The Cosmic Ray Energy Spectrum from 10^{14} to 10^{16} eV

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Abstract

High statistics measurements with the surface and buried scintillator arrays of the CASA-MIA experiment show the cosmic ray spectral knee to be a smooth transition. The measured all-particle differential energy spectrum is a power law ($dj/dE \propto E^{-\gamma}$) with a spectral index $\gamma = 2.66 \pm .02$ below 10^{15} eV, steepening to $\gamma = 3.00 \pm .05$ near 10^{16} eV. The smooth change results from using a new energy reconstruction algorithm which is insensitive to the nuclear composition of the primary particles. The observed shape of the spectrum is consistent with the composition becoming heavier through the knee region.

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 case, it is expected that heavy particles (e.g., iron nuclei) will have a higher maximum energy than lighter ones ($E_{max} \propto Z$), so we expect that the observed composition will appear to grow heavier with energy in correlation with the spectral change.

One difficulty with such models has been that they do not predict the observed sharpness of the experimentally observed knee. Recent experimental results have been well summarized elsewhere(Watson, 1997; Wiebel-Sooth & Biermann, 1999); at the preceding ICRC, eight of nine experiments reported a rather sudden spectral steepening in the range $(2 - 6) \times 10^{15}$ eV, with only the Tibet Air Shower Array exhibiting a very smooth transition in this energy range.

Many experiments have also attempted to determine the composition near the knee. Most observe the composition becoming heavier through the knee, but some (e.g., DICE) suggest it is becoming lighter (Boothby et al., 1997). Well above the knee ($> 10^{17}$ eV) a heavy, iron-like composition is seen (Yoshida & Dai, 1998). Direct analysis of CASA-MIA data (reported elsewhere in these Proceedings) suggests the mean mass is increasing in the knee region(Glasmacher, 1998; Glasmacher et al., 1999a,b)

Since the size of air showers at the ground depends on the type of primary as well as on the energy, most prior work assumed a constant composition in order to evaluate the energy spectrum. The Tibet experiment is less sensitive to such assumptions than many other experiments due to its high altitude.

2 Data and Simulation

The CASA-MIA detector (Borione et al., 1994) is a ground based array of 1089 surface particle detectors (CASA) and 1024 underground muon detectors (MIA). Data are fitted to determine the direction, core location, “electron” size N_{e*}, muon size N_μ, and other quantities of extensive air showers. The sizes are obtained by fitting an NKG function to the surface data, and a Greisen function to muon data. (The subscript “e*” emphasizes that the quantity N_{e*} does not simply denote the total number of electrons at the ground, but also includes a fraction of the abundant shower photons and positrons. Care is required when comparing “sizes” measured by different experiments.)

After strict acceptance cuts, 54 million events are used in studying the vertical ($\cos\theta > 0.97$) spectrum, representing a live-time equivalent of 342 days of continuous operation.

Simulations of air showers are necessary to interpret measurements at the ground in terms of the properties of the primary cosmic ray. The MOCCA shower simulation program was used in this work, along with a detailed detector simulation. Two different algorithms were employed to simulate hadron interactions: SIBYLL and another based on QGSJET. Studies have shown that muon and electron production in air showers generated using SIBYLL differ more from a group of commonly used hadronic algorithms than these others differ from each other. QGSJET is taken here as representative of the latter group(Knapp, 1997).

The analysis reported here was done separately for each choice of hadronic simulation. Comparison has shown that the results are not appreciably different. The same is true for related work on the composition of cosmic rays, reported elsewhere in these Proceedings (Glasmacher, 1998; Glasmacher et al., 1999a,b,c).

3 Energy Reconstruction and Spectra

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*} and N_μ has been found (from simulations) to be both logarithmically linear with energy and insensitive to the primary particle type. Figure 1 shows the relationship of the quantity $(N_{e*} + 25 \times N_\mu)$ to the primary energy for simulated iron and proton showers. Systematic differences between iron and proton energy assignments using this expression are less than 5%. The average absolute values of the energy reconstruction errors decrease from 25% near 10^{14} eV to 16% above 10^{15} eV.

The factor 25 multiplying N_μ yields the most composition-insensitive result for vertical showers generated using QGSJET. The best value varies systematically with zenith angle. Use of SIBYLL requires a different normalization and larger muon multiplier (60 instead of 25). Differences between energy assignments derived from the two simulations are smaller than reconstruction induced uncertainties.

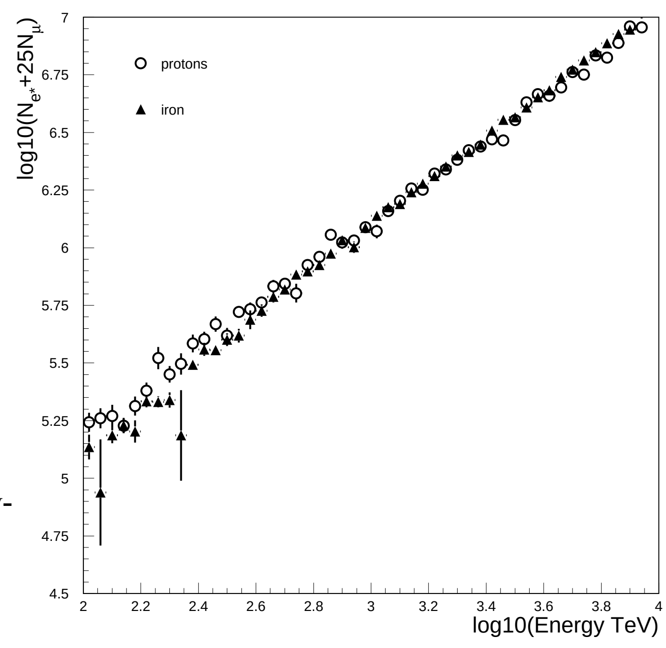

Figure 1: *Energy reconstruction parameter.*

The all-particle cosmic ray flux is obtained by computing each event’s energy as above and tabulating the number of events in small bins of $\log_{10} E$. The vertical intensity as a function of energy is given in Table 1.

$\log_{10}$ (E, TeV)	dj/dE × E (m^{-2} sec^{-1} sr^{-1})	$\log_{10}$ (E, TeV)	dj/dE × E (m^{-2} sec^{-1} sr^{-1})
2.2	$(4.94 \pm 0.02) \times 10^{-5}$	3.2	$(9.8 \pm 0.3) \times 10^{-7}$
2.3	$(3.32 \pm 0.02) \times 10^{-5}$	3.3	$(6.1 \pm 0.2) \times 10^{-7}$
2.4	$(2.29 \pm 0.01) \times 10^{-5}$	3.4	$(4.0 \pm 0.2) \times 10^{-7}$
2.5	$(1.56 \pm 0.01) \times 10^{-5}$	3.5	$(2.5 \pm 0.1) \times 10^{-7}$
2.6	$(1.08 \pm 0.01) \times 10^{-5}$	3.6	$(1.5 \pm 0.1) \times 10^{-7}$
2.7	$(7.13 \pm 0.07) \times 10^{-6}$	3.7	$(9.6 \pm 0.8) \times 10^{-8}$
2.8	$(4.89 \pm 0.06) \times 10^{-6}$	3.8	$(6.3 \pm 0.7) \times 10^{-8}$
2.9	$(3.43 \pm 0.05) \times 10^{-6}$	3.9	$(4.8 \pm 0.6) \times 10^{-8}$
3.0	$(2.27 \pm 0.04) \times 10^{-6}$	4.0	$(2.9 \pm 0.4) \times 10^{-8}$
3.1	$(1.41 \pm 0.03) \times 10^{-6}$		

Table 1: Measured vertical all particle flux.

The values are in good agreement with other experiments(Wiebel-Sooth & Biermann, 1999). Analysis at other zenith angles give consistent results, with intensities varying by less than 8%. Figure 2 shows the energy spectrum for vertical cosmic ray showers, multiplied by $E^{2.5}$. The differential energy spectrum dj/dE has a power law form with spectral indices of 2.66 ± 0.02 below the knee and 3.00 ± 0.05 above. The energy spectral change is smooth, especially when compared to that seen in N_{e*} size spectrum (see below).

The observed spectrum is compared to results from the Tibet (Amenomori et al., 1996) and Akeno (Nagano et al., 1984) arrays, where their spectra have their energy scales uniformly shifted down by 20% of their reported values. The shapes of energy spectra in the plots are unaffected by the uniform energy shift. The magnitude of the shift is modest, comparable to the uncertainty in energy of any of the experiments.
Studies have been carried out to investigate whether the smooth steepening change of the energy spectrum when compared to the size spectral knee could possibly arise from systematic errors (Glasmacher, 1998). Among these are: (i) The single-power-law relation, nearly linear, between the energy parameter and primary energy shows no systematic shifts with energy. (ii) The energy spectrum's shape and intensity have no zenith angle dependence. No systematic variation is seen with zenith angle. (iii) The error in energy reconstruction is modest, is independent of composition assumptions, and smoothly improves with energy. Studies of artificially generated spectra smeared by the measured resolution function do not significantly alter the shape of those spectra.

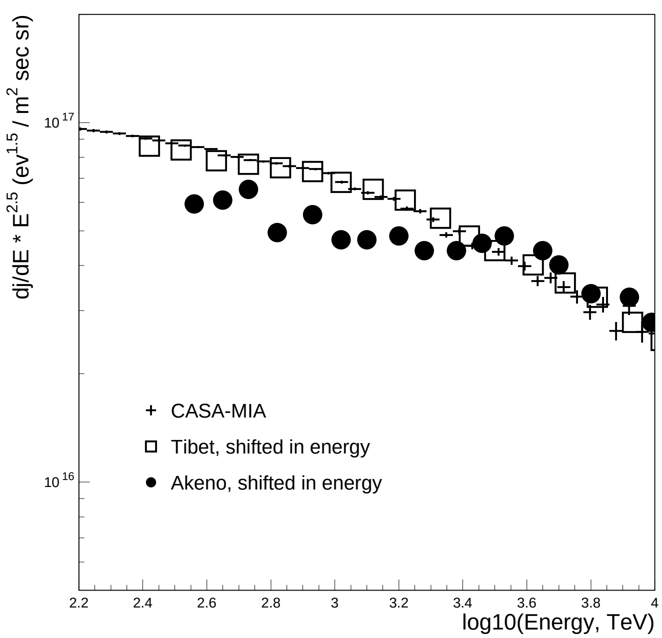

Figure 2: *Energy spectrum, compared to Akeno and Tibet.*

The N_{e*} size spectrum exhibits a much sharper spectral change. This is indirectly seen in Figure 3 which displays the measured energy spectrum derived as described above (labeled "Data"), as well as two other spectra, labeled "Fe" and "p". The latter two spectra were computed from separate energy reconstructions based only upon relationships between N_{e*} and E fitted from the simulations (Glasmacher et al, 1999c). The N_{e*} spectrum of the CASA-MIA data was converted to energy spectra using each of the two formulae. The two curves in Figure 3 therefore reflect exactly the sharper break seen in the size spectrum by itself. The smoother shape of the CASA-MIA energy spectrum calculated using both N_{e*} and N_μ is due to the insensitivity of that 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. The difference between the shapes of the energy and size spectra is consistent with the cosmic ray composition becoming heavier through the knee region.

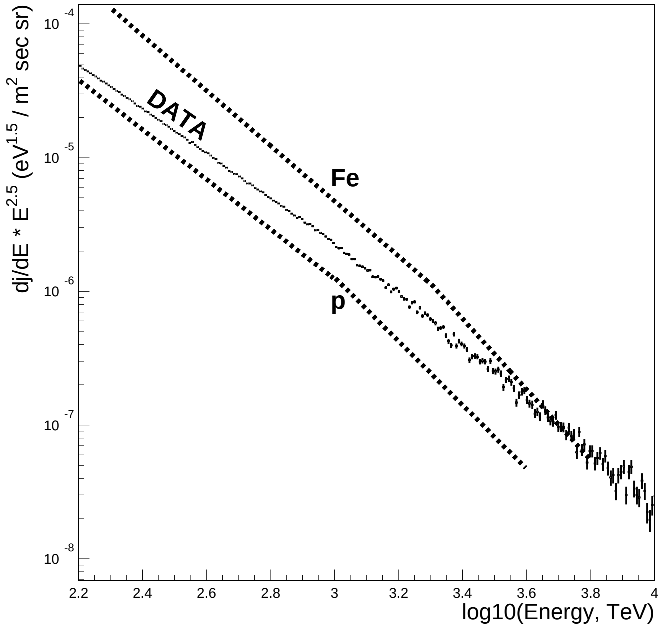

Figure 3: *Energy spectrum compared to spectrum calculated from N_{e*} alone.*

4 Summary

The all-particle energy spectrum of undergoes a smooth transition through the knee region. The smoothness of the change compared to that seen in the shower size spectrum results from a composition-independent energy reconstruction. The mean mass of cosmic rays appears to increase in correlation with the spectral change.

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