Abstract

The IceCube experiment at South Pole consists of two detector components - the IceTop air shower array on the surface and the neutrino telescope at depths from 1450 to 2450 meters below. Currently, 26 IceTop stations and 22 InIce strings are deployed. With the present size of the IceTop array, it is possible to measure cosmic rays with energies ranging from 0.5 PeV to 100 PeV. Coincident events between the IceTop and the InIce detector provide useful cross-checks of the detector performance and furthermore make it possible to study the cosmic-ray composition. This paper gives an overview on the current status of IceTop.

Key words: IceTop, cosmic rays, extensive air shower, composition

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1. Introduction

The IceCube neutrino telescope [1] being built at South Pole, consists of two major detector components. The actual neutrino telescope (InIce) is buried at depths between 1450 m and 2450 m in the antarctic ice and will consist of 4800 individual photon detectors (Digital Optical Modules), lined up on 80 strings in an hexagonal pattern. The IceTop air shower array is located on the ice surface above the InIce detector. It consists of 80 stations, close to the position of the InIce strings, with a spacing of 125 m. Presently 26 stations are operational and are arranged as shown in Fig. 1.

The IceTop air shower array is a multi-purpose detector with several scientific aspects and technical goals. It helps to understand the background of single muons in the InIce detector and acts as a veto against muon bundles from cosmic ray induced extensive air showers (EAS). Furthermore, it is used independently to detect high energy cosmic rays with energies ranging from approximately 500 TeV up to about 1 EeV (in its final stage). Coincident air shower events, measured by the IceTop and the InIce detector, make it possible to study the cosmic-ray composition since the number of muons, which are able to reach the InIce detector, is also sensitive to the mass of the primary cosmic-ray particle. In addition, coincident events provide very useful cross-checks for the precision of the direction- and energy-reconstruction in IceTop and InIce. The following sections summarize the current status of IceTop and give some examples for the performance of the detector.

2. The IceTop Array

Each of the 80 IceTop stations consists of two Ice-Cherenkov tanks with an inner diameter of 1.86 m and an ice thickness of 0.9 m as shown in Fig. 2. The tanks are buried under a thin layer of snow at a distance of about 10 m apart. The inner surface of the tanks is covered with a diffusive coating to homogeneously reflect the induced Cherenkov light. Two DOMs, identical to those used in the InIce detector, are frozen half submerged in the ice surface and measure the Cherenkov emissions in the tank. One DOM is operated at high gain (HG) and the other at low gain (LG) in order to extend the dynamic range of the tank.

After deployment of a tank the freezing process of the ice is controlled by a freeze control unit (FCU) which circulates and degrades the water in the tank while the temperature is slowly decreased. This way the water freezes from the top to the bottom of the tank and the number of bubbles is significantly reduced [2]. The freezing process of a tank...
Due to the special layout of the IceTop array with two tanks (A and B) per station, it is possible to subdivide the array into two identical sub-arrays (A and B) with just one tank per station. This way an air shower event can be independently reconstructed by the two sub-arrays. The comparison of the results gives an estimate for the stability of the reconstruction and the uncertainties of the various shower observables. An example for the $\Delta x$-distribution of the core reconstruction for the 16 station array in 2006 is given in Fig. 3 where only contained events which fulfill the SMT trigger condition were taken into account. The distribution in Fig. 3 is fitted by a Gaussian function. Since the spread $\sigma_{\Delta x}$ of this distribution emerges from the fluctuations of $\Delta x = x_A - x_B$ the uncertainties $\sigma_{A,B}$ of the individually reconstructed x-coordinates $x_A$ or $x_B$ can be obtained from

$$\sigma_{\Delta x} = \sqrt{\sigma_A^2 + \sigma_B^2} = \sqrt{2} \cdot \sigma_{A,B} \quad (1)$$

Assuming that the actual value of $x$, using the complete array, can be approximated as the average $\langle x \rangle = (x_A + x_B)/2$ of the results of the two sub-arrays, the actual uncertainty of $\langle x \rangle$ becomes

$$\sigma_{\langle x \rangle} = \sqrt{\left(\frac{\sigma_A}{2}\right)^2 + \left(\frac{\sigma_B}{2}\right)^2} = \frac{1}{2} \cdot \sigma_{\Delta x} \quad (2)$$

which is half of the spread of the $\Delta x$-distribution shown in Fig. 3. The same procedure was applied to the other shower observables revealing a core reconstruction precision of about 17 m, and an uncertainty in the zenith and azimuth angles of 1° and 2° for the 16 station array in 2006. The reconstruction quality will increase further with the size of the IceTop array. Since the results of this analysis may depend on the reconstruction algorithm, the obtained uncertainties shouldn’t be interpreted as detector resolutions but are a valuable cross-check for the stability of the reconstructions.

4. Single Station Coincidences

A precise time synchronization among all DOMs and a good knowledge about their position is a critical requirement for any physics analysis. Calibration with flashers and survey by hole logging during deployment shows that the time synchronization of an InIce string is at the level of 3 ns while the depth of the individual DOMs are known with an
accuracy of about 50 cm. The timing between the IceTop and the InIce detector components can be checked by using vertical muons which were tagged by triggering only a single station in the IceTop detector. To ensure that the single station events are not caused by tails of big air showers outside the array, only the inner stations of the IceTop array are used together with the InIce strings directly below them. With the 16 IceTop stations and 9 InIce strings in 2006, only stations 39 and 49 fulfill this requirement. For these two strings the muon speed has been individually calculated for each InIce DOM relative to the time $t_0$ of the IceTop station at the surface according to $v_i = d_i/(t_i - t_0)$ where $d_i$ is the distance between the station and the $i^{th}$ InIce DOM. In first order the arrival times of the photons at the DOMs are exponentially distributed due to the scattering in the ice. Since there are a number of other independent uncertainties in the system the exponential distribution is smeared out according to a Gaussian function. Therefore the time distributions of individual DOMs have been fitted with a Gaussian convoluted exponential function

$$\frac{dN}{dt} = \frac{1}{2} \frac{N}{\tau} e^{-\frac{t-t_0}{\tau}} e^{\frac{t-t_0}{\sigma^2}} \cdot \text{erfc}\left(\frac{t_i - t + \frac{\sigma^2}{2}}{\sqrt{2\sigma}}\right),$$  \hspace{1cm} (3)$$

where the time constant $\tau$ corresponds to the scattering length in the ice and $\sigma$ is the effective time resolution of the Gaussian function. The expression “erfc” represents the complementary error function. An example of such a fit is given by the graph included in Fig. 1. The fitted $t_i$ values for each DOM correspond to the time origin of the pure exponential function and thus to the time offset of the DOM. The distribution of muon speeds, in units of the speed of light $c$, was determined using these time offsets and is shown in Fig. 2 where the data of the two strings has been combined. Only the data of 110 out of available 120 DOMs were used since the fit failed in the other cases due to insufficient statistics. As can be seen in Fig. 2 the muon speed in the ice is compatible with the speed of light and the RMS of 0.0015 reflects the uncertainties in the timing and the location of the DOMs and of the true muon position on the surface. If only the timing uncertainty is taken into account the RMS translates to an upper limit on the timing precision of about 12 ns in 2.5 km depths. Although the precision of this method is not as good as the standard survey and calibration techniques, it is a useful and independent cross-check that there is no significant deviation from expectation.

5. Energy Spectrum & Composition

The full reconstruction of an IceTop event is an iterative process. First, the center of gravity (COG) of all tank signals is used as a first guess for the core position. In a second step the arrival direction of the air shower is reconstructed, using the time information of the signals and assuming the shower front to be a plane wave. These first guess values are taken as the seeds for a final log-likelihood minimization which fits a lateral distribution function to the tank signals calibrated in VEM. For IceTop a Double Logarithmic Parabola (DLP) was found to describe the lateral distribution the best. The reconstructed signal at a distance of 100 m from the shower axis ($S_{100}$) is used as an estimator for the primary cosmic-ray energy. The conversion between the $S_{100}$ value and the energy is based on a nearly linear relation between the two quantities but also depends on the zenith angle of the shower. For showers with zenith angles less than 30° the mean energy for $S_{100} = 20$ VEM is approximately 10 PeV and $S_{100} = 200$ VEM corresponds to roughly 100 PeV. The resulting raw energy spectrum without any acceptance correction is shown in Fig. 4. At high energies, where the events are detected and reconstructed with high efficiency, the slope of the spectrum agrees well with the spectral index $\gamma = 3.05$ found by other experiments which is represented by the solid line in Fig. 5.

Coincident air shower events, detected by IceTop and InIce, make it possible to determine the primary energy in three different ways, making IceCube a hybrid cosmic-ray...
detector and providing a cross-check for the different reconstruction methods and their systematic uncertainties. Besides the method explained above, also the lateral distribution of Cherenkov photons from the muon bundles in the InIce detector can be used to estimate the primary energy. This reconstruction is currently being developed and provides an independent approach to estimate the primary energy, however with a coarse energy resolution due to the primary-mass sensitivity of the muon number. Also the geometry of the shower can be independently reconstructed by the InIce detector. In last instance a coincident event can further be reconstructed by combining the IceTop and the InIce data. This method leads to precise and consistent results in the whole IceCube detector.

Since the number of muons in an air shower depends on the energy and the nature of the primary particle, the cosmic-ray composition can be studied by correlating the muon and the electron numbers as is suggested by the simulation study shown in Fig. 6. The energy increases along the diagonal of this plot whereas the mass of the primary goes from light (proton) to heavy (iron), roughly perpendicular to the hypothetical energy axis. However, in real data these scatter-plots look much more fuzzy due to the limited detector resolution and the occurrence of all kinds of primary particles from proton to iron. The individual energy spectra for different kinds of elemental groups can be statistically disentangled with different techniques, for instance by a two dimensional unfolding approach as used in [8]. The muon reconstruction code for IceCube/IceTop is still under development. The cosmic-ray composition study is one of the most important scientific goals for IceTop.

6. Summary

The IceTop air shower array at South Pole grows each austral summer. After the coming deployment season, 50% of the array will be completed. In parallel to the detector construction the reconstruction tools are being developed. An overview of the detector performance and the existing or planned scientific reconstruction methods has been given in this article. The current reconstruction effort focuses on the development of a new muon bundle reconstruction for IceCube to improve the energy resolution for coincident air shower events and to study the cosmic-ray composition.

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