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Neutrino Physics with IceCube

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Abstract. The IceCube Neutrino Observatory is an ice Cherenkov detector under construction at the South Pole, Antarctica. When completed, the physical volume of the detector will be approximately one km^3. The Observatory will be sensitive to a number of topics in fundamental neutrino physics, such as neutrino oscillations and decay, by virtue of its ability to distinguish neutrino flavours over a wide range of neutrino energies. We present the status of the construction of the Observatory, some recent analysis results, a brief discussion of its sensitivity to fundamental neutrino parameters and planning currently underway for low and high energy extensions to the baseline array.

1. IceCube Construction Status

The IceCube Neutrino Observatory is a kilometer-scale neutrino detector currently under construction at the South Pole, Antarctica. It will surround its progenitor array, AMANDA, which has now been fully integrated into the existing IceCube detector. IceCube is optimized to detect neutrinos over a wide range in energies, from 100 GeV to 10^9 GeV.

The buried array will ultimately consist of 80 strings inserted in the polar icecap between 1450-2450m below the surface. Each string consists of 60 digital optical modules (DOMs), and each DOM comprises a photomultiplier tube, digitizing electronics, and light sources for calibration. Most of the DOM functionality is controllable from the surface. Atop each string is a pair of tanks filled with clear ice and instrumented with two DOMs. These tanks comprise IceTop, a surface air shower array that is tightly integrated with the buried array.

In-situ measurements verify that the DOMs are capable of resolving pulses with nanosecond-level precision, and that their relative timing resolution is well under the 5 ns design specification. Their dynamic range, which with timing resolution is very important for accurate ultrahigh energy neutrino reconstruction, is better than 250 photoelectrons per 10 ns.

The array is currently roughly 25% complete, with 1424 DOMs deployed on 22 strings, and 108 DOMs deployed in 52 IceTop tanks. It has been taking data for physics analysis since May, 2007. With a trigger defined as eight or more DOMs hit within a 5 μs period, events are recorded at a rate of approximately 600 Hz, corresponding to a data rate of roughly 200 GB/day. Of this, about 30 GB/day is selected by online filters running at the South Pole and transmitted north via satellite. This filtered data serves as the primary input to IceCube data analysis.

2. IceCube Analysis Results

The flux of atmospheric muon neutrinos is IceCube's "test beam" and as such one of our first measurements was of the upward-going atmospheric muon neutrino flux.[2] This measurement was performed with the 9-string IceCube array that was completed in early 2006, showing good agreement between data and simulation in a variety of distributions (e.g., azimuthal angle).

Using the same 9-string detector configuration, a point-source analysis was also performed.[3] This analysis demonstrated that the 9-string array has similar sensitivity to the existing AMANDA array for equivalent live times, an encouraging result given that the configuration of the first 9 strings is not optimal for this type of search. The most significant excess observed was consistent with random fluctuations.

3. IceCube Sensitivity to Neutrino Flavor

3.1. Lower Energy Neutrinos

At the lowest end of the energy spectrum, ν_e and ν_τ interactions are indistinguishable from one another, but it should be possible to distinguish them both from ν_μ interactions. We are working to reconstruct *vertical* muons from atmospheric ν_μ interactions for $E(\nu_\mu) \sim 25$ GeV. This energy range gives sensitivity to the dip in ν_μ survival probability that occurs at about 28 GeV in the standard neutrino oscillation scenario (with $\Delta m^2 = 2.4\text{e-}3\ \text{eV}^2$[4]). A measurement of this oscillation with IceCube will be challenging, but might be successfully performed by comparing the upward-going to downward-going contained muon fluxes as a function of muon track length while using the neutrino interaction vertex to refine the energy measurement. The measurement would constitute a confirmation of neutrino oscillations at an energy scale about an order of magnitude above existing measurements.

3.2. Higher Energy Neutrinos

At energies above about 100 TeV, IceCube may be capable of exclusively tagging all three neutrino flavors. This ability can be exploited to explore fundamental neutrino properties. Also, exclusively identified tau neutrinos offer multiple advantages in the realm of signal identification and background rejection.

At energies of 100 TeV, a tau neutrino will produce a tau lepton with a decay length of about 5 m. This can produce a distinctive double-pulse signature in a nearby DOM due to the two showers in the event: the first shower is produced at the tau neutrino interaction vertex, the second at the tau lepton decay vertex. DOMs at greater distances will detect signals consistent with those created by an electron neutrino. At higher energies, as the tau lepton decay length grows, tau neutrinos produce more distinctive signatures such as “double bangs” and “lollipops.”[5] Generally speaking, the energy range over which IceCube should be able to exclusively identify all three neutrino flavors extends from roughly 100 TeV to 1 EeV.

The standard picture for neutrino production at cosmic accelerators involves the decay of charged pions, yielding an initial neutrino flavor ratio at the production site of $\nu_e{:}\nu_\mu{:}\nu_\tau = 1{:}2{:}0$. Invoking standard vacuum neutrino oscillations over cosmological distances, the resulting flavor ratio at a detector on Earth will be 1:1:1. Unlike their electron and muon neutrino brethren, above 100 TeV tau neutrinos are not expected to be produced in atmospheric interactions in appreciable fluxes by either mixing or charm decay. Therefore, identification of tau neutrinos at any energy accessible to IceCube would be a very strong indicator of non-atmospheric, cosmological origin.

Deviations from the predicted 1:1:1 ratio might be an indicator of new astrophysics. If the source is “muon-damped” such that muons lose energy before decaying, the detected flavor ratio changes to 4:7:7.[6] If only accelerated neutrons escape the source, resulting in a pure anti-electron neutrino beam, the detected flavor ratio changes to 5:2:2.[7] The ability of IceCube to distinguish either of these scenarios from the expected 1:1:1 ratio depends, of course, on the statistics of the source flux(es) and the fraction of all sources that behaves as described.

Deviations from a 1:1:1 ratio might also be an indicator of new particle physics. For instance, neutrino decay in the context of a normal hierarchy would result in a detected flavor ratio of 6:1:1.

With an inverted hierarchy, the detected ratio becomes 0:1:1. There is no known astrophysical mechanism by which an initial flavor ratio could give either 6:1:1 or 0:1:1 ratios at the detector. [8]

4. Extensions of IceCube to Lower and Higher Energies

Studies are currently underway to assess the feasibility of extending the energy range over which the IceCube Observatory is sensitive to neutrino signals. At the low end of the scale, in the 10-100 GeV range, simulations of a new "IceCube Deep Core" detector have been encouraging. At the high end of the scale, above about 1 EeV and extending well into GZK [9] territory, prototype acoustic and radio modules have been co-deployed with IceCube strings and are currently producing test data.

4.1. IceCube Deep Core

A densely instrumented optical sub-array buried 2000-2450 m below the surface and located at the center of the existing IceCube array would provide valuable data for the study of WIMPs, atmospheric neutrino oscillations, and atmospheric electron neutrinos. It would also give IceCube better access to potential neutrino sources in the southern sky. Using standard IceCube sensors and leveraging on the surrounding IceCube array as an active veto, IceCube Deep Core ("IC-DC") would have sensitivity to low energy neutrinos over the full solid angle. IC-DC would significantly extend IceCube's sensitivity to solar WIMP annihilations by virtue of its lower energy threshold and ability to isolate solar WIMP signals even when the sun is above the horizon. The lower energy threshold would also enable IceCube to study atmospheric neutrino oscillations, with sensitivity to matter effects.

4.2. High Energy Radio and Acoustic Arrays

To detect a statistically significant sample of neutrinos produced by GZK interactions, a "guaranteed" source of ultrahigh energy neutrinos, one needs a fiducial volume about two orders of magnitude larger than IceCube, i.e., about 100 km^3. It is financially impractical to construct such a detector using optical techniques due to the scattering and absorption lengths for Cherenkov light, but Cherenkov radio and acoustic signals have attenuation lengths in ice that can be as high as 1 km, making it practical to build a sparse array that instruments a very large effective volume.

The prototype radio array consists of three clusters with four dipoles each, co-deployed with three IceCube strings. One cluster was deployed several hundred meters below the surface; the other two at about 1.4 km below the surface. Studies of the noise environment, triggering and timing are all underway. The prototype acoustic array consists of three clusters of seven stages each, co-deployed with three IceCube strings, between 80-400 m below the surface. Measurements of noise, attenuation length and refractive index are also all underway.

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