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Nuclear Physics B (Proc. Suppl.) 110 (2002) 460–462

NUCLEAR PHYSICS B
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Study of the bending component at the knee of the cosmic ray primary spectrum

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The cosmic ray primary composition is studied around the knee ($E_0 \simeq 3 \cdot 10^{15}$ eV) of the primary energy spectrum with the EAS-TOP array. The distribution of the number of muons recorded at $r_c \approx 200$ m from the core in narrow intervals of shower sizes are compared with the expectations obtained from simulations performed with the CORSIKA/QGSJET code and a three component composition model ('p+He', N, Fe). From the analysis of vertical showers an increase in the average primary mass in the energy range $E_0 = 2 \cdot 10^{15} - 8 \cdot 10^{15}$ eV is deduced. This effect is associated to a bending of the light and intermediate component, while no change in the slope is observed for the Fe spectrum.

1. Introduction

The study of the relation between the electron and muon numbers in Extensive Air Showers (EAS), their fluctuations and relative variations still represents one of the main techniques to obtain information on the cosmic ray primary composition at energies above 10^{15} eV, and it is therefore a key to the understanding of the physical origin of the knee. The experimental data analyzed in this work have been collected from the EAS-TOP experiment, located at Campo Imperatore, National Gran Sasso Laboratories, 2205 m a.s.l., 820 $g \cdot cm^{-2}$ atmospheric depth [1]. In this analysis the electromagnetic (e.m.) detector has been used for the measurement of the shower size N_e and the muon tracker for the measurement of the muon number ($E_\mu^{th} \sim 1\ GeV$).

2. The detectors and the data

The EAS-TOP e.m. array consists of 35 modules 10 m^2 each of plastic scintillators distributed over an area of 10^5 m^2. In the present work, events with at least six neighboring modules fired, and the largest number of particles recorded by a module internal to the edges of the array ("internal events") are selected. The core location (X_c, Y_c), the shower size N_e and the slope of the lateral distribution function s are obtained fitting the recorded number of particles in each module with the Nishimura-Kamata-Greisen (NKG) expression [2]. The resolutions of such measurements have been calculated by analyzing simulated events in which all experimental uncertainties have been included. Comparing generated events with reconstructed ones for shower sizes $N_e > 2 \cdot 10^5$ where the detection efficiency is $\epsilon \sim 100\%$ we obtain : $\sigma_{N_e}/N_e \simeq 0.1$; $\sigma_{X_c} = \sigma_{Y_c} \simeq 5$ m; $\sigma_s \simeq 0.1$. The shower arrival direction is measured from the times of flight among the different modules with resolution $\sigma_\theta \simeq 0.9^o$

The muon-hadron detector in these measurements is used as a tracking module of 9 active planes. Each plane has two layers of streamer tubes (12 m length, 3 × 3 cm^2 section) for muon tracking, one layer of proportional tubes for hadron calorimetry, 8 cm of air and 13 cm of iron shield. The total height of the detector is 280 cm and the surface is 12 × 12 m^2. The X coordinate of the crossing particle is measured from the signals of the anode wires, the Y one from the induced signals on 3 cm width strips located orthogonal to the wires, the Z one from the height of the layer. A muon track is defined from the alignment of at least 6 fired wires in different streamer tube layers. The accurancy in the number of muons detected is $\delta N_\mu < 1$ for $N_\mu < 15$ reaching $\delta N_\mu < 2$ for $N_\mu < 30$.

A sample of experimental data corresponding to 270 days of data taking has been used.

PII S0920-5632(02)01534-7

3. The simulation

Events have been simulated with the CORSIKA code using QGSJET as high energy hadronic interaction model and the analytic treatment of the e.m. component given by the NKG formula. The full response of the muon detector is included by means of simulations based on the Geant code, and the measured experimental efficiencies of the streamer tubes. The fluctuations in the number of particles and the transition effects have been included in the response of the e.m. modules through Geant simulations. The simulated events for both detectors have been treated in the same way as the experimental data.

The primary spectra are simulated with power spectrum index $\gamma = 2.75$ for all elements with a factor 3 of oversampling. The nuclear elements introduced in the simulations are: p, He, N, Mg, Fe for a number of events almost equal to the experimental ones.

The capability of the CORSIKA/QGSJET code for describing the EAS properties has been extensively studied by the KASCADE group, mainly through the hadrons in EAS in the region around the knee [3], and through the EAS-TOP hadrons [4] and high energy muons plus Cherenkov light data up to about 10^{14} eV [5].

4. Analysis and results

The analysis is performed for vertical showers ($1.00 < sec\theta < 1.05$) in the range of size $5.4 < Log(N_e) < 6.6$, i.e. just across the knee ($Log(N_e) \simeq 6.13$). The parameters used in the analysis are the shower size N_e and the muon number observed in the muon detector for core distances 180÷210 m ($N_{\mu_{200}}$) providing the muon density $\rho_\mu = \rho_{\mu_{200}}$.

The observed average $< \rho_\mu >$ vs N_e relation is compared in fig. 1 with the expectations from individual components. The experimental data drift, with increasing shower size, from the helium to the N (for CNO) simulated data.

The evolution of the abundances of the individual components has been studied by fitting the experimental $N_{\mu_{200}}$ distributions, measured in ranges of shower sizes ($\Delta Log(N_e) = 0.2$), with

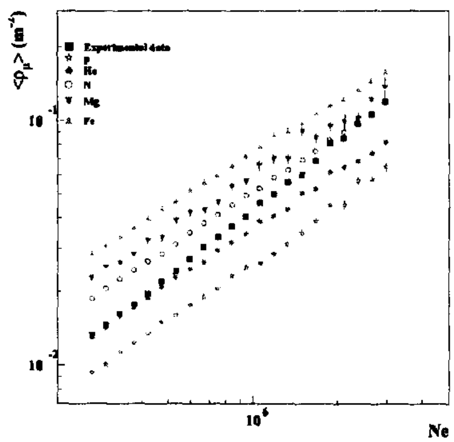

Figure 1. $< \rho_\mu >$ vs N_e relation (experimental and expectations from individual elements).

simulated distributions. A satisfactory description of the experimental data has been obtained with a three component composition : light, intermediate and heavy. The light component is simulated with a mixture of 50% proton and 50% helium, the intermediate is represented by N and the heavy by Fe. The relative abundances of the three elements in each range of N_e are obtained directly from the fits to the $N_{\mu_{200}}$ distribution (fig. 2).

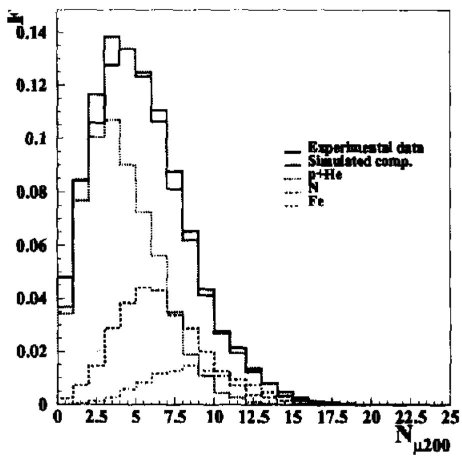

Figure 2. $N_{\mu_{200}}$ distributions data and three components fit in the range $5.8 < Log(N_e) < 6.0$. The contribution of each element is also plotted.

The relative abundances in the six ranges of shower sizes are given in fig. 3, in which the decreasing weight of the light component is observed. From these abundances, using the experimental size spectrum, and converting to energy with the same simulation, the energy spectrum of each component is derived (see fig. 4). The evolution of $< logA >$ vs energy obtained from these spectra is plotted in fig. 5.

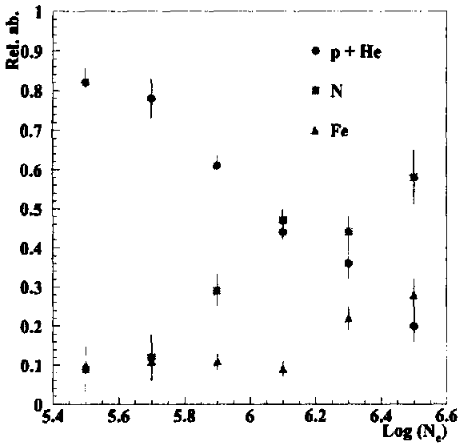

Figure 3. Relative abundances of the three components in different intervals of shower sizes.

5. Conclusions

The analysis of the distributions of the muon numbers recorded at core distances $r_c \approx 200\ m$ in narrow intervals of shower sizes allow to obtain the relative abundances inside a three component composition model. The evolution of the $< logA >$ vs primary energies shows an increase of the primary mass A with energy according with the $< \rho_\mu > -N_e$ relation also given in this work. Inside the used approximation a change in slope is observed in the light (p+He) and N component, while no break is seen in the Fe spectrum.

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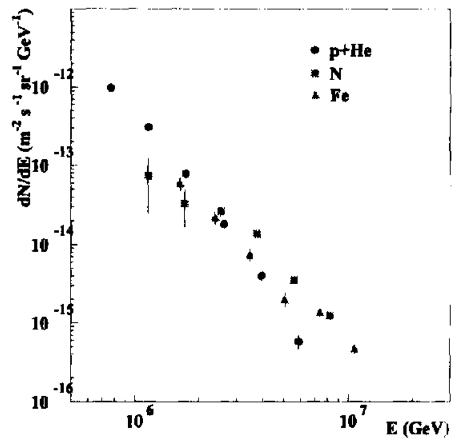

Figure 4. Energy spectra of the p+He , N and Fe with the three components model.

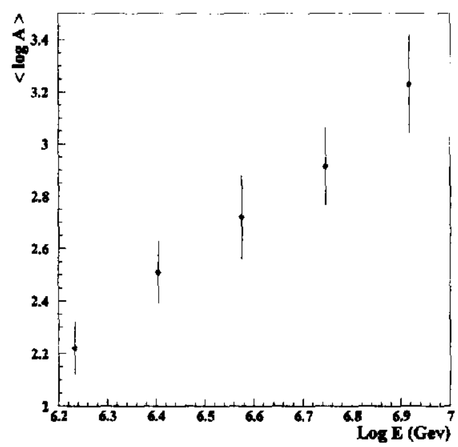

Figure 5. $< logA >$ as a function of primary energy in the region of the knee.