The IceCube Experiment

Yutong Du

Abstract

This research paper is focused on the IceCube experiment, a particle detector located at the South Pole. In this paper, I will discuss the motivations behind the construction of such a detector, the detector instrumentation and specifics about the detectors themselves, then discuss future plans the IceCube collaboration has lined out. I'm confined to only three pages of material, so I will only be able to a very general overview into this topic; references are at the end of the document for further reading.

1 Introduction

IceCube is a Cherenkov neutrino detector located at the south pole that completed construction in 2009. At over 2km in depth, it currently holds the title of the largest neutrino observatory in the world. Currently, research at IceCube is focused on studying cosmic rays and astrophysical neutrinos – that is, neutrinos that come from deep space rather than from the sun.

One of the primary motivations for the IceCube detector was the fact that in order to truly study high energy cosmic neutrinos, we would first need to build a kilometer-scale detector which could measure them. Traditionally, this would require a large amount of water (or other medium for detection), and consequently an enormous vessel to contain it. However, one of the main advantages of IceCube is that there is no need to build such a vessel. Instead, the ice itself acts as the medium for detection, and as a result we are able to build a significantly large detector at a relatively low cost, especially when compared to the traditional methods which require the vessel. In addition to this, building a detector at the south pole makes it a relatively isolated environment, which is great for detection purposes, since this naturally reduces the noise level and allows for more precise measurements.

2 Structure

Before building IceCube, we needed to first demonstrate that using antarctic ice as a detector was actually viable – this was the goal of the Antarctic Muon And Neutrino Detector Array, or AMANDA for short. AMANDA was a relatively small scale detector that used photomultiplier tubes (PMTs) attached to strings that penetrated deep into the ice, which detected the Cherenkov light that neutrino interactions with the ice would produce. From 2000 to 2009, AMANDA provided convincing evidence that the antarctic ice was was certainly a viable medium to make neutrino detections with – as a result of their conclusions, the experiment was then expanded dramatically into the kilometer-scale detector known today as IceCube.

While IceCube is generally used to refer to the experiment as a whole, it's important to note that IceCube is in fact only one of three main components. The other two are IceTop, which refers to the surface array, and DeepCore, a region within the detector with a higher density of PMTs. Macroscopically, the arrangement of the PMTs has not changed, only now there are many more of them and are also spread out over a very large area.

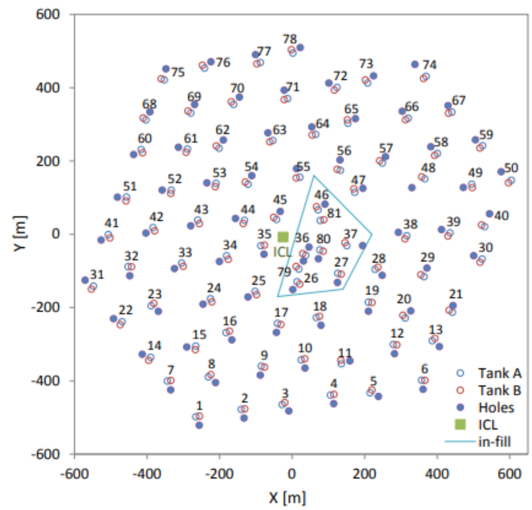

Figure 1: Schematic of IceCube Arrangement. Notice that the locations of the tanks and the holes (solid dots) which contain IceCube's detectors all follow the same grid-like pattern.

2.1 IceTop

IceTop is one of the three data-taking instruments at the IceCube detector. Completed in 2010, it focuses primarily on the detection of air showers: atmospheric particles that are created as a result of interactions between astrophysical cosmic rays and the Earth's atmosphere. It also serves as a calibration detector for IceCube. IceTop consists of an array of 81 stations located in the same grid-like arrangement that IceCube uses for their detectors (see fig. 1). Each station consists of two tanks filled with clear ice and two PMTs that detect Cherenkov light emitted by collisions from the atmospheric particles with atoms in the ice. With the capability to resolve showers with energies up to the EeV scale (10^{18} eV of energy), IceTop provides the infrastructure to look deeper into the transition between galactic and extragalactic cosmic rays, an area of active investigation. Out of the three detector components, IceTop is responsible for measuring the highest energy events.

2.2 IceCube

IceCube refers to the main underground portion of the detector, and like IceTop, it also focuses on the detection of high-energy cosmic particles. IceCube consists of 5160 PMTs [1] connected to 86 strings that are frozen into the ice. The PMTs are installed from a depth of 1450 m to 2450 m with a vertical spacing of 17 meters, making it the largest component of IceCube, and also the largest neutrino detector ever built. In terms of energy, IceCube generally measures particles in the TeV range, and very rarely at particles in the PeV range. Compared to IceTop, this is a much lower range of measurement, demonstrating the wide variety of energy ranges IceCube can detect.

IceCube collects data by analyzing the interactions between the neutrinos and the ice. When these interactions occur, other particles are created, which are then detected by the PMTs. In addition to their presence,

[1]Specifically, there are 5,160 Digital Optical Modules (DOMs), and each one of them consists of a PMT, but for simplicity's sake I skip the DOMs entirely.

IceCube is also able to determine the energy of these particles by measuring the intensity of light emitted, allowing us to reconstruct the path of the neutrino through the detector. This reconstruction process cannot be completed without time synchronization, which is accomplished at IceCube using a global clock that relays information to the detectors using copper wiring. IceCube categorizes neutrino events into two categories: track and cascades, based on the pattern of light observed from neutrino interactions. Typically, tracks are represented by an event where the photon intensity is uniform across the entire detector, whereas cascades are characterized by a large amount of photons deposited at a particular location. This is due to the different characteristic length scales for the two interactions – tracks have a length scale of several kilometers, whereas cascades are within the tens of meters.

2.3 DeepCore

DeepCore is the third and final major component at the IceCube detector. It refers specifically to a collection of 8 strings nested in the center of the array equipped with detectors spaced 7 meters apart instead of 17, allowing IceCube to lower the detection threshold to approximately 10 GeV, one order of magnitude lower than the energies IceCube can detect. DeepCore also benefits from upgraded PMTs, and also incredibly clear ice, making for the capability to make very precise measurements. Just as IceTop completes IceCube's detection capabilities for high-energy particles, DeepCore does the same but for low energy events instead.

One major benefit of this lower energy threshold is that it opens the door to new avenues of research, such as the study of neutrino oscillations and also further probing of the neutrino hierarchy. It also allows for the study of galactic supernova neutrinos – neutrinos originating from supernovae within the Milky Way – and other low-energy neutrino events (such as Gamma-Ray Burst Fireballs) in general.

3 Future Plans

IceCube records approximately 3000 events every second, which approximately amounts to 1 TB of data produced every day, of which only 100GB is sent via satellites to institutions around the world for analysis. Even so, it is physically impossible for one person (or even a team of scientists) to sift through this amount of data. Therefore, one avenue that the IceCube collaboration is currently exploring is to ask the public for assistance in classifying the types of events measured by the detector.

Not only do these community classifications inherently help researchers classify events, these classifications are also then used as training data for experimental machine learning algorithms – another avenue the team is currently exploring. This approach is not necessarily new, in the sense that the dilemma of "too much data and too little people" is one faced by many modern fields of science, and neutrino detections are no different, as its classification also relies on pattern recognition.

In addition to these efforts, there are also plans to make changes to the detector itself. In 2019, plans were made to install 750 more detectors near the DeepCore section of the detector to further increase its sensitivity; presently, it seems like this installation is still ongoing, as I haven't been able to find any sources mentioning its completion. Besides the installation of more detectors to the current IceCube array, there are also plans to further expand IceCube into a ten-cubic-kilometer detector, named IceCube-Gen2. Upon completion of Gen2, it is expected that the detector will be capable of detecting neutrinos with energies ranging from 1 GeV up to 100 EeV, safely placing it as the most versatile neutrino detector in the world.