ELSEVIER

Nuclear Physics B (Proc. Suppl.) 75A (1999) 241–243

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Energy Spectra and Composition Near the Knee

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Measurements with the CASA-MIA experiment show the cosmic ray spectral knee to be a smooth transition. The composition is consistent with direct measurements at 100 TeV but becomes heavier through the knee region. The smooth change results from using a composition-independent energy reconstruction. Data are consistent with rigidity dependent cutoffs[1].

1. Introduction

The energy spectrum of cosmic rays is a useful tool for probing their origin and acceleration mechanism. The spectrum has been previously observed by ground based experiments as two power laws, steepening from one to another around $10^{15.5}$ eV. This spectral "knee" occurs near the maximum energy believed to be attainable from supernova shock acceleration. Another possibility is that the knee forms as cosmic rays attain enough energy to escape the Galaxy. In either picture, it is expected that heavy particles (e.g., iron nuclei) will have a higher maximum energy than lighter ones, so we expect that the observed composition will appear to grow heavier with energy in correlation with the spectral change.

One difficulty with the models is that they do not predict the observed sharpness of the experimentally observed knee. Recent experimental results have been well summarized by Watson [2]; eight of nine experiments report a rather sudden spectral steepening in the range $2-6\times10^{15}$ eV, with only the Tibet Air Shower Array exhibiting a very smooth transition in this energy range [3].

Many experiments have also attempted to determine the composition near the knee. Most observe the composition becoming heavier through the knee, but a few suggest it is becoming lighter [2,4]. Well above the knee ($>10^{17}$ eV) a heavy, iron-like composition is seen [5].

Prior work typically made assumptions about a constant composition in order to evaluate the energy spectra. The Tibet experiment is least sensitive to such assumptions due to its high altitude.

2. The CASA-MIA Detector and Data

The CASA-MIA detector[6] is a ground based array of 1089 surface particle detectors (CASA) and 1024 underground muon detectors (MIA). The data acquired are fitted to determine the direction, core location, "electron" size (N_{e*}) and muon size (N_μ), among other quantities. (The subscript "e*" emphasizes that the quantity N_{e*} does not simply represent the number of electrons above some threshhold energy, but includes a fraction of shower photons and positrons as well.) Sizes are obtained by fitting a Nishimura-Kamata-Greisen (NKG) function to the surface data, and a Greisen function to muon data.

After strict acceptance cuts, 54 million events

PII S0920-5632(99)00254-6

are used in studying the vertical ($\cos\theta > 0.97$) spectrum, representing a live-time equivalent of 342 days.

3. Simulation

Simulations are necessary to connect measurements at the ground with the properties of the primary. The MOCCA [7] shower simulation program, using the SIBYLL [8] hadron interaction codes, was chosen here for this purpose.

The different air shower simulations used by different experiments make comparing results complicated. Some simulations differ enough to change the character of the results based on them. A recent comparison [9] showed that the SIBYLL hadron interaction code differs more from a group of other interaction codes (VENUS, QGSJET, HDPM, and DPMJET) than these codes differ from each other. Consequently, a rough scaling of the MOCCA/SIBYLL simulation is also employed in this analysis. This scaling alters the simulation's predictions of the N_{e*} and N_{μ} to bring them into rough agreement with the other simulations listed above. Results here will be presented twice – once using MOCCA/SIBYLL and the other using the scaled numbers – to gauge the degree to which the results might depend on the particular simulation employed.

4. Energy Spectrum

The number of muons in showers from heavy nuclei is greater than that from proton showers (at the same total energy), but the number of electrons is less. A combination of CASA-MIA observables $N_{e*} + 60 \times N_{\mu}$ has been found to be linear with energy and also insensitive to the primary particle type. Systematic differences between iron and proton energy assignments are less than 5%. The average absolute values of the energy reconstruction errors decreases from 25% near 10^{14} eV to 16% above 10^{15} eV.

Figure 1 shows the energy spectrum for vertical cosmic ray showers, multiplied by $E^{2.5}$. The differential energy spectrum has a double power law form with spectral indices of 2.66 ± 0.02 below the knee and 3.00 ± 0.05 above. The energy spectral

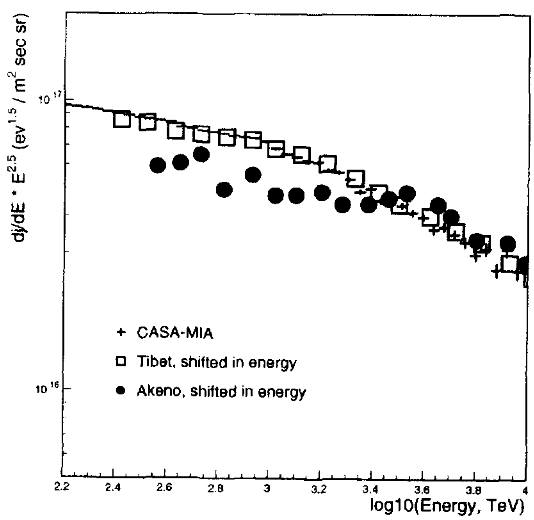

Figure 1. Energy spectrum measured by CASA-MIA, compared to other experiments.

change is smooth, especially when compared to that seen in N_{e*} size spectrum.

The observed spectrum is compared to results from the Tibet [3] and Akeno arrays [10] in figure 1, where the Tibet and Akeno spectra have their energy scales shifted down by 20% of their reported values. The shapes of the energy spectra are unaffected by the uniform energy shift.

The shape of the CASA-MIA spectrum is due to the insensitivity of the energy assignment to composition. If the energy was calculated using only the shower size, and a fixed composition were assumed, the knee would be much sharper, and similar to other experiments' results.

5. Composition

Three fitted parameters are used to compare data and simulated events: the particle density near the core, the slope of the surface lateral distrbution, and the muon density at far core distance.

Events are classified as "iron-like" or "proton-like" depending upon whether these parameters most resemble one or the other type of simulated shower. The "K" Nearest Neighbor test (KNN), is employed to quantify this decision. Each data event is put into the three-parameter space just defined. A large set of simulated iron and proton events also populate the space. More than 90% of the data events will have a majority of simulation "neighbors" of their own species; about 50% have all nearest neighbors of their own kind.

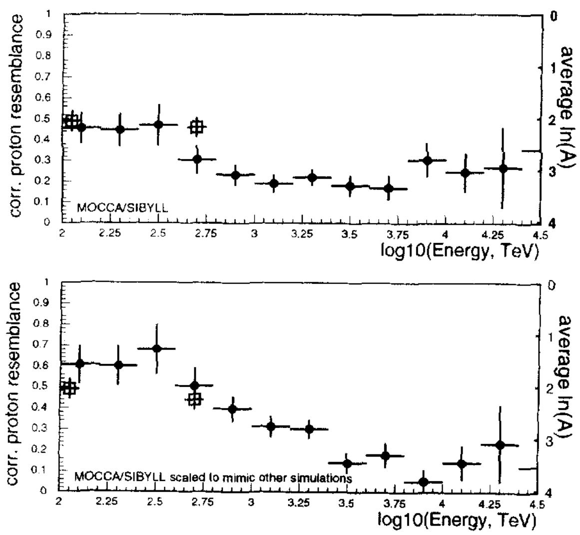

Figure 2. Composition measurement from CASA-MIA.

Figure 2 shows the normalized results of the KNN test applied to the data. If the data were purely protons it would lie along the upper boundary. Pure iron would be along the lower edge. The figure also exhibits for comparison two points showing the results if the data were composed of a nuclear mix distributed according to the direct measurements of the JACEE experiment [11]. The composition of the CASA-MIA data near 10^{14} eV, is consistent with the JACEE results.

An axis label has been added to the right hand side of the graphs in Figure 2 to show the approximate relationship of the result to the mean atomic number A. The mass separation resolution of CASA-MIA is poor, yet the trend toward heavier masses is apparent, regardless of which simulation is employed. Moreover, the change occurs at energies which correlate with the observed steepening of the energy spectrum.

Furthermore, if the classified data are grouped into two samples, "heavy" and "light", the spectral knees appear at different energies. The observations appear consistent with a fixed rigidity cutoff in the spectrum.

6. Summary

The cosmic ray energy spectrum measured by CASA-MIA exhibits a smooth spectral transition above 10^{15} eV, the smoothness a consequence of using a composition-independent energy reconstruction. The composition at 10^{14} eV is consistent with direct measurements by other experiments, and becomes heavier through the knee region of the spectrum. Energy spectra are consistent with cutoffs proportional to the particles rigidity.

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