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THE SIMULATION AND PARAMETRIZATION OF THE LATERAL DISTRIBUTION FUNCTION IN EAS AT ULTRA HIGH ENERGIES

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Abstract: To characterize the features of EASs, this study used the AIRES simulation tool (Version 19.04.0) to estimate the lateral distribution function (LDF) at very high energies of different types of cosmic ray particles. An array of zenith angles spanning from 1018 to 1020 eV was used for the proton and iron primary simulations. The EASs's LDF curves are fitted with new coefficients for various primary particles and zenith angles using a polynomial fit, and these coefficients are applicable to the energy range described before. The findings of the simulation were compared with actual data from the Yakutsk EAS array, which showed decent agreement for proton and iron at 1019 eV for angled showers at $\theta=10^{s}$.

Keywords: AIRES, Extensive air showers, Cosmic rays, Lateral distribution function.

Introduction

Atmospheric cosmic rays (CRs) with high energies have been detected using the EAS [1]. Physicist Pierre-Victor Auger of France was the first to find EAS in 1930 when he increased the amount of atmospheric particles [2].

A bit of the primary particle's kinetic energy transforms into the mass energy, And the rest is distributed across the shower. The multiplication process continues until the EAS particles' energy is inadequate to create more particles in consecutive collisions. It is known that the shower development stages are called the shower's maxima [2, 3]. Observations of Earth's cosmic radiation, which is mostly obtained from EAS observables, need the LDF of charged particles in EAS [4]. The EAS was built on top of a sophisticated technique that combines hydronic successions with electromagnetic fields.

To determine the primary cosmic radiation properties that generate EAS, it is necessary to do a comprehensive numerical simulation of the EAS [5].

As the number of charged particles in EAS continues to rise, some with energy exceeding 1010, it became imperative to model these processes [6].

Heitler provided a relatively simple model for creating electromagnetic cascades before the age of high-speed computers [7]. Heitler, Gaisser, and Rossi made more advanced analytical techniques at the time, encompassing additional physical factors [8,9]. Cotzomi investigated several findings concerning the LDF of charged particles with energies more than 1017eV in 2008 [10]. Taipa confirmed the lateral structure's age parameter in 2013 by identifying the EAS particles' chemical composition [11]. In order to verify the routes of arrival at equatorial coordinates, Ivanov published a research in 2018 detailing the distribution of zenith angles in the cosmic ray showers detected with the Yakutsk array [12].

A variety of high energy values (1018–1020 eV) at various zenith angles (0o, 10o, and 30o) were simulated using the AIRES model to determine the LDF in EAS for proton and iron primary. With the use of proton and iron primary, which release very energetic gamma particles into Earth's atmosphere, this research intends to determine the lateral density of these charged particles. Experimental results from the Yakutsk EAS observatory corroborated this estimate at an energy level of 1019 eV [13, 14].

Discrete-Time Distribution Model:

The discovery of charged particles in the EAS is of relevance to CRs, as it is from these observations that the majority of subsequent observations are inferred [11, 15]. With the help of certain values of LDF, we can determine the density of charged particles in the EAS with respect to the fundamental distance from the shower, or LDF stands for the waterfall structure at different atmospheric depths. Experiments on EAS may be conducted on land, in the ground, and even at higher elevations in the mountains [2]. The "Nishimura-Kamata-Greisen function" [16] is the most important phrase used to describe a model, and LDF is an example of it:

$$\rho(r) = 2\ \pi N\ eRM2 \times C(s) \times (R\ rM)(s-2) \times (R\ rM + 1)(s-4.5) \qquad 1$$

In this context, $\rho(r)$ denotes the particle density at a distance r from the shower core, Ne stands for the total number of electrons, which is 118 m, $\boldsymbol{M}M$ for Molier radii, s for the shower age parameter, and C (s) for the normalization factor, which is equal to 0.366 s2 * (2.07-s)1.25 [17].

Methods

In the direct energy range (1018 - 1019) eV, the Aires simulation code calculates the LDF for shower formation of primary particles (e.g., primary proton, p, and iron nuclei, Fe) generated by air showers. A system called AIRES, which stands for "AIR shower extended simulations," is used to control all relevant output data and simulate EAS particles generated after the atmospheric impact of high-energy primary CRs. [13]. The AIRES system model allows for many particles. The principal incident particle in EAS might be an iron nucleus, a proton, or any of the other primaryities listed in the AIRES manual as having ultra-high primary energies greater than or equal to 1021 eV [13, 18].

Despite the impracticality of simulating air showers at the lowest energy, the LDF may be estimated by comparing the Aires simulation with experimental findings. A polynomial fit was used, yielding a new coefficient for several energy ranges (1018–1020) eV and zenith angles. This AIRES algorithm, which is derived from the relative thinning example with a thinning factor of 10-7, is used for all simulations. For showers that started in EAS, the LDF was parameterized using a polynomial fit, which yielded three additional coefficients for various main particles:

$$\rho(R) = Bo + B1R + B2R2 \qquad 2$$

The variable ρ(R) represents the density of particles at a certain distance R from the shower core, and the variables Bo, B1, and B2 are new coefficients that are dependent on the main and secondary particles in EAS. These coefficients' values may be found in the table (1).

Table 1. Two main particles with varying energy and zenith angles are considered in the (Eq.2) with modified coefficient values.

Primary particles	**Zenith angles**	**Energy (eV)**	**Values of coefficients**		
			B_o	B_1	B_2
Proton (p)	0°	10^{18}	2.36861	3.6527	-1.37642
		10^{19}	2.96873	4.28344	-1.55657
		10^{20}	4.0965	4.10218	-1.50281
	10°	10^{18}	2.11986	4.01725	-1.47169
		10^{19}	2.96787	4.2405	-1.53624
		10^{20}	3.7441	4.39088	-1.58349
	30°	10^{18}	1.91662	3.97314	-1.42586
		10^{19}	2.85682	4.21654	-1.50182
		10^{20}	3.74527	4.36594	-1.5458
Iron nuclei (Fe)	0°	10^{18}	2.36861	3.6527	-1.37642
		10^{19}	3.15289	3.99354	-1.46961
		10^{20}	4.0965	4.10281	-1.50281
	10°	10^{18}	2.42045	3.58371	-1.35847
		10^{19}	3.23903	3.86676	-1.43385
		10^{20}	4.19395	4.00281	-1.47822
	30°	10^{18}	2.29012	3.35632	-1.26891
		10^{19}	3.06242	3.79629	-1.38382
		10^{20}	3.016631	3.93979	-1.42548

Results and Discussion

Figure 1 shows the lateral proton density in vertical and slanted showers generated using the AIRES model for three high energies: 1018, 1019, and 1020 eV.

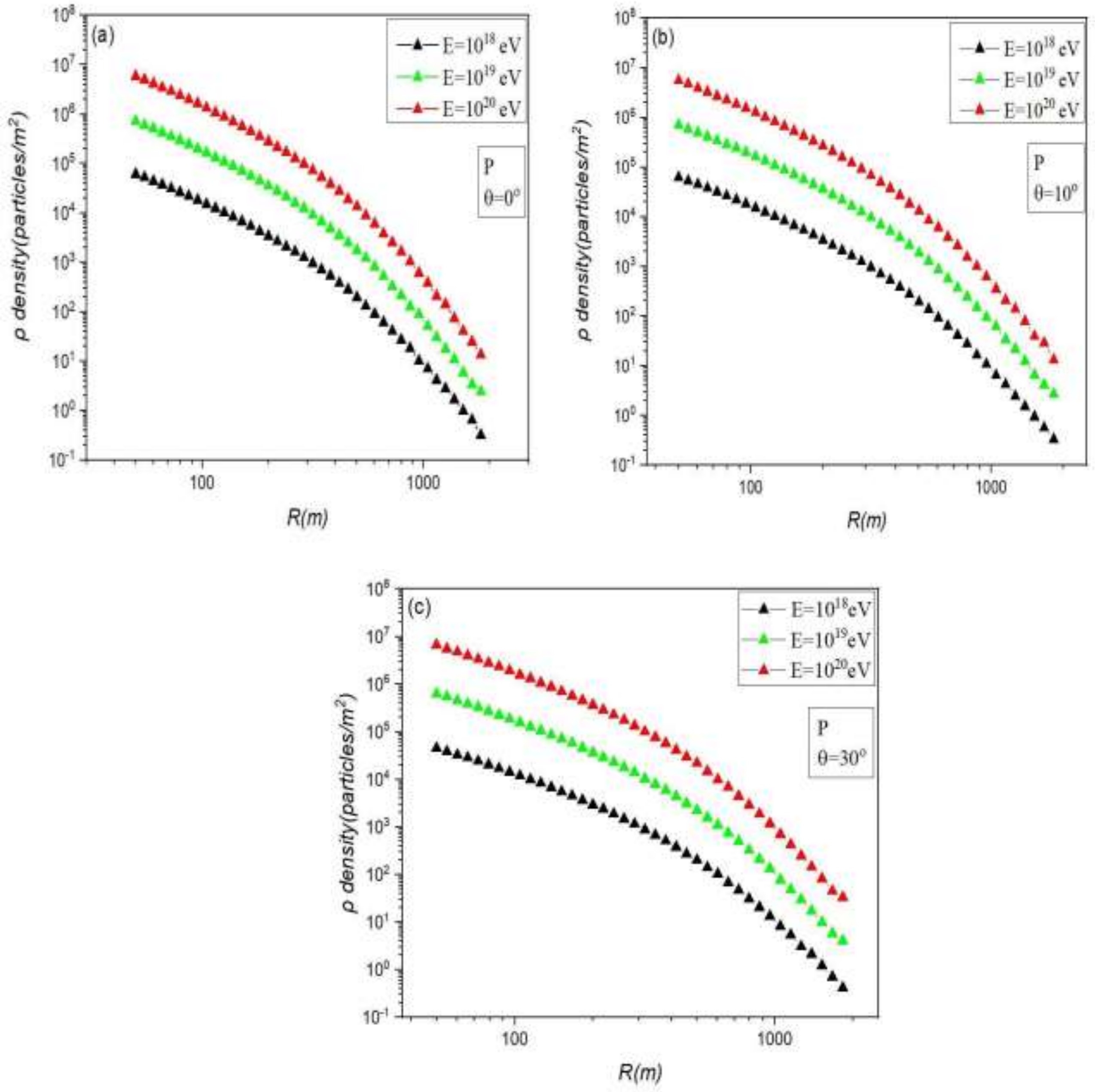

Fig. 1. The impact of the main proton's energy on the lateral density as it is represented by the AIRES code for various zenith angles and energies within the range of (1018-1020) eV for the following cases: (a) θ= 0˚; (b) θ= 10˚; (c) θ= 30˚.

For various primary energies within the range of (1018 -1020) eV, Fig. 2 shows an additional feature or significance of the impact of the zenith angle (θ = 0, 1˘0˚and 30)´ on the lateral density of iron nuclei simulated by the AIRES model.

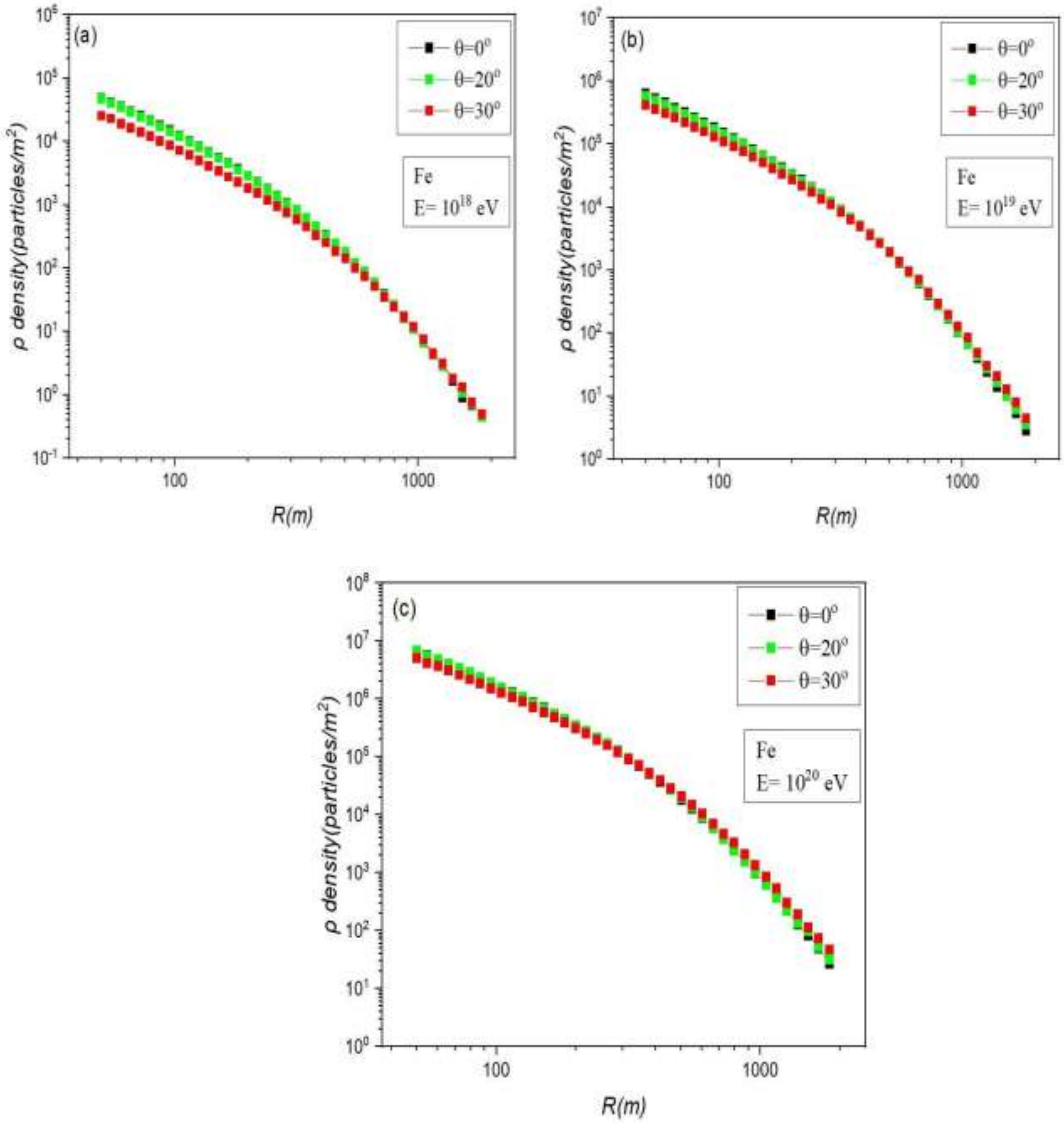

Figure 2. At the fundamental energies of 1018 eV, 1019 eV, and 1020 eV, the AIRES algorithm simulates the zenith angle impact on the lateral density of iron nuclei, Fe, at various zenith angles (θ = 0, 1, 0, and 30).

Fig. 3. Compares the main proton's simulated LDF with that of iron nuclei using the AIRES algorithm for vertical showers. The LDF of the secondary particles launched by primary proton and primary iron at energies (1018, 1019, and 1020) eV are quite similar, as seen in this picture, which is an intriguing fact.

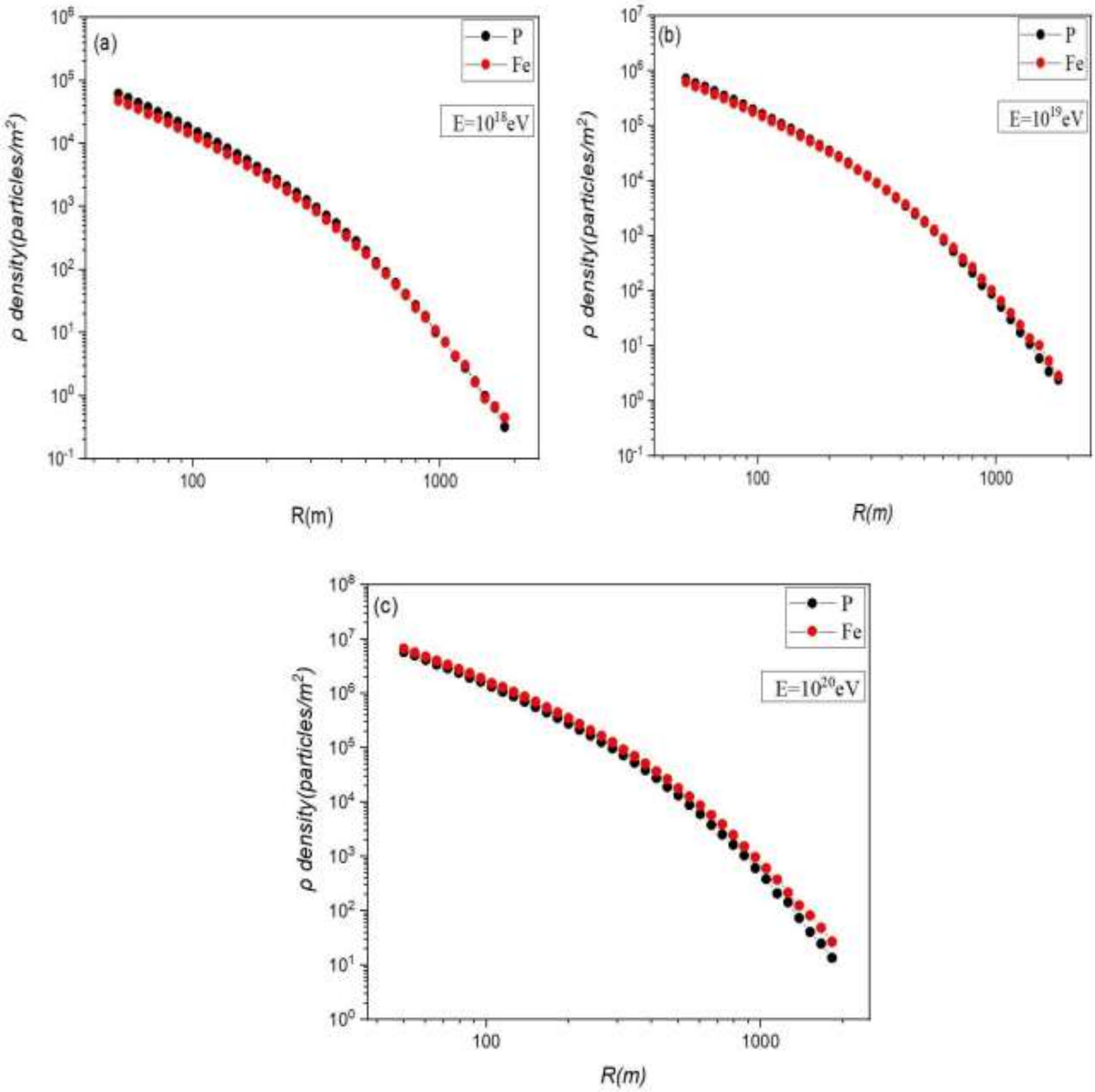

Fig 3. At various energies at the primary level, the simulated LDF of the proton (p) is compared to that of iron nuclei (Fe) under the same conditions ($\theta = 0^\circ$). (a) 1018 eV, (b) 1019 eV, and (c) 1020 eV energy levels.

Figure 4 displays a contrast between the experimental results (Yakutsk experiment) [16, 19] for primary proton, p, and iron nuclei, Fe at the energy 1019 eV for $\theta = 10^\circ$ and the parameterized LDF using polynomial fit (Eq. 2), which produced a new coefficient for various primary particles. There is a strong concordance with prior findings in Fig. 4.

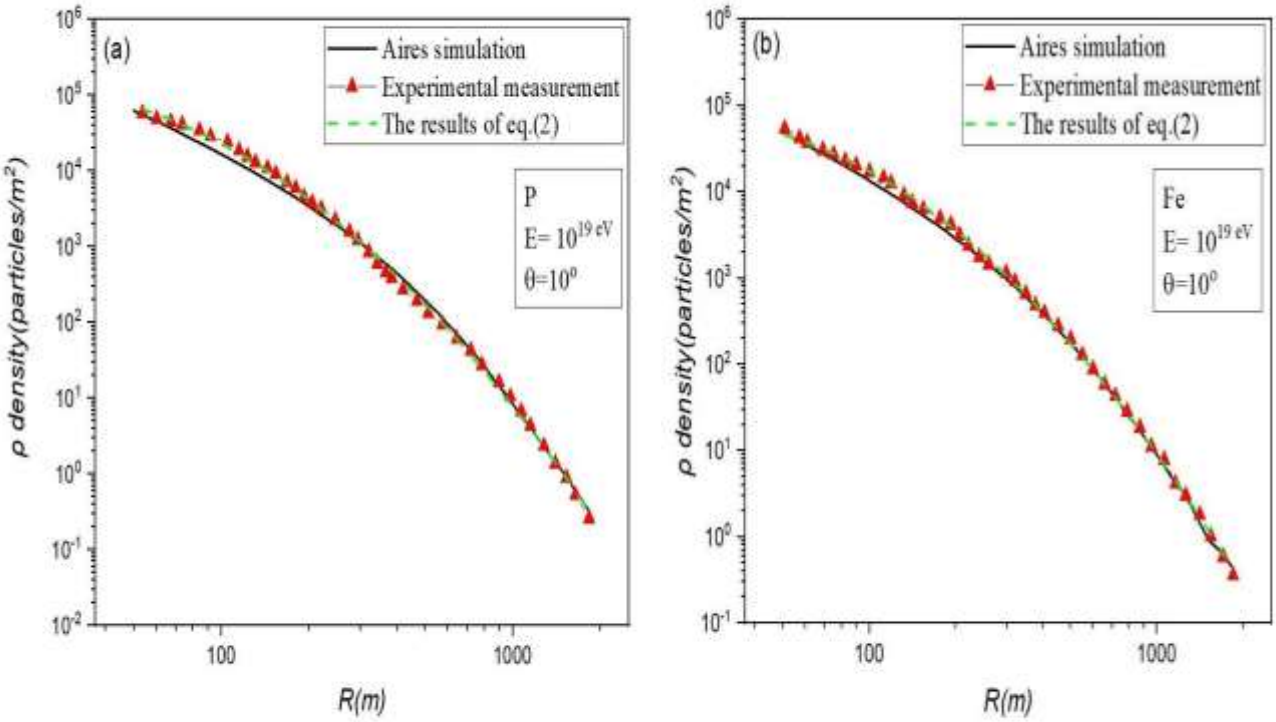

Fig 4. The experimental observations [13, 14] with θ = 10˚ at a fixed primary energy of 1019 eV and with distinct primary particles: (a) primary proton and (b) iron nuclei, are compared with the parameterization of the simulated LDF by AIRES algorithm [13, 14].

when seen in figure 1, when the primary particle energies rise, the lateral density of secondary particles also increases. See Figure 2 for an illustration of how the lateral density of secondary particles diminishes as the zenith angle rises and as the distance from the shower axis grows.

For θ = 0˚, fig. 3 shows an interesting point: the LDF of the secondary particle, which is started by the initial proton and iron nuclei at energies (1018, 1019 and 1020) eV, are very near to each other. By comparing the Aires simulation, Polynomial parameterization, with the experimental data from the Yakutsk observatory of LDF for showers, the principal particle identification was validated (fig. 4). The current LDF findings from the AIRES simulation are compared to the results from the Sciutto simulation, which demonstrated a strong match between the secondary gamma particles began by the main proton at 1019 eV with a thinning energy of ϵth = 10 -7 and θ = 0.

Conclusion

here, the widespread air shower effects were characterized by approximating the lateral distribution function at extremely high energies of several cosmic ray particles. For elementary particles in the high energy range (1018–1020 eV) at varied zenith angles (0o, 10o and 30o), the AIRES algorithm was used to simulate the lateral distribution function in vast air showers. These particles include primary proton and iron nuclei. The densities of charged particles generated in the extensive air showers were examined in relation to primary particles, energies, and the zenith angle (θ). As one moves away from the shower axis R, additional lateral distribution function coefficients are derived.

We can identify the main particles and estimate their characteristics at extremely high energies around the cosmic ray spectrum ankle by comparing the coefficients of the lateral distribution function with those observed with the Yakutsk experiment. Building a library of lateral structural samples for analysis of genuine widespread air shower events observed and recorded in the enormous air shower arrays is an important part of the current study.

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