Monocular and Stereo HiRes Spectrum Measurements

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Abstract: Monocular measurements of the UHECR flux with the HiRes detector give the largest statistical significance and the largest range of energies available. The spectrum from each of the two HiRes sites will be presented. The stereo spectrum has the best geometrical reconstruction and the best energy resolution, though it has a higher energy threshold. The stereo spectrum for the full HiRes data set will be presented and compared to the monocular spectra.

Introduction and Motivation

The High Resolution Fly’s Eye (HiRes) detector was designed to view UHECR showers in stereo. Showers viewed independently from two sites spaced 12 km apart have excellent precision in geometrical reconstruction. Independent energy measurements from two sites allows a verification of the calculated energy resolution of the detector. This is critical because an energy dependent energy resolution or non-gaussian tails on the energy resolution functions can distort the measurement of a steeply falling spectrum. However, the stereo technique has a physics threshold of near \(3 \times 10^{18}\) eV because the detector aperture begins to decrease very rapidly below this value. Monocular reconstruction is less precise but has a much more slowly changing aperture at low energies. Moreover, the geometrical and energy reconstruction can be cross-checked for the sample of events seen in both stereo and mono. There are thus good reasons to reconstruct showers from each site independently and to calculate the UHECR flux observed in this way as well.

Additionally, the first HiRes detector began to take data more than two years before stereo mode operations began in December of 1999. Thus the mono data represents the largest sample of UHECR’s obtained by any detector to date and, likewise, has the best statistical power for determining features in the spectrum. The HiRes experiment completed data taking in April of 2007.

Analysis Techniques

One determines the geometry of an extensive air shower in monocular mode by fitting the phototube trigger times to their viewing angles. With the geometry determined, the photo-electron count is then converted to a shower size at each atmospheric depth, using the known geometry of the shower, and corrected for atmospheric attenuation. We integrate the resulting function over \(X\) (using the determined values of \(N_{\text{max}}\) and \(X_{\text{max}}\)) and then multiply by the average energy loss per particle to give the visible shower energy. A correction for energy carried off by non-observable particles to give the total shower energy (\(\sim 10\%\))\textsuperscript{1} is then applied.

HiRes-I events are too short in angular spread for reliable determination of the angle and impact parameter by timing alone. For the HiRes-I analysis, the expected form of the shower development itself is used to constrain the time fit to yield realistic geometries. The shower profile is assumed to be described by the Gaisser-Hillas parameterization\textsuperscript{2}, which is in good agreement with previous HiRes measurements and with CORSIKA/QGSJET simulations\textsuperscript{1, 3}. This technique is called the Profile-Constrained Fit (PCF).

For the subset of events observed in stereo, the geometrical reconstruction is essentially determined by the intersection of the two shower-detector planes. Here the shower-detector planes are found by fit-
ting a plane to the direction vectors of the phototubes which were triggered at each detector. Even better precision is found by combining the shower time information with this simple geometrical fit. Once the stereo geometry is determined, the shower profile is reconstructed independently for HiRes I and HiRes II using similar binning techniques to those used in the monocular analysis.

Comparison of energies determined in stereo and in mono for HiRes I and HiRes II alone confirm the adequacy of the monocular reconstruction methods and the energy resolution estimates from the detector Monte Carlo.

The MC is also used to calculate the detector aperture. Simulated events were subjected to the same reconstruction algorithm and cuts applied to the data. To verify the reliability of this calculation, we compared, at different energies, the zenith angle and impact parameter distributions, which define the detector aperture. The MC predictions for these are very sensitive to details of the simulation, including the detector triggering, optical ray-tracing, signal/noise, and the atmospheric modeling. Good agreement is found for both stereo and mono distributions.

Because the stereo aperture has a more rapid dependence on energy at lower energy, we define a set of geometrical cuts such that only the saturated part of the stereo aperture is used. This is done by determining, as a function of energy, the maximum impact parameter distance to an event below which the trigger is fully efficient. Only events in this geometrical range are used for the “fully efficient” stereo aperture. We determine these cuts using the detector Monte Carlo. Since this cuts out events with marginal triggering, this set of cuts also insures that the aperture is largely insensitive to atmospheric variations.

**Flux**

We will present the stereo spectrum and the cosmic ray flux for HiRes-I above $3 \times 10^{18}$ eV, and for HiRes-II above $2 \times 10^{17}$ eV for essentially the full HiRes data set. Results relating to the ankle structure and the expected GZK cutoff will be presented. The largest systematic uncertainties are the absolute calibration of the photo-tubes ($\pm 10\%$), the yield of the fluorescence process ($\pm 10\%$), the correction for unobserved energy in the shower ($\pm 5\%$)[1], [4], and the modeling of the atmosphere. Studies of the systematics induced by these uncertainties will also be presented.

**Acknowledgements**

This work is supported by US NSF grants PHY-9321949, PHY-9322298, PHY-9904048, PHY-9974537, PHY-0098826, PHY-0140688, PHY-0245428, PHY-0305516, PHY-0307098, and by the DOE grant FG03-92ER40732. We gratefully acknowledge the contributions from the technical staffs of our home institutions. The cooperation of Colonels E. Fischer and G. Harter, the US Army, and the Dugway Proving Ground staff is greatly appreciated.

**References**