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EAS Cherenkov LDF Analysis: CORSIKA Simulations for Tunka-133 and Chacaltaya Arrays

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Abstract

This study leverages CORSIKA simulations to analyze the Lateral Distribution Function (LDF) of Cherenkov photons in Extensive Air Showers (EAS) within the knee region of the cosmic ray energy spectrum (10^15 - 10^16 eV). Focusing on primary particles like helium, proton, oxygen, and iron nuclei at varying zenith angles (0˚, 20˚, and 45˚), we aimed to reconstruct Cherenkov photons' LDF using an Exponential Function model, tailored as a function of primary energy. Our approach involved a comparative analysis of simulated LDFs with experimental data from the Tunka-133 and Chacaltaya arrays. The results exhibit a high degree of concordance between simulated and observed data, affirming the validity of our method. We developed a set of approximation functions for different primary particles and zenith angles, enhancing our ability to identify the particle type in EAS events and accurately determine its energy. The primary contribution of our work lies in its potential to rapidly compile a comprehensive LDF pattern library, instrumental for analyzing real EAS array events and reconstructing the mass composition and primary cosmic ray energy spectrum. This advancement in CORSIKA-based simulation methods marks a significant stride in cosmic ray research, offering a robust tool for detailed EAS analysis.

Highlights :

- **Validation of Simulation Accuracy:** Demonstrated high concordance between CORSIKA simulated LDFs and experimental data from Tunka-133 and Chacaltaya arrays.
- **Enhanced Particle Identification:** Development of approximation functions for various primary particles and zenith angles, improving accuracy in identifying particle types in EAS events.
- **Advancement in Cosmic Ray Research:** Potential to create a comprehensive LDF pattern library, significantly aiding in the reconstruction of mass composition and primary cosmic ray energy spectrum.

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Keywords : CORSIKA Simulations, Cherenkov LDF, EAS Analysis, Cosmic Ray Spectrum, Particle Identification

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Introduction

The cosmic rays (CRs) have an energy range of more than twelve decades with a comparable drop in intensity [1]. The precise determination of the energy spectrum and mass composition is one of the most urgent issues in the area of primary CR investigaitions. This is crucial in order to learn more about the mechanisms governing cosmic ray propagation, interstellar matter, and their genesis. Only indirect measurements are feasible in the region of ultra-high energies [2]. The energy range around 1- 3×10^{15} eV in the slop $\propto E^{-2.7}$ - $\propto E^{-3.0}$ of observed change is known the "knee" spectrum. Acceleration mechanisms and origin of primary CRs are the main unresolved issues [3]. The study the energy spectrum around the "knee" of primary CRs mass composition is essential for comprehending the origin, acceleration, and propagation mechanisms of cosmic ray spectrum [4]. Therefore, the transition from a light to a heavy composition with rising energy is related to the eneirgy limit of CR nuclie's acceleration in galactic sources [5]. The majority of CRs are thought to come from galaxy, within portion below a "knee" coming from galactic supeirnovas. Partiecles are acceilerated by shockes in the remnant of supernovae [6]. the various approaches of inquiry is based on air Cheirenkov of flux measuremeints in EAS, precisely getting the LDF. It seems feasible to use various lateral distributions for EAS componentes and their fluctuations at various distances to calculate the mass composition of primary CRs radiation. In an effort to explore new avenues for primary cosmic ray research, it has been decided to apply the atmospheric Cherenkov technique [3]. Due to the high level of shower developments and experimental noises associated with EAS, it is very difficult to estimate the energy and nature of the primaries based on ground observations. When colliding with atomic nuclei in the air, high-energy CR particles (those with energies larger than 1 GeV/nucleon) produce additional particles, creating an atmospheric cascade. The majority of secondary particles in an EAS are electrons and muons, and they typically arrieve at grounds levels over a sizable area. The majority of inteiractions are electromagneitic, and a creation of hadron and muon pairs has a cross-section that is many orders of magnitude less than that of electron pairs. Protons create electron-positron pairs in the electromagnetic shower, while electrons and positrons from Bremsstrahlung produce photons. Cherenkov photons is produced in the shower by relativistic charged particles. Ground-based cosmic ray detection and measurement is the only option above 10^{14} eV, which entails the detection of one or more secondary CRs components. The atmospheric Cherenkov technique, which involves detecting the LDF Cherenkov of photons flux in large air showers, is one of the most practical methods. The registreation of the extremely breif burst (Cherenkov) of flux produced by the cascad of relatievistic charge pareticles created when a very high~energy CR particles impeinges on a atmospiere is a foundation of the atmospheric Cherenkov technique [7]. Relatievistic electron of (CRs) in the "EAS emit Cherenkov radiation in the atmosphere, which contains vital information about the development of the shower, the PCR particlies.. The energy as well as primary particle type, observation level, height of the first collision, and shower axis direction all affect the Cherenkov light LDF [8]. One of the essential instruments of numeriecal simulaition for researching" EAS features and processing and analyzing experimental data is the Monte Carlo approach (from the characteristics of Cherenkov radiation, determined of the primary particle enerigy type as well as direction of the shower axis of secondary charged particles). Agnetta et al., [9] have provided comprehensive details on the experimental setup, simulation, and Cherenkov light technique detection in EAS. On the other side, Akchurin et al.,[10] have provided thorough measurements of the profiles of high-energy electromagnetic and hadronic showers. Electrons with energies between 8 - 200 GeV were used to measure the LDF Cherenkov of photons flux produced during the shower development phase. Discussion of the comparison between the Cherenkov flux light profiles and the outcomes of Monte Carlo simulations. The Cherenkov flux photons generated " EAS was observed via Galbriath and Jelleiy in "1953" [11]. The Whippl telescop detectied Crab Nebulia [12, 13] on the basis of imaging the air shower. The Tunka-133 and Chacaltaya EAS arrays are used the present work to simulate LDF Chereinkov of photons flux for condetions and configurations [14, 15]. It is carried out utilizing the QGSJET model for the CORSIKA code for the simulation of hadronic processes that are used to simulate the electromagnetic component of the EAS and Cherenkov photons [16]. Exponential Function, a method for describing the lateral distribution for EAS LDF Cherenkov of photons flux, was used to approximate the results of the numerical simulation of LDF Cherenkov of photons flux density, and this study examines the potential for applying it to the reconstruction of events recorded on the Tunka-133 and Chacaltaya EAS arrays. The primary benefit of this method is the ability to recreate the Cherenkov radiation events detected by the Tunka-133 and Chacaltaya EAS arrays. An excellent potential for primeary parteicle identiefication as well as the characterization of the energy around "the knee area" has been demonstrated by comparing the approximated LDF Cherenkov of photons flux with the reconstructed EAS events recorded by the Tunka-133 as well as Chacaltaya EAS Cherenkov flux array.

Lateral Distrib e ution of Atmosph i ric Cherenkov Radiation

this work, a hadron interaction model QGSJET for the CORSIKA algorithm is used to simulate the evoluition of the atmospheiric cascaide for the lateral distiribution of LDF photons flux for Cherenkov. The most popular tool for simulating atmospheric cascades is cosmic ray simulations by CORSIKA [16]. The program simulates interactions and decay of numerous hadrons, electrons, photons, muons, and nuclei in the atmosphere. In case of unstaible secondary partiecles, the parteicles are tracked as they travel through the atmoisphere until its interact with air nucleus or until they decay. The simulaitions yield precise data on the energy, type, momenta, position, as well as arrieval time of ecreated secondary parteicles at a predetermined altitude above sea level. protons, light, medium, as well as heaviy nucliei up to iron are "the fundamental particles that can be taken into account. The observaition leveil was assumed to be 516 g cm^{-2};which corresponids to the Chacailtaya CR stations while Tunka-133 was

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assumed to be 670 g cm^{-2}. Particularly for the hadronic cascades with energy at the "knee," this observation level is very close to the EAS shower maximuim. As a result, compared to lower observation levels, the variations in shower development are not as significant. This enables the simulations to produce flatter disteibutions of the various EAS shower componentes, specifically the flux of air Cherenkov light [17].

Method

CORSIKA Simulations

The specifics of shower evolution are extremely complicated to be completely delineated by uncomplicated analytical modeling. In addition, the MC simulation of interaction and transport of every single particle is needed to execute for accurate shower modeling evolution. Lately, MC packages have been employed for simulating EAS using CORSIKA, the hadronic interaction model is utilized for this event generator QGSJET [16]. Therefore, the air shower simulation programs are made up of a variety of interconnected procedures that run on a data set with a variable number of records, changing the contests and increasing or decreasing the size of the data set according to predetermined laws. Internal control procedures in the CORSIKA simulation engine continuously check and report particles touching the ground and / or moving over predetermined observing surfaces between the ground and injection stages. Where the number of showers is determined and then the identity of the elementary particle is determined, as well as its energy can interact together with atoms of the atmosphere. Then we define the name of the task, as well as the kinetic energy of electrons, muons, and gamma rays. Next, we define the thinning energy and the zenith angle and then choose the observing levels for the array to be used. And finally, we define the name of the secondary particles resulting from the chain reaction. The diffractive interactions possess a straight influence onto the shower progress. Also, that fact is clearly confirmed by graphing the densities of showers versus the shower core of atmosphere, at certain value of energies of 10^{15} and 10^{16} eV. The graphs were plotted depending on the data incoming from simulations executed via the CORSIKA system for hadronic interaction model QGSJET. The simulation was employed to investigate the production of primary particles (proton as well the iron nuclei) resulted from air showers within the range of primary energy (101^{5}-101^{6}) eV and explore the LDF Cherenkov flux photons growth of created subsequent primary CRs of the extremely high value of energy react with the atmosphere and organize overall correlated production data.

The Cherenkov flux photons in EAS produced by different primary particles in the energy range (10^{15}–10^{16} eV) is shown in Figure 1. The obtianed LDF of atmospiheric LDF of photons flux for Chereinkov resulting from distinct CRs nuclei was shown in the area of the "knee". Show influence zenith angles and energies of the simulation LDF for Cherenkov flux photons for different primary particles by Chacaltaiya with Tunka-133 arrays for particles are primary oxygen, helium, iron nuclei, and proton for different primary energy.

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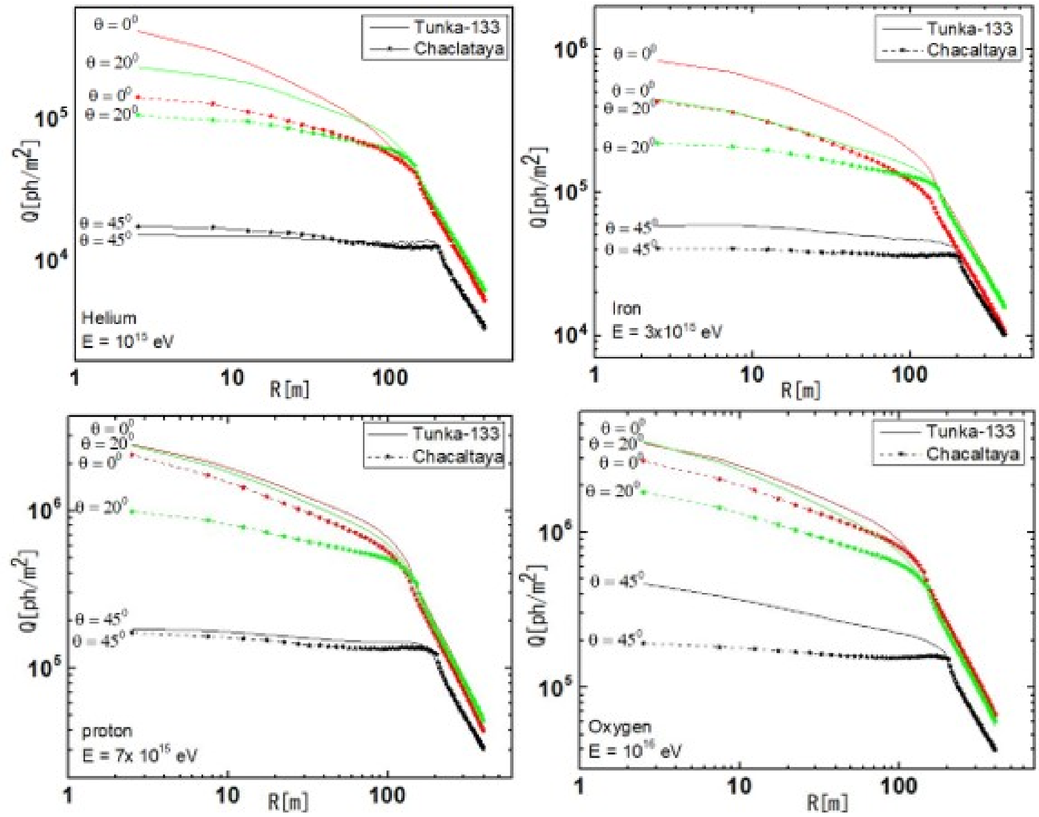

Figure 1. *The comparison between Chacaltaya and Tunka-133 arrays for different zenith angles and several primary particles (helium, iron nuclei, proton, and oxygen) by using CORSIKA code of Cherenkov light LDF at the different primary energy.*

Results and Discussion

Parameterization of the Lateral Distribution

Various parameterizations are used to approximate the resulting lateral distributions. The LDF of Cherenkov photons in EAS is parameterized and a particular assumption is the basis for most reconstruction methods. Practical parameterization is essential for event analysis and primary particle characteristic reconstruction. Figure 2 shows the findings for several basic particle approximations. Additionally, the suggested parameterization is used to approximate the LDF Cherenkov of photons flux produced by helium, iron nuclei, proton, as well as oxygen. The Chereinkov light LDF showers that originated in the EAS were parameterized using an exponential function, which produced various parameters for the primary particles as follows:

when is the densiety of EAS shower a function of the priemary energy; , , and, are obtianed coefficeints for Cherenkov photons LDF (see the Table 1). These coefficeints are obtianed by fitting the CORSIKA results, which are given by the polynomial form:

where , , and, are parameiteres of Eq. (2) as a funiction of the primary energy and, , and are their coefficeints (see the Figure 2).

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Primary particles	$K(E)$	Coefficients			
		a_0	a_1	a_2	a_3
P	C_1	-0.86126	-24.80306	-208.61533	118.86495
	C_2	83.17814	80.39021	49.32528	-0.9945
	C_3	1.26734	1.28711	1.2592	1849.60556
	ξ_1	3.29002	26.11111	217.12133	-27.25218
	ξ_2	1.20671	9.54119	68.42865	26485.14832
	ξ_3	1169.71658	1102.07871	1102.75785	-142.30949
	r_0	7.08781	6.27649	6.43017	1272.409
Fe	C_1	86.23676	59.78296	46.00644	8.274
	C_2	1.33741	1.21566	1.34987	-25.927
	C_3	2.26595	21.77746	153.23286	1.86
	ξ_1	0.82059	8.07847	40.86455	83.484
	ξ_2	1253.03081	1094.68689	1101.96244	1.264
	ξ_3	8.18762	7.46504	6.00806	-10.55
	r_0	114.98125	1468.11536	23410.17673	0.408
He	C_1	184210.8	5.63×10^[illegible]	-7.48×10^[illegible]	124.128
	C_2	353.53	7.11×10^[illegible]	-5.86×10^[illegible]	0.183
	C_3	112.5	-6.93×10^[illegible]	8.06×10^[illegible]	28.38
	ξ_1	-52708.5	-4.06×10^[illegible]	-5.09×10^[illegible]	1.115
	ξ_2	354834.54	1.14×10^[illegible]	-1.58×10^[illegible]	52.07
	ξ_3	356.31	867.14	225.9	547.85
	r_0	112.24	773.25	4.73	-65.214
O	C_1	338.23	8.78×10^[illegible]	-7.38×10^[illegible]	2.088
	C_2	48.09	8.27×10^[illegible]	-6.2×10^[illegible]	89.457
	C_3	253138.19	2.48×10^[illegible]	-2.53×10^[illegible]	1.352
	ξ_1	-4.26×10^[illegible]	3.48×10^[illegible]	1.52×10^[illegible]	-11.254
	ξ_2	341.67	8.77×10^[illegible]	-7.37×10^[illegible]	0.554
	ξ_3	48.63	8.15×10^[illegible]	-6.09×10^[illegible]	1.12×10^[illegible]
	r_0	-33747.79	451.56	684.9	229.28

Figure 2. *Coefficeints the exponential function (Eq.1) by Parameterizing the CORSIKA code simulation of various primary particles in the specified energy range (10^{15}-10^{16}) eV and different zenith angles (0˚, 20˚, and 45˚).*

An exponential function was used once again to parameterize the LDF for Cherenkov photons flux of showers that started in EAS, The function can produce various parameters for various primary particles and is represented as follows:

when is the density of EAS shower as a function of the zenith angles; , , and, are obtained coefficients for Cherenkov light LDF (see the Table 2). These coefficeints are obtianed by fitting the CORSIKA results, which are given by the polynoimial form:

where , , and, are parameters of Eq. (4) as a function of zenith angles and, , as well as are their coefficeints (see Figure 3).

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Primary particles	$Q_{(\theta)}$	Coefficients			
		a_o	a_1	a_2	a_3
p	C_1	97.77	1.54×10^{-17}	-1.3×10^{-36}	297.07
	C_2	5916.11	-4.93×10^{-13}	2.51×10^{-32}	35.53
	C_3	62389.11	9.92×10^{-12}	-2.92×10^{-31}	963402.16
	ξ_1	350.56	7.24×10^{-17}	-5.52×10^{-36}	5.66×10^{6}
	ξ_2	96.56	2.2×10^{-17}	-1.9×10^{-36}	298.57
	ξ_3	399198.83	4.1×10^{-12}	-4.25×10^{-31}	30.62
	r_0	586.9	295.5	542.42	11540.62
Fe	C_1	32094.02	4.97×10^{-12}	-1.5×10^{-31}	28205.409
	C_2	347.37	7.96×10^{-17}	-6.19×10^{-36}	280.65
	C_3	280192.9	3.71×10^{-12}	-5.02×10^{-31}	78.16
	ξ_1	-1.57×10^{6}	3.62×10^{-10}	1.97×10^{-30}	33668.68
	ξ_2	365.006	6.4×10^{-17}	-4.64×10^{-36}	65080.05
	ξ_3	46.87	1.19×10^{-17}	-8.58×10^{-37}	280.1
	r_0	- 4919.06	341.89	-66120.98	76.82
He	C_1	-105444.04	3.3×10^{-12}	-8.52×10^{-31}	-1.22×10^{6}
	C_2	4.14×10^{6}	5.73×10^{-10}	5.26×10^{-31}	321.16
	C_3	477.9	-8.25×10^{-18}	1.76×10^{-36}	37.75
	ξ_1	61.5	8.75×10^{-18}	-5.84×10^{-37}	-55072.2
	ξ_2	- 65156.3	2.04×10^{-12}	-5.42×10^{-31}	-673779.47
	ξ_3	2.6×10^{6}	3.61×10^{-10}	9.94×10^{-33}	323.05
	r_0	481.89	98.56	341.77	33.8
O	C_1	62.1	8.23×10^{-18}	-5.34×10^{-37}	-8684.63
	C_2	- 445.26	-1.87×10^{-13}	1.005×10^{-32}	211092.35
	C_3	29289.72	4.46×10^{-12}	-1.16×10^{-31}	337.41
	ξ_1	439.68	1.99×10^{-17}	-1.12×10^{-36}	81.36
	ξ_2	105.96	1.27×10^{-17}	-1.17×10^{-36}	-17764.59
	ξ_3	- 3859.09	-3.53×10^{-13}	1.33×10^{-31}	415600.6
	r_0	50299.73	8.92	542.03	337.58

Figure 3. *Coefficients the Exponential Function (Eq.3) by Parameterizing the CORSIKA code simulation for the different primaries within the energy range (10^{15}-10^{16}) eV and different zenith angles (0˚, 20˚, and 45˚).*

Figure 4 EAS shows the parametirization as a function of the zenith angle as well as primary energy in EAS shower using exponential function model (exp Dec3 within the different energies like (1×10^{15}, 3×10^{15}, 7×10^{15}, and 1×10^{16}) eV for several zenith angles (0˚, 20˚ and 45˚) for several primary particles such as helium, proton, oxygen, as well as iron nuclei.

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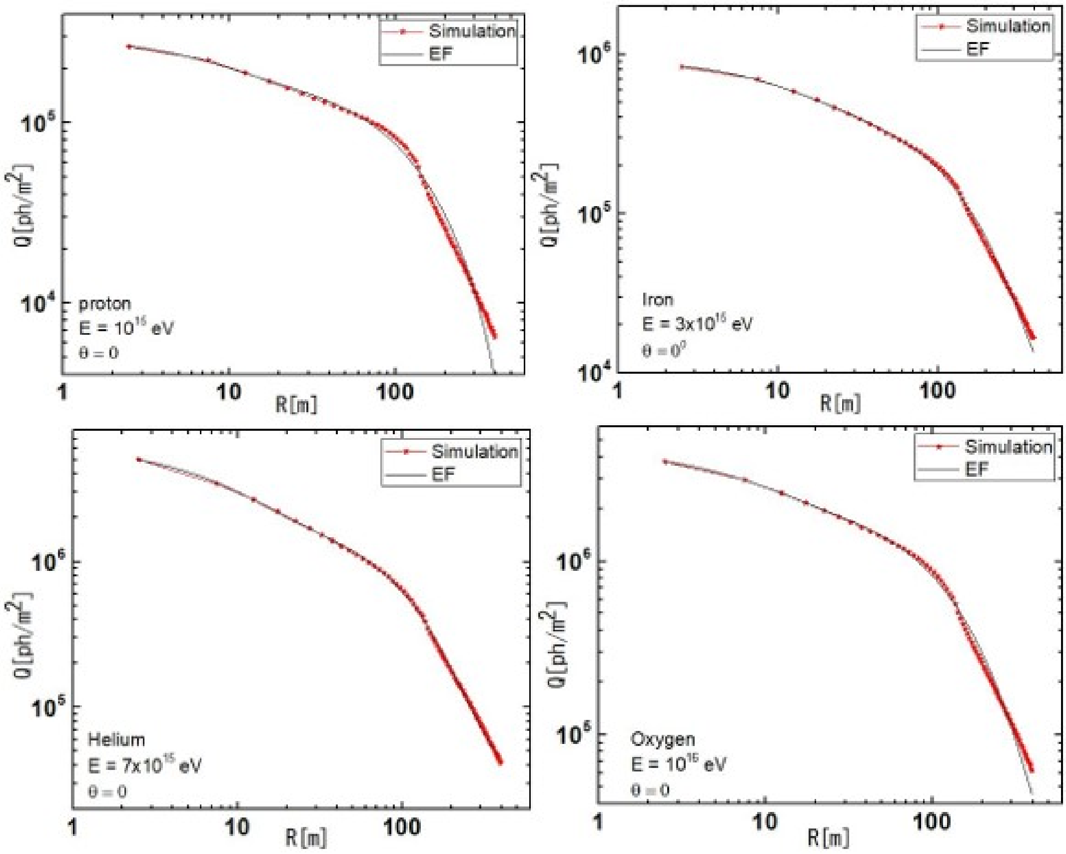

Figure 4. *The comparison between the simulation Cherenkov photons LDF by CORSIKA code (symbol line) and one calculated with an exponential function (solid line) for several primary particles like (helium, iron nuclei, proton, and oxygen) by vertical EAS showers at the various primary energy.*

Comparison of Parameti riz ed LDF with the E xperimental D ata

In the field of CR astrophysics, which is a dynamic topic at the forefront of fundamental research, the Tunka-133 and Chacaltaya EAS arrays investigate cosmic rays of exceptionally high energy. Two main objectives must be met in order to construct the Tunka-133 and Chacaltaya arrays: the first is to investigate the cascades of elemientary pariticles in the atmoisphere that are started by primary pariticles, and the second is to reconstruct the astrophysical characteristics of the energy spectrium, including their intensity, mass composition, primaries, and place of origin. Zenith as well as azimuth angles, primary energy, shower cor location, indivedual LDF, the density of photon flux for Cherinkov are the important factors in EAS measurements. The possibelity for the reconstiruction of the types of EAS primary particles can be demonstriated in Figures 3 , 4. Figure 3 demonstraites the compaeison of approximated Cherinkov photons flux LDF (dash lines)' with that measiured with the Chacaltaya EAS array "(symbols) at the energies 10^{15} and 10^{16} eV for the vertical EAS showers for various primary particles (p, O_2, He, and Fe). Figure 4 compares the approximated LDF Cherenkov of photons flux (dash lines) with those recorded with the Tunka-133 EAS array (symbols) for two main particles (P and Fe) for energies 10^{15} and 10^{16} eV at the zenith angle (θ=20^0).

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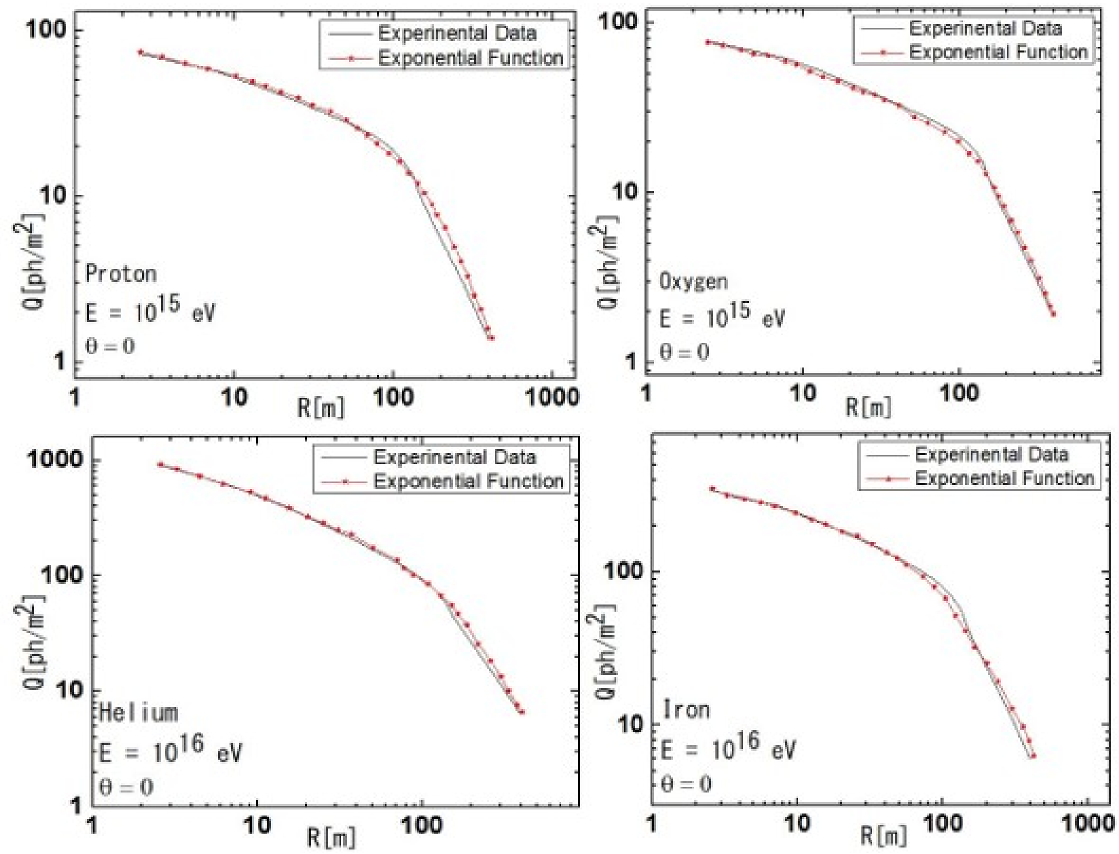

Figure 5. *Comparison between the parameteirized LDF of photons flux for Chereinkov (symbol line) obtained by (exponential function) and the experimiental data by Chacailtaya EAS array[5] (solid line) of various primary particles at the energies 10^{15} as well as 10^{16} eV.*

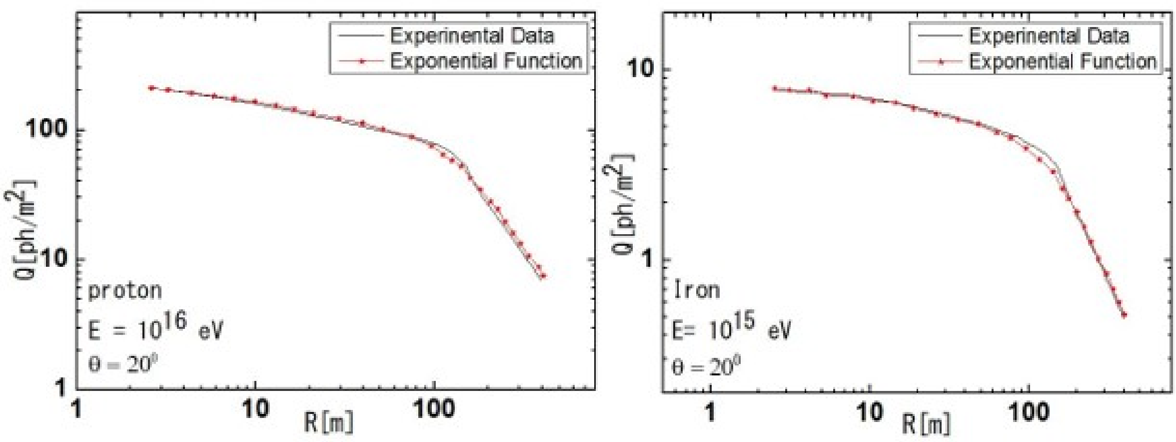

Figure 6. *Comparison between the parameterized Cherenkov photons LDF (symbol line) obtained by (exponential function) with the experimental result by Tunka-133 EAS array [8] (solid line) for the primary particles like (Fe and P) and the energies 10^{15} and 10^{16} eV.*

Conclusions

The CORSIKA code has been used to simulate the LDF of Cherenkov photon flux from particles of EAS initiated by the primary oxygen, helium, iron, as well as proton in the energy range of 10^{15} to 10^{16} eV. Sets of approximation functions for various primary particles and various zenith angles were built based on this simulation with an exponential function. The ability to identify the particle causing EAS showers and determine its energy in the knee regein of the CRs spectrium has been demonstrated by comparing the approximations of the LDF Cherenkov photons with those measured with the Tunka-133 and Chacaltaya EAS arrays. The main benefit of the suggested method is the potential for quickly assembling a representative library of the LDF patterns that could be analyzed to examine actual events captured by “EAS” arrays and for reconstructing of the mass composietion as well as the priemary CR energy spectrium.

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