Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 4 (HE part 1), pages 143–146

ID 1294

Cosmic Rays in IceCube: Composition-Sensitive Observables

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Abstract: Cosmic ray showers that trigger the IceTop surface array generate high energy muons that are measured by the IceCube detector. The large surface and underground area of this 3-dimensional instrument at completion guarantees significant statistics for shower energies up to about 1 EeV. Since the number of muons is sensitive to the type of the primary cosmic ray nucleus, these events can be used for the measurement of cosmic ray composition. Using the data taken in the existing array, we measure the observables sensitive to the primary mass as a function of shower energy estimated by the surface array. The result is compared to simulations of the coincident events of different primary nuclei.

Introduction

Cosmic rays follow a steep power-law spectrum which spans a wide energy range up to a few 10^{20} eV. One of the interesting features in the all-particle energy spectrum is that the cosmic ray spectrum steepens around 3 PeV, which is called the 'knee'. The origin of the knee is generally understood to be due to the limiting energy attained during the acceleration process and/or leakage of charged particles from the galaxy. The mass composition of cosmic rays at the knee region provides important clues to their origin.

The IceCube Observatory located at the South Pole, a 3-dimensional instrument which consists of the IceTop surface detector and IceCube optical sensor arrays, is uniquely configured to measure cosmic ray composition. The IceTop surface array will consist of 80 pairs of frozen water tanks which measure the energy deposition at the surface, and 80 strings of 60 digital optical modules (DOMs) in ice will measure Cherenkov photons from muon bundles. The DOMs are attached to a cable every 17 m, between depths of 1,450 and 2,450 m. A pair of the IceTop tanks separated by 10 m is located above each IceCube string and a tank employs two DOMs which are identical to in-ice DOMs but with different PMT gains, which results in a wide dynamic range.

Data and simulation

IceTop/IceCube coincident data taken in 2006 were used for this analysis. In 2006, 16 pairs of IceTop tanks and 9 IceCube strings were operational. Events were recorded when the following trigger conditions were satisfied: 6 hits within 2 μs for IceTop DOMs, and 8 hits within 5 μs for in-ice DOMs. The coincident rate is about 0.2 Hz. A threshold of 300 TeV allows us to measure cosmic rays below the knee.

Air shower events were simulated with CORSIKA[1], and GHEISHA[2] and SIBYLL-2.1[3] were selected as the low and high energy hadronic interaction models, respectively. Proton and iron showers were generated over an area of 4.5 km^2 covering the IceTop array, from energies of 50 TeV to 5 PeV, using the South Pole atmospheric model[4]. The events were generated according to E^{-1} spectrum and re-weighted to the cosmic ray energy spectrum with spectral index of -2.7 below the knee at 3 PeV, and -3.0 above it.

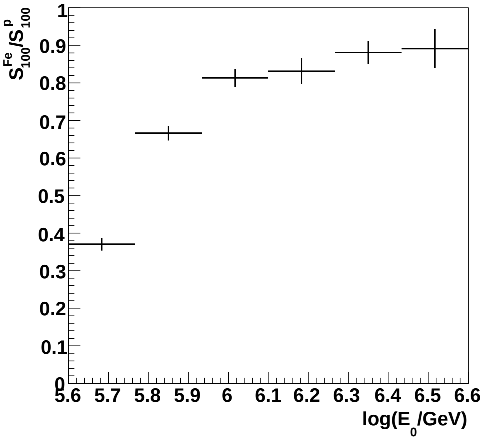

Figure 1: Ratio of S_{100}^{Fe} to S_{100}^{p} as a function of the total energy per nucleus (E_0).

As a first guess, the shower core is determined by calculating the center of gravity of tank positions by weighting with the square root of pulse amplitude. The shower direction is determined on the basis of shower front arrival times measured by the IceTop tanks. The energy deposition at the surface as a function of distance from the shower core is fitted to the function given by[5]:

$$f(r) = S_{100}\left(\frac{r}{100\mathrm{m}}\right)^{-\beta-\kappa\log(r/100\mathrm{m})} \tag{1}$$

where r is a distance from shower core, κ is 0.303 for hadronic showers, and S_{100} is the signal in vertical equivalent muon (VEM) per tank at 100 m from the shower core. The parameter β is roughly correlated with shower age via $s = -0.94\beta + 3.4$. S_{100} is an energy estimator and depends on primary mass, as shown in Figure 1.

The events which passed the following quality cuts are used in this study:

- Reconstructed shower core lands 60 m inside of IceTop array.
- β in Eq. (1) is less than 6.
- Reconstructed zenith angle is less than 20°.

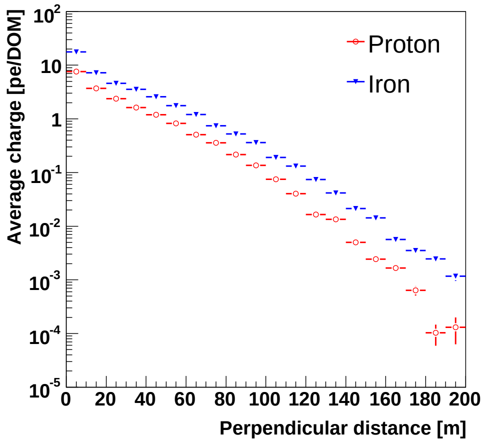

Figure 2: Average charge per in-ice DOM is shown as a function of a perpendicular distance from a primary track for proton and iron showers [$0.5 < \log(S_{100}) < 1.3$].

- The number of hit strings is greater than 1.

The number of hit strings is required to be equal to or greater than 2 since the lateral distribution fit in ice which will be described in the next session fails if a reconstructed track is vertical.

Cosmic ray composition

The IceCube detector is located deep in ice, so only muons can reach the detector, and useful information about primary cosmic rays can be inferred from muon bundles with the 3-dimensional instrument. The total number of muons in a bundle is dependent on the type of primary nucleus. Cherenkov photons from the muon bundle are detected by optical sensors in ice, and the photon intensity is measured as a function of perpendicular distance from a primary muon track and fitted by an exponential function. The primary muon track is the shower axis determined by the IceTop array. Figure 2 shows the average charge per in-ice DOM as a function of the distance from a primary track to each hit DOM in a range of S_{100} between 0.5 and 1.3 showing separation between proton and iron

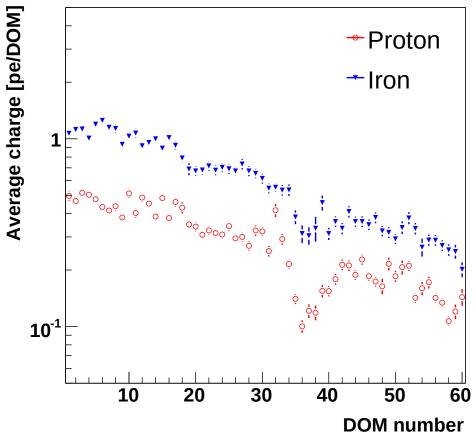

Figure 3: Average charge vs. DOM number for proton and iron showers [$0.5 < \log(S_{100}) < 1.3$].

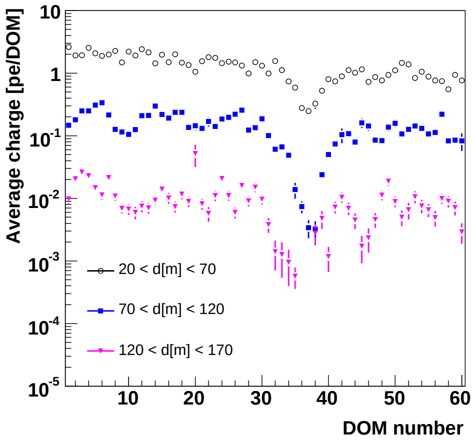

Figure 4: Average charge vs. DOM number for proton showers only at different distance ranges [$0.5 < \log(S_{100}) < 1.3$].

showers. It was found, for the SPASE/AMANDA detectors, that the photon intensity at 50 m (K_{50}) is most sensitive to the mass of primary cosmic rays[6]. Ranging-out of muons and depth dependence of light scattering in the ice are taken into account in the lateral distribution fit. However, these corrections are not made in Figure 2. Once we find all observables sensitive to primary mass, we will feed them into a neural network (see [7] for detailed description) for composition analysis.

Figure 3 shows the average charge as a function of DOM number for proton and iron showers. Overall the average charge decreases with depth, featuring changes in the optical properties of ice. For instance, a thick dust layer observed by a dust logger during string deployment is seen around DOM 36. Figure 4 shows the same as Figure 3 but with three different distance ranges only for proton showers, and indicates that using the hits close to muon bundles gives measurement less dependent on ice properties. An appropriate correction for the dust layer needs to be made, or those DOMs around the dust layer can be removed in the analysis.

In addition to charge, we looked into timing information to see whether or not it is sensitive to primary mass. The size of the muon bundle depends on the type of the primary nucleus at a given energy and can affect the time residual (observed minus expected times from the primary muon track). The expected time is the travel time of a direct Cherenkov photon from the primary muon track to each hit DOM. The time residual distribution is fitted by $\exp(-\alpha t)$ from 50 to 400 ns where the tail of the distribution is straight in log scale, and the slope, α, of the distribution as a function of DOM number is shown in Figure 5. Separation between proton and iron showers is seen, and the slope varies depending on depth of DOM and rises at dusty layers.

Discussion

We investigated observables sensitive to primary mass. In addition to charge information from the DOMs in ice, the slope of the time residual distribution seems to be sensitive to the type of the primary cosmic ray, though it has dependence of optical properties of ice. However the dependence of ice properties can be reduced by making an appropriate correction for dusty layers or by excluding the DOMs in the thick dust layer around DOM 36. Moreover, DOMs close to a muon bundle appear to be best suited for such an analysis. Once

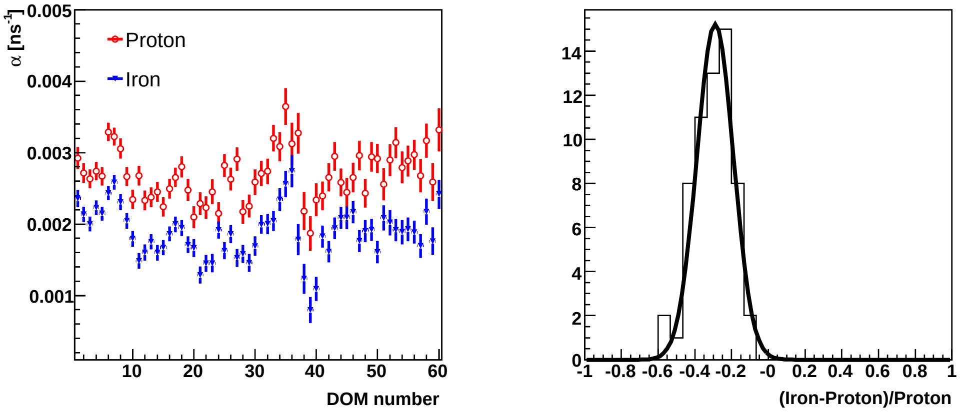

Figure 5: Slope (α) of the time residual distribution as a function of DOM number (left) and distribution of $(\alpha^{Fe} - \alpha^{p})/\alpha^{p}$ (right) are shown.

we have all observables sensitive to primary mass, the neural network can be employed for cosmic ray composition studies.

Acknowledgments

This work is supported by the U.S. National Science Foundation, Grants No. OPP-0236449 and OPP-0602679 (University of Delaware).

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