Nuclear Instruments and Methods in Physics Research A 742 (2014) 35–41

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Cosmic ray spectrum, composition, and anisotropy measured with IceCube

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ARTICLE INFO

Available online 14 November 2013

Keywords:
Cosmic rays
Energy spectrum
Nuclear composition
Anisotropy

ABSTRACT

Analysis of cosmic ray surface data collected with the IceTop array of Cherenkov detectors at the South Pole provides an accurate measurement of the cosmic ray spectrum and its features in the “knee” region up to energies of about 1 EeV. IceTop is part of the IceCube Observatory that includes a deep-ice cubic kilometer detector that registers signals of penetrating muons and other particles. Surface and in-ice signals detected in coincidence provide clear insights into the nuclear composition of cosmic rays. IceCube already measured an increase of the average primary mass as a function of energy. We present preliminary results on both IceTop-only and coincident events analysis. Furthermore, we review the recent measurement of the cosmic ray anisotropy with IceCube.

1. IceCube and cosmic rays

Acceleration of galactic cosmic particles in the shock waves of nearby supernova remnants is believed to produce the features observed in the energy spectrum of primary particles detected at Earth. The gradual steepening of the cosmic ray flux at a few 10^{15} eV, called the “knee”, and other structures at higher energies are interpreted as the signatures of these sources [1,2]. The transition from galactic to extragalactic components of cosmic particles is predicted [3] at a few 10^{17} eV or 10^{18} eV depending on whether the extragalactic component is purely protonic or a mixture of different nuclei. At energies between 10^{15} eV and 10^{17} eV, all air shower experiments observe an increase in the measured average mass, compatible with an energy dependent change of cosmic ray composition. Above 10^{17} eV and up to 10^{18} eV, measurements of composition indicate a decrease of the average mass [4].

IceCube (Fig. 1) is a multi-purpose astrophysical observatory installed at the South Pole in operation since 2005 [5]. It consists of a surface array of Cherenkov tanks, called IceTop, and a large array of optical modules in the deep ice between 1.45 and 2.45 km below the ice sheet. Data of the surface array allow reconstructing direction and energy of down-going primary cosmic rays in the energy range from about 10^{14} TeV to 10^{19} EeV. The main purpose of the deep detector array is to detect astrophysical neutrinos, but it also permits the reconstruction of penetrating cosmic ray muons [6]. Since May 2011, IceCube is taking data in its full configuration. The deep detector is an array of 86 cables (strings), each instrumented with 60 digital optical modules [7] (DOMs). A DOM contains a (10 in. Hamamatsu) photomultiplier and the readout electronics.

Near the top of each string at an altitude of 2835 m a.s.l. (atmospheric depth of about 680 g/cm^2), 81 pairs (stations) of cylindrical Cherenkov tanks form IceTop, covering an area of about 1 km^2 [8]. Each tank contains two standard IceCube DOMs and detects secondary particles (low-energy photons, electrons, and muons) from air showers. At the time of deployment, the top of each tank was at the same level as the surrounding snow. However, snow drifting causes the increase of the overburden with time. The snow depth over each tank is directly measured every year and can be indirectly estimated from the muon/electron ratio in calibration curves (Fig. 2). IceTop DOM charges are calibrated using signals from single muons, expressed as an independent unit called “Vertical Equivalent Muon” (VEM) [8].

At the altitude of IceTop, secondary particles are sampled near the shower maximum. This allows precisely measuring the energy spectrum of primary cosmic rays with an energy resolution of about 10% above 10^{16} eV. Events seen in coincidence by both IceTop and the deep detector (see Fig. 3) give clear insights into the nuclear composition of cosmic rays for energies that span from PeV to EeV. The deep detector measures the signal of penetrating muons (more than about 500 GeV at production) from the early stage of shower development. The in-ice DOMs detect the light

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http://dx.doi.org/10.1016/j.nima.2013.10.069

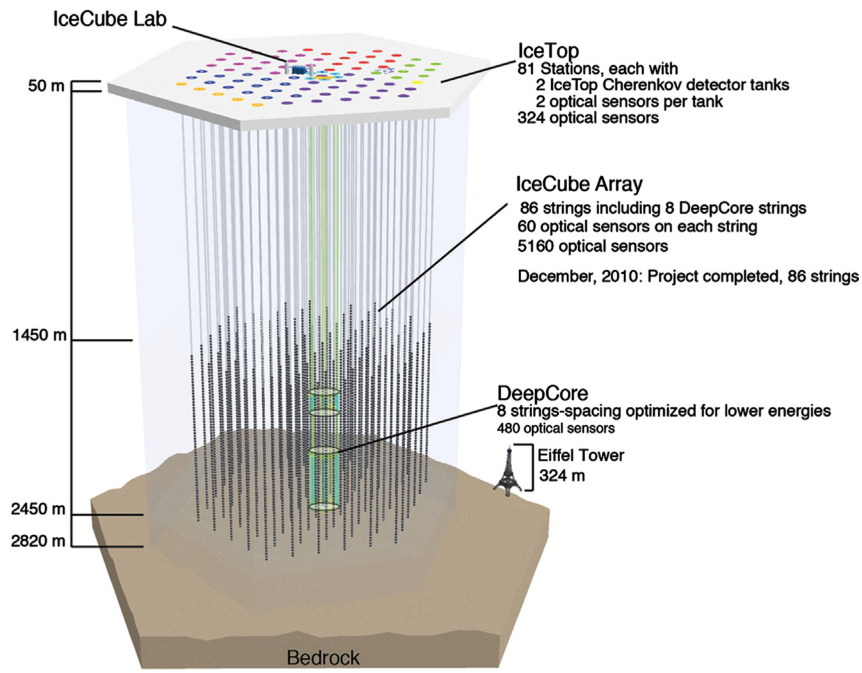

Fig. 1. Sketch of the IceCube Observatory. IceCube in its 2006–2007 configuration is shown in red and referred to as IT26/IC22 (26 IceTop stations/22 in-ice cables). Other configurations are IT40/IC40 (2007–2008) in green, IT59/IC59 (2008–2009) in purple, IT73/IC79 (2009–2010) in blue, and IT81/IC86 (2010–2011 and subsequent seasons) in yellow. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

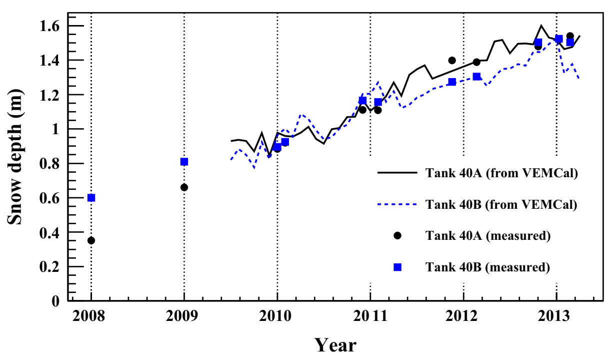

Fig. 2. Accumulation of snow over time, for the two tanks of one IceTop station [9]. Direct measurements of snow depth are shown with solid symbols. Indirect measurements using calibration curves (VEMCal data) are shown with lines.

emitted due to energy loss of high energy muons inside the detector volume. The amount of Cherenkov light generated is proportional to the deposited energy, which is in good approximation with a function of the muon multiplicity alone. At a fixed time, the light collected from these muons has traveled a certain distance and the coherent wave front of photons emitted at a given time is used to reconstruct track direction and energy loss profile. Penetrating muons are more abundant in iron showers than in proton showers since shower development starts higher in the atmosphere. The in-ice signal of iron showers is therefore larger for a given energy and zenith angle.

During the construction phase, IceTop measured the cosmic ray energy spectrum at energies between 1 PeV and 100 PeV when only 26 stations were operational [10]. Using coincident events, the cosmic ray spectrum and average nuclear composition were measured between 1 PeV and 30 PeV [11]. Furthermore, the large statistics and good angular resolution allowed detection of cosmic ray anisotropies in the Southern sky at the *per mille* level on angular scales down to a few degrees [12,13].

This paper emphasizes and highlights the latest results from analyses of cosmic ray events collected with 73 stations of IceTop (IT73) and 79 cables of IceCube (IC79). The latest measurements of energy spectrum and composition cover the energy range from about 1 PeV to 1 EeV and include zenith angles (θ) up to about 40°. Only events with reconstructed shower cores contained within the IceTop array were considered. In Section 2 the primary energy spectrum obtained with events of IT73-only is presented. In Section 3 the measurement of composition with coincident events of IC79/IT73 is discussed. In Section 4 a recent study of the anisotropy comparing IceTop and deep detector measurements is reviewed. An outlook on the status of the extension of the current analysis to include more inclined events is given in Section 5.

2. Cosmic ray primary spectrum with IceTop

Using data taken between June 1, 2010 and May 13, 2011 (effective livetime of 327 days), about 37 million events of cosmic rays were reconstructed. These events are a selection of IceTop events with $\cos\theta > 0.8 (\theta < 37°)$ and triggering 5 or more stations. For the analysis, only "contained" events were considered. These events had reconstructed cores within an area delimited by the outermost stations.

The surface shower particle density decreases rapidly with the distance from the shower axis. This lateral distribution function (LDF) carries information about the energy of the primary particle. The charge expectation value S (expressed in VEM) in an IceTop tank at distance r (expressed in m) from the shower axis is described by a "double logarithmic parabola" [8]

$$S(r) = S_{125} \cdot \left(\frac{r}{125}\right)^{-\beta-\kappa\,\log_{10}(r/125)} \quad (1)$$

where S_{125} is the charge in VEM at 125 m (Fig. 4). This description is empirical and derived from simulation. In log–log format, β represents the slope of $\log_{10} S(r)$ at 125 m and κ represents its curvature. Assuming a fixed value of κ=0.303 was verified not to impair reconstruction quality of simulated events. Signals measured between about 30 m and 300 m from the shower axis are well described by Eq. (1) for primary zenith angles in the range 0–40°. For