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Extremely high energy neutrinos in six years of IceCube data

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Abstract. The IceCube neutrino observatory is capable of detecting ultra-high-energy cosmic neutrinos even above PeV – EeV energies. These extremely high energy (EHE) neutrinos ($\geq$ 10 PeV) are produced from interactions of the most energetic cosmic rays ($\geq$ 1 EeV) and ambient photons/matter in the sources or diffuse photon fields such as the cosmic microwave background. Therefore, observations of these EHE neutrinos can be used to probe the origin of the highest energy cosmic rays with energies extending up to 100 EeV. We present the results of an updated analysis of the EHE neutrino sample with energies greater than $\sim$ 1 PeV in 6 years of IceCube data (3 years of partially completed IceCube data (2008-2011) and 3 years of completed IceCube data (2011-2014)). While one event depositing an energy of 770$\pm$200 TeV was observed, it is incompatible with a hypothesis of cosmogenic origin. The resultant improvement in the upper limit corresponds to a factor of more than 2.5 from the previous study of two years of data from the nearly completed IceCube detector. Our limits disfavor the parameter space of sources of ultra-high-energy cosmic rays for which the cosmological evolution is stronger than the star formation rate, where the source candidate classes of active galactic nuclei (AGN) and gamma-ray bursts (GRB) belong, assuming the cosmic-ray composition is proton dominated. Results from a 7-year data analysis by adding another year's worth of data to the current sample are also anticipated soon.

1. Introduction

Astrophysical neutrinos are expected to result from interactions of ultra-high-energy cosmic rays (UHECRs) with surrounding photons and/or matter. These neutrinos, which are undeflected in galactic and extra-galactic magnetic fields and unattenuated in the photon-filled universe, play an important role as information carriers for hard-to-identify cosmic accelerators. Moreover, cosmogenic neutrinos [1], also known as GZK neutrinos, which result from interactions of the highest energy cosmic rays with background photons in the Universe [2], are expected to be present in the energy region above $\sim$10 PeV, together with neutrinos resulting from interactions in the source. These neutrinos are some of the most promising information carriers from the high-energy, distant universe with energies beyond a PeV. They can provide direct evidence of the highest-energy cosmic-ray sources. However, since the expected flux levels of these high-energy neutrinos are so low, a very large-scale neutrino detector is required. IceCube is a cubic kilometer scale deep underground Cherenkov neutrino detector at the South Pole. The IceCube detector construction was completed in December 2010. The array comprises 5160 optical sensors on 86 cables, called strings, over a 1 km^3 instrumented volume of ice at a depth of 1450-2450 m. Additional optical sensors frozen into tanks located at the surface near the top of each hole

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constitute an air shower array called IceTop. From 2008-2009, 2009-2010 and 2010-2011, 40, 59, and 79 cables out of 86 were deployed and were taking data with an approximate fiducial volume of 0.5, 0.7, and 0.9 km^3, respectively. Since 2011, IceCube has been recording data with the fully completed array. The analysis described here used data taken between 2008 and 2014. The previous search for cosmogenic neutrinos was performed with 2 years' worth of data, in which data from the first year was obtained with 79 strings and that from the second year was recorded with the full array. While two PeV events were discovered by the search [3], no cosmogenic neutrinos were observed [4] and stringent limits were placed on cosmogenic neutrino model fluxes. It was shown that astrophysical objects with populations following a strong cosmological evolution, such as Fanaroff-Riley type II radio galaxies, are unlikely to be sources of the highest energy cosmic rays. We present the preliminary results of an analysis searching for neutrinos with energies above a PeV using 6 years of IceCube data recorded between April 2008 and May 2014 with an effective livetime of 2050 days.

2. Cosmogenic neutrino events in IceCube

Cosmogenic neutrino fluxes are, to first order approximation, characterized by broken power laws above a few PeV. A hard power-law spectrum (a spectral index of ~ -0.7) is expected in the energy region below 100 PeV. This feature is robust against different models of the highest energy cosmic-ray sources, as it corresponds to the energy threshold of photopion production of the highest energy cosmic ray protons with well-measured cosmic microwave background photon fields. Additionally, the neutrons created in the photopion interactions decay into electron anti-neutrinos with energies around a few PeV. Some models predict an additional neutrino flux in the lower energy region around 1 PeV [5]. This contribution is highly dependent on higher-energy (infrared, optical, and ultraviolet) background photons, as well as on the transition energy between galactic and extragalactic cosmic rays. Above $\sim$1 EeV, the spectrum is expected to soften to $\sim E^{-2.0}$ until $\sim$100 EeV where the spectrum becomes even steeper depending on the assumed maximal energies of the cosmic-ray spectra at the production site. The effective experimental detection area, or the exposure of this analysis, scales approximately linearly up to $\sim$EeV energies. The cosmogenic neutrino events observable by IceCube are expected to be dominant in the energy range below a few EeV, above which a softer spectrum is expected.

When UHECRs interact with the photon field, only ν_e and ν_μ are produced. Due to flavor oscillation, $\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1 on Earth. IceCube is sensitive to all three flavors of neutrinos. The largest contribution in the detection of high-energy-neutrino-induced events above a PeV is from the "through-going muon" channel, in which muons are created by ν_μ charged current (CC) interactions outside the IceCube fiducial volume and then propagate through the detector emitting Cherenkov light from stochastic energy losses. Since average muons propagate more than 10 km above $\sim$1 PeV, the sensitivity of IceCube is extended to neutrino interactions far outside the IceCube detector volume. Similarly, the contribution from "through-going tau" tracks from ν_τ CC interactions is important in the energy range where the GZK neutrinos are expected, since the tau decay length becomes more than a few kilometers for $\geq$ 10 PeV, whereas it is a few tens of meters for PeV taus. In addition, particle showers produced at the neutrino interaction vertex position are observed as "cascade" events. Cascade events are induced by neutral current (NC) interactions of all three flavors of neutrinos as well as by ν_e CC interactions. While the cascade channel is limited to interactions occurring inside or near the IceCube detector, energy deposits of these particle showers in the detector are typically larger than those of muon or tau tracks with equal energy. There is also an interesting contribution from the Glashow resonance [6] at 6.3 PeV, which occurs when an anti-electron neutrino interacts with an electron in the Earth. This interaction results in an electron-, tau-, or hadron-induced particle shower or a muon track.

At energies above $\sim$1 PeV, the Earth is opaque to neutrinos as the neutrino-nucleon cross

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section increases with energy. Thus, extremely high energy (EHE) neutrinos above the PeV scale and their charged secondaries are able to reach IceCube only from above and slightly below the horizon. Furthermore, the topological features of neutrino-induced events change with energy in each detection channel. For instance, neutrino-induced muons exhibit increasingly stochastic energy losses at high energies. In addition, neutrino-induced tau events drastically change from spherical to track-like shapes with increasing energy, and above a few PeV electron-induced particle showers become elongated due to the LPM effect [7].

3. Signal selections

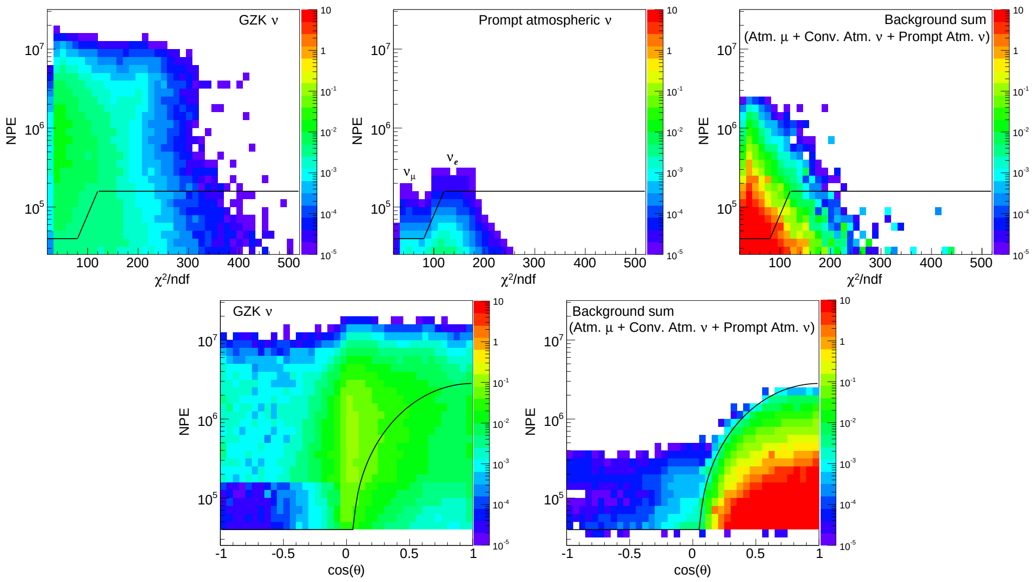

Figure 1. Event number distributions before the Level-3 cut (upper panels) and Level-4 cut (lower panels) of the sample corresponding to 2050 days of livetime. The signal distributions in the left panels are from [10], including all three flavors of neutrinos. The solid lines in each panel indicate the selection criteria, with only events falling above the lines being kept. Event distributions from different detector configurations are added. The selection criteria are constant for the samples taken in different data-recording periods. The Level-3 cut is defined as a function of NPE, the number of total photo-electrons or the sum of integrated waveforms in each event divided by single photo-electron charge, and χ^2/ndf, a fit quality parameter of the zenith angle reconstruction. Atmospheric muons in the background shown in the right panels are simulated with pure iron primary cosmic rays. In the case of pure proton primary cosmic rays, the background events are estimated to be ∼80% reduced. The upper middle plot shows the prompt atmospheric neutrino flux to be essentially eliminated by the Level-3 cut. The Level-4 cut is defined as a function of NPE and cosine of reconstructed zenith angle ($cos(\theta)$).

The primary background in this analysis consists of downward-going muon bundles made up of large numbers of muons produced by high-energy cosmic-ray interactions in the atmosphere. The secondary background is atmospheric neutrinos. Atmospheric neutrinos are produced by the decay of charged mesons produced from cosmic ray interactions with the atmosphere. In the energy region under study, prompt atmospheric neutrinos from decays of short-lived heavy mesons are considered to dominate in event rate over conventional atmospheric neutrinos from pion and kaon decay. Unlike conventional atmospheric neutrinos, which are dominated by ν_μ, prompt neutrinos are composed of approximately equal fluxes of ν_μ and ν_e. While there must be a non-zero flux of prompt atmospheric neutrinos, this has not been experimentally observed; thus, a relatively large theoretical uncertainty still remains. In the current study, the model from [8] is considered as the default model.

The majority of low-energy atmospheric-muon-induced events, typically with energies less than a few TeV, deposit relatively little energy in IceCube compared to the target neutrino induced events, and so can be removed from the sample by cutting based on the number of Cherenkov photons observed. This is accomplished by requiring that the calculated number of photo-electrons (NPE) in each event be greater than 30,000. Then the sample is subject to the "Level-3" cut, which aims to remove atmospheric neutrinos, particularly the prompt muon and electron neutrinos with a large theoretical uncertainty, and atmospheric muons whose directions are not reliably reconstructed. This was achieved by setting a higher NPE threshold for the events with a large χ^2/ndf value which is a goodness-of-fit parameter from an event reconstruction using a simple track hypothesis. The smaller χ^2/ndf value is expected for the more well-reconstructed track-like events. The "Level-4" criterion is optimized to remove well-reconstructed atmospheric muons in the downward-going directions. Figure 1 shows the event distributions together with Level-3 and Level-4 selection criteria. The atmospheric background is reduced down to the level of approximately 0.069 events per 6 years of livetime at Level-4, including 0.017 events of atmospheric muons, 0.019 events of conventional atmospheric neutrinos, and 0.033 events of prompt atmospheric neutrinos. The final "Level-5" criteria assure that there are no IceTop hits from cosmic-ray air showers associated with events by requiring the number of correlated IceTop hits to be less than two. A similar, but more detailed, analysis using the IceTop hits can be found in [9].

4. Results and summary

After the unblinding of the data, it was found that one upward-going cascade-like event with an energy deposit of 770$\pm$200 TeV is observed in 2050 days for the sample. The detection of one neutrino event, together with the non-detection of neutrino events with higher energies, is tested against the atmospheric-background-only hypothesis with a binned likelihood ratio method. The obtained p-value indicates that the atmospheric-background-only hypothesis for the event observation is rejected at 99.3% CL. Furthermore, the event observation is found to be inconsistent with the cosmogenic neutrino hypothesis with a p-value of 0.8%, while the generic signal model which follows the E^{-2} power law is compatible with a p-value of 90% with the likelihood ratio test. The expected event rates from cosmogenic neutrino models, the p-value of the test model with current observations, and the model-dependent upper limit relative to default normalization are presented in Table 1. The current analysis is sensitive to the cosmogenic neutrino model with cosmological evolution of the source following a star formation rate (SFR) for the first time. Taking the detection of one event into account, a strong quasi-differential model-independent 90% CL limit on neutrino fluxes shown in Fig. 2 is obtained assuming a 1:1:1 neutrino flavor ratio. The result indicates that the cosmogenic neutrino models with cosmological evolution of the highest energy cosmic-ray sources stronger than the SFR are disfavored, which excludes the hypothesis of active galactic nuclei and gamma-ray burst being the sources responsible for the dominant highest-energy cosmic-ray flux, assuming a dominant proton composition of these cosmic rays.

The highest-energy region performance of IceCube is expected to be sufficient for the detection of cosmological neutrinos if the highest-energy cosmic rays have proton-dominated compositions. However, the non-observation of a cosmogenic neutrino candidate event by IceCube disfavors models with cosmological evolution stronger than the SFR, and has resulted in a stringent upper limit on the neutrino flux above $\sim$10 PeV. A future analysis will include another year of data and will provide an important insight into sources of the highest energy cosmic rays.

ν Model	Event rate	p-value	Model-dependent UL
Ahlers *et al.* [10] ("best fit" 10 EeV transition)	4.2	3%	0.7
Ahlers *et al.* [10] ("maximal flux" 10 EeV transition)	8.6	0.05%	0.35
Kotera *et al.* [5] star formation rate (SFR)	2.8	16.6%	1.2
Kotera *et al.* [5] Fanaroff and Riley Class II (FRII)	11.7	0.002%	0.3

Table 1. Expected number of events from several neutrino models, p-values from the model hypothesis tests, and the 90% CL model-dependent upper limits on flux normalization relative to default model fluxes.

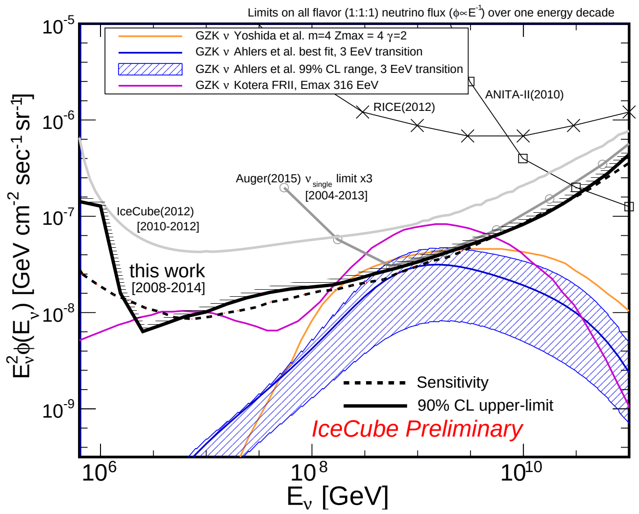

Figure 2. All flavor neutrino flux quasi-differential upper-limits and sensitivities of the IceCube detector. Several model predictions (assuming primary protons) are shown for comparison: Ahlers-*best* (the best fit, incorporating the Fermi-LAT bound) with an associated fitting error region [10], Kotera-$FRII$ [5] Yoshida-(4, 4) ((m, Z_{max}) = (4,4)) [11]. Model fluxes are summed over all neutrino flavors, assuming standard neutrino oscillations. The model independent differential upper limits by other experiments are also shown for Auger [12], RICE [13], ANITA-II [14] These limits are converted to the all flavor limit assuming standard neutrino oscillation and a 90% quasi-differential limit per one energy decade when necessary.

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