

## HiRes/MIA Measurements of EAS Development Between $10^{17}$ and $10^{18}$ eV

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### Abstract

Analysis of data from the hybrid prototype HiRes and MIA experiment indicates a cosmic ray mass composition changing towards to a lighter nuclear mixture in the range from  $10^{17}$  to  $10^{18}$  eV. The results on EAS longitudinal development and muon content are used to extract the composition information. QGSJet and SIBYLL hadronic models are used to study the model dependence of the results.

## 1 Introduction

The High Resolution Fly's Eye (HiRes) and the Michigan Muon Array (MIA) operated in conjunction with each other for almost three years from 1993 to 1996. This joint experiment combines two of the most effective measures of nuclear composition of primary cosmic rays together for the first time. These are the shower longitudinal development, as indicated by the depth of shower maximum,  $X_{max}$ , measured by HiRes and the muon content of the shower, indicated by the muon size,  $N_{\mu}$ , measured by MIA. The experiment combines the longitudinal and lateral information of each shower that triggered both HiRes and MIA in the shower reconstruction, therefore significantly enhancing the resolution in shower geometry, energy,  $N_{\mu}$  and  $X_{max}$ . This paper reports on the analysis of this unique data set consisting of showers measured in coincidence by the hybrid experiment.

This work very much depends on a realistic instrument Monte Carlo simulation to mimic the detector response, incorporate the atmospheric effects, and most importantly, introduce the hadronic interaction model into the analysis. Such a MC generator offers the opportunity to directly compare the experimental data with predictions from models. The QGSJet and SIBYLL hadronic interaction model have been used in this paper. This MC generator is described in greater details in a separate paper [1].

## 2 Data and cuts

The hybrid experiment collected 4034 events from August 1993 through May 1996. Most of the events have cores located in a circle of 3 km radius centered on MIA, which is about 3.3 km away from the prototype HiRes

detector. 2491 events survived the reconstruction procedure. The event reconstruction is split into shower trajectory geometry determination, shower development profile fitting and muon size fitting [2,3,4]. The track-detector plane, track to tube timing information from HiRes and shower front timing information from MIA are combined in an iterative  $\chi^2$  fit procedure to determine the shower geometry. Three cut conditions are used to ensure fitting quality: 1) angular length of the track is greater than  $20^\circ$ ; 2) distance from shower core to the center of MIA is less than 2 km; and 3) the accumulated geometric fitting error contributing to the uncertainty of  $X_{max}$  is less than  $50 \text{ g/cm}^2$ . These cuts ensure that the resolution of shower arrival direction is less than  $1^\circ$ , the resolution of the perpendicular distance from the track to the HiRes detector is less than 70 m and the resolution of the shower core location is less than 50 m. To determine the shower profile, light signals in  $1^\circ$  bins are fit to trial light signals produced within the corresponding segments of the shower trajectory. The trial signal is calculated based on an assumption of a Gaisser-Hillas profile function, the fluorescence and Cerenkov light production by the shower electrons, transmission of photons through air, including Rayleigh and Mie scattering, and the detection efficiency and electronic gains of the detector. Five additional cut conditions are used to refine the data set: 4) track length is greater than  $250 \text{ g/cm}^2$  in grammage; 5) shower maximum is in the field of the view of the detector; 6) the shower profile fitting uncertainty on  $X_{max}$  is less than  $50 \text{ g/cm}^2$ ; 7)  $\chi^2$  for profile fitting is less than 10 and 8) an event's minimum viewing angle (the angle between a pmt direction and the shower track) is greater than  $10^\circ$ , guarding against large Cerenkov contamination of the signal. After those cuts, the  $X_{max}$  and energy resolution is  $40 \text{ g/cm}^2$  and 15% respectively.  $N_\mu$  is found by performing a maximum likelihood fit in which the pattern of hit and unhit MIA counters is compared with that expected for a shower of size  $N_\mu$  having a given lateral distribution, in which all the other parameters are fixed, and landing at the indicated perpendicular core distance [4]. The resolution in  $N_\mu$  is about 20%, with an extra cut on muon hits in an event being great than 80.

There are about 800 high quality events left after those cuts. The current analysis is based on this the data set. The events cover an energy range from 0.06 to 2.2 EeV with zenith angles from  $5^\circ$  to  $45^\circ$ .

### 3 Results

A traditional way to extract the nuclear composition of primary cosmic rays with the Fly's Eye technique is to measure the elongation rate (E.R.) [5]. The result from current analysis is plotted in Fig. 1. The shaded area in the figure indicates the average  $X_{max}$  and average energy with their systematic uncertainties, which are explained below, in eight energy bins. The envelope of the central shaded area corresponds to the additional statistical errors both for  $X_{max}$  and  $\log_{10} E$ . Following a straight line hypothesis, a bootstrap [6] calculation for the elongation rate is carried out and yields

$$E.R. = 91.4 \pm (15.3) \pm 9.6 \quad (g/cm^2), \quad (1)$$

where the last term refers to the statistic error and the one in the brackets to the systematic error.

The main sources of the systematic error are identified as a) aerosol scattering of light, characterized by a horizontal attenuation length (a.l.) at 350 nm (nominally a.l. = 10 km) and the scale height (s.h.) of aerosol particle density (nominally s.h. = 1.2 km); b) the angular distribution of aerosol scattering which is described by the phase function and c) the angular distribution of Cerenkov light characterized by its width,  $\theta_0$ . The aerosol distribution and attenuation length can change depending on the weather and range from 0.6 to 1.8 km for s.h. and 8 to 15 km for a.l. [7] under the desert condition at Dugway. These are extreme ranges and give us upper limits on the systematic uncertainty caused by lack of precise knowledge of the aerosol scattering. When dealing with this scattering, we need to know the angular distribution of the scattered light. We use three parametrizations for the phase function [8] corresponding to the expected range of variation in desert aerosols. We switch between them in our systematic error analysis. The other uncertainty comes from the uncertainty of the Cerenkov light angular distribution in a shower. The characteristic width of the

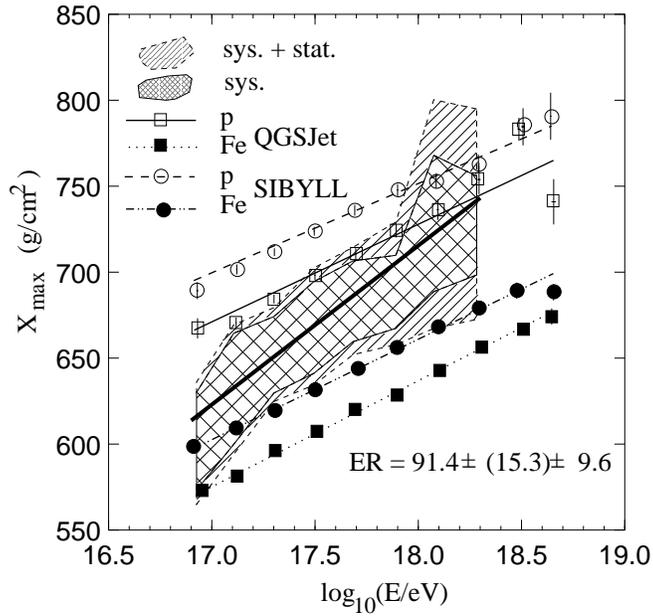


Figure 1: Preliminary HiRes prototype results on the depth of maximum as a function of primary energy. The best fit to the data is shown as the thick solid line with bands indicating statistical and systematic uncertainties. Model predictions are shown for proton and iron primaries under the assumption of either the QGSJET or SIBYLL hadronic model.

angular distribution is about  $4.0^\circ$  with a uncertainty of about  $1^\circ$  [9]. The effect can be significant because it changes the amount of direct Cerenkov light accepted by the detector and can therefore change the triggering efficiency. The systematic error increases by about 20% from  $12.2 \text{ g/cm}^2$  by simply adding this uncertainty into the systematic error analysis. Some other sources of uncertainty, e.g. associated with the fixed parameters in the Gaisser-Hillas function, cause much smaller effects than those listed.

The points shown in Fig. 1 are the result of Monte Carlo simulations using 8000 triggering proton showers and 4000 triggering iron showers generated for each hadronic interaction model. The simulated data are reconstructed with the same procedures as the experimental data. The performance of this MC generator and how a specific hadronic interaction model is folded in is described elsewhere [1]. The atmospheric parameters in reconstruction are set to their nominal values. For the QGSJet case, the E.R. for proton and iron are  $56.8 \pm 2.1 \text{ g/cm}^2$  and  $61.7 \pm 0.8 \text{ g/cm}^2$ , respectively; for the SIBYLL case, they are  $51.9 \pm 1.6 \text{ g/cm}^2$  and  $58.4 \pm 0.8 \text{ g/cm}^2$ . The significant difference in E.R. between the experimental data and the predictions from MC indicates that the composition of primary cosmic rays is changing towards a lighter nuclear mixture over the specified energy range.

The input depth of shower maximum and energy from the shower MC generator, free from the detector acceptance and reconstruction effects, are also plotted in Fig. 1. The dotted and dashed lines represents the proton and iron cases respectively. We see that the differences between the inputs and the outputs of the MC generator are within the statistical error, indicating very little bias in triggering or reconstruction.

We are in the process of making a similar comparison between the muon data and predictions of the simulations. The total muon content of a shower  $N_\mu$  is a function of primary energy and mass composition, with iron showers containing approximately 50% more muons than a proton shower of the same energy. A plot of  $\log_{10} N_\mu$  vs.  $\log_{10} E$  yields a slope of  $0.81 \pm 0.01$  for the QGSJET model and  $0.83 \pm 0.01$  for the SIBYLL model, after taking account of triggering and resolution, and after taking account of our standard cuts. The figures are almost identical for proton and iron showers for a particular model. (The corresponding

figures without triggering and reconstruction are  $0.860 \pm 0.005$  for QGSJET and  $0.841 \pm 0.005$  for SIBYLL). The reconstructed slopes can be compared with the slope of the MIA data,

$$\text{slope} = 0.73 \pm 0.03. \quad (2)$$

Apart from the statistical error given here, there is a systematic error which could be as large as 0.08. Part of that systematic comes from a conservative assessment of uncertainties in MIA counter efficiencies. It is known that the efficiencies degraded during the life of the experiment from an average of 93% to an average of 78%. We take these numbers as the range of efficiencies encountered during the collection of the present data. We repeat the fitting of  $N_\mu$  over this range of efficiencies and use the bootstrap method to estimate the resulting systematic uncertainty in the slope. The other part of the systematic error comes from uncertainties in the three parameters of the Akeno lateral distribution function quoted by the Akeno group [10]. We have again used the bootstrap method to estimate this contribution by changing the muon parameters by their uncertainties. The total systematic error comes to 0.08. However, we have not yet performed the same exercise on the Monte Carlo slopes. We would expect the lateral distribution systematic to cause a similar shift (perhaps of different magnitude) in the proton and iron slopes.

Thus, based on this slope information only, there is support for the trend seen in the  $X_{max}$  data of a change towards a lighter mass composition over this energy range. At the present time work is continuing on the absolute normalization of the muon sizes. A figure showing the  $\log N_\mu$  vs.  $\log E$  behaviour of the data and simulations will be presented at the conference.

## 4 Conclusion

We have shown that the HiRes prototype  $X_{max}$  measurements are consistent with the composition of primary cosmic rays crossing over from relatively heavy to lighter nuclei in the range from  $10^{17}$  to  $10^{18}$  eV. This observation is consistent with the trend seen in results from the Fly's Eye experiment [5].

An exact point-by-point comparison with the Fly's Eye elongation rate data is difficult because there was no attempt to remove the effects of trigger and reconstruction bias in that analysis. Like the present study, the method used was to compare the measured elongation rate with Monte Carlo predictions which included these biases, biases which are of different magnitude in the Fly's Eye and HiRes experiments. The Fly's Eye points are approximately  $20 \text{ g/cm}^2$  shallower than the present data, with a somewhat flatter elongation rate. However, a trend towards lighter composition is apparent in both sets of results. Such a trend is independent of the hadronic model used, since all models (KNP, minijet, QGSJET and SIBYLL) predict a flatter elongation rate than seen in the data.

In the current analysis we also find that the slope of the MIA  $\log N_\mu$  vs.  $\log E$  relationship gives support to the HiRes/Fly's Eye result, with a value also indicating a move towards a lighter mass composition.

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