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Spectrum and mass composition of the cosmic rays around the knee

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Abstract. The knee region (10^{15} - 10^{16} eV) of the primary cosmic ray spectrum has been studied by the EAS_TOP experiment at Campo Imperatore (2005 m asl, 820 g cm^2, National Gran Sasso Laboratories 1989-2000). The region is characterized by the variation in the slope of the spectra of the lighter component while the iron spectrum remains unchanged. The results are in agreement with the expectations from the standard acceleration and propagation models of the primary cosmic ray radiation in the Galaxy.

Key words. Cosmic rays: energy spectrum – Cosmic rays: chemical composition

1. Introduction

The evolution of the cosmic ray primary spectrum and composition in the energy interval 10^{15} - 10^{16} eV is one of the most puzzling features of the cosmic ray spectrum as it represents on one side the upper limit to the energy reachable by the most accepted sources as SNR and on the other to the confinement efficiency by the galactic magnetic fields. The experimental evidence is the observation of the ”knee”, i.e. the spectral index variation of the all particle power law spectrum from approximately -2.7 to -3.1 across the given energy region. Understanding the evolution of the mass and spectrum of different chemical components of the primaries provide a clue for the comprehension of the galactic cosmic ray sources. Moreover solving the problem about the origin of the cosmic rays in the PeV region is a prerequisite for the understanding of the behaviour of the GZK region. Because of the low fluxes measurements cannot be ”direct” and have to be performed by means of ground based arrays sampling at the observation level the distribution of the secondary particles (Extensive Air Showers, EAS) produced in atmosphere by the interaction of the primary cosmic rays. The most important observables at the ground are therefore the electromagnetic (photons and electrons), muonic and hadronic components. The detection technique suffers from two main constrains: a) the measurements are not calorimetric and b) the EAS development is driven by the high energy hadron interactions in an energy region where the accelerator measurements are not available.

2. The experimental setup

The EAS_TOP array was located at Campo Imperatore (2005 m asl, 820 g cm^{-2} atmospheric depth). It consisted of:
- the e.m. detector: 35 scintillator modules 10 m^2 each fully efficient for Ne > 10^5 for mea-

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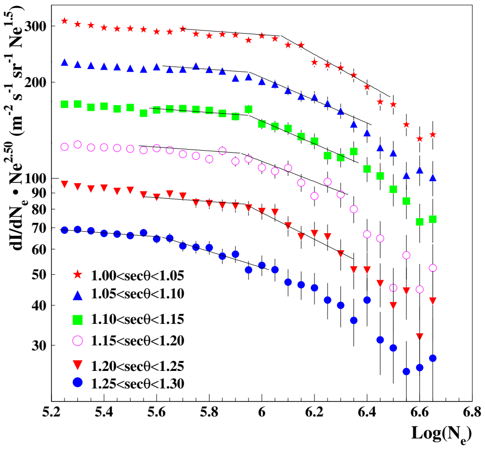

Fig. 1. Differential size spectra measured at different zenith angles. Fits show the knee position and its shift with the zenith angle.

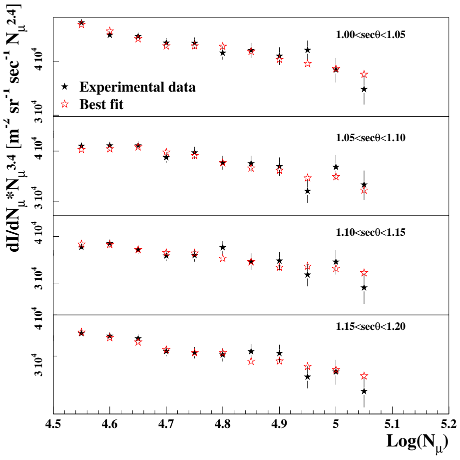

Fig. 2. Differential muon number spectra measured at different zenith angles and comparison with two slope fit.

surements of the shower size (Ne), core location and arrival direction (EAS_TOP Coll. 1993)

- the muon-hadron detector: 140 m^2 calorimeter with 9 layers of 13 cm iron absorber and streamer tubes operating in "quasi proportional mode" for hadron calorimetry at $E_h > 50$ GeV and in streamer mode for muon counting at $E_\mu > 1$ GeV (EAS_TOP Coll. 1999)

- the Cherenkov light detector: 8 telescopes loading 0,5 m^2 area light collectors equipped with imaging devices and wide angle optics for a total field of view of 0,16 sr (EAS_TOP Coll. 1992).

The EAS_TOP array operated also in coincidence with underground LVD and MACRO muon detectors at $E_\mu > 1.3$ TeV and full effective area A_μ of the order of 1000 m^2.

3. The knee

The measured shower size (Ne) (EAS_TOP Coll. 1999) and muon size (N_μ) (EAS_TOP Coll. 2000) spectra are shown in fig. 1-2. The shower size decreases as expected as a function of the atmospheric depth and the integral intensities above the knee are consistent at all angles (and so at all atmospheric depth) showing a "normal" behaviour of the showers in this energy interval, the obtained attenuation length being 222 ± 3 g cm^{-2}. A variation of slope is observed both in the electromagnetic and muon components (EAS_TOP Coll. 2004) allowing the hypothesis that, in both spectra, the same chemical component of the primary spectrum is responsible for the spectrum bending. The information on the dominating component at the knee can be obtained by comparing the Ne and N_μ spectra. To follow such hypothesis the experimental Ne and N_μ spectra have been compared with the simulated ones for the primary elements p, He, CNO and Fe. A primary energy spectrum reproducing the experimental Ne spectrum has been simulated for each element and from this energy spectrum the muon size flux has been obtained and compared with the experimental one. The result is shown on fig. 3 for vertical showers ($\theta \leq 17.7°$). The spectra simulated following QGSJET are consistent with the experimental data and the agreement is very good for helium primaries. From fig. 5 it can be concluded that simulated proton and iron spectra are not compatible with the experimental data even inside the uncertainties due to the used hadronic in-

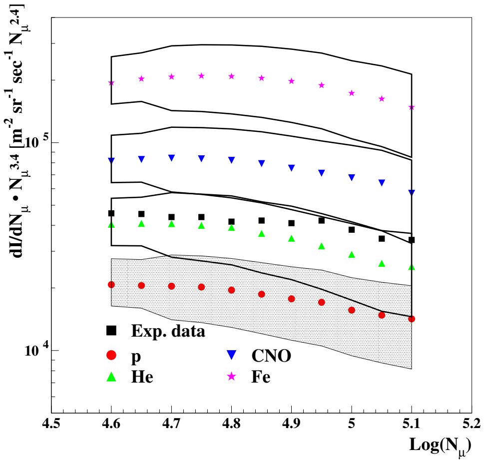

Fig. 3. Experimental muon number spectrum compared with the expectations from different primaries.

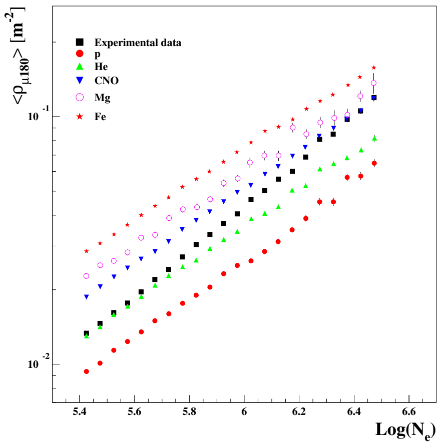

Fig. 4. Muon density at 180 m from EAS core vs Ne: experimental data and expectations from simulations for different elements.

teraction models (VENUS= higher, NEXUS= lower).

3.1. The composition from Ne and GeV muon data

The cosmic ray composition has been studied using as observables the shower size Ne and the muon density ρ_μ at 180-220 m from the shower core. In fig. 4 the experimental data are compared with the expectations obtained for individual elements from proton to iron nuclei. No single element reproduces the trend of the experimental data. As the shower size increases, the mean muon density evolves from light elements, in particular helium, to nitrogen and magnesium. This is an indication that the average mass of the primary cosmic rays increases with the size of the showers and therefore with the primary energy over the observed range. The evolution of the relative abundances of the light (p,He), intermeditate (CNO) and heavy (Fe) primary components have been derived by fitting the muon number distributions in fixed intervals of shower size. The size spectrum corresponding to each mass group is obtained from such relative abundances using as normalization the experimental size spectrum. The relative abundances in three mass group and the corresponding energy spectra are plotted in fig. 7-8 together with the extrapolation from direct measurements. It can be seen that the energy range between 10^{15} - 10^{16} eV is characterized by a steeper spectrum of lighter and later of the medium weight component while the heavy one (Fe) remains unchanged. The obtained spectra are consistent with the extrapolation from direct measurements.

4. Conclusions

The study of the cosmic ray primary spectrum and composition in the energy interval 10^{15} - 10^{16} eV has been carried out through the analysis of the e.m and muon components of the Extensive Air Showers. The experimental Ne and $N\mu$ spectra around the knee are consistent and in agreement with simulations. The hypothesis that the same primary component dominates the spectra in the given energy interval is in very good agreement with the expectation for helium primaries. The result also agrees with the direct JACEE measurements and the combined EAS_TOP Cherenkov light (EAS_TOP and MACRO Coll. 2004) and MACRO (EAS_TOP and MACRO Coll. 2004) data. If the helium primaries are responsible

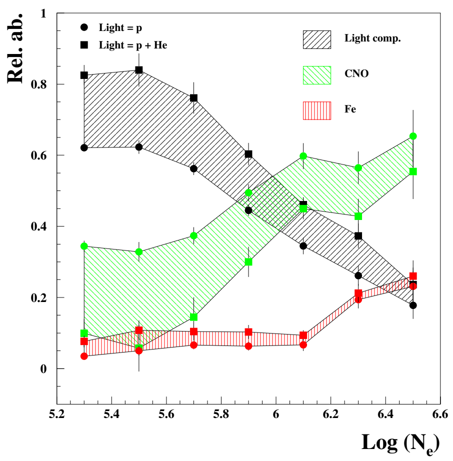

Fig. 5. Relative abundances of three mass group in intervals of shower size.

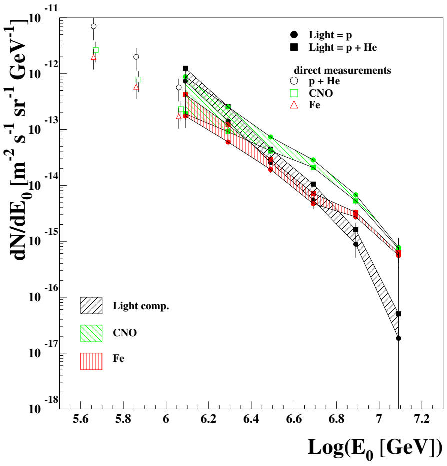

Fig. 6. Energy spectra of the three mass group. The direct measurements are also reported.

for the observed knee, the corresponding bending energy is E_k^{He} = (3.5 ± 0.3) × 10^6 GeV. The evolution of the light, intermediate and heavy mass group across the knee region suggests: steep spectrum of the light mass ($\gamma_{\rho,He}$ > 3.1); possible change in slope of the intermediate mass group at 6-7 × 10^6 GeV or a spectrum on average harder (γ_{CNO} = 2.75) than the light component; constant slope for the spectrum of the heavy group (γ_{Fe} = 2.3 - 2.7) consistent with direct measurements. The average mass increase of the primary radiation in the energy interval 1.5 x 10^6– 1.5 ×10^7 GeV amounts to $\Delta(lnA)$ = 1.5± 0.5 corresponding to a rather fast leakage of the light mass group. The consistent picture of the knee and the observed evolution of spectra and composition for different mass group are in general agreement with the expectation from the standard acceleration and propagation models of comic rays in the Galaxy, predicting rigidity dependent breaks in the spectra of different primaries. The confirmation of such hypothesis requires the detection of the break in the iron spectrum by means of measurements extending up to 10^{18} eV. Together with the presented results the detection of the knee of the iron component would confirm that the knee of the all particle cosmic rays spectrum has astrophysical motivations. This is the primary goal of the KASCADE-Grande array (KASCADE-Grande Coll. 2003) in data taking since January 2004 in the energy range 10^{16} - 10^{18} eV. The experiment is located in Forschungzentrum Karlsruhe (Germany) and has been realized as an extension of the previous KASCADE array with the e.m. detectors of the EAS_TOP experiment (Grande).

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