited energy (left) and measured zenith angle (right) of the 80 events in the 6-year HESE sample (black points) along with the predictions for atmospheric muon background (red) and atmospheric neutrino background (blue), the upper limit on the prompt neutrino flux (magenta) and the best fit single power law (solid gray line) and double power law (dashed gray line) to the events above 60 TeV.

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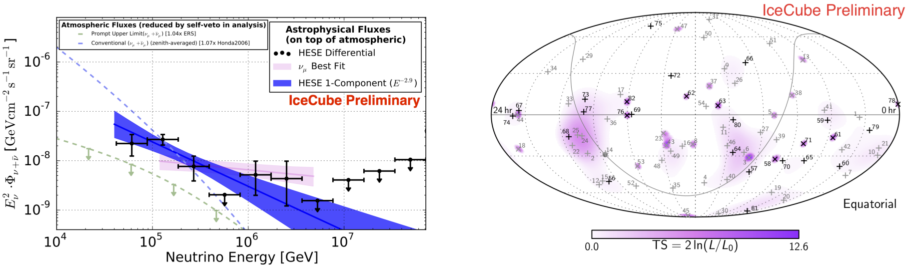

Fig. 2. Left: The best fit single power law to the HESE data, the blue region is the 1σ uncertainty on the fit. For comparison, the fit to the upgoing muon neutrino sample is shown in pink.[7] The black points are the result of a combined likelihood fit to all background components plus an astrophysical flux with an independent normalization in each bin, assuming E^{-2} spectrum. The dashed lines are the fluxes of conventional (blue) and prompt (green) atmospheric neutrinos, without the effect of the HESE veto. Right: HESE tracks (×) and cascades (+) and the test statistics from a point source clustering test at each location (pink), in equatorial coordinates.

The best fit single power law in the energy range 60 TeV – 10 PeV is $E^2\phi(E) = 2.46 \pm 0.8 \times 10^{-8}(E/100TeV)^{-0.92}\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. This is a softer spectral index than was fit to the 3-year data sample, but is still consistent with the earlier result. Figure 2 shows the best fit spectrum alongside the best fit to the high energy upgoing muon neutrino selection.[7] The fit to the upgoing muon neutrino sample has a harder spectral index than the best fit to HESE, but the results are compatible with each other within uncertainties, and there are insufficient statistics in the HESE sample to determine whether or not the data is described by a broken power law. In the near future, IceCube will perform a global fit incorporating multiple astrophysical neutrino selections in order to investigate more complex spectra than a single power law.

A skymap of the observed HESE events is shown in Fig. 2. A maximum likelihood search for neutrino point sources yielded no significant evidence for clustering, the p-value is 77% for the clustering test on all events.

As yet, no tau neutrino signature has been uniquely identified in IceCube.[8] The standard particle identification (PID) in IceCube divides events into either tracks or cascades, with no power to determine whether there is a double cascade signature as expected from a high energy tau neutrino. An investigation of the HESE sample was made wherein we adapted the IceCube likelihood fit[9] to search for double cascades.[7] A ternary PID was defined based on the results of the double cascade likelihood fit. No tau neutrino candidates were identified, with an expectation of about 2 events assuming an astrophysical neutrino flux of $E^2\phi(E) = 1.5 \pm 0.8 \times 10^{-8}(E/100TeV)^{-0.3}\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. which is drawn from the upgoing muon neutrino sample. The resulting flavor ratio triangle has a best fit of 0.51:0.49:0 ν_e:ν_μ:ν_τ, which is shown in Fig. 3. This is still statistically compatible with expectation; non-observation of tau neutrinos corresponds to a p-value of 9.3%.

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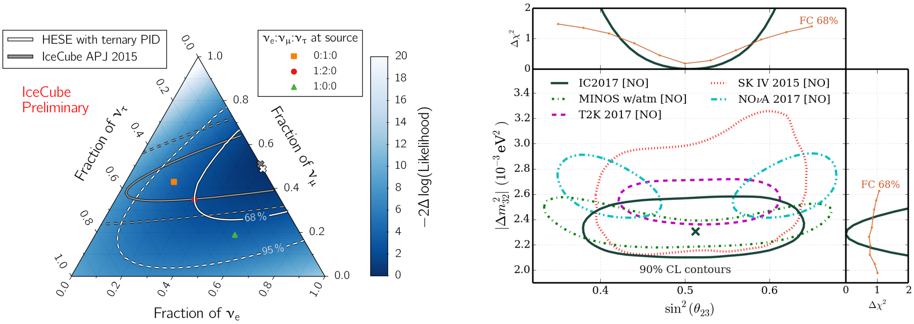

Fig. 3. Left: Flavor ratio triangle showing previously published results[10] (white) and results using the HESE sample with ternary PID applied (gray). The x marks the best fit point and 68%(solid) and 95% (dashed) contours are shown. The expected neutrino flavor in IceCube based on a 1:2:0 ν_e:ν_μ:ν_τ ratio at the source is marked with a red circle, expectations are also shown from 0:1:0 (orange square) and 1:0:0 (green triangle) ratio at source. Right: The 90% confidence level contours on the atmospheric oscillation parameter measurements from IceCube, MINOS,[11] T2K,[12] NOνA[13] and Super-Kamiokande.[14]The 1-D projections are shown in the outer plots.

3. Atmospheric Neutrino Oscillation

Although atmospheric neutrinos are an irreducible background to astrophysical neutrino searches, they are a useful source for studying neutrino oscillation physics, with different energies, baselines and systematic uncertainties than long baseline accelerator experiments. The muon neutrino survival probability is proportional to $sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$ where Δm_{32}^2 is the mass splitting between the 2 and 3 neutrino mass eigenstates, L is the distance traveled by the neutrino and E is the neutrino energy.

The key experimental parameter, L/E, has a wide range in IceCube, with lengths ranging from 20 km for directly downgoing neutrinos to 1.3×10^4 km for directly upgoing neutrinos. For the upgoing neutrinos, the survival probability is minimal at an energy of 25 GeV. DeepCore is sensitive to neutrino interactions at energies down to 5 GeV. IceCube reconstructs the energy and direction of low energy events contained in DeepCore, using the rest of the IceCube DOMs as a veto. Events are assigned a track or cascade PID. The signature of muon neutrino disappearance is a deficit of upgoing track-like events compared to the no-oscillation hypothesis. A smaller deficit appears in cascade-like events due to disappearance of muons with short tracks which are identified as cascades.

IceCube measured the atmospheric muon neutrino disappearance signal at energies between 6 and 56 GeV in 3 years of IceCube data.[15] The best fit atmospheric neutrino oscillation parameters, assuming normal mass ordering, are $\Delta m_{32}^2 = 2.31^{+0.11}_{-0.13} \times 10^{-3}$ eV^2 and $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$. The 90% confidence level contours are shown in Fig. 3, along with results from other experiments. IceCube's results are consistent with other experiments, and complementary due to the different neutrino energies and systematic uncertainties.

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4. IceCube-Gen2

Determining the point sources of neutrinos will require more statistics and a larger detector. The future of IceCube is envisioned as the IceCube-Gen2[16] detector which consists of a widely spaced array of strings surrounding the original IceCube detector, with a large surface veto array in order to improve acceptance of downgoing signals and lower the detection threshold energy in the Southern sky. DeepCore will be upgraded with a denser infill which is optimized for low energy neutrino detection, with sufficient sensitivity to determine the neutrino mass ordering (NMO). We are investigating updated sensor designs with multiple PMTs and new calibration devices to better determine the optical properties of the ice.

5. Summary

IceCube has measured a diffuse flux of astrophysical neutrinos, in multiple event selections. The sources are as yet unknown, but HESE tracks and throughgoing high energy tracks are already being sent as public alerts for follow up by other telescopes[17] as part of a multi-messenger astrophysics program. In the near future, the astrophysical neutrino search will extend to lower energies and uncontained cascades, and combined fits of multiple astrophysical neutrino event selections are in progress. IceCube has also made competitive measurements of atmospheric muon neutrino disappearance. Measurements of atmospheric tau neutrino appearance are in progress, and calibration continues to be updated in order to reduce systematic uncertainties. Studies for the next generation IceCube detector, IceCube-Gen2, are in progress.

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