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Simulation of the time structure of Extensive Air Showers with CORSIKA initiated by various primary particles at Alborz-I observatory level

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ABSTRACT

A detailed simulation of showers with various zenith angles in atmosphere produced by different primary particles including gamma, proton, carbon, and iron at Alborz-I observatory level (35°43′N, 51°20′E, 1200 m a.s.l = 890 gcm^{-2}), in the energy range 3×10^{13} eV–3×10^{15} eV, has been performed by means of the CORSIKA Monte Carlo code. The aim of this study is to examine the time structure of secondary particles in Extensive Air Showers (EAS) produced by the different primary particles. For each primary particle, the distribution of the mean values of the time delays of secondary particles relative to the first particle hitting the ground level in each EAS, $< \tau_i > = < t_i - t_p >$, and the distribution of their mean standard deviations, $< \sigma_i >$ in terms of distance from the shower core are obtained. The mean thickness and profile of showers as a function of their energy, primary mass, and zenith angle is described.

1. Introduction

A careful knowledge of the mass composition of high energy cosmic rays provides an actual understanding of their origin, acceleration mechanisms and propagation from the sources to the Earth. Cosmic rays are composed of practically all elements of the periodic table extend over an enormous energy range of about 10^9 eV up to 10^{20} eV. Within this range the particle flux drops rapidly with increasing energy, by about 30 orders of magnitude. At low energies the particle flux is large enough to determine the mass composition of cosmic rays directly by sophisticated detectors operating on balloons or satellites. On the other hand, at the highest energies, where only a few particles are expected per km^2 and century, huge ground based experiments usually look for primary cosmic ray induced Extensive Air Showers (EASs) and the (average) mass can coarsely be estimated only. Hence several parallel approaches can increase the accuracy of mass composition of ultra-high energy cosmic rays. The shape of time structure of secondary particles in different EASs is one of the approaches. Arrival time of secondary particles in an EAS is generally used to determine its shower axis direction or the same arrival direction of primary particle towards the Earth atmosphere. Different velocities of particles and specially their path lengths through the atmosphere make thickness of the shower disk and different arrival times. The variation of the arrival times of particles at an special point of the EAS lateral extension reveals the EAS thickness, while the variation of the time delays with the distance of the shower core shows the curvature of the EAS front and its arrival direction (Fig. 1). Linsley (1986) showed that the shower thickness can be parameterized as a function of the distance of particle from the shower core, r, as expression $\sigma_{sh} = (1.6 \text{ ns})\ (1 + r/30)^{1.65}/\sqrt{n(r, \theta)}$. Where r is the distance of the detector from the shower core in meters, and $n(r, \theta)$ is the number of shower particles crossing the detector located at a distance r from the core of a shower with zenith angle θ. Whereas the nature of the primary cosmic ray and its interactions with atmospheric nuclei produces an especial time structure of secondary particles in an EAS, the time structure may be considered to distinguish primary particles from each other. The temporal feature of particles in different EASs initiated by different primary cosmic rays has been studied by many authors (Melcarne, 2011; Linsley and Scarsi, 1962; Agnetta, 1997; Ambrosio, 1999). A new method has also been proposed to determine the mass composition of primary cosmic rays using the azimuthal asymmetries in time distributions of secondary particles in non-vertical showers (Dova, 2009). Alborz-I array will consist of 20 scintillation detectors placed at the Sharif University of Technology campus ((35°43′N, 51°20′E, 1200 m a.s.l = 890 gcm^{-2}) is designed to study the knee region of cosmic ray spectrum. The configuration of Alborz-I array is a result of detailed simulations on trigger conditions and angular resolution for 20 detectors on a surface area of about1600 m^2 (Abdollahi, 2016). In the first phase of construction, the central cluster

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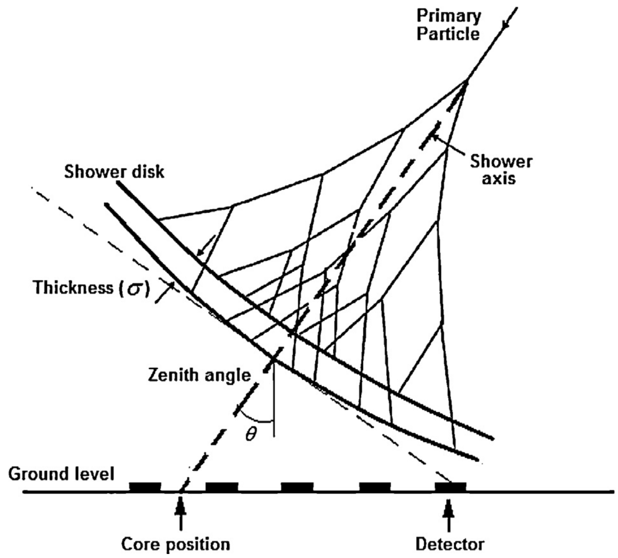

Fig. 1. A sketch of an air shower approaching a ground array, and produced shower disk.

Table 1
Simulated events for different primary particles with several energies and zenith angles.

Primary particle	3×10^{13} eV	10^{14} eV	3×10^{14} eV	10^{15} eV	3×10^{15} eV
P	0°	0°	0°, 25°, 45°	0°	0°
C	0°	0°	0°, 25°, 45°	0°	0°
Fe	0°	0°	0°, 25°, 45°	0°	0°
Gamma	0°	0°	0°, 25°, 45°	0°	0°

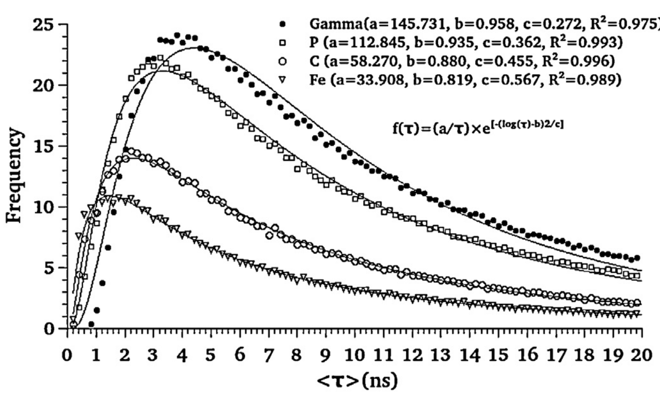

Fig. 2. The time distribution for all secondary charged particles related to Gamma, Proton, Carbon, and Iron, with energy of 3×10^{14} eV and zenith angle of $\theta = 0°$. Each distribution is mean over 100 showers.

of the array has been launched and is recording air showers and soon its initial data will be analyzed. Since the Alborz-I array measures only the time difference between the arrival of secondary particles into detectors and are not sensitive to particles, hence the time distribution of the various particles will not be considered separately. Our goal is to use the results of these simulations for the experimental data of the Alborz-I array, which will be available soon. In the current work, we present simulations of high-energy showers generated by different primary particles including gamma, proton, carbon, and iron at Alborz-I observatory level, in the energy range 3×10^{13} eV–3×10^{15} eV by means of the CORSIKA Monte Carlo code and the time characteristics of secondary charged particles are compared.

2. Generation of CORSIKA simulation events

The Monte Carlo air shower simulation program CORSIKA (version 74000) has been used for the simulated data. Present results have been obtained by coupling the QGSJET II-04 model (qgsjet-II-04.f package) (Kalmykov and Ostapchenko, 1993), for hadronic interactions above $E_{lab} > 80$ GeV, and GHEISHA (Gamma Hadron Electron Interaction SHower code) (Fesefeldt, 1985) for interactions below this energy. A sample of 1000 showers for each primary particle, with energy of E_0, and zenith angle of θ were generated. Table 1 shows the energy, and zenith angle values of showers produced by different primary particles (including of Proton, Carbon, Iron, and Gamma).

We simulated these EAS events based on the characteristics of our site, ALBORZ-I observatory, with an observation altitude 1200m above sea level and the values of geomagnetic field components, $B_x = 28.06\,\mu$T, $B_z = 38.37\,\mu$T, which were obtained from U.S. Geomagnetic Data Center http://www.ngdc.noaa.gov/seg/potfld/geomag.html. The energy distribution of recorded events by this observatory has a maximum value around 3×10^{14} eV (Abdollahi, 2016), so the inclined showers are simulated in this energy. The arrival time, t_i, and the location, (x_i, y_i), of each secondary charged particle with respect to the shower core are stored. The cut-off energies of the air shower particles for sets (Hadrons, Muons) and (electrons, photons) are 300 MeV and 3 MeV, respectively. These parameters are used for the results obtained in this paper. It is worth mentioning for Gamma initiated showers due to negligible muon component, muons have not taken into account.

3. Analysis method

The output of the simulated events, (t_i, x_i, y_i), are processed with an analysis program to obtain the arrival time delay of each particle, $\tau_i(r)$, at core distance bin, [r-2.5 m, $r+2.5$ m], with respect to the arrival time of first particle hitting the ground level within a surface area with radius 250 m, t_p, in an EAS as $\tau_i(r) = t_i(r) - t_p$. Obviously this limitation in position of the first particle hitting the ground, r_p, is not important for vertical showers because r_p is fairly near the shower core but it becomes important in inclined showers. Then the mean value of the time delay, $\bar{\tau}(r)$, is calculated in each distance interval for each shower as follows:

$$\bar{\tau}(r) = \frac{1}{N}\sum_{i=1}^{N}\tau_i(r), \quad (1)$$

where N is the number of particles at core distance bin [r-2.5 m,

Table 2
The different statistical values of time lag distribution for a sample of the distance bin 50–55 m for Gamma, P, C, and Fe.

Quantity	Gamma	P	C	Fe
Number of particles	1282 ± 512	1121 ± 557	653 ± 219	426 ± 101
Most probable of the time lag (ns)	3.8 ± 1.2	3.2 ± 1.2	2.2 ± 1.2	1.8 ± 1.2
Mean time lag (ns)	8.6 ± 0.3	7.9 ± 0.5	7.2 ± 0.4	6.4 ± 0.4