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Measurement of the Cosmic Ray Energy Spectrum from 10^{17} to $10^{18.3}$ eV Using a Hybrid Technique

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Abstract. We measure the energy spectrum of cosmic rays between 10^{17}eV and 10^{18}eV using a hybrid detector consisting of the High Resolution Fly's Eye (HiRes) prototype and the MIA muon array. The spectrum is consistent with earlier Fly's Eye measurements and marginally supports the steepening of the spectrum near 4×10^{17}eV found by previous experiments.

1 Introduction

In the region above the knee, the Fly's Eye experiment (T. Abu-Zayyad *et al.* , 2000) and Haverah Park (A.A. Watson , 1991) experiments observed a fine structure in the energy spectrum of cosmic rays, i.e. there exists a break around 4×10^{17} eV and a dip around 3×10^{18} eV. The Fly's Eye experiment has reported a changing composition from a heavy mix around 10^{17}eV to a proton dominated flux around 10^{19}eV (D. J. Bird *et al.* , 1993). The recently reported HiRes/MIA (T.Abu-Zayyad , 2000) hybrid observation on the cosmic ray composition in a narrower energy region, $10^{17} \sim 10^{18}$ eV, shows a general agreement with Fly's Eye experimental result. All these results make this particular energy region much more interesting than the expectation from a naive rigidity model. These measurements imply that there may be multiple sources of cosmic rays for the cosmic rays in this energy range.

With the help of the shower muon arrival time information from the MIA experiment (A. Borione , 1994), the HiRes/MIA hybrid experiment measures shower geometry quite well. This substantially enhances the energy resolution of the detector at energy around 3×10^{17} eV. The energy spectrum is measured with the hybrid experimental data during 1993 to 1996.

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2 Hybrid Observation and preparation of data

During the lifetime of the HiRes/MIA hybrid experiment between Aug. 23, 1993 and May. 24, 1996 the total effective coincident exposure time was 1532 hours. A total of 2881 coincident events were recorded. For each event, the shower trajectory, including arrival direction and core location, is obtained in an iterative procedure using the information from both HiRes and MIA (T.Abu-Zayyad , 2001). 2491 events survive this reconstruction procedure. Further cuts are performed in order to achieve the high resolution in energy and shower maximum essential to the composition analysis. The criteria are based on a thorough Monte Carlo simulation of the detectors as described below. After these quality cuts, 929 events above 10^{17} eV are used for this energy spectrum measurement.

Of all geometrical parameters, the shower-detector-plane is the most crucial and depends strongly on how many tubes are triggered and how long the track formed by those tubes is. The number of muons detected by MIA is the other contributor to precise time fitting. In order to locate the shower maximum, it and a good fraction of the rest of the profile must be seen by the detector. Moreover, as mentioned before, we must avoid those events which are dominated by Cerenkov light. Poorly fitted events are also to be rejected. A set of quality cuts addresses all these issues.

7000 proton and 6000 iron induced showers are generated with a spectrum of trial energies from 10^{17} to 6×10^{18}eV. The differential spectral index is set as -3.0. After same reconstruction and cuts as the real data passing through, the simulated events demonstrate rather good resolution in geometric and physical parameters. Table 1 lists all response functions of the detector based on the Monte Carlo simulation. 4

Fig. 1 shows the energy distributions after cuts from both real experiment and simulation. This demonstrates the consistency between the simulation and real experiment.

QGSJET	proton		iron	
	σ	mean	σ	mean
E (%)	12	5	8	-14
$X_{\max}$ (g/cm^2)	47	12	46	8
X_{core} (m)	42	-2	40	-1
Y_{core} (m)	57	-2	55	2
space angle	0.88°		0.83°	

Table 1. Resolution figures for a E^{-3} differential spectrum seen by HiRes and MIA. Quality cuts have been applied. Space angle errors are median values.

3 Aperture Calculation

Based on the 7000 proton, 6000 iron Monte Carlo events mentioned before plus 2000 simulated events at every point above 10^{18} eV for both proton and iron, Fig. 2 shows the detector aperture as a function of energy. Above $10^{17.6}$ eV, this simulation shows that the detection efficiency is saturated. The feature of a flat aperture as a function of energy, due to the MIA detector, is a very useful constrain for the cosmic ray intensity measurement. The price for this feature, however, is that the aperture is rather small. This simulation provides a calculation of the aperture near detector threshold with good precision. The fluorescence detector has a sharp threshold around 10^{17} eV. Since the efficiency drops to lower than 10% below $10^{17.2}$ eV, events below this energy are not included in the analysis.

The Monte Carlo simulation is also useful to study the dependence of the detector aperture on the type of primary cosmic rays. Our simulation using proton and iron primaries shows that the aperture is very similar even near the detector threshold. The event selection criteria and the requirement for a minimum number of μ's to reach the ground and trigger MIA diminishes any difference between the triggering induced by protons or heavier nuclei.

4 Result and discussion

Fig. 3 shows the cosmic ray energy spectrum from $10^{17.2}$ eV to $10^{18.3}$ eV. In order to see the detailed structure of the energy spectrum, the intensity is multiplied by E^3. The data supports an overall power law spectrum with an index about 3.090 ± 0.066 and a intensity of $10^{-29.7\pm1.5} eV^2 \cdot m^{-2} \cdot sr^{-1} \cdot s^{-1}$ at 10^{18} eV. A maximum likelihood estimate has been employed for this fitting. The data for this spectrum is listed in Table III including the number of events (NOE) and aperture at specific energies. Only the Poisson error in intensity J is listed. At low event numbers, the Poisson error is an underestimate of the true error. Various authors have proposed better approximations to the true error (see, for example (V. Regener , 1951)). The fit results are insensitive to these refinements, however.

As a comparison, the stereo Fly's Eye (D. J. Bird *et al.* , 1993) measured energy spectrum is plotted in the same figure. The difference between the two measured intensities

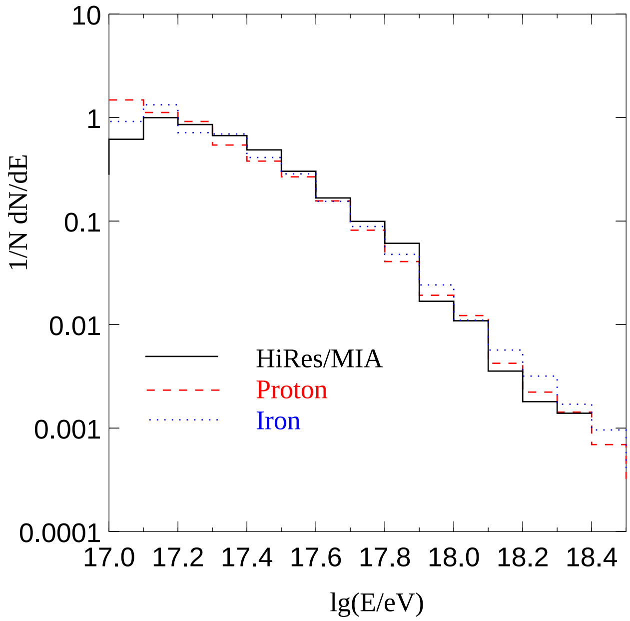

Fig. 1. Event Energy distribution. The solid line represents the data while the dashed line represent simulation result for protons and dotted line for iron primaries assuming a E^{-3} spectrum. The vertical axis represents the number of events within a bin of log_{10}E.

is less then 28% below 3×10^{17} eV. The absolute energy scale has a systematic uncertainty about 25% (T.Abu-Zayyad , 2000) in this experiment and 40% (D. J. Bird *et al.* , 1994) in Fly's Eye experiment. The corresponding uncertainties are shown in Fig. 3 with the two slant arrow bars. The two measurements of the cosmic ray energy spectrum are consistent within errors.

The 6 data points below 5×10^{17} eV strongly support a $E^{-3.01}$ spectrum with good statistics. A maximum likelihood fit to those 6 points is shown as the dashed line in Fig. 3. The logarithm likelihood is evaluated by choosing a Poissonian distribution function, i.e. the likelihood is defined as

$$\mathcal{L} = \prod_i \frac{e^{-\mu_i} \mu_i^{n_i}}{n_i}, \quad (1)$$

$\log_{10}$ (E/eV)	$J(E)$	Δ J	NOE	Aperture
	$10^{-28}/(eV \cdot m^2 \cdot sr \cdot s)$			$(km^2 \cdot sr)$
17.254	3.95	0.32	147	1.6
17.351	2.10	0.17	145	2.4
17.449	1.19	0.10	130	3.1
17.548	0.551	0.054	104	4.2
17.649	0.235	0.028	69	5.2
17.746	0.133	0.018	53	5.7
17.873	0.0513	0.0069	55	5.7
18.096	0.0091	0.0022	17	5.9
18.299	0.00207	0.00084	6	5.8

Table 2. The cosmic ray energy spectrum from 10^{17} eV to 3×10^{18} eV. NOE stands for number of events.

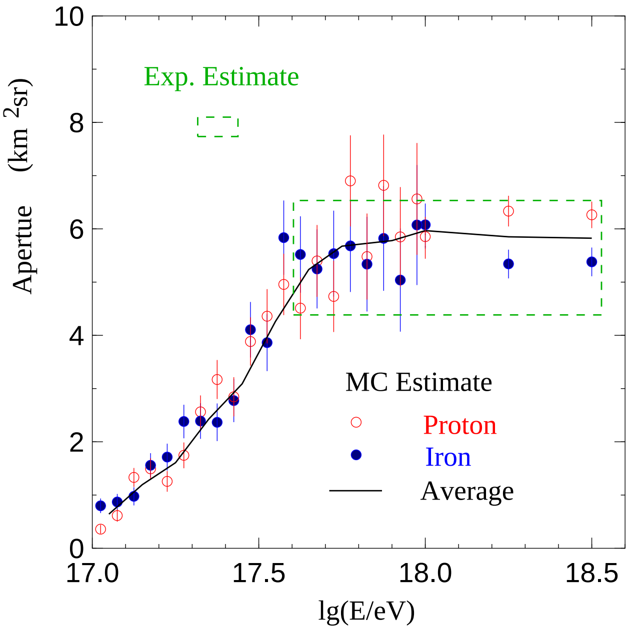

Fig. 2. The detector aperture as a function of primary energy. Dots connected by the solid line represent the simulated result. The area marked by the dotted line gives the range of the experimentally estimated aperture with its uncertainty.

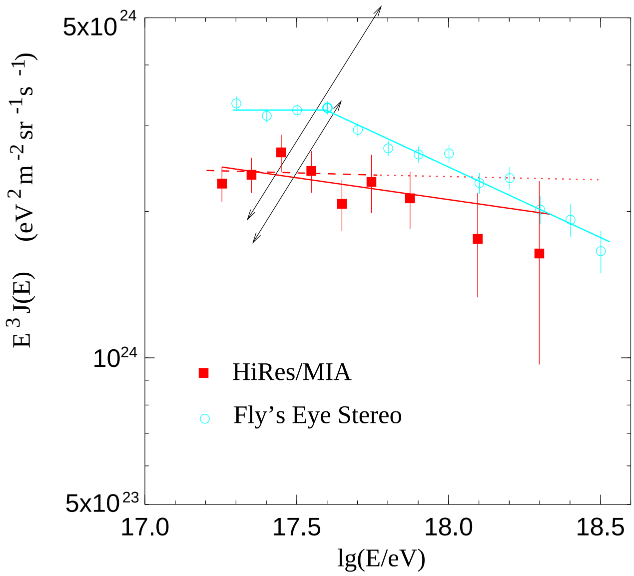

Fig. 3. The differential energy spectrum of cosmic rays in the vicinity of 3×10^{17} eV. The spectrum is multiplied by E^3. The intensity of cosmic rays measured in this experiment (squares) is lower than the Fly's Eye experiment (dots), but is within the uncertainties in energy scale determination indicated by the slant bars in the figure. The solid line represents the best fit to all the data in this experiment. The dashed and dotted line represents the best fit to the 6 lowest energies points and its extrapolation to higher energy.

where the index i runs over all the data points, the expectation value μ_i in the i-th energy bin is the expected number of events. If the $E^{-3.01}$ spectrum is assumed to be true also for the remainning three points at higher energy, a combined test over these three points shows that the probability is 5.9%(W.T.Eadie *et al.* , 1971). This indicates a marginal confirmation of the spectral break in the cosmic ray spectrum measured by Fly's Eye and Haverah Park(A.A. Watson , 1991) experiments.

5 Uncertainty in energy measurement

The systematic error in the energy is about 25% and comes from fluorescence efficiency uncertainty (T. Abu-Zayyad *et al.* , 2000), detector calibration uncertainty(T. Abu-Zayyad *et al.* , 1999) and the atmospheric corrections (D. J. Bird *et al.* , 1994). The first two are intrinsically independent of the primary particle energy over this range. The fluorescence efficiency has been measured with an error of 10%. The percentage atmospheric corrections are also independent of energy because the sample of showers is restricted to core locations within 2 km of the MIA detector center. Therefore there is no significant atmospheric path length difference between an EAS and the detector for different energies. An energy independent systematic fractional error in energy has no effect on the measured elongation rate. The magnitude of the systematic error in energy due to atmospheric attenuation can be estimated by varying the atmospheric parameters over the range described above. It is not greater than 10%. The detector calibration systematics is less than 5%.

6 Comparison with Previous Experiments

The cosmic ray energy spectrum measured by all modern experiments are summarized in the Fig.4 covering the whole energy range from 3×10^{14} to 3×10^{18} eV. The consistency between this experiment and the Fly's Eye stereo data has been discussed previously. The present experiment marginally confirms the break in the spectrum at 4×10^{17} eV. By comparing with the observations (M. Nagano *et al.* , 1984) in the "knee" region, both the intensity and spectrum index imply a good continuity with the results at energies lower than 3×10^{16} eV. The change in cosmic ray intensity around 3×10^{17} eV is comparable in power law index with the change that occurs around the "knee". A confirmation of this break with better statistics and similar energy resolution is important. All the other experimental results are consistent with the Akeno result: the spectrum follows a single index power law between 10^{16} and 10^{17} eV.

7 Conclusion

The HiRes/MIA hybrid experiment has measured the cosmic ray energy spectrum between $10^{17.2}$ and 3×10^{18}. The spectral index and intensity are -3.090 ± 0.066 and $10^{-29.7 \pm 1.5} eV^2 \cdot m^{-2} \cdot sr^{-1} \cdot s^{-1}$ at 10^{18} eV. The result is in agreement with the Fly's Eye experiment within errors. This result marginally supports the Fly's Eye stereo observation of a break in the energy spectrum around 4×10^{17} eV.

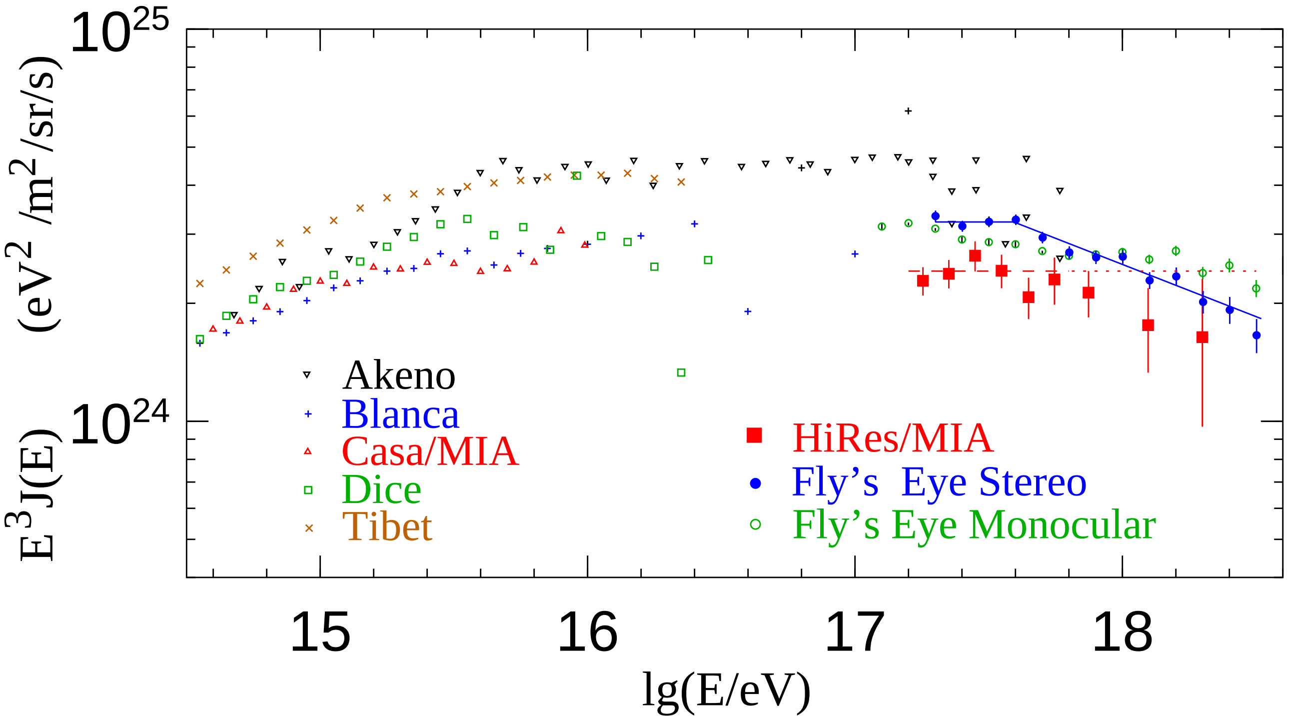

Fig. 4. Energy spectrum of cosmic rays from $10^{14.5}$ to 10^{18} eV. This intensity is multiplied by by E^3. Data in the vicinity of 3×10^{15} eV are adopted from (L. F. Fortson *et al.* , 1999) (Blanca paper).

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