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Comparison of the electron and muon data in Extensive Air Showers with the expectations from a cosmic-ray composition and hadron interaction model (*)

EAS-TOP COLLABORATION

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Summary. — The cosmic-ray primary spectrum and composition are studied at $E_0 > 10^{14}$ eV by means of the multicomponent Extensive Air Shower detector of the EAS-TOP experiment at the National Gran Sasso Laboratories. The measured muon lateral distribution function ($E_\mu > 1$ GeV) and the N_e-N_μ relation in the energy range around the knee of the primary energy spectrum ($E_0 \approx 3 \cdot 10^{15}$ eV) are compared with the expectations of a simulation based on the Dual Parton Model (CORSIKA code) and a cosmic-ray composition model based on the extrapolations of the low-energy direct measurements. First data obtained for vertical showers show that both average values and fluctuations are well reproduced. The same interaction model together with mixed compositions, not requiring dramatic changes, fit the data also above the knee (up to $E_0 \approx 10^{16}$ eV).

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1. – Introduction

The measurement of the cosmic-ray primary composition around the knee of the energy spectrum ($E_0 \sim 3 \cdot 10^{15}$ eV) is of fundamental significance for its interpretation and can provide fundamental clues for understanding the problem of cosmic-ray acceleration and propagation processes inside the Galaxy.

Due to the decreasing fluxes, for $E_0 > 10^{14}$ eV cosmic rays have to be studied through the secondaries they produce in the atmosphere (the Extensive Air Showers, EAS). Above such primary energies not only the cosmic-ray composition, but also the features of the hadronic interactions are not known from direct measurements (maximum energies $E_{\text{lab}} \approx 1.5 \cdot 10^{14}$eV at $Sp\bar{p}S$ and $E_{\text{lab}} \approx 1.7 \cdot 10^{15}$ eV at Tevatron for $p\bar{p}$, while the interesting direct information in nucleus-nucleus interactions, *e.g.*, S-S, is limited to $6.4 \cdot 10^{12}$ eV at *SpS*) and moreover the available data in accelerator experiments are usually obtained in a rapidity range different from the region relevant to cosmic-ray data.

These problems, the extent of fluctuations, and the limitations due to the necessity of performing the observations from ground level (*i.e.* at fixed target thickness), cannot allow firm conclusions until a full set of observables will be available (electromagnetic, muon, hadron, Čerenkov-light components). This is the goal of the EAS-TOP experiment at the Gran Sasso Laboratories.

The interpretation of the measurements requires the use of full simulations of the fundamental processes, the development of the cascades in the atmosphere, and the responses of the detectors.

It is therefore of fundamental importance to perform analysis of individual and coincidence components, and to check the used interaction models and simulation procedures.

At Gran Sasso first data have been reported by the EAS-TOP and MACRO collaborations [1] concerning the phenomenological and physical interpretations of the electromagnetic (e.m.) and TeV muon components of EAS. Such data have shown that a mixed composition as resulting from the extrapolation of the low-energy direct measurements can account for the experimental data. Similar relative abundances of the different components are consistent with the data also above the knee.

In this paper we will report a first comparison of the data obtained through the e.m. and the GeV muon detectors at EAS-TOP with the results of a high-energy interaction model and cascade simulation program based on the Dual Parton Model (CORSIKA code).

2. The detectors

The EAS-TOP installation is located at Campo Imperatore (2005 m a.s.l., 810 g/cm^2 atmospheric depth), above the underground Gran Sasso Laboratories.

2'1. *The electromagnetic array.* – The e.m. array consists of 35 modules of plastic scintillators (10 m^2 each, 4 cm thick), distributed over an area of $\approx 10^5$ m^2 [2]. The triggering energy loss threshold in each module is $E_t \sim 3$ MeV (0.3 of a minimum ionizing particle m.i.p.). In the present analysis we select events in which at least six (or seven) neighbouring modules are fired and the maximum number of particles is registered by a module internal to the edges of this subarray (internal trigger events). The core location (X_c, Y_c), the shower size (N_e) and the slope of the lateral distribution function (l.d.f.) are obtained from a χ^2 fit to the charge measurements sampling the particle densities ϱ in each module. The theoretical l.d.f. used in the analysis is the Nishimura-Kamata-Greisen expression [3]:

$$\varrho(R) = c(s) \cdot (N_e / R_0^2) \cdot (R/R_0)^{s-2} \cdot (1 + R/R_0)^{s-4.5} \tag{1}$$

being R the core distance and $R_0 = 100$ m.

The shower size $N_{e_{\text{m.i.p.}}}$ obtained in m.i.p. units is converted to the total number of $e^{\pm}$ above zero energy (N_e) by a Monte Carlo simulation using the GEANT code [4]. A value of the ratio $N_{e_{\text{m.i.p.}}}/N_e$ of 1.2 has been found for vertical showers.

The resolutions in measuring the core location, the shower size and the slope of the l.d.f. (s), have been calculated as a function of the size N_e by analyzing showers simulated including all experimental uncertainties. Comparing the input with the reconstructed events for shower sizes $N_e > 2 \cdot 10^5$, where the detection efficiency is $\varepsilon \sim 100\%$, we obtain

$$\sigma_{N_e}/N_e \approx 0.1\,,$$

$$\sigma_{\Delta X_c} = \sigma_{\Delta Y_c} \approx 5 \text{ m}\,,$$

$$\sigma_s \approx 0.1\,.$$

The EAS arrival directions are measured from the times of flight among the different modules.

The angular resolution σ_θ is calculated from the measurement of the shape of the moon shadow on the flux of primary cosmic rays. The resolution obtained for internal trigger events is $\sigma_\theta = 0.83° \pm 0.1°$, including possible systematic effects.

2·2. *The muon detector.* – The muon hadron detector [5], located at the edges of the scintillator array, is a tracking module consisting of 9 active planes, 30 cm away from each other, interleaved with iron absorbers 13 cm thick, the total height is about 280 cm, the surface is $A \sim 12 \times 12$ m^2. Each plane is made of two layers of streamer tubes (3×3 cm^2 section, 12 m length) for muon tracking and one layer of tubes operating in «quasi-proportional» regime for hadron calorimetry.

The X coordinate of muon track is obtained from the signals of the anode wires (368 in a layer), the Y coordinate from the induced signals on strips orthogonal to the wires. The distance among the wires and the width of the strips is 3 cm. The Z coordinate is given by the height of the layer with respect to the ground.

The muon tracking is performed by 16 layers of streamer tubes, the upper two layers, not shielded by the iron absorber, are not used. A muon track is defined from the alignment of at least 6 hits (wires on) in different layers of tubes. The probability to detect a vertical muon with energy $E = 1$ GeV is around 97%, decreasing at 52% for zenithal angle $\theta = 45°$. The efficiency of the off-line reconstruction program depends on muon density: in particular, the number of lost tracks is ≈ 2-3% for events with less than 6-7 muons in the detector and $\approx$6-7% for events with more than 20 tracks.

3. – The analysis

3.1. *The data.* – In this analysis we select a subsample of data ($\sim 280\,000$ events) with the following requirements:

i) internal trigger events as defined in subsect. **2**.1;

ii) showers with zenithal angle $\theta < 17.7°$ (vertical showers);

iii) core located at distance $R_c > 40$ m from the centre of the muon detector.

For each shower we measure by the e.m. array the size (N_e), the arrival direction (θ and ϕ) and the core location (X_c, Y_c) to get the distance R_c.

The number of muons detected by the tracking detector in the (X, Z)-plane N_μ^x is used to obtain the muon density (ϱ_μ) and hence the total muon number (N_μ). To calculate N_μ and ϱ_μ we consider the acceptance of the detector that is a function of the EAS zenithal angle and subtract the average accidental muon contribution.

3.2. *The simulation.* – The CORSIKA code [6] (based on the Dual Parton Model of high-energy hadronic interactions and the GHEISHA code for energies below 80 GeV), and a mixed composition model (derived from the extrapolation from the lower energy data) have been adopted for the simulation (see table I).

The number of primaries $N^{(i)}$ simulated for each element is given by the relation

$$N^{(i)} = \frac{F_{\text{int}}^{(i)}(\gamma^{(i)} - 1)}{5 \cdot 10^{13}} \int_{E_0^{\inf(i)}}^{\infty} \left(\frac{E}{5 \cdot 10^{13}\,\text{eV}} \right)^{-\gamma^{(i)}} \mathrm{d}E \qquad (\text{particles m}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}), \tag{2}$$

where the flux of particles $F_{\text{int}}^{(i)}$ at $5 \cdot 10^{13}$ eV and the lower energy $E_0^{\inf(i)}$ for each element are given in table I.

A meaningful sample of vertical showers with energy $5 \cdot 10^{13}\,\text{eV} < E_0 < 5 \cdot 10^{15}\,\text{eV}$ (corresponding to 20 hours of data taking) and $5 \cdot 10^{15}\,\text{eV} < E_0 < 2 \cdot 10^{16}\,\text{eV}$ (corresponding to 6 days of data taking) have been simulated.

The output of the simulation gives for each event the size (N_e), the zenithal (θ) and azimuthal (ϕ) angles of the shower direction and the distance R_c.

The size N_e is calculated with the Nishimura-Kamata-Greisen formalism [3] and transformed into the measured $N_{e_{\text{m.i.p.}}}$. From this value we obtain the number of particles incident on each module through expression (1) and we simulate its

TABLE I. – *Mixed-composition model parameters*: 1*st column*: *chemical element.* 2*nd column*: *energy spectral index.* 3*rd column*: *particle intensity above* 50 TeV. 4*th column*: *lower energy for simulating data.* 5*th column*: *number of events per hour calculated inside an effective area*, $A \sim 140\,000$ m^2 *and a solid angle* $\Omega \sim 0.3$ sr.

	γ	F_{int}(50 TeV)	$E_0^{\inf}$(TeV)	No. of events per hour
p	2.74	$5.45 \cdot 10^{-5}$	90	4722
He	2.68	$6.95 \cdot 10^{-5}$	120	2398
N	2.56	$3.53 \cdot 10^{-5}$	145	1012
Mg	2.63	$1.81 \cdot 10^{-5}$	150	457
Fe	2.63	$1.96 \cdot 10^{-5}$	160	445

fluctuations. We impose the EAS-TOP trigger conditions for internal events and when the event satisfies the trigger requirements we calculate the size, the core and the direction of the shower using the off-line programs.

For each event we consider also the muons striking around and on the muon detector; the simulation gives the spatial coordinates x, y, z and the three momentum components p_x, p_y, p_z of these particles.

The interactions of the muons crossing the tracking detector and its response are simulated using the GEANT code. This tool allows to create an output (wires and strips on for each layer) that has the same format of a real event, so we can calculate the number of muons on the detector and then the ϱ_μ and N_μ with the same program used in the off-line analysis.

4. – The results

The aim of this analysis is to compare the experimental data to the simulated ones: in particular, the muon lateral distributions $\varrho_\mu(R)$, N_μ as a function of N_e, and the fluctuations of N_μ have been examined.

4·1. *The lateral-distribution functions.* – The average muon density has been calculated grouping the events in five bins of R_c (in meters): $40 < R_c < 80$, $80 < R_c < 120$, $120 < R_c < 160$, $160 < R_c < 200$ and $R_c > 200$.

In fig. 1*a*) and 1*b*) we compare the experimental muon lateral distribution with the simulated ones with mixed, pure-proton, pure-helium and pure-iron compositions in two intervals of N_e: $10^{5.0} < N_e < 10^{5.3}$ and $10^{5.3} < N_e < 10^{6.0}$, respectively. These results are well fitted by the Greisen parametrisation [7]:

$$\varrho_\mu(R_c) = C \cdot R_c^{-0.75} (1 + R_c/R_0)^{-2.5}, \tag{3}$$

where C is a normalization factor and R_0 gives the slope of the lateral distribution. The value of R_0 found for the data and used to calculate N_μ also for simulated events is 455 m.

We see that the average experimental values of muon densities and the slopes of the l.d.f. are well reproduced by the mixed composition.

4·2. *The N_μ–N_e relation.* – The mean values of N_μ in a few intervals of N_e ([1]) are plotted in fig. 2 for experimental and simulated events. The value of N_μ has been calculated from the expression

$$N_\mu = 3.7 \cdot R_0^{1.25} \cdot R_c^{0.75} \cdot (1 + R_c/R_0)^{2.5} \cdot \varrho_\mu(R_c). \tag{4}$$

The measured and simulated data, fitted with the usual relation:

$$N_\mu = k \cdot N_e^\alpha \tag{5}$$

give $\alpha \approx 0.74$ for the experimental data and $\alpha \approx 0.79$ for the simulated mixed composition (see *e.g.*, Khrenov [8]).

([1]) An approximate conversion from N_e to E_0 in this energy range and for vertical showers is $N_e \approx 74.5 \cdot E_0^{1.22}$ for primary protons.

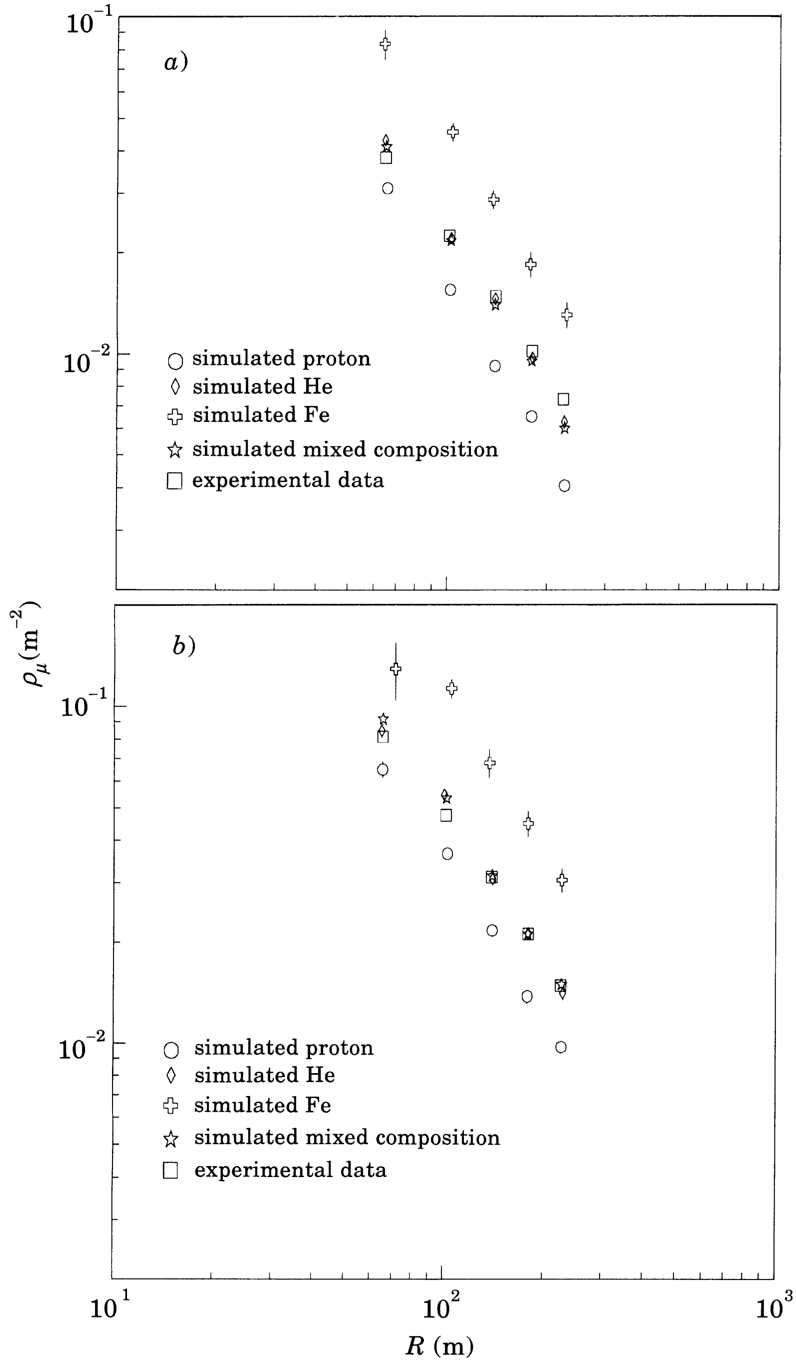

Fig. 1. – *a*) Comparison of muon lateral distributions of experimental data and simulated ones in the range $10^{5.0} < N_e < 10^{5.3}$. *b*) Comparison of muon lateral distributions of experimental data and simulated ones in the range $10^{5.3} < N_e < 10^{6.0}$.

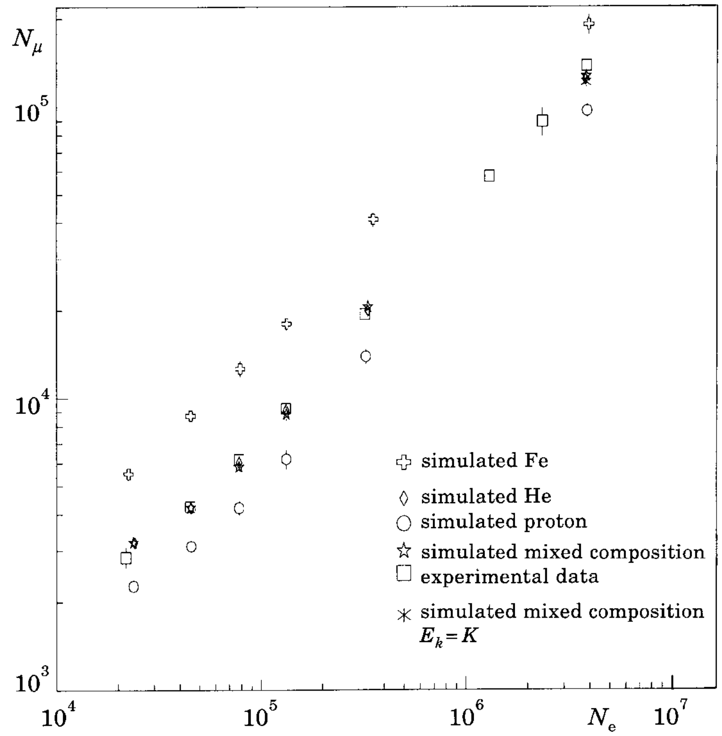

Fig. 2. – Experimental and simulated relation N_μ *vs.* N_e.

In the region above the knee ($N_e > 1.3 \cdot 10^6$) [9] we used two different composition models obtained:

i) by following the Peters-Zatsepin relationship [10] in which the dependence of the energy at the knee is given by

$$E_{\text{knee}}(Z) = Z \cdot E_{\text{knee}}(p)\,, \tag{6}$$

where $E_{\text{knee}}(p) = 3 \cdot 10^{15}$ eV is the value of the energy at the knee for primary protons, and Z the atomic number;

ii) by considering for each nucleus (in fig. 2 $E_k = K$)

$$E_{\text{knee}}(Z) = E_{\text{knee}}(p)\,. \tag{7}$$

The difference $\Delta\gamma$ between the values of spectral index (γ) below and above the knee is the same for each element of the composition ($\Delta\gamma = 0.50$).

The mixed composition fits the data in a large range of shower sizes, and also concerning the point above the knee the quoted models, that imply smooth changes in composition, are adequate.

4'3. *The fluctuations.* – The fluctuations of the muon numbers are analysed, in the range $10^{5.3} < N_e < 10^{5.7}$ and $60\ \text{m} < R_c < 160\ \text{m}$, by calculating for each event

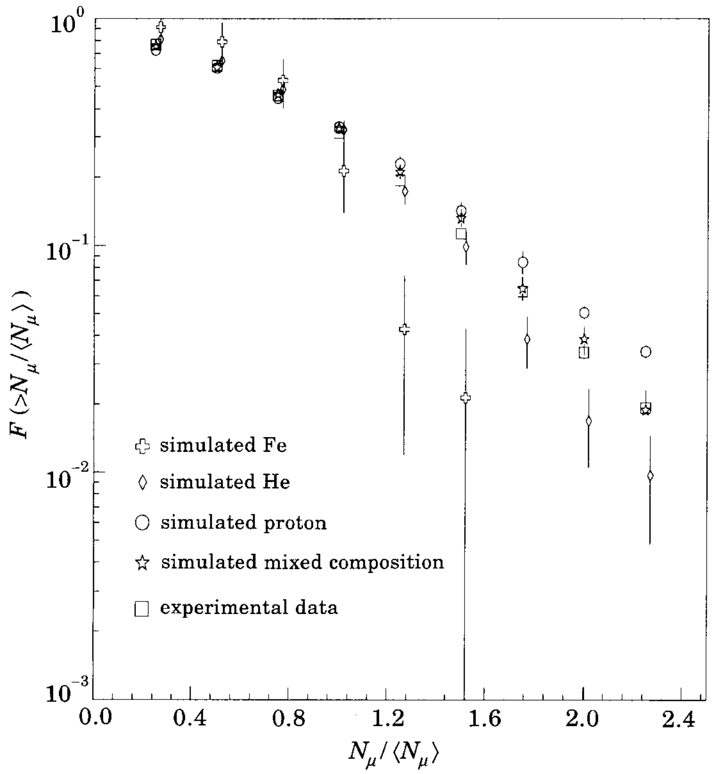

Fig. 3 – Experimental and simulated integral distributions of the ratio $N_\mu/\langle N_\mu\rangle$ for $10^{5.3} < N_e < 10^{5.7}$ and 60 m $< R <$ 160 m.

the ratio $N_\mu/\langle N_\mu\rangle$ in which N_μ is given by expression (4), and $\langle N_\mu\rangle$ by expression (5) for each component.

In fig. 3 the integral distribution of such ratio is plotted: the mixed composition shows a good agreement with the data also in the region of larger fluctuations, dominated by the fraction of light nuclei.

5. – Conclusions

The following conclusions can be inferred:

1) A mixed cosmic-ray primary composition based on the extrapolation of the direct low-energy measurements and the Dual Parton Model of high-energy hadronic interactions (CORSIKA code), below the knee of the energy spectrum ($E_0 < 3\cdot 10^{15}$ eV), reproduce the experimental data for the average muon lateral distributions, the relationship between N_e and N_μ ($E_\mu > 1$ GeV), and the N_μ fluctuations (for fixed N_e).

2) For energies above the knee of the cosmic-ray spectrum, the behaviour of experimental data is well described by models that do not require sharp changes in the composition itself (*e.g.*, the Peters-Zatsepin composition prediction, but also

a model with $E_{\mathrm{knee}}(Z) = E_{\mathrm{knee}}(p)$ for all nuclei). A wider range of primary energies, with improved statistics, is required to distinguish among different models.

The analysis of all the EAS parameters (electromagnetic, muon, hadron, Čerenkov-light components) recorded by the EAS-TOP experiment in individual events, is now expected to provide significant data for an unambiguous measurement of the evolution of the cosmic-ray composition around the knee of the primary energy spectrum.

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It is a pleasure to dedicate this paper to Prof. G. T. Zatsepin on the occasion of his 80th birthday, remembering his contribution to high-energy cosmic-ray physics.

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