Energy Estimation of Ultra High Energy Cosmic Hadrons and Gamma Rays by Lateral Distribution Functions of Extensive Air Showers

A. Geranios[*], **D. Koutsokosta**[†], **O. Malandraki**[‡], **H. Rosaki-Mavrouli**[*]
S. Maltezos[§] **and A.Mastichiadis**[†]

[*]*Nuclear and Particle Physics Department,University of Athens, Panepistimioupoli, Greece*
[†]*Physics Department, Section of Astrophysics, Astronomy and Mechanics,University of Athens, Panepistimioupoli, Greece*
[‡]*Institute for Astronomy and Astrophysics, National Observatory of Athens, Greece*
[§]*Physics Department, School of Applied Sciences, National Technical University of Athens, Zografou 15780, Greece*

***Abstract*. The determination of energy of Ultra High Energy Cosmic Rays (E $\geq 5*10^{19}$ eV) is one of the important issues concerning these particles. For this purpose, Monte Carlo simulations are used to create a large number of vertical and inclined extensive air showers in order to estimate the primary energy based on the lateral distribution function of recorded electrons and muons. This methodology could be applied to all cosmic ray experiments using a surface array of Cerenkov detectors, like, for example, the P. Auger Observatory.**

***Keywords*: UHECR hadrons photons**

I. INTRODUCTION

Despite the fact that Ultra High Energy Cosmic Rays (UHECR) have been detected for more than four decades their origin still remains elusive. Among others, the experimental estimation of their particle composition, direction of arrival and energy have been investigated.

Due to their negligible rate, UHECR are studied by Extensive Air Showers (EAS), which are created in the atmosphere when they interact with it. As EAS are approaching the surface of the earth, their structure longitudinally and laterally can be studied by measuring the secondary particles produced using fluorescence and Cerenkov detectors, respectively.

The known candidates for creating Extensive Air Showers are nuclei, photons and neutrinos as they have to be stable and if charged, heavy enough to avoid loosing their energy by synchrotron radiation in the galactic or intergalactic magnetic field [1].

The Pierre Auger Observatory [2] located in Argentina is a hybrid detector composed of a fluorescence detector and a ground array of Cerenkov detectors. With an effective area of 3000 km^2 is the most efficient way to detect the very rare UHECR and estimate their energy, particle composition and direction of arrival.

The Ground Array of an experiment like P. Auger records the particle density of the secondary particles reaching the ground. The lateral structure of the shower is then studied using the Lateral Distribution Function (LDF) which is the density of electrons and muons as a function of the radial distance from the core of the shower at ground level.

In this paper, we use the AIRES Monte Carlo code [3] to simulate EAS created by hadrons and gamma ray photons of energy between 10 and 100 EeV and of zenith angles varying from 0 to 60 degrees. The selected energy range is suited to detector arrays like the P. Auger Observatory of which the separation of the Cerenkov detectors is 1.5 km. The shower is simulated with the MC code AIRES for electrons and muons since both contribute to the pulse created by Cerenkov detectors [4]. This component of EAS fits to the surface detector of Auger, measuring particles laterally. All lateral variations range from 50 m to 2000 m in 40 consecutive bins.

II. HADRON INITIATED SHOWERS

Proton and iron initiated showers represent the limits in atomic mass of the probable candidates of cosmic rays in more conventional astrophysical theory. The chemical composition of cosmic rays is believed to be 85% protons, 5% He, 0.1% the light or L-group (Li, Be, B), 0.42% the medium or M-group (C, N, O, F), 0.04% Fe and 1-2% electrons, photons, neutrons [5].

Nucleus initiated cascades start earlier and develop more rapidly than equivalent proton ones. That will change the records of both the fluorescence detector and the ground array: the position in the shower of the maximum of the number of charged particles X_{max}, the LDF, the curvature and thickness of the shower front and the muonic population.

Due to the random fluctuations in the first steps of the cascade, two different nuclei of the same energy may be undistiguishable, so a single shower can't provide evidence for the nature of the primary nucleus. But a statistical study can reveal the different distribution of variables related to the speed of shower development, especially muon production and depth of maximum, X_{max}.

X_{max} fluctuations are controlled by fluctuation in the first interaction point and hence by the mean free path of the primaries within the atmosphere. These X_{max} fluctuations become smaller with increasing energy and increasing atom mass as it is shown in figure 1.

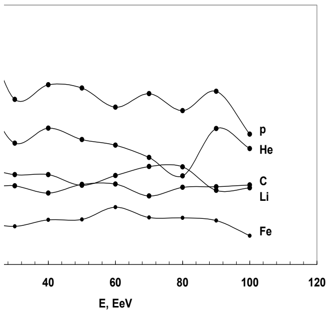

Fig. 1: Fluctuation of shower maximum versus primary energy for p, He, Li, C and Fe initiated showers. It is obvious that for lighter composition statistical deviation between 100 showers is greater. The total number of simulated showers is 5000.

Auger surface detector at large core distances on the ground records muons earlier than e^+/e^-. Showers initiated by heavy nucleus have a larger muon component, so using the shape parameter [6], defined as the ratio of the "early signal" to the "late signal" one can distinguish the two primaries but the discriminating power of this method may be degraded at large zenith angles, where the electromagnetic shower is reduced.

III. PHOTON INITIATED SHOWERS

Photon initiated showers are almost pure electromagnetic due to the low cross section for photo-production of mesons on nuclei compared to the pair production. In this case the muon/(e^++e^-) ratio at ground level will be much less than in a nucleus-induced shower. In some sense, a photon behaves as a nucleus much lighter than a proton: fewer muons, larger X_{max}, larger front curvature. For primary energy of 10^{20} eV, X_{max} is expected to be almost 1050 g/cm^2 for photon-generated showers instead of 800-900 g/cm^2 for hadronic showers. That means that for an Observatory like Auger a photon initiated shower does not reach its maximum before hitting the ground for zenith angles less than 40 deg (Figure 2).

IV. ENERGY ESTIMATION

To estimate the primary energy of hadrons and photons initiating atmospheric showers we use the AIRES Monte Carlo code to simulate EAS created by protons, helium, lithium carbon and iron nuclei and gamma ray photons of energy between 10 and 100 EeV and of zenith angles varying from 0 to 60 degrees.

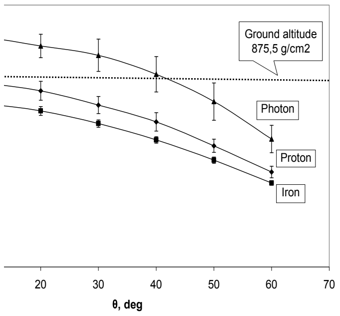

Fig. 2: X_{max} versus zenith angle for proton, iron and photon initiated showers of initial energy 100 EeV. Each X_{max} value represents the mean value of 100 showers

For the energy estimation a favorable condition is the radial distance at which fluctuations of the particle densities are minimal [7]. For our calculations we adopt S(1000) (particle density at 1000 m from the core of the shower) due to the fact that at the distance of about 1000 m the fluctuations of the particle densities start to be minimal [8].
To estimate the primary particle energy (E) we simulate a large number of EAS created by vertical hadrons and gamma photons of energies ranging from 10^{19} to 10^{20} eV and we obtain the corresponding S(1000) values. Fig. 3 shows the variation of primary energy E with S(1000) for proton, helium, lithium, carbon, iron nuclei and gamma ray photons.

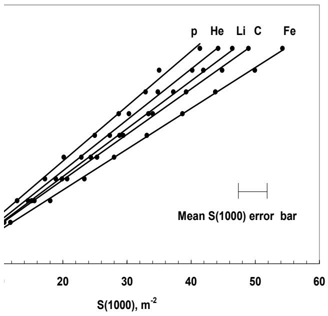

Fig. 3: Variation of primary energy E with S(1000) density for six primary particles. A number of 6000 showers were simulated for this figure.

The analytical form of the equations we obtain from linear best fit is,

$$E = 5.25 * 10^{a} * S(1000) - b * 10^{18} \qquad (1)$$

The parameters of this equation for the different primaries are shown in Table I.

Using the above formulas we calculate the energy for the different primaries (Table II)

TABLE I: Best fit values of and b for the above equation for the different nuclei.

Primary	α	b
Proton	17.68	2.35
Helium	17.65	3.11
Lithium	17.62	2.96
Carbon	17.60	2.22
Iron	17.55	2.68
Gamma ray photon	18.60	26.4

TABLE II: Calculated energy E_c and mean percentage deviation from the simulation primary energy (E_s) for proton, helium, lithium, carbon and iron vertical showers.

	proton	helium	lithium	carbon	iron	photon
E_s (EeV)	E_c (EeV)	E_c (EeV)	E_c (EeV)	E_c (EeV)	E_c (EeV)	E_c (EeV)
10	9.5	8.7	8.9	9.5	9.0	1.8
20	20.4	20.3	19.1	20.5	19.4	24.8
30	30.0	31.1	30.2	30.3	30.9	35.1
40	40.9	41.2	40.5	41.0	40.8	49.5
50	48.3	50.6	50.4	50.7	49.5	75.1
60	60.4	61.0	60.2	59.2	59.0	73.6
70	69.8	67.9	71.5	67.5	69.3	65.4
80	80.3	78.5	78.5	79.8	78.9	66.1
90	85.6	91.1	88.8	91.5	90.3	76.4
100	102.0	101.0	98.0	100.0	98.4	78.1
dev.	2.1	3.12	2.5	1.9	2.5	27.9

V. CALCULATION OF VERTICAL DENSITY $S_0(1000)$

The parameter S(1000) used previously for the estimation of the energy of UHECR applies to vertical showers only. Due to the increasing slant depth (875.5 g/cm^2 for vertical showers) for inclined showers the density S(1000) is modified with zenith angle. In order to define an equation converting the density of the inclined shower $S_\theta(1000)$ to the vertical density $S_0(1000)$ we simulated EAS created by various primaries of energy 100 EeV with zenith angles between 0 and 60 degrees. Figure 4 shows the variation of $\ln[S_\theta(1000)/S_0(1000)]$ as a function of (secθ-1) for proton, helium, lithium, carbon, iron and photon showers.

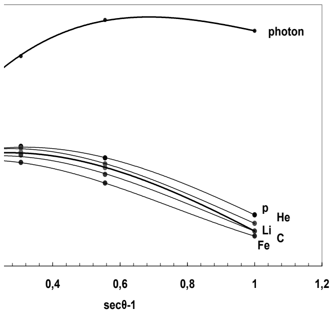

Fig. 4: Variation of $\ln[S_\theta(1000)/S_0(1000)]$ as a function of (secθ-1) for proton, helium, lithium, carbon, iron and photon initiated showers of primary energy 100 EeV.

The best fit for all the curves is a polynomial of third degree

$$S_0(1000) = \frac{S_\theta(1000)}{exp\{[(\frac{X_0}{L_3})(sec\theta-1)]^3-[(\frac{X_0}{L_2})(sec\theta-1)]^2+[(\frac{X_0}{L_1})(sec\theta-1)]-Q\}}$$

where X_0=875.5 g/cm^2 is the average atmospheric depth at Auger. Best fit parameters L_1, L_2, L_3 and Q are shown in table III.

TABLE III: Best fit parameters L_1, L_2, L_3, and Q for primary particle proton, helium, lithium, carbon, iron and photon

Primary particle	L_1 (g/cm^2)	L_2 (g/cm^2)	L_3 (g/cm^2)	Q (g/cm^2)
Proton	375.49	422.42	807.18	0.029
Helium	377.84	395.79	728.54	0.0061
Lithium	447.78	434.49	833.19	0.0207
Carbon	461.01	409.55	728.92	0.0282
Iron	573.12	410.08	694.31	0.0161
Photon	111.01	300.35	630.87	0.0375

By applying the above formula we determine $S_0(1000)$ for each angle and compare it to the simulated density of the vertical shower.

TABLE IV: Calculated vertical density at 1000 m for proton, helium, lithium, carbon and iron initiated showers of primary energy 100 EeV.

	proton	helium	lithium	carbon	iron	photon
θ (deg)	S_0 (m^{-2})	S_0 (m^{-2})	S_0 (m^{-2})	S_0 (m^{-2})	S_0 (m^{-2})	S_0 (m^{-2})
0	42.6	44.5	47.4	50.3	55.1	5.2
10	40.3	44.5	46.1	48.6	53.1	5.4
20	41.1	43.5	45.4	47.5	54.6	5.8
30	41.2	44.1	46.5	48.6	54.1	5.3
40	41.9	44.7	47.0	50.1	54.3	5.3
50	41.2	44.0	46.2	48.5	54.2	5.4
60	41.4	44.2	46.5	49.0	54.2	5.4

TABLE V: Calculated energy (E) and mean percentage deviation from the simulation primary energy (100 EeV) for inclined proton, helium, lithium, carbon and iron showers.

	proton	helium	lithium	carbon	iron	photon
θ (deg)	E (EeV)	E (EeV)	E (EeV)	E (EeV)	E (EeV)	E (EeV)
0	105.0	101.0	101.0	103.0	100.0	82.1
10	98.9	101.0	98.0	99.3	96.2	85.8
20	101.0	98.9	96.4	97.0	99.0	94.8
30	101.0	100.0	98.8	99.4	98.2	83.9
40	103.0	102.0	99.9	103.0	98.6	84.1
50	101.0	100.0	98.1	99.1	98.3	87.4
60	102.0	101.0	98.7	100.0	98.4	86.1
Mean dev.	2.0	0.9	1.6	1.6	1.6	13.7

VI. CONCLUSIONS

In this analysis we propose a way to estimate the energy of primary cosmic particles identified as proton, helium, lithium, carbon and iron nuclei and gamma ray photons arriving at the earth with varying zenith angles, provided that we know their directions. We concluded that the above primary nuclei behave according to their atomic number Z whereas photons behave as nuclei much lighter than a proton. Heavy nuclei create EAS that initiate higher in the atmosphere and develop more rapidly than the ones created by protons. Due to the random fluctuations in the first steps of the cascade, two different nuclei of the same energy may be undistiguishable, so a single shower can't provide evidence for the nature of the primary nucleus. This means that a statistical study is necessary. The method is based on a large number of Monte Carlo simulations of the LDF evolution of EAS adapted to the P. Auger Observatory. The mean accuracy of the energy estimation of the primary hadrons approaches a rather good value 1.5% and for gamma ray photons the mean accuracy is 13.7 % which is a good value given the fact that these showers cannot be observed after their maximum at the Auger site.

The simulation data of this study could also be used for the determination of the isotopic composition of the cosmic rays at least for photon, proton and iron nuclei. Provided that the energy of the primary particle is estimated using another method (fluorescence detector data in a hybrid event) and the density at 1000 m from the shower core at ground level is known, one could determine the nature of the primary particle using the position of the point (density,energy) in figure 3.

VII. ACKNOWLEDGMENTS

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