
ELEMENTARY PARTICLES AND FIELDS

Experiment

Cosmic Ray Spectrum and Composition from Three Years of IceTop and IceCube

K. Rawlins^{*}
(for the IceCube Collaboration)

University of Alaska Anchorage, Anchorage, AK 99508, United States

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Abstract—The IceCube Observatory includes both a deep in-ice array of 86 strings of sensors, and a surface array of 81 stations of frozen water tank detectors (IceTop). These multiple detectors make it possible to measure different cosmic ray air shower components, and to combine these measurements to determine both the spectrum and composition of cosmic rays. This work focuses on two analyses of 3 years of IceCube/IceTop data, from 2010–2013. In one, IceTop alone is used to measure an all-particle spectrum using an assumed composition model. In the other, coincidence events which trigger both IceTop and IceCube are used to create individual spectra for four different nuclear groups (protons, helium, oxygen, and iron).

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1. INTRODUCTION

The IceCube Neutrino Observatory sits in a unique position to make measurements of cosmic ray spectrum and composition in the energy range between the knee and the ankle, from tens of PeV to EeV. The surface detector located at an atmospheric depth of ~ 680 g/cm² is near the $X_{\max}$ of showers in much of this energy range. Its multiple detector components give it unique leverage to measure multiple air shower components in coincidence. The Observatory has the potential to study cosmic rays, and in particular to disentangle observables related to primary energy and primary mass, in an energy range where the origin of these particles is thought to make a transition from galactic to extragalactic.

The deeply-buried or “in-ice” detector consists of 5160 Digital Optical Modules (DOM’s) deployed between 1450 and 2450 m deep in the Antarctic ice [1]. This instrument is sensitive to the high-energy (TeV) muon component of cosmic ray air showers from above. Meanwhile, the IceTop detector [2] consists of ice Cherenkov tanks, deployed on the surface above the IceCube strings. IceTop triggers on the electromagnetic and low-energy (GeV) muon components of the air showers. An IceTop “station” is a pair of tanks 10 m apart, and the stations are arranged on a triangular grid approximately 125 m apart, covering an area of approximately 1 km².

This work discusses two cosmic ray analyses: the *IceTop-alone* analysis, in which the shower size is used as a proxy for primary energy, and the *Coincidence* analysis, in which surface data is combined with TeV muon data from the in-ice detector to additionally distinguish primary mass for events which hit them both. Both analyses use 3 years of data: 977.6 days of lifetime between June 1, 2010, and May 2, 2013. The first year of this data was taken in IceCube’s IT73-IC79 configuration, while the next two come from IceCube’s completed IT81-IC86 configuration. In order to analyze the three years together and compare to Monte Carlo simulations using IT73-IC79, the IT81-IC86 data was “retriggered” to the slightly smaller IT73-IC79 configuration.

2. THE IceTop-ALONE ANALYSIS

For all air showers that trigger IceTop, a maximum-likelihood reconstruction algorithm attempts to find the best shower track (core position and track direction), as well as fit the Lateral Distribution Function (LDF) of the charges deposited in the tanks as a function of radial distance. The LDF, described in more detail in [2], has two free parameters: S_{125} and β . S_{125} is the signal strength at a reference distance of 125 m, measured in units of vertical equivalent muons (VEM); β is a measure of the slope of the LDF and related to the age of the shower.

The IceTop detector is covered by a changing and irregular layer of snow overburden. Because of this, the reconstruction algorithm has to account for the

^{*}E-mail: krawlins@alaska.edu

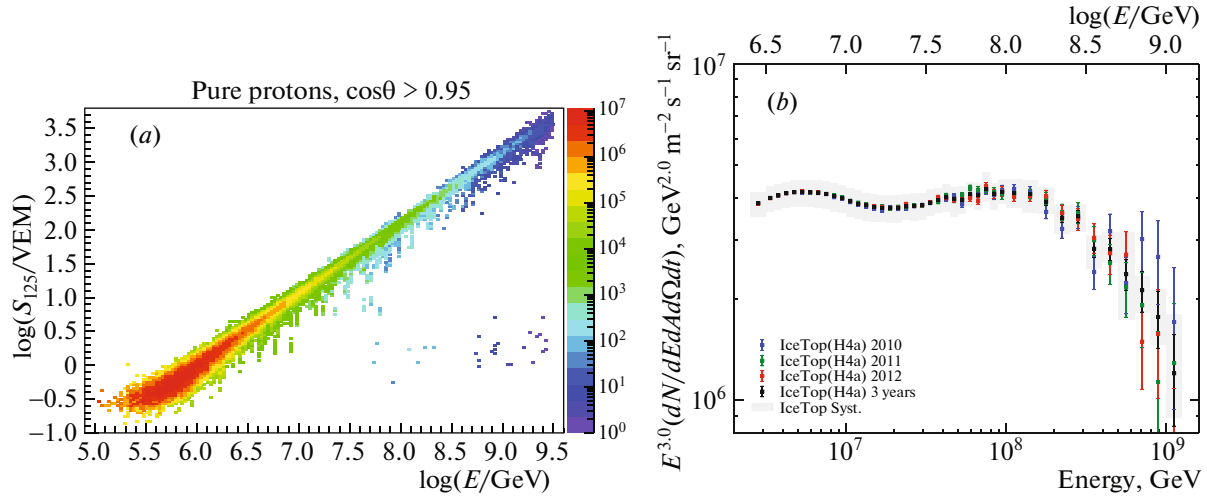


Fig. 1. (a) S_{125} as a function of primary energy, which has minimal sensitivity to composition. (b) All-particle energy spectrum from the *IceTop-alone* analysis, for the three years analyzed (separately, and together).

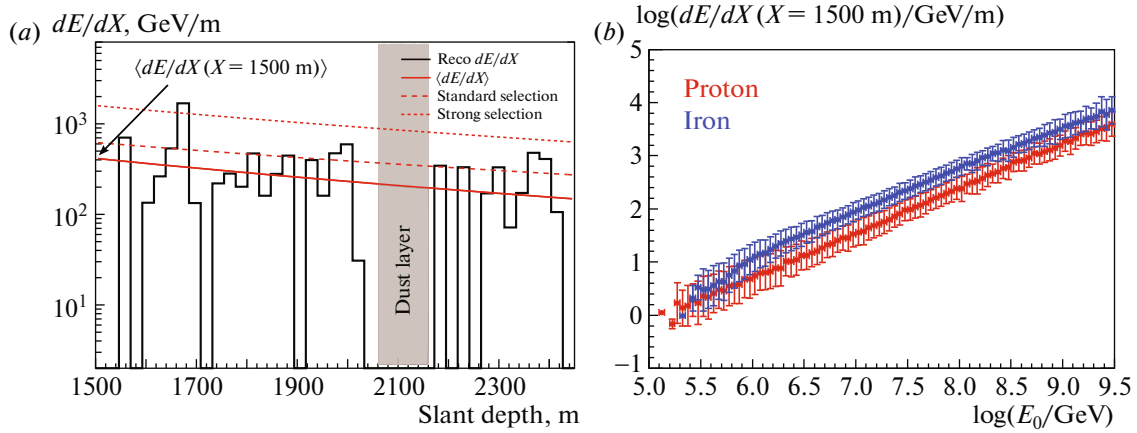


Fig. 2. (a) An example of an energy loss profile measured in the in-ice detector. The solid curve is the fit dE_{μ}/dX , and the dashed and dotted lines show the two different thresholds for the “standard” and “strong” selection of stochastics. (b) dE_{μ}/dX at 1500 m as a function of primary energy, which is highly composition-sensitive.

attenuation of shower particles in the snow. Signals are assumed to attenuate exponentially with slant depth through the snow to the detector, according to an “effective attenuation length” λ . This attenuation length is expected to change over time as the snow load increases and the signals in IceTop become on average more muonic. So, each of the three years is treated with a snow λ individually optimized for that year: 2.1 m for 2010/11, 2.25 m for 2011/12, and 2.25 m for 2012/13.

Quality cuts, described in more detail in [3], are used to restrict the data sample to well-reconstructed events. In particular, effort is made to remove “un-contained” events, whose true core lands outside the physical extent of the IceTop array and which are not reconstructed reliably.

Monte Carlo events from four simulated nuclear

groups (protons, helium, oxygen, and iron) are used to map $\log(S_{125})$ into $\log(E)$ [4]. Figure 1a, made from simulations at near-vertical zenith angles, shows how $\log(S_{125})$ has a linear relationship to the shower’s primary energy $\log(E)$. A general map of one into the other can be made by slicing this figure into bins of $\log(S_{125})$ and finding the mean $\log(E)$ within each. This was done separately for four different ranges of zenith angle, with the shallowest at $\cos(\theta) = 0.80$. The exact shape of this relationship does have some minor sensitivity to composition, so a particular composition model must be assumed (such as H4a [5], which is what was assumed for this work) in order to take the body of IceTop data and translate it into an all-particle spectrum. IceTop alone, in this work, is not capable of distinguishing different masses from each other.

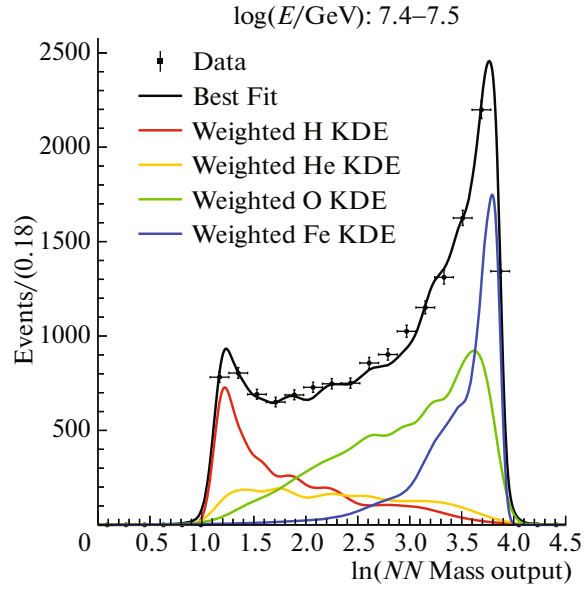


Fig. 3. A set of example “template histogram” PDF’s, together with one constructed from data, for a particular bin of reconstructed energy ($\log(E/\text{GeV}) = 7.4\text{--}7.5$). From [3].

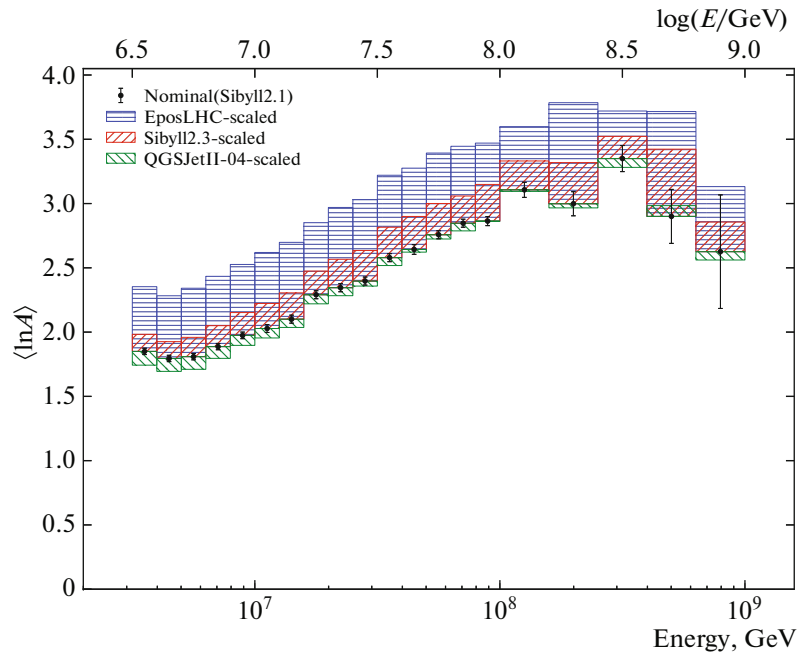


Fig. 4. Mean logarithmic mass $\langle \log A \rangle$, for the baseline analysis using SIBYLL2.1, and with estimates of the effect of using alternate hadronic interaction models instead. From [3].

3. THE COINCIDENCE ANALYSIS

When an air shower triggers both the IceTop detector and its deeply-buried in-ice companion, additional information can be gained from the energy loss profile of the high-energy muons that penetrate to depth [6]. Although coincident events are fewer in number, by combining surface observables from IceTop and in-ice observables together, the primary energy and primary mass can be disentangled.

A separate reconstruction algorithm constructs a detector response matrix for muons depositing energy

as they transit the in-ice detector, and for each event, inverts this detector response matrix to map the energy loss profile as a function of slant depth [7], as shown in Fig. 2a. Then, the energy loss profile is fit, to extract a) the average energy loss behavior and b) the size and quantity of deviations from that average behavior due to stochastic losses (the “stochastics”). The energy loss dE_μ/dX is a highly composition sensitive observable, as shown in Fig. 2b. It is measured at a fixed slant depth of $X = 1500$ m, which corresponds roughly to the top of the IceCube detector.

The number of high-energy stochastics is measured in two different ways: a *standard selection* and a *strong selection* requiring higher stochastic energy loss. Both of these variables also exhibit composition sensitivity.

A neural network (NN) is then used to translate observables from both detectors into both primary energy and primary log mass. A total of five input variables are used: shower size S_{125} and the zenith angle $\cos(\theta)$ from IceTop, and dE_{μ}/dX at $X = 1500$ m and the two measures of number of stochastics from IceCube. Two hidden layers, with respectively seven and four neurons, map these to the two outputs of energy and mass (a 5-7-4-2 network) [8, 9].

Within each bin of reconstructed energy, the reconstructed log masses measured by the NN are collected into “template histograms”, one for each of the four simulated elemental types. An example of the four template histograms for one energy bin is shown in Fig. 3. In this figure, the histograms are smoothed into probability density functions (PDF’s) using an adaptive KDE method. Template histograms constructed from *data* are then compared, and the best fractions of each nuclear type to fit the data is calculated. Fig. 3 also shows a data histogram for this bin, and the four nuclei are shown with the proportions that yield the best fit to the data.

4. SYSTEMATIC UNCERTAINTIES

Both analyses are vulnerable to sources of systematic error. Some are related to the analysis technique itself, for instance (in the IceTop-alone analysis) bin migration in energy or zenith angle due to inaccurate track reconstruction, and uncertainties in the energy reconstruction due to the choice of composition model, or (for the Coincidence analysis) uncertainties related to the chosen NN architecture, or kernel width of the KDE treatment for template histograms. Some are related to the detector itself, such as in the calibration of the IceTop tanks ($\sim 3\%$), the interpolation of the amount of snow coverage over the tanks ($\sim 3\%$), or the light yield in the ice from the combined effects of ice properties and DOM efficiency. Lastly, there are uncertainties due to hadronic interaction model used in simulations for this analysis.

The IceTop-alone analysis is vulnerable to the tank calibration, snow systematics, and the assumption of a composition model, since these affect the mapping of S_{125} into $\log(E)$. They are shown as a grey band in Fig. 1b. The Coincidence analysis, meanwhile, is additionally vulnerable to the uncertainties affecting muons in the ice: the light yield, and the hadronic interaction model. The overall uncertainty from light yield (a combination of effects from absorption, scattering, hole ice effects, and

DOM efficiency) is estimated at $+9.6\% - 12.5\%$. Hadronic interaction model effects were studied using smaller samples of Monte Carlo simulations using EPOS-LHC, SIBYLL2.3, and QGSJET-II-04, and comparing to the baseline simulation based on SIBYLL2.1. Changes in S_{125} and dE_{μ}/dX (the two most important input parameters to the analysis) were measured in these alternative datasets, and events *shifted* in S_{125} and dE_{μ}/dX by these changes were processed through the analysis framework to estimate the impact on the final result. Figure 4, which shows the mean logarithmic mass of cosmic rays as a function of energy, includes the effect of these shifts representing alternate models. EPOS-LHC is the most different; its prediction of fewer muons overall makes IceCube data look more iron-like. Although the hadronic model affects the absolute mass, it does not change the overall shape of the trend.

5. RESULTS AND DISCUSSION

Figure 1b shows the result of the IceTop-alone 3-year analysis. Figure 5 shows a similar set of results for the Coincidence analysis, which agrees with the IceTop-alone analysis within the systematic errors. Both the IceTop-alone and IceTop-IceCube coincidence analyses show a hardening of the spectrum at around 20 PeV, and a softening again past 100 PeV. These features are consistent with previously-published results, and are present in all three years of data. The energy spectra of the three individual years agree well with each other within their systematic errors. The energy spectra of the two analyses agree within 2%, which is within the estimated systematic error due to the IceTop-alone analysis’s assumption of a composition model.

Despite the large systematic uncertainties, clear differences in behavior between the four elemental groups are visible: protons and helium turn down steeply at lower energies, and oxygen and iron maintain a harder spectrum up to higher energies. The spectra are most consistent with the H3a and H4a models, and also somewhat consistent with the phenomenological GST and GSF models.

The average composition increases from the lowest energies up to ~ 100 PeV, where the slope of the trend flattens. Approaching 1 EeV, where the statistical errors become significant, the average mass could be consistent with either a flat or a lightening composition, and in this energy range this measurement is heavier than those reported by other experiments.

Many improvements to reconstruction techniques in both IceTop and IceCube are now underway, as well as generation of updated cosmic ray simulations of the IT81-IC86 detector. These improvements, as well as the increased statistics of multiple years of

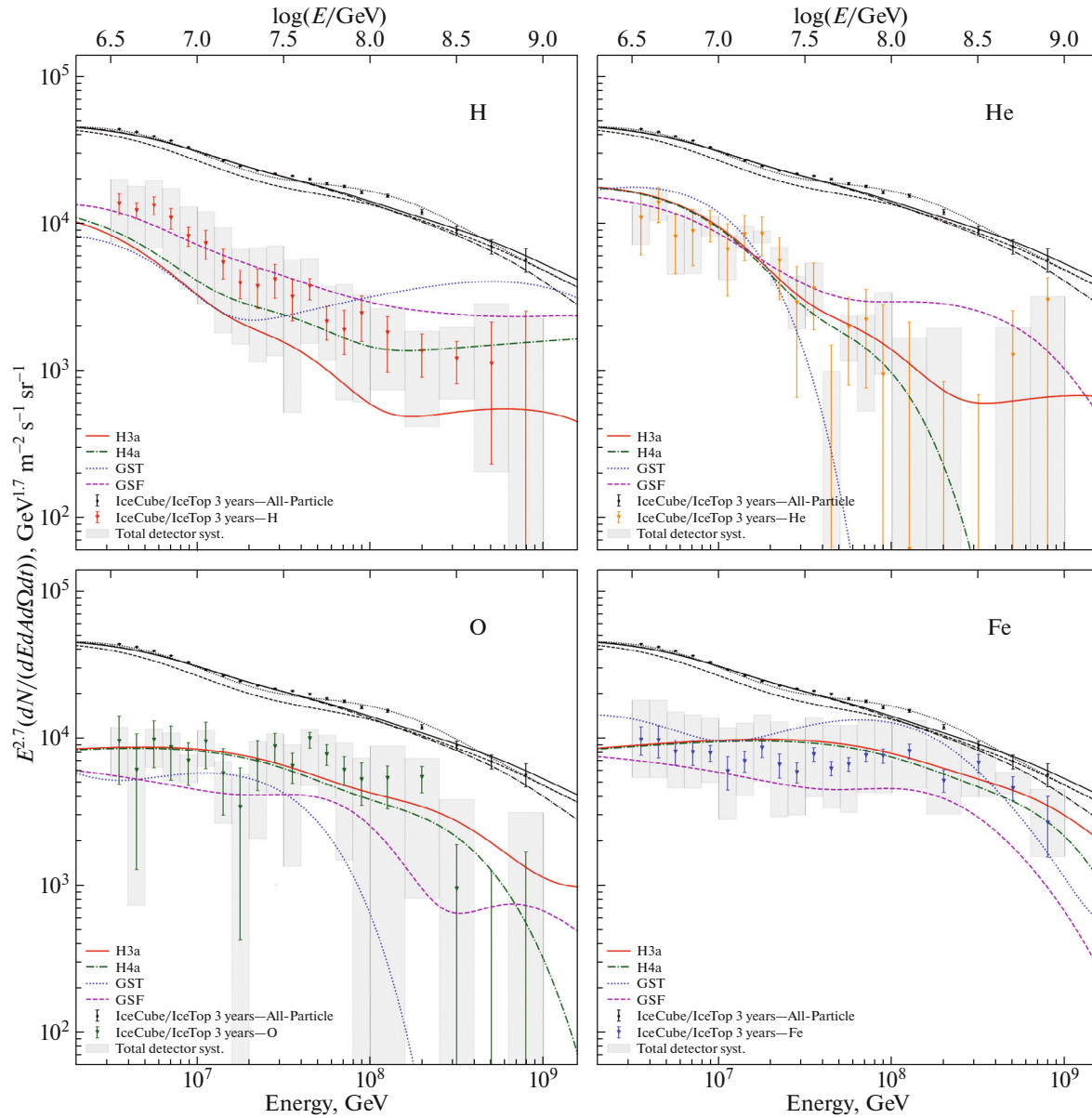


Fig. 5. Energy spectra from the *Coincidence* analysis, broken down into the four nuclear groups, using SIBYLL2.1 for baseline simulations. The grey bands represent systematic errors from detector effects (snow correction, energy scale of IceTop, and light yield in the deep ice). From [3].

data, should allow IceCube to further refine these measurements in the future.

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