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The IceTop Air Shower Array: detector overview, physics goals and first results

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

Abstract: IceTop, the surface component of the IceCube Neutrino Observatory at the South Pole, is an air shower array with an area of $1\,\mathrm{km}^2$. The detector is primarily designed to study the mass composition of primary cosmic rays in the energy range from about 10^{14} eV to 10^{18} eV by exploiting the correlation between the shower energy measured in IceTop and the energy deposited by muons in the deep ice. Construction of IceCube, including the IceTop component, was completed in December 2010. The final detector configuration, first operation and performance experiences, the development of an analysis framework, and first results will be reported.

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1 Introduction

The Neutrino Observatory IceCube is a 1-km^3 detector situated in the ice of the geographic South Pole at a depth of about 2000 m. IceTop, the surface component of IceCube, is an air shower array covering an area of $1\,\mathrm{km}^2$. The prime purpose of IceTop is the determination of the mass composition of primary cosmic rays in the energy range from about 10^{14} eV to 10^{18} eV. In the ‘knee’ region, at several PeV, the spectral index of the observed cosmic ray energy spectrum changes. Several experiments found this change to be accompanied by a change in the chemical composition of the primaries. However, details of the features are not well known. In particular, there may be at the high end of the IceTop energy range another change of the spectral index and an accompanying change of the composition, possibly indicating the transition from galactic to extra-galactic origin of cosmic rays. An improvement of the experimental situation in this energy range – between direct measurements with balloons and satellites and the highest energies tackled by experiments like HiRes and Auger – is one of the main goals of cosmic ray physics with IceCube.

The mass determination from extended air showers (EAS) is notoriously difficult because the measurements are indirect and have to rely on models for the hadronisation processes. Observables sensitive to the primary mass composition are mainly the height of the shower maximum (measured through fluorescence, Cherenkov or radio emission) and the number of muons in a shower. Concerning the muon rate, the highest energy muons stemming from the first interactions in the higher atmosphere are most closely correlated to the mass of the primary nucleus. IceCube, in combination with IceTop, offers the unique possibility to observe these muons, typically with initial energies above about 500 GeV, in the deep ice in coincidence with the mostly electromagnetically deposited shower energy measured at the surface. This provides an exceptionally powerful method for the determination of the mass composition.

To scrutinize the dependence on hadronisation models, several alternative methods for studying mass composition have been developed by the IceCube collaboration. Other mass sensitive observables are for example: the shower absorption in the atmosphere at different zenith angles, the number of dominantly low-energy muons in the surface detector, and other shower properties such as shower age and shower front curvature.

The IceTop array has additionally been used to study high-p_T muons, PeV-gammas and transient events, such as the radiation effects of solar flares. It also serves as a veto for the detection of downward-going neutrinos with IceCube and for direction calibration.

2 The detector

The IceCube construction was completed in December 2010. The results presented here are based on data taken with smaller detector configurations.

IceCube: The main component of Icecube is an array of 86 strings equipped with 5160 light detectors in a volume

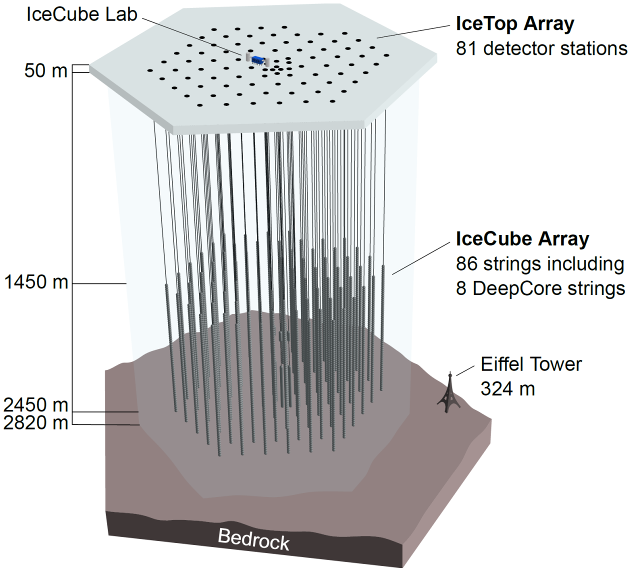

Figure 1: The IceCube Observatory with its components DeepCore and IceTop.

of 1 km^3 at a depth between 1450 m and 2450 m (Fig. 1). In the lower part of the detector a section called DeepCore is more densely instrumented. The main purpose of IceCube is the detection of high energy neutrinos from astrophysical sources via the Cherenkov light of charged particles generated in neutrino interactions in the ice or the rock below the ice.

IceTop: The IceTop air shower array is located above IceCube at a height of 2832 m above sea level, corresponding to an atmospheric depth of about 680 g/cm^2. It consists of 162 ice Cherenkov tanks, placed at 81 stations and distributed over an area of 1 km^2 on a grid with mean spacing of 125 m (Fig. 1). In the center of the array, three stations have been installed at intermediate positions. Together with the neighbouring stations they form an in-fill array for denser shower sampling. Each station comprises two cylindrical tanks, 10 m apart from each other, with a diameter of $1.86\,\mathrm{m}$ and filled with $90\,\mathrm{cm}$ ice. The tanks are embedded into the snow so that their top surface is level with the surrounding snow to minimize temperature variations and snow accumulation caused by wind drift. However, snow accumulation (mainly due to irregular snow surfaces) cannot be completely avoided so that the snow height has to be monitored (see ref. [1]) and taken into account in simulation and reconstruction (currently this is still a source of non-negligible systematic uncertainties).

Each tank is equipped with two 'Digital Optical Modules' (DOMs), each containing a $10''$ photo multiplier tube (PMT) to record the Cherenkov light of charged particles that penetrate the tank. In addition, a DOM houses complex electronic circuitry supplying signal digitisation, readout, triggering, calibration, data transfer and various control functions. The most important feature of the DOM electronics is the recording of the analog waveforms in $3.3\,\mathrm{ns}$ wide bins for a duration of $422\,\mathrm{ns}$. DOMs, electronics and readout scheme are the same as for the in-ice detector.

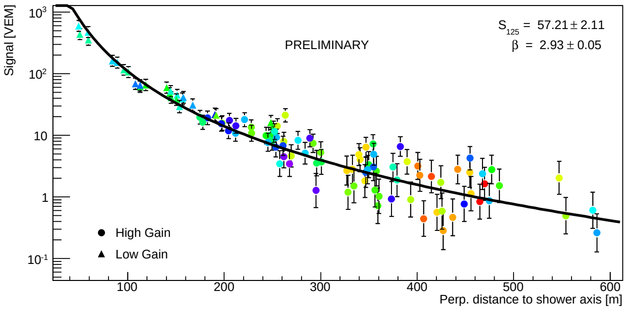

Figure 2: Reconstruction of shower parameters from the lateral distribution.

The two DOMs in each tank are operated at different PMT gains ($1 \cdot 10^5$ and $5 \cdot 10^6$) to cover a dynamic range of more than 10^4. The measured charges are expressed in units of 'vertical equivalent muons' (VEM) determined by calibrating each DOM with muons (see ref. [1]).

To initiate the readout of DOMs, a local coincidence of the two high gain DOMs of a station is required. This results in a station trigger rate of about 30 Hz compared to about 1600 Hz of a single high gain DOM at a threshold of about 0.1 VEM. The data are written to a permanent storage medium, and are thus available for analysis, if the readouts of six or more DOMs are launched by a local coincidence. This leads to a trigger threshold of about 300 TeV. Additionally, IceTop is always read out in case of a trigger issued by another detector component (and vice versa). For each single tank above threshold, even without a local coincidence, condensed data containing integrated charge and time stamp are transmitted. These so-called SLC hits (SLC = 'soft local coincidence') are useful for detecting single muons in showers where the electromagnetic component has been absorbed (low energies, outer region of showers, inclined showers).

For monitoring transient events via rate variations, the time of single hits in different tanks with various thresholds are histogrammed.

3 Shower reconstruction

For each triggered tank in an event, time and charge of the signal are evaluated for further processing. Likelihood maximisation methods are used to reconstruct location, direction and size of the recorded showers. In general, signal times contain the direction information, and the charge distribution is connected to shower size and core location. The standard analysis requires five or more triggered stations leading to a reconstruction threshold of about $500\,\mathrm{TeV}$. A constant efficiency is reached at about $1\,\mathrm{PeV}$, depending on shower inclination. For small showers an effort was launched to decrease the threshold to about $100\,\mathrm{TeV}$ with a modified reconstruction requiring only three stations.

The lateral signal distribution is fitted by a function which describes the logarithm of the tank signals as a second order polynomial in the logarithm of the distance from the shower axis (Fig. 2). Characterizing the shower size the signal S_{125} at a reference radius $R_{\mathrm{ref}} = 125\,\mathrm{m}$, coinciding with the grid spacing, has been used for the analyses presented in this paper. Studies of alternative lateral distribution functions are reported in a separate contribution to this conference [2].

The true energy spectrum is obtained by unfolding the S_{125} distribution in different zenith angular ranges. Since the unfolding matrices depend on the primary mass composition, a mass model has to be assumed [3] or the correlation with mass sensitive observables, most notably the muon number in the deep detector, has to be exploited for an essentially two-dimensional unfolding [4].

The energy resolution improves with energy and approaches 0.05 in $\log_{10} E$, or 12 % in E, at about 10 PeV for zenith angles less than 30°. The angular resolution is better than 1°, almost independent of energy and zenith angle. The detector coverage is $A\,\Omega \approx 3\,\mathrm{km}^2\,\mathrm{sr}$ for IceTop alone and $A\,\Omega \approx 0.3\,\mathrm{km}^2\,\mathrm{sr}$ for coincidences with the in-ice detector.

4 First results

Energy spectrum: The shower reconstruction from IceTop signals has been developed mainly using data taken with 26 stations (nearly 1/3 of the complete detector) in 2007. The spectra of the shower size parameter S_{125} for three different zenith angular ranges are shown in Fig. 3. Except for the threshold region, this parameter is a close proxy for the primary energy for a given zenith angle range. The relation between S_{125} and the true energy is mass dependent. Under the assumption of an isotropic cosmic ray flux, the S_{125} spectra for different zenith angles should yield the same energy spectrum. It has been shown that this can only be achieved under the assumption of a mixed composition [3].

A first evaluation of IceTop data from the 2010 season with 79 IceCube strings and 73 IceTop stations is reported elsewhere in these proceedings [5].

Mass composition using IceTop and deep-ice coincidences: As emphasized in the introduction, a strength of IceCube is the possibility to measure high energy muons in the deep ice in coincidence with the shower reconstructed in IceTop. The first analysis of such coincident data is presented at this conference [4]. The data set is constrained to a small fraction of the detector and a relatively short time period (about 1 month). However, the results are currently more affected by systematic uncertainties than by statistics.

Figure 4 shows a simulation of the correlation between the parameter K_{70}, which measures the muon energy in the deep ice, and the shower size parameter S_{125}, which is a measure of the electromagnetic component of the shower. Different primary masses populate different bands in this

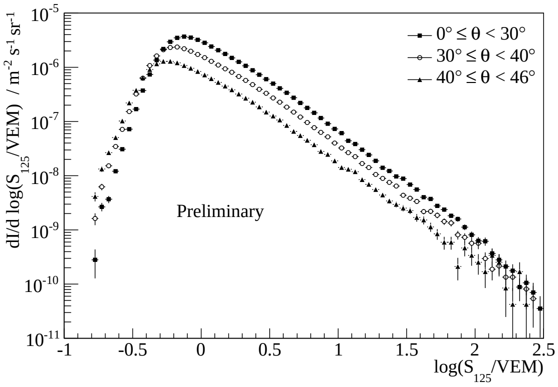

Figure 3: Measured spectrum of the shower size parameter S_{125} for three different zenith angular ranges (data from 6 months with 26 IceTop stations).

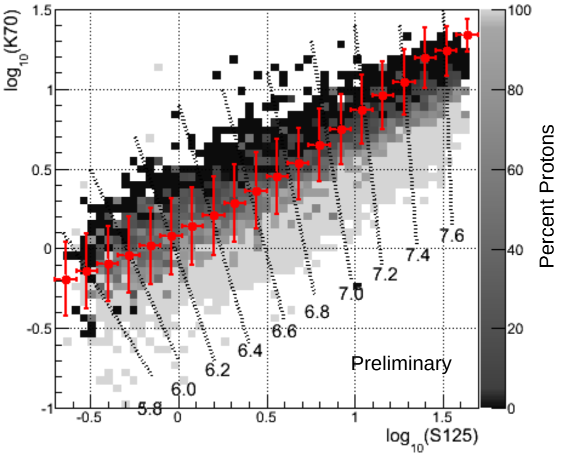

Figure 4: Mass composition measurement: plotted is the muon energy parameter K_{70} measured in the deep ice versus the shower size S_{125}. The band is obtained by simulating proton and iron primaries. The shading indicates the proton content, with 100% protons at the bottom und 100% iron at the top. Indicated are also curves of constant primary energy as determined by a neural net (the labels are in units $\log_{10} E/\mathrm{GeV}$). The points and the vertical bars are averages and dispersions, respectively, of the measured experimental distributions of a $\log_{10} S_{125}$ bin (indicated by the horizontal bars) projected unto the $\log_{10} K_{70}$ axis.

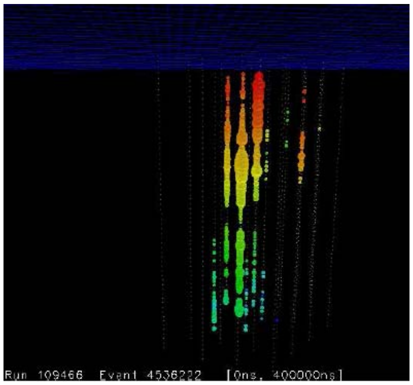

Figure 5: IceCube event display showing light signals in DOMs: Candidate muon bundle with a high-p_{T} muon (on the right).

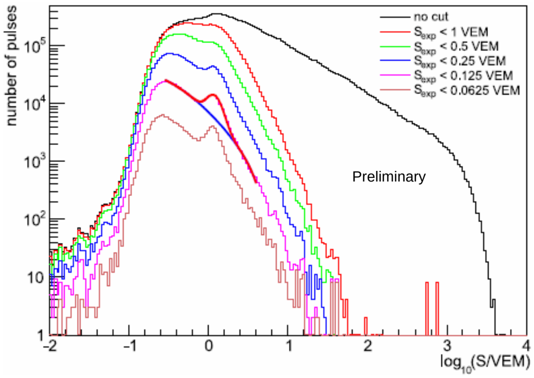

Figure 6: Muon counting in IceTop: Distribution of tank signals for various cuts on the signal expectation S_{exp} in the energy range between 1 and 30 PeV.

plot. Indicated are also curves of constant primary energy. The data points in $\log S_{125}$ bins are plotted with the dispersion of their distribution along the K_{70} axis.

With a neural network, the primary energy and a parameter related to $\ln A$ (A is the atomic mass number) has been determined yielding an energy and average $\ln A$ spectrum between 1 and 50 PeV. The method allows for the extraction of multiple mass contributions from fits to the neural network output, see details in ref. [4].

High-p$_\mathrm{T}$ muons: Prompt decays of heavy flavour hadrons occurring in the first interactions are expected to produce muons with large transverse momentum. The predictions are still very model dependent. In these proceedings, an analysis is presented [6] where high-p$_\mathrm{T}$ muons have been found as single tracks separated from a muon bundle by more than 200 m (Fig. 5). Current work concentrates on understanding the systematic uncertainties in the resulting p$_\mathrm{T}$ distribution.

Searching for PeV gamma rays: IceCube can efficiently distinguish PeV gamma rays from the background of cosmic rays by exploiting coincident in-ice signals as veto. Gamma-ray air showers have a much lower muon content than cosmic ray air showers of the same energy. Candidate events are selected from those showers that lack a signal from a muon bundle in the deep ice. Results of one year of data, taken in the 2008/2009 season when the detector consisted of 40 strings and 40 surface stations, are presented at this conference [7]. The projected gamma-ray sensitivity of the final detector is also given.

Muon counting in IceTop: The muon content of a shower is a mass sensitive observable since heavier primaries tend to have a higher muon abundance. Although the number of high energy muons in the muon bundle near the shower core is most sensitive, muons counted at the surface (at typically much lower energies than in the deep ice) provide additional information on the mass. The comparison of both methods allows one to test hadronisation models.

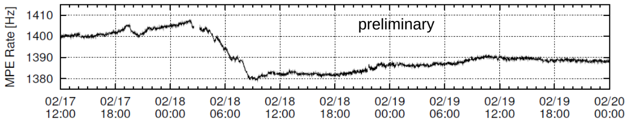

Figure 7: Average scaler rates of several tanks in IceTop during a period in February 2011 when a Forbush decrease occured.

Muonic and electromagnetic signals in IceTop can in general not be distinguished. However, muons show up as a relatively constant signal of about 1 VEM at larger distances from the shower axis where the expectation value of a tank signal, S_{exp}, becomes small compared to a muon signal (S_{exp} is obtained from the fit to the lateral shower distribution). As shown in Fig. 6, the muon signal becomes more and more prominent when requiring smaller S_{exp}. For $S_{exp} < 0.125$ VEM the figure illustrates that the number of muons can be well fitted. Comparing these muon numbers as a function of energy to simulations of different primary masses an independent information on the mass composition is obtained.

Heliospheric physics: The IceTop tanks detect secondary particles produced by cosmic rays in the multi-GeV energy regime interacting in the atmosphere with a counting rate exceeding 1 kHz per detector. With IceTop, heliosperic disturbances of this rate can be studied with very good time resolution. Since each detector has a different threshold setting, it is also possible to estimate the energy spectrum of the cosmic rays related to such events. In an IceCube contribution to this conference [8] the performance during a Forbush decrease observed in February 2011 is demonstrated (Fig. 7).

Other cosmic ray results: At this conference the Icecube Collaboration also reports results on the observation of cosmic ray anisotropies in the southern sky [9]. These results and the cosmic ray studies in ref. [10] use all muons detected in the deep detector which gives a much larger angular coverage.

References

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[9] IceCube Collaboration, papers 305, 306, 308, these proceedings.
[10] IceCube Collaboration, papers 85, 662, these proceedings.