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The EAS-TOP studies of the cosmic ray primaries in the knee region

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The energy region 10^{14} - 10^{16} eV has been studied through the electromagnetic and muon detectors of the EAS-TOP array. At the knee a composition dominated by helium primaries (possibly responsible of the main break observed in the shower size spectrum) provides the optimum fit to both N_e and N_μ spectra. The distributions of the muon numbers in intervals of shower size (N_e) are consistently represented by the steepening of the spectrum of the p-He component, and then of the CNO one. No steepening is observed for the primary iron spectrum. The main conclusions are consistent with the observations in coincidence with the TeV muons observed by MACRO in the deep Gran Sasso underground laboratories. We discuss such main features, the relation with the direct measurements, and some tests of the hadronic interaction model used for the interpretation (QGSJET in CORSIKA).

1. Introduction

The cosmic ray primary spectrum and composition in the knee region have been studied by the EAS-TOP array through the e.m. and muon components. The array, located at Campo Imperatore, 2005 m a.s.l., 820 g/cm^2, National Gran Sasso Laboratories, included: an e.m. detector with collecting area $A_{eff} \approx 10^5$ m^2 and sensitive area A_{act} = 330 m^2 [1], and a tracking muon detector of 140 m^2 area, with energy threshold $E_\mu^{th} \approx 1$ GeV [2]. Moreover it could operate in coincidence with the LVD and MACRO detectors located in the underground Gran Sasso laboratory, for which $E_\mu^{th} \approx 1.3$ TeV. We summarize here the main results concerning the composition at the knee and its evolution with primary energy.

2. Energy spectrum and composition

The knee has been studied in the e.m. and muon size spectra, shown in figs. 1 and 2, by comparing their shapes inside different angular bins (fig. 2), corresponding to different atmospheric depths . The two spectra are fitted with two power-laws intersecting at the knee: $\frac{dI}{dN_{e,\mu}} = S_{ke,\mu}\left(\frac{N_{e,\mu}}{N_{ke,\mu}}\right)^{-\gamma_{e,\mu}^{1,2}}$ where $N_{e,\mu}$ is the e.m. (N_e) or muon size (N_μ), $N_{ke,\mu}$ is the knee position in the e.m. and muon size spectra, $\gamma_{e,\mu}^{1,2}$ are the spectral indexes below (1) and above (2) the knee and $S_{ke,\mu}$ is the intensity at $N_{ke,\mu}$. The χ^2 values show that a double fit is a better representation of the data also for the muon size spectrum for which the poissonian fluctuations are particularly relevant [4]. The two spectra are compatible at all zenith angles, both concerning the intensities and the spectral slopes. The intensities $I(>N_{k,e})$ and $I(>N_{k,\mu})$ are at all zenith angles inside 23%, i.e. inside the experimental uncertainties. Concerning the spectral indexes, their relation is studied by means of the parameter α, i.e. the exponent of the relation: $N_\mu \propto N_e{}^\alpha$, obtained from the two spectra as $\alpha = (\gamma_e - 1)/(\gamma_\mu - 1)$. E.g. for events with zenith angles $\theta < 20^o$, we obtain α_{spec} = 0.70 $\pm$ 0.03 and 0.80 $\pm$ 0.07, respectively below and above the knee. The α_{spec} values, in the considered angular bins, are distributed around the value 0.75 $\pm$ 0.02 with a spread of about 6%. The parameters α for the hadronic interaction models included in CORSIKA [5] are: α^{QGSJET} = 0.792 $\pm$ 0.007 [6], α^{VENUS} = 0.820 $\pm$ 0.007 [9], α^{NEXUS} = 0.77 $\pm$ 0.02 [7], α^{DPMJET} = 0.789 $\pm$ 0.008 [8], i.e. in very reasonable agreement with the experimental measurements obtained through the slopes of the e.m. and muon spectra (α_{spec}). The e.m.

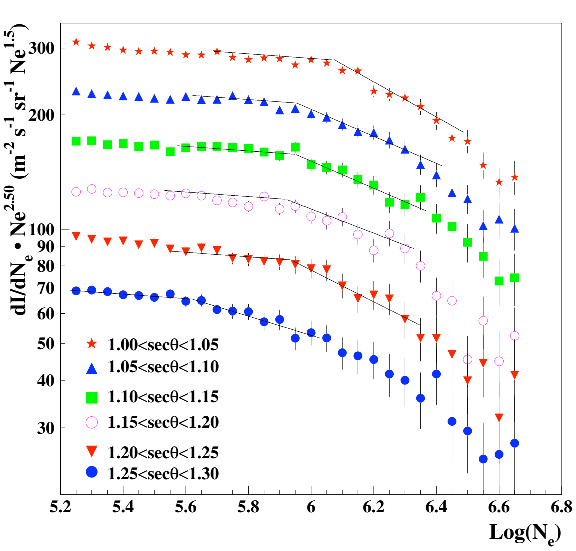

Figure 1. Shower size spectra measured at different zenith angles (i.e. atmospheric depths), showing the knee position, and its shift with zenith angle.

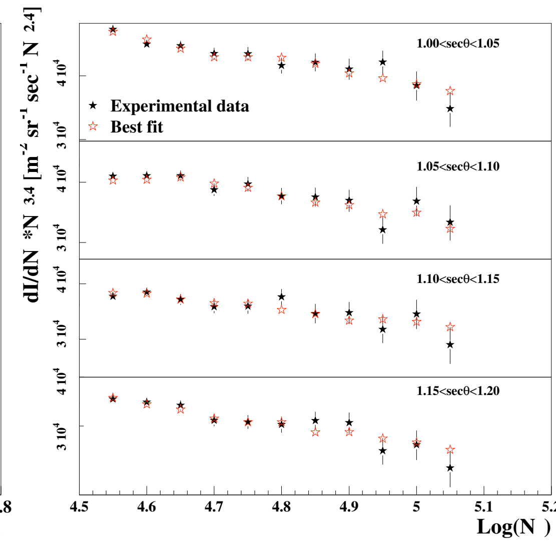

Figure 2. Muon size spectra measured at different zenith angles, together with the best fits obtained by the two slope power-laws.

and muon size spectra are therefore compatible with the hypothesis that in both of them we observe the same primary component, and such assumption provides a tool for its identification. In fig. 3, the experimental muon number spectrum is compared with the expectations from individual primaries, whose fluxes $I(E_0)$ reproduce the shower size spectrum in the region of the knee following QGSJET. The upper and lower limits resulting from the uncertainties related to the hadronic interaction model are also given (higher values for VENUS, lower for NEXUS). Such analysis leads to the conclusion that helium primaries dominate at the knee, a conclusion that, as we see from fig. 3, is consistent for the considered interaction models.

Concerning the evolution of the primary composition over primary energy, the average values of muon numbers (presented as muon densities at fixed core distances, to avoid any assumption or uncertainty related to the muon lateral distribution function) in intervals of shower size are shown in fig. 4 for the experimental data and simulated single element spectra: the increasing average primary mass is seen from the shift of the experimental data from average helium to CNO. The experimental value of α obtained from fig. 4 is α_{exp} = 0.907 ± 0.004 (a value obtained from the whole N_e-N_μ behavior and therefore sensitive also to the changes of primary composition, and different from α_{spec}, obtained from the N_e and N_μ spectra, which is possibly dominated by a single component). It results that the values reported for the different interaction models and expected for a constant composition are clearly incompatible with α_{exp}. Even assuming an evolution of primary composition as derived from the JACEE data [12], the change in α would be of 0.006, i.e. negligible with respect to the observed differences between the expected values for a constant composition and the experimental one. We conclude therefore that none of the quoted models can explain the slope of the N_e-N_μ relation without requiring an increasing of the average primary mass with primary energy.

The spectra of the *light* (p,He), *intermediate* (CNO), and *heavy* (Fe) primaries are obtained by fitting the muon number distributions in intervals of N_e, the "theoretical" values being provided by simulations based on QGSJET for primary spectra with slopes γ = 2.75. Results of the fits as relative abundances (vs. E_0) are

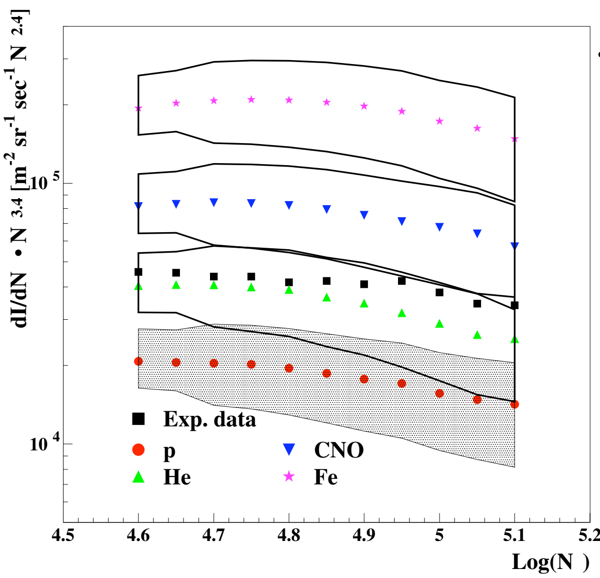

Figure 3. Experimental muon number spectrum compared with the expectations from individual primaries, whose fluxes $I(E_0)$ reproduce the shower size spectrum in the region of the knee.

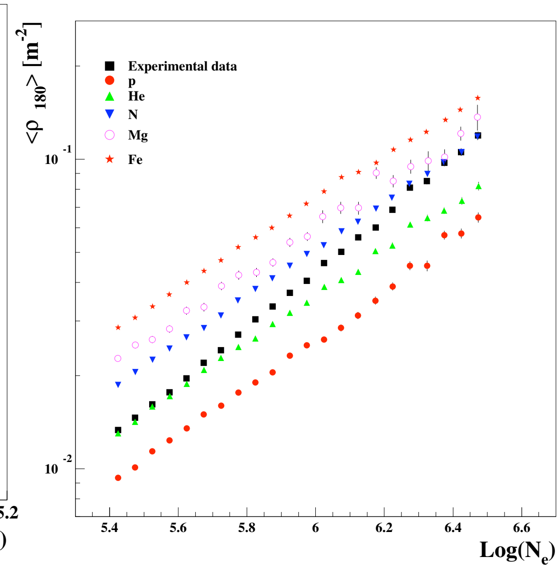

Figure 4. $< \rho_\mu >$ at r_{core} between 180 and 210 m vs N$_e$ (measured and expected from QGSJET for individual elements).

reported in fig. 5 (the lighter component is considered as made of "pure protons" or of "50% p + 50% He", which accounts for the uncertainty bands). For the average behaviors we obtain: i) a steep spectrum for the $light$ component ($\gamma_{p,He} > 3.1$); ii) a spectrum harder for the $intermediate$ one ($\gamma_{CNO} \simeq 2.75$) possibly bending inside the considered energy region, iii) a constant slope for the spectrum of the $heavy$ primaries ($\gamma_{Fe} \simeq 2.3 \div 2.7$), consistent with the direct measurements.

Since the main changes in the hadronic interactions would finally manifest into different energy distributions of the secondaries, a check of the reported change in composition can be obtained by means of a similar muon number analysis vs. shower size performed by means of the E$_\mu$ > 1.3 TeV muons recorded by MACRO [11]. The relative abundances of the $light$ and $heavy$ components obtained through the quoted analysis are reported in fig. 6. The interpretation is also performed through simulations based on QGSJET, and the results are in good agreement with the one obtained through the GeV muon analysis.

3. Conclusions

The experimental data on the EAS e.m. and muon components with GeV and TeV energy thresholds (i.e. from secondaries produced in the central and fragmentation regions) are consistent with each other and with the expectations from QSGJET. The dominant primary component at the knee is identified in helium nuclei. Such result is in agreement with the EAS-TOP Cherenkov ligh and MACRO data [10], that support a cosmic ray flux at about 100 TeV dominated by helium primaries, and consistent with the JACEE [12] and KASCADE results

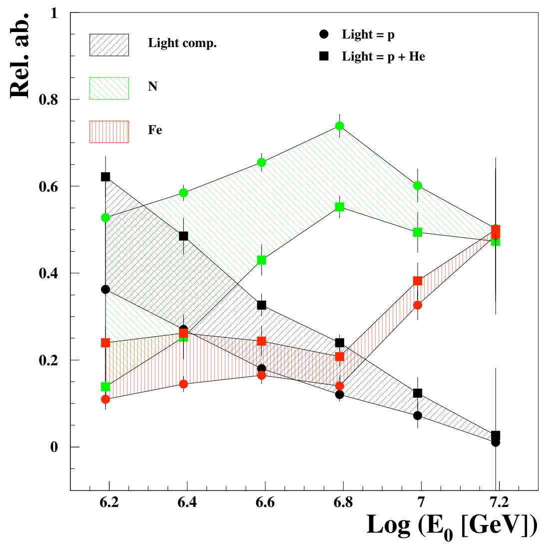

Figure 5. Relative abundances of the three mass groups as a function of primary energy (EAS-TOP GeV muon data).

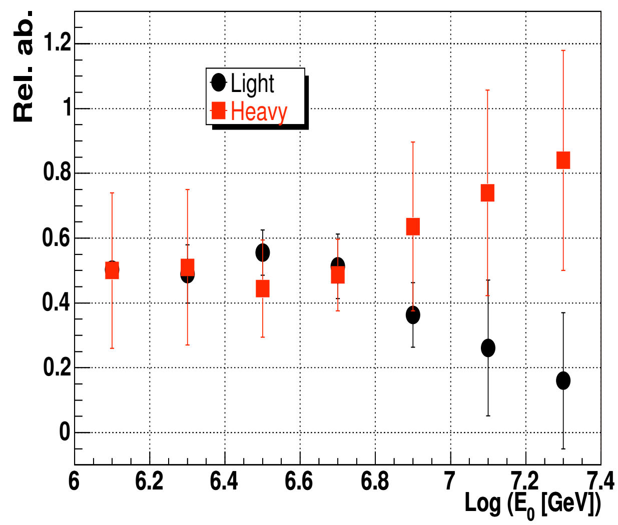

Figure 6. Relative abundances of the *light* = p+He and *heavy* = Mg+Fe mass groups as a function of primary energy (EAS-TOP and MACRO data).

[13]. The knee (observed in the N_e and N_μ spectra) is associated to breaks in the energy spectra of the *lighter* components, also in accord with the N_e and N_μ analysis of KASCADE [13].

We want to remember the contribution given by Giuliana and Carlo Castagnoli not only to the EAS-TOP experiment, but to the growth of our group and of cosmic ray physics in Italy. We are left with their memory and their teachings.

References

[1] EAS-TOP Coll, N.I.M., A 336 (1993) 310
[2] EAS-TOP Coll, N.I.M., A 420 (1999) 117
[3] EAS-TOP Coll, Astrop. Phys., 10 (1999) 1
[4] EAS-TOP Coll, Astrop. Phys., 21 (2004) 583
[5] D. Heck et al, FZK-Report 6019 (1998)
[6] N.N. Kalmykov et al., Nucl. Phys. B, 52B (1997) 17
[7] H.J. Drescher et al., Phys. Rep. 350 (2001) 93
[8] J. Ranft, Phys. Rev. D51 (1995) 64 ; hep-ph/9911232 (1999)
[9] K. Werner, Phys. Rep. 232 (1993) 87
[10] EAS-TOP and MACRO Colls, Astrop. Phys., 21 (2004) 223 and these proceedings
[11] EAS-TOP and MACRO Colls, Astrop. Phys., 20 (2004) 641
[12] K. Asakimori et al., Astrop. J. 502 (1998) 278
[13] KASCADE Coll, Astrop. Phys., in press and these proceedings