Study of the energy scale of HiRes event reconstruction

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***Abstract*. The High Resolution Fly's Eye (HiRes) experiment observed ultra-high energy cosmic rays using a pair of fluorescence detectors. With these, HiRes performed the first observation of the GZK suppression at a significance of more than 5 standard deviations. Since then, new measurements have been made of local atmospheric conditions, detector characteristics, fluorescence yield, and mean dE/dX of showers. A study to determine the effect of applying the results of these measurements on the energy scale and monocular event reconstruction will be presented.**

***Keywords*: Ultra-High Energy Cosmic Rays, HiRes, energy scaling**

I. Introduction

Since 1966 there has been a theoretical upper limit of energy to which cosmic rays can reach. Greisen [1] and separately Zatsepin and Kuz'min [2] proposed that ultra-high energy protons would interact with Cosmic Microwave Background (CMB) photons and lose some of that energy through photopion production. The energy that would remain in the proton held a threshold of $\sim 6 \times 10^{19}$ eV while the flux of cosmic rays with energies greater than this would be highly suppressed.

The High Resolution Fly's Eye (HiRes) was the first to experimentally observe the Greisen-Zatsepin-Kuzmin (GZK) suppression [3]. In order to obtain this result much of the analysis used standard calibration values. Using different forms of detector calibrations, atmospheric parameterizations, and properties of fluorescence observation we are able to validate the obtained energy spectrum.

II. The HiRes Experiment

The High-Resolution Fly's Eye (HiRes) experiment operated between May 1997 and April 2006. It consisted of two detectors which observed the nitrogen fluorescence produced by cosmic ray extensive air showers as they penetrated the atmosphere. The HiRes-I and HiRes-II sites were positioned 12.6 km apart in the Dugway Proving Grounds in Utah.

HiRes-I consisted of 20 telescopes with viewing elevation angles between 3° and 17° with 360° azimuthal coverage and an additional 2 telescopes with viewing elevations between 17° and 31° overlooking HiRes-II (added in October, 2005). HiRes-II used 42 telescopes observing between 3° and 31° in two separate rings that also had 360° azimuthal coverage. HiRes-I used sample-and-hold electronics while HiRes-II used 100 ns FADC electronics. Both sites used cameras made from clusters of 256 photomultiplier tubes (PMTs) set up in a 16×16, hexagonally close-packed array and set at the focal point of each telescope. Each tube had a $1° \times 1°$ viewing angle, giving each telescope a $14° \times 16°$ viewing area.

Each site was able to run independently, allowing analysis to be performed in monocular mode for each site individually [4] [5]. If an event was observed by both sites, it was reconstructed using a stereoscopic analysis [6] as well.

III. HiRes Energy Scaling

Calibration of the detector is vital to understand how well the experiment observed cosmic ray showers. Multiple forms of lasers and light sources were used to determine the response of the detector for various aspects of the experiment. A portable xenon flash lamp with a combination of filters was used as a monthly standard-candle calibration for the PMTs. As an alternative, a nightly YAG-laser could be used to calibrate the PMTs.

The final reconstruction used an average reflectivity for all mirrors at each of the two sites. New measurements were taken of each mirror and applied to the reconstruction and the Monte Carlo. These were then compared to the original value.

Since the atmosphere not only acts as a scintillator to produce the light collected by HiRes, but is also responsible for scattering that light, knowledge of the atmosphere is highly important. The amount of light produced is proportional to the number of electrons and depends on the pressure and the density of the atmosphere:

$$\epsilon_\lambda = N \frac{\sigma_\lambda}{1 + \frac{P}{P'_\lambda}}$$

where ϵ_λ is the (wavelength-dependant) number of fluorescence photons generated per unit path length, N is the density of nitrogen molecules, and σ_λ is the optical cross section. P'_λ is the pressure due to quenching of excited-state nitrogen molecules. The US standard atmosphere model used in the final reconstruction was measured against events using collected radiosonde data out of the Salt Lake City, Utah airport.

Lasers fired throughout the run night help us understand the attenuation in the atmosphere due to aerosols. Steerable laser systems are used to calibrate the complete aperture around both sites. From this data, the vertical aerosol optical depth (VAOD) can be determined on an hourly basis. A constant VAOD of 0.04 was used in the final energy reconstruction. A study using the hourly database was performed on the Monte Carlo in order to compare the effects of using the average value.

The atmosphere is the calorimeter with which we measure the energy of an event by fluorescence light. The fluorescence yield of the shower must be understood in order to accurately reconstruct the energy of the primary cosmic ray. Cosmic ray showers consist primarily of electrons and positrons with $\sim 10\%$ of the energy of primary cosmic ray used to create non-interacting particles. Measurements are taken in laboratory settings to parameterize the mean fluorescence yield of electrons. Many groups have performed this measurement ([8], [9], [10], [11]). The spectrum of nitrogen fluorescence obtained by Bunner, normalized to the Kakimoto fluorescence yield (Fig. 1), was used to determine the reconstructed energy of the showers. A study was performed comparing the Bunner spectrum to the FLASH spectrum and separately the Kakimoto normalization was compared to an average made from all experiments.

Processing time is a major consideration when simulating showers. To reduce this time, energy thresholds can be set to ignore particles below a given energy. Song's [12] proposal of estimating the missing energy of particles below the energy thresholds was used in the final reconstruction. Nerling [13] has shown an alternative by calculating the missing energy. A study was performed on the Monte Carlo to determine the energy differences obtained in the two ways.

IV. HiRes Energy Scaling Results

The results of the energy scaling studies will be presented at the 31^{st} International Cosmic Ray Conference.

V. Acknowledgements

This work is supported by the US NSF grants PHY-9321949, PHY-9322298, PHY-9904048, PHY-9974537, PHY-0098826, PHY-0140688, PHY-0245428, PHY-0305516, PHY-0307098, PHY-0649681 and by the DOE grant FG0392ER40732.

We gratefully acknowledge the contributions from the technical staffs of our home institutions. The cooperation of Colonels E. Fisher, G. Harter and G. Olsen, the US Army and the Dugway Proving Ground staff is greatly appreciated.

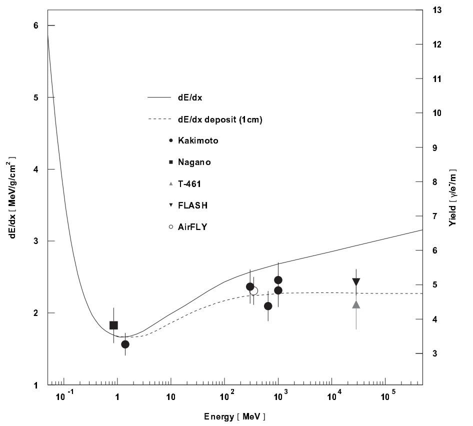

Fig. 1. The fluorescence yield measurements performed by various experimental groups.

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