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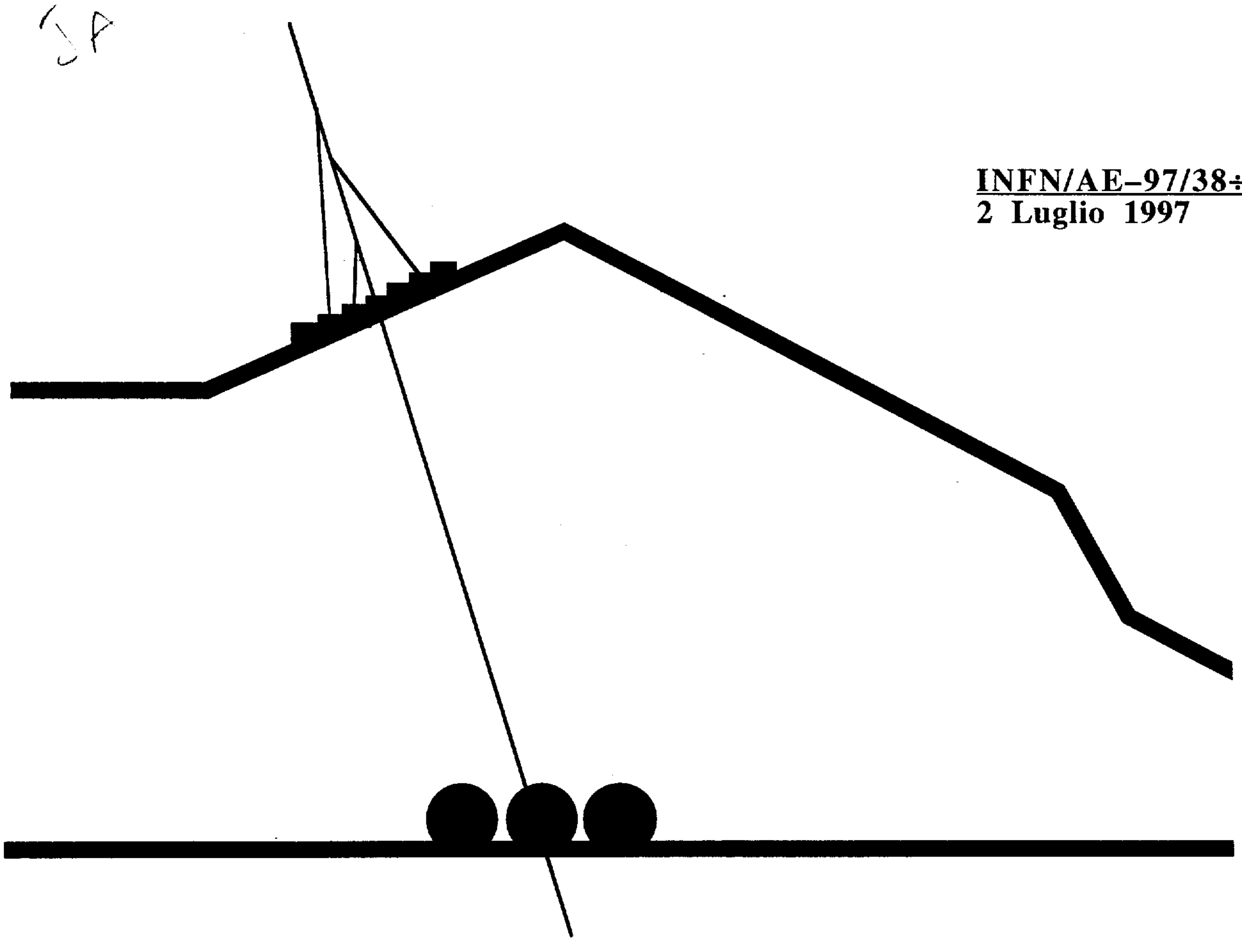

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STUDY OF THE KNEE OF THE COSMIC RAY SPECTRUM IN THE ELECTRON COMPONENT

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ABSTRACT

The shape of the EAS size spectrum around the knee is discussed following the EAS–TOP electromagnetic detector data. The shower size at the knee (Ne_k) attenuates in atmosphere as expected from the attenuation length of the EAS particles.

INTRODUCTION

The detailed study of the shape of the break of the size spectrum of EAS (G.V. Kulikov & G.B. Khristiansen 1958) is of main significance to check the different hypothesis about its origin (see e.g. A.D. Erlykin & A.W. Wolfendale 1997). We will therefore discuss the general features of the "knee" as observed by the EAS–TOP array (EAS–TOP Collaboration 1995), with improved statistics and analysis. Observations in different components are in progress (G. Navarra 1996, M. Aglietta et al. 1997).

The EAS–TOP array is located at Campo Imperatore (2000 m a.s.l., 810 g/cm^2 atmospheric depth, National Gran Sasso Laboratories).Its aims are to perform multi-component observations of Extensive Air Showers in the range between 10^{14} and 10^{16} eV, i.e. around the observed "knee". It includes detectors of the electromagnetic (e.m.), muon, hadron, atmospheric Cherenkov light components. Moreover it can run in coincidence with the muon detectors operating in the deep underground Gran Sasso laboratories (MACRO, LVD at muon energy threshold $E_\mu^{th} \approx 1.4$ TeV). Present data have been collected in 256 days of running time (with a 6% inefficiency due to dead time).

THE SHOWER SIZE SPECTRUM

The e.m. detector is made of 35 scintillator modules (10 m^2 each, 4 cm thick, divided into 16 individual units), organized in circles (6 or 7 modules each) of radii r= 50-80 m, interconnected with each other, for trigger and data taking organization. The core location, the slope (s) of the lateral distribution function (*ldf*) and the shower size (Ne) are determined by means of a χ^2 fit in which the particle densities recorded by each module are compared with the theoretical NKG *ldf* (with Moliere radius equal to 100 m). The accuracy in the measurement of the size Ne has been obtained by analyzing showers simulated including all experimental dispersions: for $Ne > 10^5$ we obtain $\Delta Ne/Ne < 15\%$ ($\Delta Ne/Ne < 10\%$ for $Ne > 10^{5.2}$). A detailed description of the event reconstruction and of the experimental setup can be found elsewhere (M. Aglietta et al. 1993).

The shower size expressed in units of *m.i.p.* ($Ne_{m.i.p.}$) is converted to the total number of charged particles (Ne, defined as the number of charged particles with energy $E > 0$ at the depth of the detector following the Greisen formula) by taking into account the transition effect in the scintillators: $Ne/Ne_{m.i.p.} = 1.18$.

The full response of the detector to e.m. cascades has been verified by means of a test performed, with the same scintillators and electronics operating on the field, at a CERN positron beam up to e$^+$ energies E_{e^+} = 50 GeV.

At the purpose of studying the distortions of the shower size spectrum introduced by the event reconstruction we have carried out a detailed simulation that includes the triggering condition, the experimental fluctuations and the analysis procedures. Events are generated on a trial spectrum (I_{mc}) with a unique power law index, then, after the whole data processing, we compare the resulting spectrum (I_{ex}) with the reference one. Thus the function reproducing I_{mc}/I_{ex} vs the shower size is obtained and used to correct each bin content (the values of I_{mc}/I_{ex} changes from 0.8 at $Log(Ne) = 5.3$ to 0.93 at

$Log(Ne) = 6$, and reaches 1 for $Log(Ne) = 6.5$). We thus obtain a measurement of the differential flux where instrumental effects are not larger than 5% in each size bin.

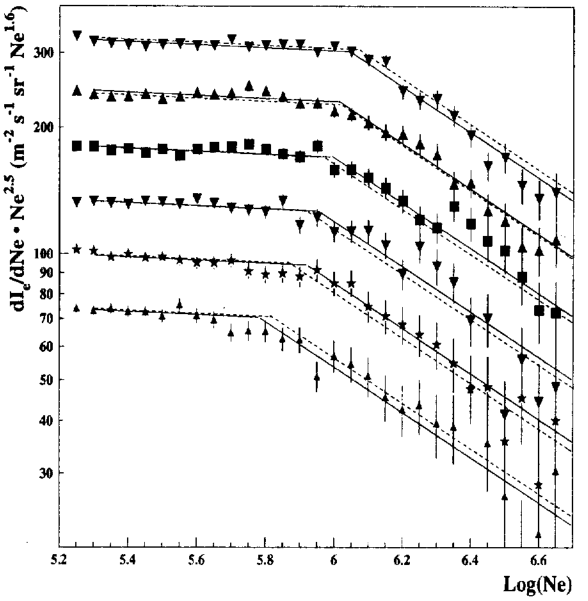

Fig. 1: Differential shower size spectra measured in different zenith angle intervals

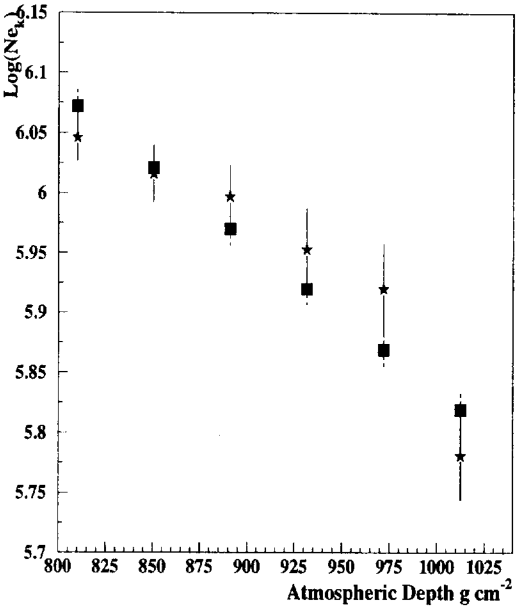

Fig. 2: Shower size value of the knee (Ne_k) measured at different atmospheric depths. Stars represent the values obtained by the first fitting procedure, squares by the second one (see text)

Figure 1 shows the shower size spectra, measured in different zenith angle intervals ($\Delta \sec\theta = 0.05$ each), multiplied by $Ne^{2.5}$ to evidence the change of slope at the knee.

We fit the spectra with the following expression:

$$I_e(Ne) = I_k \cdot (Ne/Ne_k)^{-\gamma_{e_1},\gamma_{e_2}}. \tag{1}$$

At first we calculate, for each zenith angle, the values of γ_{e_1}, γ_{e_2}, I_k and Ne_k. We obtain that the slopes of the spectra are compatible inside the experimental errors. So in the following we will use their weighted means, and their values will no longer be fitted:

$$\gamma_{e_1} = 2.54 \pm 0.02$$
$$\gamma_{e_2} = 3.04 \pm 0.10.$$

This allows to have more detailed informations about the behaviour of Ne_k and I_k vs the atmospheric depth.

The data can be fitted using two different procedures; in the first one the spectra are fitted independently and thus we obtain 6 couples of values of I_k and Ne_k. In the second approach all data together are fitted, leaving as free parameters the size and the primary intensity at the knee of the vertical spectrum and, in the hypothesis that I_k do not depend on the atmospheric depth, the exponential dependence of Ne_k vs x. The two results are shown in figure 1, the first one is represented by solid lines and the second one by dashed lines: inside the experimental errors both fits reproduce the data.

Figure 2 shows the measured dependence of Ne_k on the atmospheric depth (x). The two fits provide compatible results and show the Ne_k exponential decrease with x. Such attenuation factor ($L_k^{exp} = 347.8 \pm 3.2gcm^{-2}$) is in agreement with the attenuation length of shower particles ($\Lambda =$

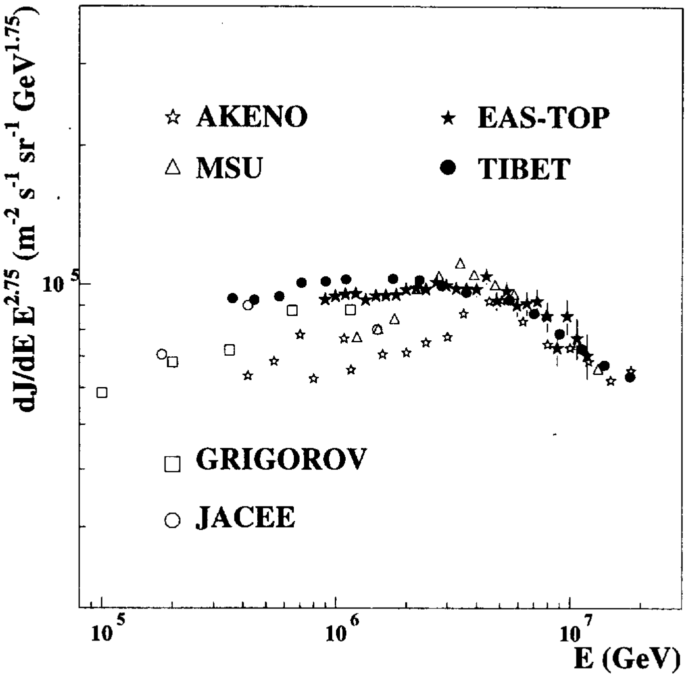

Fig. 3: The all particle spectrum measured at EAS-TOP compared with the results obtained by other experiments operating outside the atmosphere or at earth.

$205 \pm 10.gcm^{-2}$) measured from the constant intensity cut (the expected relation between the two values being $L_k^{exp} \approx 1.6\Lambda$). This is also confirmed by the values of I_k obtained at different x that are nearly constant. Supposing Ne_k constant and I_k depending on x the fitting procedure do not converge.

We thus obtain a quantitative information on the dependence of Ne_k vs x and confirm that the knee of the primary spectrum observed at different atmospheric depths changes as expected from the EAS absorption in atmosphere, showing that the knee is measured at the same primary energy at all atmospheric depths. The result is obtained using the data from a single array, thus overcoming problems due to different calibrations.

Considering only the 3 points around the knee we obtain, from the fits in all angular bins (following the second procedure), χ^2/*dof*= 1.16. This is an indication that the experimental points are in good agreement with the assumed shape of the knee (i.e. a rather "sharp" one).

THE ALL PARTICLE SPECTRUM

To convert the size spectrum to energy spectrum, complete simulations of the shower development in atmosphere have been performed using the CORSIKA code (Capedevielle et al. 1992). Running the same number of events of fixed primary energy and different masses, the mean values of the shower size and its fluctuations have been obtained at the atmospheric depth of $810gcm^{-2}$. The results for the mean values are parameterized using this expression:

$$Ne = \alpha(A)E_0^{\beta(A)} \tag{2}$$

where the primary energy is expressed in TeV and the parameters α and β are equal to:

$$\alpha(A) = 177.8A^{-0.521} \qquad \beta(A) = 1.107A^{0.035}. \tag{3}$$

The fluctuations for primary protons are:

$$\frac{\sigma(Ne)}{Ne} = 1.378E_0^{-0.235}. \tag{4}$$

Before converting from shower size to primary energy the effect of fluctuations of the EAS development is taken into account. Simulating events over a power law spectrum (again with a unique index) we compare the shower size spectra before and after introducing the fluctuations, obtaining an expression which is used to multiply the experimental result before converting to energy (such factor is 1.15 for $Log(Ne) = 5.5$ and 0.94 at $Log(Ne) = 6.5$). All possible distortions of the primary spectrum are studied without introducing the knee, in order to check that no step of the analysis introduce such feature; and the result is negative.

To convert from shower size to primary energy an effective c.r. primary mass is used:

$$A_{eff}(Ne) = \frac{\sum_i A_i \Phi_i(Ne)}{\sum_i \Phi_i(Ne)} \tag{5}$$

where $\Phi_i = b_i \cdot E_o^{-\gamma_i}$. b_i and γ_i are obtained from the extrapolations of the direct measurements (JACEE Collaboration 1995 and Müller et al. 1991) up to $E_k(A) = Z\, 3 \cdot 10^{15}$ eV, and $\gamma_i \Rightarrow \gamma_i + 0.5$ for $E_o > E_k(A)$ and all nuclear mass groups. The validity of the extrapolation of the lower energy composition data, up to the knee and above (following the Peters Zatsepin model), is supported by the $Ne - N\mu$ data both for $E_\mu > 1.4$ TeV (M. Aglietta et al. MACRO and EAS–TOP colls. 1994) and $E_\mu > 1$ GeV (EAS–TOP Collaboration 1997).

Assuming constant composition above the knee would imply a change of 10% intensity at 10^{16} eV.

The resulting intensity below the knee is $\approx 20\%$ higher than the MSU (Fomin et al. 1991) and Akeno (Nagano et al. 1984) data, and $\approx 10\%$ lower than the recent Tibet ASγ measurements (Amenomori et al. 1996). The data show a good connection with the results obtained by experiments operating on balloon or satellites. At the knee and above, there is a general agreement between all data sets.

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