Cosmic Ray elemental composition study by using the lateral particle density distribution in showers induced by primaries in the $1 - 10^4$ TeV energy range

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***Abstract*. Important information on the origin of high-energy Cosmic Rays can be obtained by studying their composition. In this paper a study on the elemental Cosmic Ray composition by using the lateral particle density distributions in Extensive Air Showers (EAS) is presented. EASs induced by protons, He nuclei, CNO group, NeMgSi group and Fe nuclei were simulated in the energy range 1-10000 TeV. The lateral particle density distribution was estimated, an unfolding procedure to separate the different mass groups is discussed.**

***Keywords*: Cosmic Rays, composition, lateral distribution**

I. Introduction

The study of composition of high energy Cosmic Rays can provide important information about their origin, acceleration and propagation mechanisms. Cosmic Rays in the energy region below the knee are of galactic origin and the most probable sources and acceleration sites are the galactic supernovæ remnants (SNR). In the higher energy region of the spectrum, however, there are no galactic sources capable to accelerate particles up to these energies. An important indication of the transition between galactic and extragalactic Cosmic Rays could be a change in the elemental composition. At energies up to 100 TeV the mass composition can be measured directly by satellite or balloon experiments, while above 100 TeV the mass composition must be evaluated by means of indirect technique involving the detection of Extensive Air Showers generated by the primary particle in the atmosphere. Although the estimation of the energy and of the direction of Cosmic Rays are relatively easy, the estimation of the identity of the primary from the study of EASs characteristics is a very difficult topic. The differences between the nuclear species are small and covered by the variation of the primary energy, by uncertainty in hadronic interaction models and by shower fluctuations.

In this work we present a study of the elemental composition of cosmic rays by using the lateral particle density distribution obtained by the simulation of Extensive Air Showers generated by the interaction of different primary Cosmic Rays with the Earth's atmosphere. Four parameters were introduced in order to characterize the lateral distribution generated by different primaries of different mass. A selection function was set to separate different primaries in the energy range $(1 \div 100)$ TeV.

II. Monte Carlo data sample

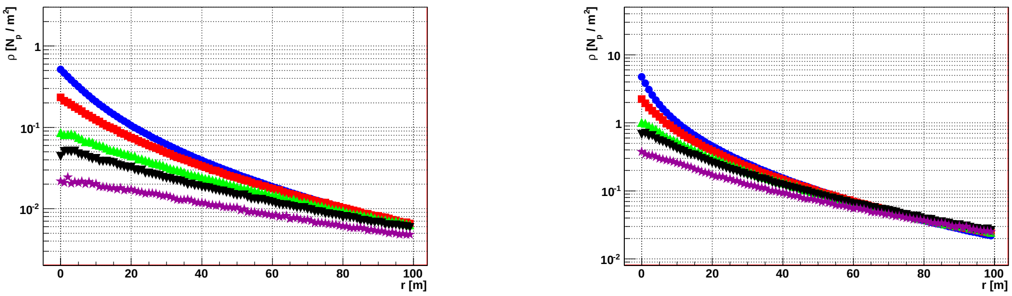
The Monte Carlo data used in this analysis were generated by using the CORSIKA (v. 6.7.20) [1] code including QGSJET-II [2] and GEISHA [3] hadronic interaction models. Showers produced by protons, helium nuclei, CNO group, NeMgSi group and iron nuclei were generated in the energy range $(1 \div 10^4)$ eV with a power law spectrum and in the zenith angle range $(0° \div 45°)$. The spectral indexes used in this simulations was chosen according to RUNJOB measurements [4]. Each shower was sampled at the altitude of 4000 m a.s.l. The showers were processed by a code simulating an ideal pixel-like detector with active elements (scintillators, gaseous detectors and so on) of the order of 50×50 cm^2. In this paper we considered a detector of about 200×200 m^2 and with an active area of about 90%. The detector geometry was simulated as well as the detector efficiency ($\sim$ 95%). A general trigger was simulated requiring a minimum number of 40 charged particles. The Monte Carlo sample used in this analysis is described in table I.

TABLE I
The full Monte Carlo data sample used in this analysis

E [TeV]	p	He	CNO	NeMgSi	Fe
1-3.16	360000	36000	27000	27000	27000
3.16-10	60000	6000	4500	4500	4500
10-31.6	12000	1200	900	900	900
31.6-100	6000	600	225	225	225
100-316	3600	120	45	45	45
316-1000	3600	120	27	27	27
1000-3160	300	30	15	15	15
3160-10000	300	30	15	15	15

III. The analysis method

The analysis described in this work is based on the study of the lateral particle density distribution obtained by analyzing the Monte Carlo data sample generated. The analysis was performed by evaluating the charged particle density as a function of the distance (r) from the



(a) M2: 800-3000

(b) M3: 3000-12500

Fig. 1. Lateral particle density distribution obtained for each primary in the M2 and M3 multiplicity bins. blue circle for proton, red square for helium, green triangle for CNO, black triangle for NeMgSi, purple star for iron.

core position for each cosmic ray primary types. Data were selected by applying the following criteria:

1) core position in the central area of the ideal detector
2) a minimum of six particles in an area of 8 meters radius centered at the shower core position
3) a zenith angle in the range $(0° - 30°)$

The events were sorted in four multiplicity bins (M_i), as reported in table II.

TABLE II
MULTIPLICITY BINS USED IN THIS ANALYSIS AND MEAN ENERGY FOR EACH PRIMARY

Multiplicity	**Mean energy [TeV]**				
	p	α	CNO	NeMgSi	Fe
150 - 800	1.8	1.9	2.2	2.8	3.2
800 - 3000	4.2	5.9	8.0	8.8	10.5
3000 - 12500	13.8	17.9	24.6	27.5	23.4
12500 - 50000	49.1	60.3	74.6	89.5	104.3

For each multiplicity bin, the particle density distribution was evaluated. As an example, in fig. 1 the particle density distributions obtained for different primary types and in the M2 and M3 multiplicity bins are reported. The curves show clearly different shapes depending on the mass of the primary particle. The profiles generated by the light-component are steeper than the profiles generated by heavy-component. The analysis of these curves was performed and the following composition sensitive parameters were determined:

1) ρ_0: the particle density measured in an area of 2-meters radius centered on the core position
2) β: the ratio between the particle density measured at 25 m from the core position (ρ_{25}) and the ρ_0 density
3) $B = \sum_0^{25} \rho_i/\rho_0$: sum of the values of the ratio between ρ_i and ρ_0 up to 25 m far from the core position
4) $D^{(j)}$: gradient of the particle density distribution computed by using different weights. $w_k^{(j)}$

Where $D^{(j)}$ is defined as:

$$D^j = [\frac{\rho_0 - (\rho_1 + \rho_2)}{\rho_0} \cdot {w_1}^{(j)}]$$

$$+[\frac{(\rho_1 + \rho_2) - (\rho_3 + \rho_4)}{\rho_1 + \rho_2} \cdot {w_2}^{(j)}]$$

$$+[\frac{(\rho_3 + \rho_4) - (\rho_5 + \rho_6)}{\rho_3 + \rho_4} \cdot {w_3}^{(j)}] \quad (1)$$

TABLE III
PARAMETERS SELECTION VALUES

$Multiplicity \backslash Parameter$	ρ_0	β	B	D_0
M_1 (150 - 800)	1	0.1	5	-
M_2 (800 - 3000)	1	0.25	5	-
M_3 (3000 - 12500)	2.5	0.25	5	0
M_4 (12500 - 50000)	5	0.25	5	0.5

The distributions of the four parameters described previously were studied for all the primary cosmic rays simulated. As an example, in figures 2 (a) and (b) the distribution of the β parameter for the M3 multiplicity bin and of the D^0 parameter for the M4 bin are shown respectively. The plots show different distributions for different masses of the primary cosmic rays. The analysis of the distributions of the parameters introduced in this work allowed to set threshold values in order to separate different primary masses.

The threshold values above were used to determinate a discrimination function $F(\rho_0, \beta, B, D_i)$ allowing to separate different primary masses. To study the separation capability of the function $F(\rho_0, \beta, B, D_i)$, we used a set of threshold values, reported in table III. A first test was performed in order to separate the light cosmic ray component and the heavy cosmic ray component.

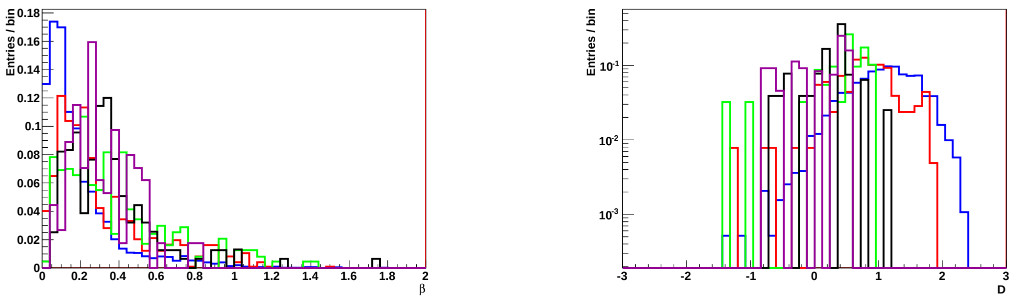
By applying the threshold values reported in III, the probability to identify different cosmic ray primaries was evaluated and reported in table IV. The table shows that at high multiplicities it is possible to discriminate the heavy component with a negligible contamination of the light component. In figure 3 the probabilities to identify different primaries are reported.

IV. CONCLUSIONS

In this paper a study of cosmic ray composition in the energy range $(1 \div 10000)$ TeV based on the lateral particle density in simulated EASs is reported. An ideal

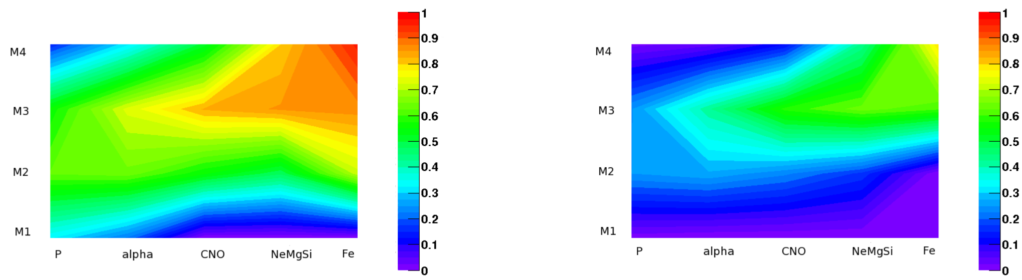
TABLE IV
PROBABILITY OF IDENTIFICATION OF COSMIC RAY PRIMARIES USING CUTS ON β AND B.

$Multiplicity \backslash Primary$	p	α	CNO	NeMgSi	Fe
$\beta > 0.25$, $B > 5$					
M_1 (150 - 800)	0.009	0.000	0.000	0.000	-
M_2 (800 - 3000)	0.250	0.270	0.231	0.167	0.000
M_3 (3000 - 12500)	0.248	0.419	0.583	0.636	0.604
M_4 (12500 - 50000)	0.016	0.040	0.125	0.433	0.792



(a) β (b) D^0

Fig. 2. Distribution of the β and D^0 parameters in the M3 multiplicity bin. Blue line for proton, red line for helium, green line for CNO, black line for NeMgSi, purple line for iron



(a) B (b) β B

Fig. 3. Distribution of the probability to select different primary types in the four multiplicity bins

pixel-like detector operating at high altitude was also simulated. A discrimination function was set to separate different primary mass. The function allows to select the heavy cosmic ray component with low contamination of light cosmic ray component.

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