Primary spectrum and composition with IceCube/IceTop

Thomas K. Gaisser for the IceCube Collaboration

Bartol Research Institute and Department of Physics and Astronomy
University of Delaware
Newark, DE 19716 USA

Abstract

IceCube, with its surface array IceTop, detects three different components of extensive air showers: the total signal at the surface, GeV muons in the periphery of the showers and TeV muons in the deep array of IceCube. The spectrum is measured with high resolution from the knee to the ankle with IceTop. Composition and spectrum are extracted from events seen in coincidence by the surface array and the deep array of IceCube. The muon lateral distribution at the surface is obtained from the data and used to provide a measurement of the muon density at 600 meters from the shower core up to 30 PeV. Results are compared to measurements from other experiments to obtain an overview of the spectrum and composition over an extended range of energy. Consistency of the surface muon measurements with hadronic interaction models and with measurements at higher energy is discussed.

Keywords: cosmic-ray spectrum, composition

1. Introduction

The IceCube Neutrino Observatory includes a surface detector above the deep array as illustrated in Fig. 1. With an area of \( \approx 1 \text{ km}^2 \), IceTop is sensitive to the primary spectrum from PeV to EeV. The surface array consists of 81 stations each with two tanks separated from each other by 10 m and filled with clear ice [1]. Each tank (see Fig. 2) is viewed by two digital optical modules (DOMs), one running at high gain and the other at low gain to achieve a dynamic range of \( \approx 10^4 \) for the energy deposited in each tank. The IceTop DOMs are fully integrated into the data acquisition system of IceCube so that timing across the full array is accurate to \( \approx 3 \text{ ns} \). The spectrum measurement with IceTop benefits from the high altitude of the array (equivalent to a depth of \( \approx 690 \text{ g/cm}^2 \)), which allows a measurement of the spectrum with very good energy resolution.

Events with trajectories that pass through IceTop and the deep array of IceCube can be reconstructed in both parts of the detector. The signal in the deep array is due to energy deposition by muons sufficient energy at production to reach the deep array (500 GeV minimum and typically \( \sim \text{TeV} \)). The ratio of muons in the deep detector to the shower size measured at the surface is sensitive to primary composition. This measurement is related to the classic \( \mu/e \) ratio measured at the surface. Heavy nuclei of a given primary energy produce more muons than protons of the same energy in both cases. However, the systematics of the two analyses are different because the TeV muons are from higher energy interactions in the shower than the GeV muons at the surface. Making both measurements on the same set of showers therefore has the potential to improve the understanding of systematic differences in hadronic interaction models. We return to this point in Section 4 below.

The first deep underground muon detector near Cornell University in upstate New York [2] also set up a small air shower array on the surface. With underground detectors of order 1 m\(^2\) at a depth of 600 m and surface detectors spaced by \( \approx 60 \text{ m} \), the aperture was tiny (\( \sim 0.01 \text{ m}^2 \text{sr} \)). The first serious measurement of coincidences between a surface array above a deep detector was EASTOP-MACRO [3]. The aperture for observing
coincident events was $\sim 100 \text{ m}^2\text{sr}$, and the muon energy threshold at the surface was $\approx 1.3 \text{ TeV}$. The South Pole Air Shower Experiment (SPASE-2) was used in coincidence with the Antarctic Muon and Neutrino Array (AMANDA), the forerunner of IceCube, for a composition analysis with coincident events. Its aperture was also $\sim 100 \text{ m}^2\text{sr}$. For comparison, the aperture of IceCube for coincident events is $\approx 0.25 \text{ km}^2\text{sr}$. The earlier air-shower experiment, SPASE-1, was decommissioned in 1995, but it also ran in coincidence with AMANDA during construction. The configuration of a two-dimensional muon survey of AMANDA-B10 from the surface arrays is shown in Fig. 3.

2. Energy spectrum using IceTop only

Showers in IceTop are reconstructed by fitting a lateral distribution function to the observed signal, taking account of arrival time fluctuations as described in Ref. 11. Because snow accumulates at a different rate over each IceTop tank, measured signals are corrected before fitting to the lateral distribution function. The correction is made with a simple exponential absorption factor, $\exp(-X_s/\lambda \cos \theta)$, with the snow depth interpolated between biennial measurements at each tank. The average spacing between stations in IceTop is 125 m. Correspondingly, the shower size is characterized by the fitted signal ($S_{125}$) at 125 m perpendicular from the shower trajectory. The energy spectrum is obtained from comparison of the measured size spectrum to a Monte Carlo simulation of shower size vs primary energy for different groups of nuclei.

One of the main systematic uncertainties is the composition model (relative contribution of different mass groups vs energy) assumed to obtain the mean primary energy for a given $S_{125}$. The H4a model of Ref. 10 is used to make the size to energy conversion. The sensitivity to composition is checked by making the conversion at each of four zenith angle bins assuming pure protons and assuming pure iron. Under the assumption of pure protons, the spectrum at the larger zenith angle is lower than that for the vertical. Under the assumption of pure iron for the primary composition, the angular dependence of the spectra in the angular bins is reversed. This behavior reflects the fact that proton shower penetrate more deeply than iron showers for a given primary energy. When the H4a model of composition is used, the spectra obtained at the four different zenith angles
are closer to each other. In principle, the composition could be inferred by adjusting the relative fractions at each energy to get the same primary spectrum for each zenith bin, as required by the fact that the true spectrum is independent of the zenith angle at which it is measured. In practice, such an approach is difficult because of fluctuations. The angular dependence of the spectra reconstructed assuming H4a is used as a measure of the systematic uncertainty from composition.

The energy spectrum measured in 2010-11 with the nearly complete IceTop detector (IT-73 with 73 of 81 stations in operation) [11] showed clearly that the spectrum between the knee and the ankle cannot be described by a single power law. The high resolution measurement with IceTop clarifies the structure seen in previous experiments. The same analysis has now been applied to three years of IceTop data (2010-2013), with the data from the complete 81 station array analyzed using only the IT-73 tanks for consistency with the first year analysis [7]. The three-year analysis includes an improved treatment of the time-dependent correction for snow above the detector. By comparing reconstructed events in areas with deeper snow to those in areas with little or no snow, the effective attenuation parameter was optimized to 2.1 m for the first year of the analysis and 2.25 m for the subsequent two years. (For snow density of $\approx 0.4$ g/cm$^2$, 2.1 m corresponds to an effective attenuation length of 84 g/cm$^2$.) Work is underway to account for the fact that it is mainly the electromagnetic component of the signal that is affected by snow [12].

The IceTop 3-year data are shown along with data from KASCADE-Grande [8] and TUNKA [9] in Fig. 4 compared to an $E^{-3}$ differential power law shown by the solid line. There is a hardening of the spectrum around $2 \times 10^{16}$ eV and a steepening above $2 \times 10^{17}$ eV, sometimes referred to as the second knee.

3. Coincident events

With a sample of coincident events, each of which is measured both by IceTop and by the deep array of IceCube, the degeneracy between energy and composition with the IceTop only analysis can be removed. The coincident event analysis [13] uses a neural network (NN) to determine both energy and composition from the three-year sample of coincident events that are well contained and reconstructed in both IceTop and IceCube. An updated description of the coincident analysis is given in Ref. [7]. Figure 5 compares the energy spectrum obtained from the coincident analysis with the IceTop only spectrum. The good agreement below $10^{8}$ GeV confirms that the composition systematic has been dealt with in a reasonable way in the IceTop only analysis, which has the higher statistics.

The principal observables on which the network is trained (using simulated data) are $S_{125}$, $\cos \theta_{\text{zenith}}$ and $E_{\mu}^{1500}$, the reconstructed energy loss per meter of muons in the shower as it enters the deep array at 1500 m. The reconstruction is based on the observed energy losses within the detector. In addition, two measures of the number of stochastic energy losses in the reconstructed in-ice track (moderate and high) are used. The NN is trained and tested on half the showers simulated with Sibyll-2.1 [14] and FLUKA [15] for protons, helium, oxygen and iron primaries. The output variables are the shower energy and a measure of $\langle \ln(A) \rangle$ for each event. Applying the trained NN to the other half of the simulated data leads for each energy bin to a set of his-
tograms for each mass group. Events in these “template” histograms are classified by a proxy for \( \ln(A) \). Applying the NN to the data leads to an energy estimate for each event and a single histogram for each energy bin. The \( \langle \ln(A) \rangle \) for each bin is obtained by finding the best fit of the four template histograms to the data histogram for the corresponding energy bin.

The main composition-dependent variable in the NN analysis is \( E_{\mu}^{1500} \). Its sensitivity is illustrated in Fig. 6 from simulations of protons and iron. An important systematic uncertainty in the coincident analysis is absolute calibration of the light yield in the detector. To the extent that the main source of differences among interaction models is the number of \( \sim \) TeV muons, those systematic uncertainties will scale similarly to the light yield. Figure 7 shows \( \langle \ln(A) \rangle \) from the coincident analysis at its nominal value (black stars) and scaled according to the various systematic effects listed.

The central values from the IceCube coincident analysis are shown as the red points in Fig. 7 superimposed on the compilation from the review paper of Kampert and Unger [16]. The values of \( \langle \ln(A) \rangle \) are obtained in Ref. [16] by interpolating measured values of shower maximum between values of \( X_{\text{max}} \) for protons and iron from simulations. Here we show the diagram interpreted with Sibyll-2.1 to be consistent with the coincident analysis. The solid lines are included in the figure from Ref. [16] to indicate the range of the data summarized.

4. Surface muons

The DOMs in IceTop tanks record waveforms from the Cherenkov light produced by charged particles with speeds above the Cherenkov threshold in the clear ice. The amount of light depends on the track length in the tank but not on the identity of the particle(s) that produced it. There are, however, several possibilities for obtaining some information about the muon content of air showers with IceTop. For example, there is potential information in the structure of the waveforms which might serve to distinguish muons from electromagnetic signals, which are primarily due to conversion of photons in the tanks.

A simpler method is to make use of the fact that the characteristic charge distribution of muons passing through a tank is understood well from the calibration procedure. Figure 8 shows the charge distribution from one calibration run for a high-gain DOM in one tank. The calibration data are obtained from uncorrelated hits collected without an air shower trigger, so they are from

Figure 6: Reconstructed energy loss as a function of primary energy for showers initiated by protons (red) and by iron nuclei (blue).

Figure 7: Energy dependence of \( \langle \ln(A) \rangle \) from the coincident analysis for various assumptions on each of the sources of systematic uncertainty.

Figure 8: Comparison of \( \langle \ln(A) \rangle \) from the IceCube coincident analysis with a compilation of data [16]. (See text for discussion.)
the continuous flux of photons, electrons and muons produced by interactions of relatively low energy cosmic rays in the atmosphere.

Signals in IceTop tanks are defined in units of VEM obtained by monthly calibration runs for each tank (see Fig. 9). In particular, the lateral distribution of an air shower is expressed in terms of VEM as a function of core-distance. In the inner region of a shower, a signal of \( \sim 1 \text{ VEM} \) can be produced either by a combination of electromagnetic quanta with appropriate total track length or by a muon or by a combination of the two (if the muon stops in the tank). In the outer region of the shower, however, a signal near one VEM is likely to be from a muon. The "outer region" is defined as the distance beyond which the fitted lateral distribution for a shower falls below one VEM. Figure 10 illustrates how the muon peak becomes more pronounced at larger core distance. Figure 11 is a two dimensional representation of the same information. The "thumb" at 1 VEM reflects the muons.

Muon signals in air showers cannot, however, be fit directly from the shape of the muon peak in calibration runs because the air shower context is different. In addition, the showers need to be analyzed as a function of zenith angle and energy. The analysis starts by making distributions like that in Fig. 11 for each bin of zenith angle and energy. Then the data are further divided into bins of core distance, defined as distance in the shower plane perpendicular to the reconstructed trajectory of the shower. Two examples are shown in Figs. 12 and 13 at distances corresponding to the vertical dashed lines in Fig. 11. These figures show the data sample for an energy bin around 3 PeV centered around core distances of 257 and 646 m. The muon peak becomes increasingly prominent relative the the electromagnetic component as distance increases.

The data are fit by three components as indicated in the two examples: (1) one or more muons, (2) 0 muons (electromagnetic), and (3) background. (The small background of accidental hits not related to the shower is determined from the distribution of hits outside the time windows of events in the sample.) The shape for the muon contribution is obtained starting with GEANT4 simulations of the tank response to one
muon as a function of zenith angle. Because a tank can be hit by more than one muon, the actual muon signal distribution may be broader than for a single muon. The shape of the $\geq 1\mu$ peak is characterized by $\langle N_\mu \rangle$ in which the shapes for 1, 2, and 3 muons are combined with weights according to a Poisson distribution determined by fitting with $\langle N_\mu \rangle$ as a parameter. The relative normalization of the sum of the electromagnetic only (major) and background (small) contribution to the fit must correspond to the total Poisson probability of having 0 muons, while the normalization of the muon contribution (1) is the Poisson probability of having at least one muon. The detailed procedure is described in Ref. [18]. Once the mean muon number in a given radial bin is fixed, the muon density is obtained by dividing by the total projected area of tanks in that radial bin. The lateral distribution of muons found in this way can be described by the Greisen function,

$$
\rho_\mu(r) = \rho_\mu(r_0) \left( \frac{r}{r_0} \right)^{3/4} \left( \frac{r_1 + r}{r_1 + r_0} \right)^{-\gamma}
$$

where $r_1 = 320\text{ m}$ and the reference radius is $r_0 = 600\text{ m}$. The normalization parameter, $\rho_\mu(r_0)$ and the slope parameter $\gamma \approx 2.5$ are fitted for each primary energy, where the relation between $S_{125}$ and primary energy is determined as in Ref. [18].

The result is a set of muon lateral distributions determined directly from IceTop data for a range of zenith angles and primary energies. From these lateral distributions, the muon density at 600 m is determined as a function of energy and compared in Fig. [14] to data at higher energy from Hi-Res-MIA [19] in Fig. [14]. The densities expected from primary iron (blue, upper line) and from protons (red, lower line) are also shown (derived from SIBYLL 2.1).

The method was first presented and preliminary results shown in Ref. [18]. The later analysis [17] presented at ICRC 2015 includes a comparison with simulations (with Sibyll 2.1), shown here in Fig. [14]. The result is consistent with expectations to the extent that the measurements are between protons and iron. In particular, there is no evidence for a significant excess of muons in data up to 30 PeV compared to simulations, in

![Figure 12: Data in tanks in the radial bin around 257 m corresponding to Fig. [11] (Figure from [17]).](image1)

![Figure 13: Data in tanks in the radial bin around 646 m corresponding to Fig. [11] (Figure from [17]).](image2)

![Figure 14: Muon density at 600 m as a function of energy. (Figure from [17].)](image3)
contrast with the situation at 10 EeV where there appear to be more muons in data than expected [20]. Also, the post-LHC models seem to have 30% more muons than Sibyll 2.1 at least up to 30 PeV (J. Gonzalez, private communication).

The muon content of showers at the surface is sensitive to primary composition. As for the coincident events, more muons are expected for events generated by heavy primaries than by light primary nuclei of the same energy. However, the muons come from different stages of shower development and reflect different properties of the parent hadronic interactions in the two cases. Muons at the surface typically have energies of a few GeV and are produced by decay of mesons produced in interactions of order 100 GeV. In contrast, the ~ TeV muons in the coincident analysis should be produced earlier in the shower and descended from hadronic interactions an order of magnitude higher. For this reason, a full composition analysis with surface muons will be important for comparison with the coincident analysis. Differences in hadronic interaction models are likely to affect the two analyses differently. Finding consistency between the two may therefore be helpful in placing constraints on interaction models as well as on composition.

Building on the tools developed for the measurement of muons at the surface in IceTop, it is possible to develop an analysis that will return the muon content on an event-by-event basis. This is done by fitting each shower with two lateral distribution functions, one for the electromagnetic component and the other for muons. In this analysis, individual signals are assigned a probability of containing a muon based on the known properties of the muon and electromagnetic signals in IceTop discussed above. The concept and preliminary examples were presented at the 2015 ICRC [21]. Because of the sensitivity of the muon number to primary composition, this would make it possible to assign a probability of light vs. heavy primary to each event. In addition to the value for composition analysis, such a method would also make possible a composition-dependent version of the IceCube cosmic-ray anisotropy analysis [22]. It would also allow a better snow correction by identifying the electromagnetic contribution.

5. Other approaches

There are several other approaches to using muons in IceCube to help determine the primary cosmic-ray composition. A comparison of muon bundles in the deep part of IceCube to simulations shows promise because of its large reach in energy, from tens of TeV to well into the EeV energy range [23]. The analysis uses the connection between primary mass and number of muons and finds a steadily increasing mass, consistent with the coincident event analysis of Section 3 and somewhat in tension with the summary of Ref. [16] above $10^{17}$ eV (compare Fig. 8).

Still other approaches involve what might be called the geometry of muons in air showers. The typical size of a muon bundle in the deep detector below 1.5 km.w.e. is less than the string spacing of 125 m. It is therefore possible to identify individual outlying muons separated from the main bundle by more than the string spacing. The lateral distribution of ~TeV muons in IceCube is discussed in Ref. [24]. To achieve a separation of, for example 135 m, a vertical muon with sufficient energy to reach IceCube (500 GeV) needs a transverse momentum of 6 GeV/c if it is produced at an altitude of 25 km, the typical interaction height for a heavy nucleus [25]. The relation between heavy nuclei and protons for production of high transverse momentum particles is complex. On the one hand, heavy nuclei have first interactions higher in the atmosphere, but on the other the energy per nucleon is lower, so the fraction of high-transverse momentum is lower. The analysis therefore depends both on simulations of the detector response and on the hadronic interaction models used. Finding a consistent interpretation thus has the potential of clarifying both aspects.

Another approach under investigation is to use the timing of muons at large distances to reconstruct the distribution of muon production heights as in Auger [26]. The goal is to measure the muon production profile and hence to obtain the muon depth of shower maximum as a composition-dependent parameter. This analysis should naturally be associated with the measurement of surface muons discussed in the previous section.

6. Future

Motivated by the observation of high-energy astrophysical neutrinos in IceCube [27, 28], planning for an expanded detector is underway [29]. The basic concept [30] is to increase the neutrino detection volume by an order of magnitude using 120 new strings with ≈ 240 m spacing around the present detector, which has a string spacing of 125 m. Studies of ice properties with the present detector show that the vertical instrumentation can be increased by 27% (1360-2621 m compared to 1450-2450 m) at present.

The primary goal of IceCube Gen2 is to obtain sufficient statistics to characterize the astrophysical spectrum and determine, for example, whether there is a
high-energy cutoff above several PeV and whether there are both galactic and extra-galactic components in the astrophysical signal. It will also significantly increase the sensitivity for the search for cosmogenic neutrinos with much higher energies. The PINGU [31] component of Gen2 will provide increased density of instrumentation in the current DeepCore portion of IceCube for neutrino oscillation physics including the mass hierarchy.

Plans also call for a surface array with sufficient detector density to act as a veto for downward cosmic-ray background. This would make it possible to include events generated by charged-current interactions of muon neutrinos in the ice above the deep detector.

From the point of view of cosmic-ray physics, it is important to note that expanding the surface array in proportion to the area of the deep detector leads to a quadratic increase in acceptance for coincident events compared to the present detector. The acceptance for coincident events of a surface array of area $A_s$ centered above a deep detector of area $A_d$ at depth $d$ is

$$A \Omega \approx \frac{A_s A_d}{d^2}.$$  

(2)

Taking $d = 2$ km, the acceptance of the present IceCube for coincident events is $\approx 0.25$ km$^2$sr. With an area of $A_s = A_d \approx 7$ km$^2$ the corresponding number would be a factor of $\approx 50$ larger. In addition, for purposes of the veto, it is desirable to have a surface array that extends beyond the footprint of the deep detector. Studies are ongoing to optimize the surface component of Gen2 for both veto and cosmic-ray physics.

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