Status, performance, and first results of the IceTop array
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We describe the design and performance of IceTop, the air shower array on top of the IceCube neutrino detector. After the 2008/09 antarctic summer season both detectors are deployed at almost 3/4 of their design size. With the current IceTop 59 stations we can start the study of showers of energy well above $10^{17}$ eV. The paper also describes the first results from IceTop and our plans to study the cosmic ray composition using several different types of analysis.

1. Introduction

IceTop is the air shower array part of the IceCube neutrino telescope [1]. It supports IceCube in terms of relative and absolute pointing and guard against high energy air showers being mis-reconstructed as ultrahigh high energy neutrinos. With nearly 1 km$^2$ area and atmospheric depth of 690 g/cm$^2$ IceTop is also an excellent tool for cosmic ray physics research.

The combination of IceTop with the InIce muon detector operates as huge three dimensional muon telescope that has big advantages in studies of the cosmic ray spectrum and composition. This device can

- measure the cosmic ray energy spectrum by studies of the shower hits in the surface detectors
- measure the cosmic ray spectrum and composition by studies of the angular distribution of the muon bundles in the in-ice array.
- measure the spectrum and composition using coincident IceTop/InIce events

IceCube can not measure the number of TeV muons under ice. It, however, measures the energy released by these muons in their propagation in 1 km of deep ice. The average surface energy of vertical muons that reach IceCube with sufficient energy to create signals is slightly higher than 500 GeV.

We briefly discuss the design and current status of IceTop, its calibration and performance, early air shower results, and outline the possible cosmic ray measurements with this detector.

2. IceTop design

IceTop will consist of 80 stations that are located at an average distance of 125 meters from each other close to the top of each IceCube string. Each IceTop station consists of two frozen water tanks. IceTop tanks are plastic tanks with white diffusive reflecting inner surface of radius 0.93 m and height of 1 m. The freezing is a long complicated process because the water in the tank has to be freed of the dissolved air which after freezing creates bubbles that make the tank volume not uniform in optical clarity. In spite of the average antarctic summer temperature of -25°C, the freezing usually takes about two months.

Each tank is equipped with two digital optical modules (DOMs) identical to those used by IceCube in-ice array that collect the Cherenkov light emitted by the shower particles that enter the tank. Note that the shower gamma rays convert in the tank and the experiment measures the energy flow of the extensive air shower (EAS).

A DOMs contain a 10” Hamamatsu R7081-2 photomultiplier tube, onboard high voltage converter, flashers and onboard digitization electron-
ics: two 420 ns, 300 MHz chips, each with four channels with different gains \[2\]. The two tank PMTs are run on different gains, one on high \((5\times10^6)\) gain (HG) and the other on low \((10^5)\) gain (LG) for better dynamic range.

Events with signal above threshold only in one tank of the station are considered hits by individual cosmic ray electrons, gamma rays, muons or hadrons. Coincident hits in both tanks of a station are considered air shower events.

3. Status of IceTop in 2008

The deployment of IceTop tanks goes simultaneously with that of InIce strings. In the beginning of 2008 both IceTop and IceCube had 40 stations and strings. Nineteen new stations and strings were deployed during the most recent season and this year the experiment will be almost 3/4 complete.

Figure 1. Map of the IceTop array. One sees tanks in stations deployed before the 2007/08 season (crosses), during that season (x’s) and in the 2008/09 season, where only the planned positions of the stations are shown with circles.

Figure 1 shows the plan of the array at the end of January 2009. The inter-station distances vary between 110 and 145 meters.

3.1. IceTop triggers and filtering

IceTop trigger requires coincidences between six DOMs in a time window of 5\(\mu\)s. This is called Simple Multiplicity Trigger (SMT). When this occurs the whole detector (all IceTop and InIce DOMs) is read. The frequency of IceTop SMTs in 2008 was 17 Hz. The bandwidth for data transfer from South Pole is not large enough to send all triggered events to the North. For this reason filtering is required for the event fraction that is transmitted. The filtering also checks on the number of stations that participate in the trigger and requires at least 3 stations for STA-3 and 8 stations for STA-8 events. The frequency of STA-3 events in 2008 was 12 Hz. All coincident triggers between IceTop and InIce SMT (STA-3 + InIceSMT) and 5% of the coincidence events of InIce SMT with surface activity (InIce SMT + IceTop) are also transmitted. Table 1 shows the different filters that were active in 2008.

Table 1
Frequency and percentage of different trigger events transmitted from South Pole

| Event type                  | frequency | % transmitted |
|-----------------------------|-----------|---------------|
| STA-3                       | 12.0 Hz   | 20            |
| STA-8                       | 0.5 Hz    | 100           |
| STA-3 + InIce SMT           | 2.2 Hz    | 100           |
| InIce SMT + IceTop          | 30.7 Hz   | 5             |

4. IceTop performance

A very important component of understanding the experimental performance is the calibration of the detector, starting with comparison of the signals in high and low gain DOMs and the individual calibration of each DOM. DOMs are with different sensitivity that depends on features such as the total tank reflectivity, ice quality and temperature (that changes following the outside air temperature). For this reason IceTop had special muon calibration runs that did not require shower triggers. These runs allow us to compare the muon signals in each tank and convert the
charge of the DOM signal from photoelectrons to VEMs (Vertical Equivalent Muons) which makes the whole array response uniform. Fig. 2 shows the muon peak in one of the DOMs of station 30.

Some tanks are studied with small muon telescopes set in different locations on top of the tank. Coincidences between the tank and the muon telescope are used to study the tank response to muons hitting the tank at different positions. Five such histograms for DOM 61 of station 30 are also plotted in Fig. 2.

One VEM value for this DOM is around 170 photoelectrons depending on the exact fit of the distribution. The peak of the distribution is slightly higher than those of most muon telescope coincidences as the tank is hit by inclined muons that have longer pathlength in the tank and thus generate more light. The use of VEM in the shower analysis and the muon calibration makes the detector uniform. A new procedure is currently implemented that will allow us to have continuous muon calibration.

5. First results from IceTop

The first results on the cosmic ray spectrum were obtained by the cosmic ray working group are best presented in the PhD thesis of S. Klepser [4,5] from the 2007 IceTop array that consisted of 26 stations. This array was fully efficient for proton showers with energy above 1 PeV.

The work started with a study of the lateral distribution of the air shower signal in VEM, which was fitted from experimental data as

\[ S(r) = S_{\text{ref}}(r/R_{\text{ref}})^{-\beta - \kappa \log_{10}(r/R_{\text{ref}})} , \]

where \( r \) is the perpendicular distance from the shower axis, \( S_{\text{ref}} \) is the expected signal at distance \( R_{\text{ref}} \) and \( \beta \) is a slope parameter related to the shower age. From simulations \( \kappa \) was found to be constant at 0.3.

As shown in Fig. 4 this form is quite different from the electron density as described in Greisen’s formula. The reason is that IceTop tanks measure also shower gamma rays and muons that have different lateral spreads from the shower electrons.
**Signal strength**

**Distance from core, meters**

**E₀ = 10⁸ GeV**

Figure 4. Lateral spread of the shower VEM signal from a proton shower in IceTop tanks compared to Greisen’s electron and muon lateral spread for showers of energy 10⁸ GeV.

$S_{ref}$ equal to the average grid of 125 m was used in the analysis to relate to the proton primary energy $E_0$. A response matrix was calculated to relate the primary and reconstructed energy using $S_{125}$ in the case of protons and iron showers. At energy of 3 PeV the accuracy in the shower core determination was 9 meters and the relative error in $log_{10}(E)$ was 0.05 for zenith angles less than 30°.

Showers in three zenith angle ranges were analyzed. Assuming pure proton or iron composition led to different primary spectra in the three angular ranges, while the assumption of mixed composition led to a single spectrum with a knee at $3.1\pm0.3$ (stat.) $\pm0.3$ (syst.) PeV and spectral indices of $2.71\pm0.07$ (stat.) below and $3.11\pm0.01$ (stat.) above the knee with systematic uncertainty of 0.08. The absolute normalization of the spectrum is lower than in most other measurements.

This research was conducted when the IceTop detector Monte Carlo code was in a very early stage of development. The current version of the code is much improved and currently a new analysis is being performed.

6. **Studies of composition sensitive parameters**

There are several composition sensitive parameters that can be measured by IceCube as a cosmic-ray detector:

- The energy deposited by the shower muon bundle in 1 km of ice. Note that at primary energy $10^{17}$ eV the average muon bundle in iron showers deposits about 2.4 times more energy than that of proton showers.

- The waveforms in IceTop tanks can be used for a study of the GeV muon density, at least far away from the shower axis.

- The lateral distribution of the shower signal is flatter for showers of heavy nuclei.

- The risetime of the air shower front depends on the depth of shower maximum $X_{max}$, and is different for proton and iron showers.

- The angular distribution of the showers in IceTop depends on the cosmic-ray chemical composition as the showers initiated by heavy nuclei are absorbed much faster as a function of zenith angle.

- The angular distribution of muon bundles in-ice in non-coincident events is also sensitive to the composition since proton showers generate higher energy muons that can penetrate to the detector at high zenith angles compared to those of heavier primaries.

Our strategy will be to use as many complementary observations as possible in order to decrease some of the uncertainties inherent in the interaction models needed for simulations and interpretation of the data. All the parameters listed above will be studied, and the first four, which are applicable to IceTop and InIce coincident events, will be determined for each coincident event. One should not forget that coincidental events are very close to vertical.

**Angular dependence of showers in IceTop**

As demonstrated by the preliminary analysis [5]
the angular dependence of rates on the surface is sensitive to composition. We are in the process of analyzing the full run of the IceTop 26-station configuration in 2007, which contains sufficient statistics to extend the analysis above $10^{17}$ eV. This analysis uses cuts, such as containment of the air shower core in the perimeter of the array.

We will continue to use this method for the full IceTop. It has two important features, the larger acceptance as compared to coincident events and its different dependence on models of hadronic interactions. With the full kilometer squared array we expect sufficient statistics to cover the 1-2 EeV energy bin. The method depends on shower absorption and is closely related to a measurement of depth of shower maximum. It is therefore complementary to the analysis with coincident events that depends on the ratio of the signal of high energy muons to shower size.

**Study of muon bundles in coincident events:** The acceptance of the telescope formed by IceTop and the deep IceCube neutrino telescope is approximately $1/3 \text{ km}^2\text{sr}$, sufficient to detect tens of events per year above $10^{18}$ eV. If Ref. [3] is correct, we may find evidence suggestive of a transition from galactic to extra-galactic cosmic rays below this energy. Although full acceptance will only be achieved at the end of the deployment period, already after the 2008/09 season deployment IceCube is large enough to explore fully the knee region up to $10^{17}$ eV. Expected event rates per year (assuming 70% efficiency) are indicated in Table 2.

### Table 2

| E (PeV) | Rates yr$^{-1}\ln(E)$ |
|---------|-----------------------|
|         | IT40                  | IT80                  |
| 1.0     | $2 \times 10^6$       | $10^6$                |
| 10.0    | $3 \times 10^4$       | $1.4 \times 10^5$     |
| 100.0   | 320                   | 1600                  |
| 1000.0  | 2.5                   | 12                    |

As an example of what could be achieved by further analysis we show in Fig. 5 a scatter plot of the total number of photoelectrons (NPE) InIce versus the shower energy reconstructed from the a month of IT40 data. The black dots show the average NPE as a function of energy. The cuts in the reconstruction require shower containment on the surface and InIce plus a good reconstruction quality. The NPE is not yet corrected for the distance between the DOMs and the bundle trajectory. With the statistics shown we can study the composition in the energy range of $10^{5.8}$ to $10^{6.5}$ GeV. The highest energy events collected already approach $10^8$ GeV.

The data and analysis underlying this figure also illustrate the power of coincident events for energy calibration in IceCube. Events in which the shower core is inside IceTop can be reconstructed and energy assigned with a statistical uncertainty of order $\delta E/E = 0.1$. To the extent that the muon content of air showers in the energy range from 1 to 100 PeV are well understood, these coincident events can be used to calibrate the in-ice signal expected for deposition of an amount of energy expected from the muon bundle in the deep array. The study of muon bundles InIce is complicated by the very large fluctuations in the high energy muons energy loss.

![Figure 5. The total number of photoelectrons (NPE) in IceCube is plotted as a function of the reconstructed air shower energy in IT40.](image-url)
For downward events, where the signal is dominated by atmospheric muons, one can use the muon intensity (to the extent that it is known) to estimate the effective attenuation length (a combination of scattering and absorption [6]). This is done simply by calculating the expected intensity of muons at each depth from a standard parameterization [7] (accounting for propagation in the ice [8,9]) and fitting the observed DOM counting rate at each depth with a parameter that represents the attenuation length of Cherenkov light at that depth. We have checked that the effective attenuation length derived in this way agrees well with direct measurements [6]. Such a simplified analysis is useful and fast for simulation of downward muon bundles where essentially all events are signal.

The detailed study of muon bundles may also help us identify the production of very high \( p_T \) muons in high energy showers.

### Identifying surface low energy muons from the detected waveforms:

In addition to our principal discriminator of primary composition, which is the ratio of shower size at the surface to muon signal in the ice, we also have the possibility of recovering some information about the relative contribution of GeV muons to the signal at the surface, which is also sensitive to composition. Fig. 6 shows the waveforms of the signals in an air shower of reconstructed energy \( 5 \times 10^8 \) GeV seen by a detector at distance of 50 m from the shower axis and one at a distance of 250 m.

The reconstructed energy of this shower is \( 5 \times 10^8 \) GeV and zenith angle of 40°. The waveform from the tank that is closer to the axis contains 11.34 VEM and width consistent with the shower front thickness. The waveform at 250 meters from the axis contains 1.13 VEM and is much more ragged. It seems possible that a muon hits first the tank and few low energy electrons and photons hit the tank later. We will investigate such waveforms coming from Monte Carlo events when the IT40 Monte Carlo produces sufficient statistics.

One can in principle deconvolve the waveforms and estimate the number of muon peaks contributing to the signals in the tanks. Such a treatment will be most effective in large air showers and at a significant distance from the shower core where the relative contribution of muons to the signal is higher. Thus such an analysis will be most appropriate when a large fraction of IceTop is deployed. Close to the shower core, as in Fig. 6 the estimate of the muon number may be more difficult. The fine timing resolution of the IceCube DOMs (3-4 ns per bin) may allow us to identify the GeV muons in air showers of primary energy above \( 10^{17} \) eV.

### REFERENCES

1. T.K. Gaisser, arXiv:0711.8353, prepared for the 30th ICRC, Merida, Mexico.
2. R. Abbasi et al. (IceCube Collaboration) arXiv:0810.4930
3. R.U. Abbasi et al. (HiRes Collaboration) Ap J, 622:910 (2005).
4. S. Klepser, PhD Thesis, Humbold Universität zu Berlin (2008).
5. S. Klepser, arXiv:0811.1871
6. K. Woschnagg et al. (IceCube Collaboration) JGR 111:D13203 (2006).
7. T.K. Gaisser & T. Stanev, in Review of Particle Physics, Claude Amsler et al., Phys. Lett. B667:246 (2008).
8. P. Lipari & T. Stanev, Phys Rev D44:3543 (1991).
9. D. Chirkin & W. Rhode, arXiv: hep-ph/0407075