The IceCube Neutrino Observatory - Design and Performance

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The IceCube neutrino observatory is currently under construction near the geographic South Pole. Upon completion in 2011 it will consist of two complementary parts, an in-ice array with up to 4800 digital optical modules (DOMs) and a surface array with 320 DOMs. Up to 80 strings of the in-ice detector with 60 modules per string will instrument a cubic kilometer of ice between 1450 to 2450 m depth and will enable the detection of high energy neutrinos produced in astrophysical sources or in the atmosphere. Two surface ice tanks will be installed close to the position of each string, both instrumented with two DOMs. These 160 tanks allow for cosmic ray composition studies. In addition, they are used to reject part of the background in the in-ice array and for the calibration of string modules. After describing the detector design, the performance of the currently installed 9 in-ice strings and 32 surface tanks will be discussed.

1. Introduction

High energy neutrinos are expected to be produced together with charged cosmic rays and high energy photons in cosmic objects where particles are accelerated to extreme energies, up to 10^{11} GeV. This is several orders of magnitudes higher than the energy reached by the LHC collider. Typical candidates for cosmic accelerators in our galaxy are supernova remnants and mini-blazars or active galactic nuclei in the extragalactic space. Because of interstellar magnetic fields, charged particles measured with cosmic ray detectors can not be traced back to their source. But they carry information on energy and on composition as the fraction of protons, light and heavier nuclei, allowing to develop and to prove models for cosmic charged particle accelerators.

In the past few years the high energy gamma ray telescopes H.E.S.S. and MAGIC [1, 2] have measured and investigated a large variety of cosmic objects which are now established accelerators of electromagnetic particles. Whether these sources are also hadron accelerators can be proven by measuring neutrinos produced in hadron decays.

In addition, neutrinos have the advantage that they are not affected by interactions with

cosmic background radiation which limit considerably the energy spectrum and the range of cosmic messengers as protons and gammas. However, the very small interaction cross section makes neutrino detection extremely difficult and requires very large target volumes. They can be realized with natural materials of good transparency such as water or ice. A charged current interaction of a muon-neutrino with the detector medium results in a muon with almost the same direction as the incoming neutrino. This high-energy muon irradiates Cherenkov light, which can be measured by photomultipliers. For the reduction of the atmospheric muon background, the detector is positioned deep below the surface. High energy neutrino interactions can be identified if the earth is used as background shield, i.e. one has to look for muons traversing the detector from below,

The first high energy neutrino detectors Baikal [3] and AMANDA [4] have been working successfully for about a decade. With AMANDA, more than 4000 muon-neutrino events have been measured in five years. The event sample is compatible with the hypothesis that all neutrinos were produced in the atmosphere of the northern hemisphere [5]. With the IceCube neutrino observatory a volume of 1 km^3 will be instrumented until

Figure 1. Schematic view of a Digital Optical Module.

2011. The installation started beginning of 2005.

2. Digital Optical Modules

In experiments based on the detection of Cherenkov light, photomultipliers with large photocathode and high sensitivity are required to allow single photo-electron measurements. A schematic view of the digital optical module (DOM) in Fig. 1 shows the 25 cm Hamamatsu photomultiplier R7081-02 and several electronics boards enclosed by a 35.6 cm diameter glass pressure sphere. The design was driven by the requirement that a maximum of functionality has to be realized within the DOM to obtain independent units which are able to communicate with the on-ice data acquisition system (DAQ) and with their neighbours within a string. The photomultiplier high voltage is produced internally from ± 48 Volt DC with a special HV-generator connected to the HV divider. A processor on the Main Board organizes the internal DAQ tasks as the readout of analog signals, their digitization, buffering and transfer to the surface station. The

software allows furthermore to perform internal tests and the setting of parameters and conditions. Another board is dedicated to the calibration of DOMs. It contains six horizontally flashing LEDs and six LEDs flashings upward at 46° . This allows signal time measurements with DOMs of neighbour strings or with the upper DOM within the string.

There are three DOM assembly and test sites, at DESY, at Madison and at Stockholm/Uppsala which have a common production rate of 50 DOMs per week. All sites are using identical materials, assembling tools and procedures. To guarantee a life time of about 15 years in ice, where repairs are impossible, extensive performance tests run at each site in special dark freezer labs. The quality of the photomultiplier signals and of the internal DAQ is tested in two cycles at different temperatures ($+25$, -45 , -20 , -55°C). The production efficiency is higher than the required 95%. Before installation, an additional functionality test is performed at the South Pole. In total 5200 DOMs, 4800 for IceCube and 400 for IceTop will be built and tested through 2009.

3. Detector

The IceCube neutrino telescope consists of three components, IceCube, IceTop and AMANDA as shown in Fig. 2. The installation of IceCube started with the first string in January 2005 and was continued in the last austral summer with eight additional strings. These nine strings indicated in Fig. 2 are working successfully since March 2006. Each string consists of 60 DOMs positioned at a depth between 1450 m and 2450 m with a DOM spacing of 17 m. The distance between strings is 125 m.

The major work- and cost-intensive effort is the hot water drilling of string holes. The hole drilling equipment is an improved version of the AMANDA drill and can 60 cm diameter holes in about 40 hours. With a pressure of 68 atmospheres the drill head blasts a jet of 80°C hot water into the ice. String deployment needs about 10 hours and involves the mounting of 60 DOMs, of pressure sensors and thermistors, as well as the drop of the string cable to the final depth

Figure 2. Schematic view of the IceCube neutrino observatory. The strings operating since March 2006 are indicated red. The cylinder marks the position of the AMANDA detector.

of 2450 m. Some of the strings are equipped with a dust logger to survey the quality of the ice, or with a strong laser for time calibration and event simulation. It is planned to deploy 12 strings in December 2006 and January 2007 and 14 strings per year in the following seasons. The whole detector with up to 80 strings will be ready in 2011 forming one Giga-ton of instrumented volume.

Parallel to the IceCube string deployment, two IceTop tanks will be installed close to the IceCube holes just below the snow surface. Fig. 3 gives a schematic view of a tank. It is a cylindrical container filled with water which freezes under controlled conditions to avoid air bubbles. Two DOMs are looking into the ice from above. Since March 2006, 32 tanks are measuring charged particles of cosmic air showers. High energy muons which reach the IceCube strings can be used for the calibration of both detectors and as a veto to reduce the background in IceCube. Finally in 2011, 160 tanks will be installed forming a surface array of 1 km^2 .

Figure 3. Schematic view of an IceTop tank.

The AMANDA detector, taking data with 19 strings since the year 2000 [4], will be enclosed completely by IceCube when the new 12 strings are installed end of January 2007.

4. Performance

The performance of the first IceCube string and of the 8 IceTop tanks, both installed beginning of 2005, was published after one year of successful data taking [6]. The autonomous DOMs have the advantage, that their functionality can be checked immediately after the string deployment. The dark noise rate is continuously monitored and drops from several kHz caused by triboluminescence processes during the freeze-in to about 750 Hz, which is lower than for AMANDA modules. Different methods are used for the time calibration of DOMs. One measures the round trip time where a pulse is sent from the DOM readout board in the counting room down to the DOM main board and back to the surface. This time depends on the cable length and must be constant. In another method the LEDs of the DOM flasher board are flashing light in direction of the upper adjacent DOM. This DOM measures the first photon arrival time which also must be constant. With both methods, used for regular calibrations runs, the relative time resolution was estimated to be better than 2 ns.

The present detector configuration allows for more detailed performance studies using atmospheric muons as test beam. The timing sta-

Figure 4. Down-going atmospheric muon in IceCube in coincidence with an air shower in IceTop.

bility is controlled measuring the time difference of muon Cherenkov photons reaching adjacent DOMs. The difference is very stable over the year and the time resolution is again better than 2 ns for all adjacent DOM pairs.

For the 9-string detector configuration the rate of downward-going cosmic ray muons is 150 Hz. In a period of three months of detector lifetime 156 upward-going muons have been measured, induced by atmospheric neutrinos from the northern hemisphere. The 32 IceTop tanks register cosmic air showers with a rate of 7 Hz. Fig. 4 shows a typical downward-going muon connected to an air shower seen in IceTop.

First physics analyses have been started with the data of the 9-string IceCube detector configuration, which has about three times the size of AMANDA. Fields of interest are the search for muons induced by muon-neutrinos traversing the

earth, and for electromagnetic showers within the detector which can be produced in charged current electron-neutrino interactions. The IceTop air shower data are used to improve algorithms for the reconstruction of shower direction and energy, as well as for the IceCube calibration, and muon background reduction.

5. Summary

The present installation of the IceCube neutrino observatory with 9 in-ice strings and 32 IceTop tanks has taken data since March 2006. The data quality concerning noise, timing and amplitude is consistent or even better than the requirements and expectations. Although the main activities are focussed on the improvement of reconstruction algorithms and the Monte Carlo description, first physics analyses have been started. With the deployment of 12 strings and 20 IceTop tanks in December 2006 and January 2007 and 14 strings and 28 tanks in the following years, the observatory will continuously grow with increasing physics potential. In 2011 the in-ice detector will be completed with up to 80 strings and 1 km³ instrumented volume as well as IceTop with 160 surface tanks of 1 km² sensitive area.

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