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The Cosmic Rays Interaction with the Atmosphere and Estimation of the Number of Primary Particles in the Emission of Cherenkov

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ABSTRACT

In the range from (10^{14}-10^{16}) electronvolts (eV), this research hopes to determine the number of charged particles (N) as a function of the energy of the main particle. (E_o)The maximum depth of the Extensive Air Shower (EAS), $X_{max,}$ is also determined for electromagnetic and hadronic cascades in the same energy range. The inelasticity parameter's (k) role in describing neutrino counts as they fluctuate. The major objective is to evaluate the potential for determining the particles responsible for these showers and their energies around the cosmic ray (CR) spectrum's bend point for different fundamental particles (iron nuclei, proton, lithium, Helium) and at different zenith angles. This research looks at the production of Wide Air Showers and the emission of Cherenkov photons because of the collision of primary cosmic ray particles with atmospheric nuclei. As a function of the original energy (E_o) between (10^{14}-10^{16}) eV, the expected number of charged particles can be calculated. The maximum depth of shower growth (X_{max}) is computed for electromagnetic and hadronic chains, and the longitudinal evolutions of Extensive Air Showers are analyzed. We characterize inelasticity and its effect on neutrino generation using the parameter (k). In order to verify the results, researchers compare the Tunka-25 Tunka-133 vast air shower array facility's observations with their personalized calculations of the Cherenkov light Detection Function (LDF). This research aids in the comprehension of the interactions between primary cosmic ray particles and atmospheric nuclei by casting light on the behavior of Extensive Air Showers and Cherenkov photon emission in the energy range of (10^{14}-10^{16}) eV. A new angle on these events is provided by looking at the influence inelasticity (parameter k) has on neutrino production. In addition, the distinctive nature of research is reinforced by comparison with data from the Tunka-25 and Tunka-133 vast air showers array facility, which validates findings and provides insights into the identification of fundamental particles and their energies. In the region of (10^{14}-10^{16}) eV, the main particle's energy is correlated with the number of charged particles present (N) in the system. To further understand how these showers form, compute their maximum depth (X_{max}) using both electromagnetic and hadronic chains. An analysis of inelasticity (parameter k) shows how crucial it is to comprehend neutrino generation. For various primary particle types and zenith angles (0^o,10^o and 30^o), our comparison of the Cherenkov light LDF with measurements from the Tunka-25 and Tunka-133 extensive air showers array facility demonstrates the possibility of identifying these particles and determining their energy levels near the bend point of the cosmic ray spectrum.

Keywords: CRs, EAS, LDF, Cherenkov light, Tunka25

1. INTRODUCTION

Cosmic rays (CRs) constantly assault the Earth's atmosphere at a rate of around 1000 particles per square meter every second, and they may include anything from hydrogen to heavier nuclei like Iron. These high-energy particles are almost entirely alien in origin and travel across cosmic spaces at vanishingly small densities (Strong et al. 2007).

About 98% of the CR flux consists of lighter nuclei and protons, whereas just 2% is made up of 'exotic' particles and electrons. Around 87% of the hadronic component is made up of protons, with other notable contributors being Helium (He), carbon (C), and Iron (Fe) (Longair 1992). The first approximation results for the CR spectrum show the number of particles per energy unit. ($dN(E)/dE \propto E^{-2.8}$) Scales as E (-2.8). This spectrum includes a broad variety of energies, from the low end at 10^{8} eV to the high end at 3.2×10^{20} eV, the famously high-energy proton (Bird et al. 1993; Taubes 1993). There are two notable peaks in the CR energy spectrum: the "ankle" and the "knee." These anomalies may be interpreted as aberrations in the spectral slope and the particle composition of cosmic rays. The "ankle" is a flattening of the spectrum seen about $5 x 10^{18}$eV, which is referred to as the energy (Bird et al. 1993).

Cherenkov radiation, which happens when an electron moves through a medium faster than the phase velocity of light in that medium, is one of the most amazing phenomena connected to cosmic rays. Cherenkov light is produced inside extended air showers (EAS) when charged particles travel through the atmosphere, and it is vital to our ability to deduce the make-up and energy of the fundamental cosmic particles (Bolotovskii 2009; Mavrodiev et al. 2004).

The power equation characterizes primary cosmic ray flow.$\frac{dN}{dE}\alpha E^{-\gamma}$. Across a large energy range. The rate of particles striking Earth decreases from roughly one per second per square meter at 10^{11} eV to about one per year per square meter at $5x10^{15}$ eV. The flow drops to around one particle per century per square km at energies above 10^{19} eV [7].

At around 5×10^{15} eV, there is a transition from a power-law index ~5 .10^{15}eV from $\gamma \approx 2.7$ to $\gamma \approx 3.1$, and this transition creates a characteristic called the "CR spectrum knee." Potential explanations for this change include interactions with the interstellar medium or atmospheric processes, as well as differences in acceleration mechanisms acting above and below the knee (Haungs et al. 2006). Primary photons or electrons generate extensive air showers that are mostly composed of electromagnetic cascades. They occur from the decay of short-lived pions. That's why their evolution is so unlike the muonic and hadronic parts (Blümer et al. 2009; Haungs et al. 2006).

$$\rho_e(r) = C(s).\frac{N_e}{2\pi r^2}\cdot(\frac{\mathrm{r}}{\mathrm{r_m}})^{\mathrm{s}-2}\cdot(1+\frac{\mathrm{r}}{\mathrm{r_m}})^{\mathrm{s}-4.5} \qquad (1)$$

Where: ρ_e= density of electron/ m^3; N_e= electrons number; r=distance from the centre of shower; $C(s) = \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-s)}$ (normalizing factor); s= age of shower, and r_m=Moliere radius.

The age of shower s is a parameter for shower evolution, and it is s= 0 at the shower start, 1 at the maximum particle number, and s= 2 if the shower has < 1 particle remaining. For shower ages between 0.8 and 1.6, the Nishimura Kamata Greisen (NKG) function accurately describes the lateral distribution of electromagnetic cascades. At sea level, the Moliere radius, or r_m, is around 79 meters (Hovsepyan et al. 2005; Raikin et al. 2019).

Cosmic ray detection and energy estimate are two areas where knowledge of the intricate interactions and features of cosmic rays, air showers, and Cherenkov radiation would be quite useful.

The other important EAS parameters are: longitudinal development] and the inelasticity. The longitudinal development is a number of charged particles as a function of the atmospheric depth. The maximum depth shower, X_{max}, in air showers is an essential characteristic defined by the energy of primary particle, its mass, process of primary particle interaction, and shower development in air. The maximum numbers of charged particles in atmosphere are preformed for secondary muons, pions, electrons, and the number of particles. The inelasticity is the fraction of the total primary energy directed into new pion production (both π± and πo) in hadronic cascade which describe and depend on the parameter K. The dependence of inelasticity used for describing the variation of muons number in the hadronic cascade. Also the properties of the longitudinal development of the electromagnetic and hadronic showers were Studied and the impact of the inelasticity on the hadronic shower. The important quantity that rules the shower development is the inelasticity. This quantity combines the multiplicity and the energy of the secondaries, thus describing how much of the energy of the incoming particle is transferred onto secondary particles. Therefore, it is more relevant than the particle multiplicity alone. The inelasticity can be divided into two types: High inelasticity and Low inelasticity. High inelasticity means that the energy is dissipated quickly and the shower develops fast. Low inelasticity means that the leading particle carries off most of the energy, leading to slow developing and long showers. The inelasticity of a single interaction is described by a parameter k which is defined as the fraction of the total energy directed into new pion production (both π± and πo).

2. Literature Review:

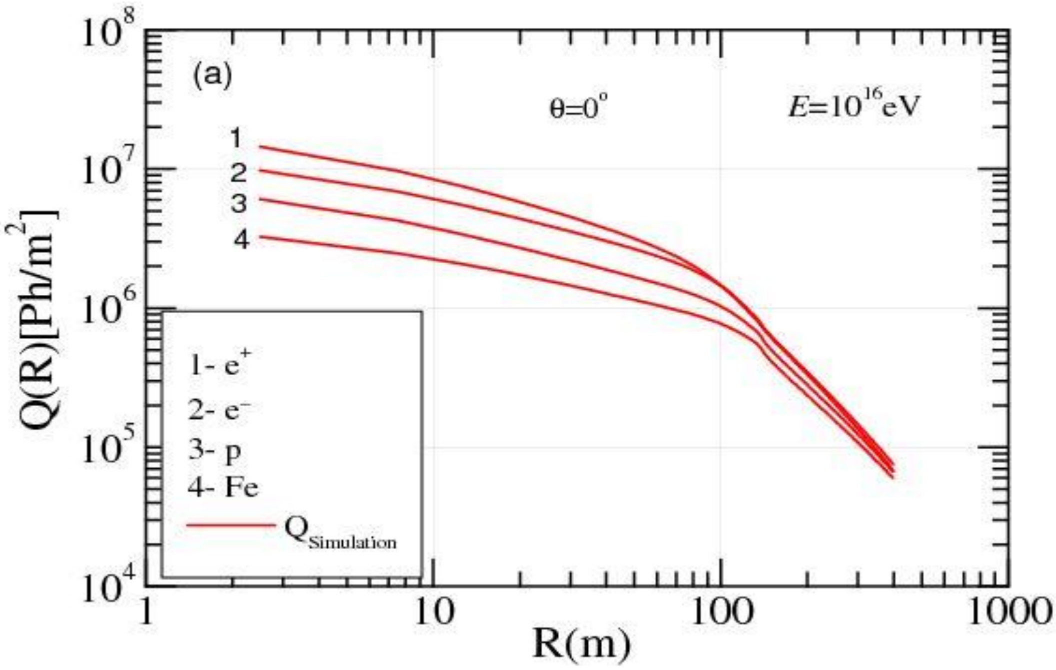
One of the most basic difficulties in studying cosmic rays is trying to determine the exact make-up and energy of primary cosmic rays. Alexandrov and coworkers first presented an innovative approach to this problem in the year 2000 (Alexandrov et al. 2001). They arrived at this conclusion by studying the amount of Cherenkov light in the atmosphere, namely during extensive air showers (EAS). For EAS sparked by primary protons and iron nuclei, the team used the CORSIKA algorithm to determine the corresponding Cherenkov light flux densities. This study elucidated the features of various cosmic ray particles by throwing light on their mass composition and energy of primary cosmic ray radiation. The study of Cherenkov light in EAS took a giant leap forward in 2002 when Korasteleva, Kuznichev, and Prosin announced their findings. (Korosteleva et al. 2003). Based on extensive examination of data from the QUEST experiment at the EAS-TOP array and simulations done using the CORSIKA algorithm, they presented a novel fitting function for the lateral distribution of Cherenkov light in EAS. This unique lateral distribution function (LDF) provided a fresh perspective on explaining the spread of Cherenkov light at distances ranging from 10 to 250 meters from the shower axis (Antonov et al. 2019). Particularly, their suggested LDF had two forks and included a single form parameter (P) that was defined as the ratio of light fluxes at 100 meters and 200 meters from the shower axis. Insights gained from this study on the Cherenkov light distribution inside extended air showers (EAS) are crucial for the detection and measurement of cosmic ray energies (Bellido et al. 2018). These studies have made significant contributions to cosmic ray research, especially in the area of analyzing Cherenkov radiation amid massive air showers. Alexandrov et al.'s ground breaking approach for estimating cosmic ray mass and energy using the Cherenkov radiation flow is an invaluable tool for calculating these crucial properties (Grupen 2020). Korasteleva, Kuznichev, and Prosin's novel fitting function for the Cherenkov light distribution is a helpful resource for scientists studying Cherenkov light's peculiar behaviour in EAS.

3. METHODOLOGY:

In this extensive research, we explore the complex world of primary cosmic ray interactions with atmospheric nuclei. Wide Air Showers are produced as a result of these collisions, and the accompanying emission of Cherenkov photons provides a vital hallmark of these high-energy cosmic occurrences. In particular, we explore the range of energies from 10^{14} to 10^{16} electronvolts (eV), where our estimates for the number of charged particles, N, as a function of the primary energy, E_o, are most accurate. Since it covers such a large variety of high-energy occurrences, this energy range is of great importance to the study of cosmic rays. These fundamental cosmic rays produce Extensive Air Showers, and we analyze their temporal evolution in great detail to learn more about them. The greatest depth at which these showers occur, sometimes denoted by the notation X_{max}, is of particular importance to us. In order to better understand the dynamics of these cosmological interactions, we run this study for both electromagnetic and hadronic cascades. As we go further into the topic, we introduce a crucial quantity called "k," which is essential for characterizing inelasticity. The lack of elasticity in the cosmic ray showers is a major component in the generation of muons. Muons are secondary particles that provide crucial insight into the nature and intensity of the parent cosmic ray from which they originated. Muon generation in cosmic ray showers may be better understood and predicted if the rigidity of these interactions is characterized. We do this vital verification phase to guarantee the precision and credibility of our study. We next evaluate the results of our calculations against those from the Tunka-25 and Tunka-133 facility's huge air showers array. This installation acts as an actual observatory, giving us access to data that supports our claims. Having our theoretical models and computations checked against what is seen in nature is crucial in the field of high-energy particle physics.

4. RESULTS:

The findings of a simulated investigation on the lateral dispersion of Cherenkov light within the context of the Tunka25 and Tunka-133 Extensive Air Shower (EAS) array are shown in **Fig. 1 (a, b).**



a)

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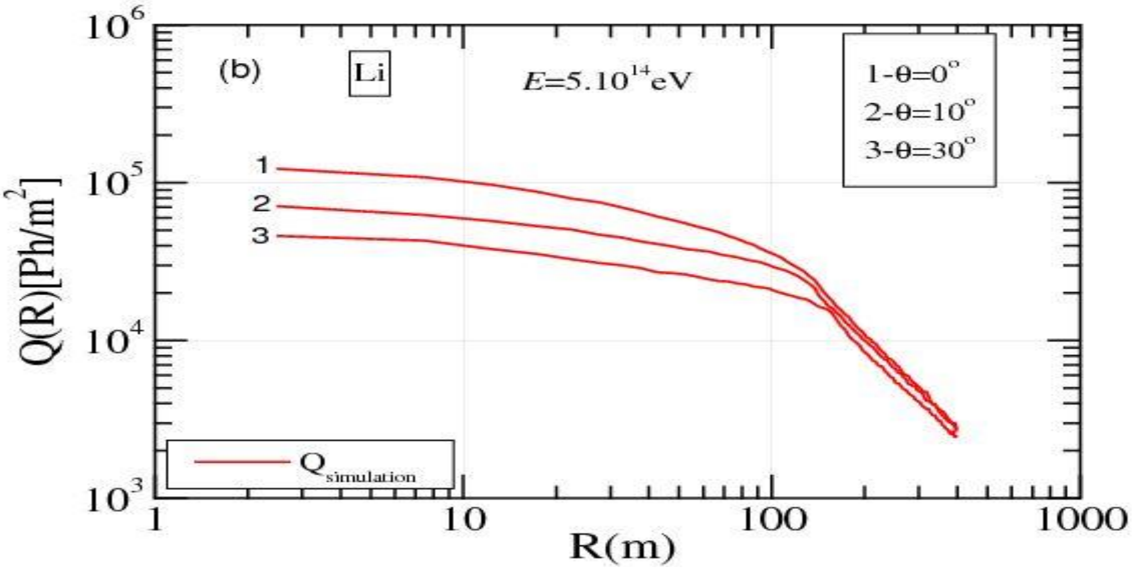
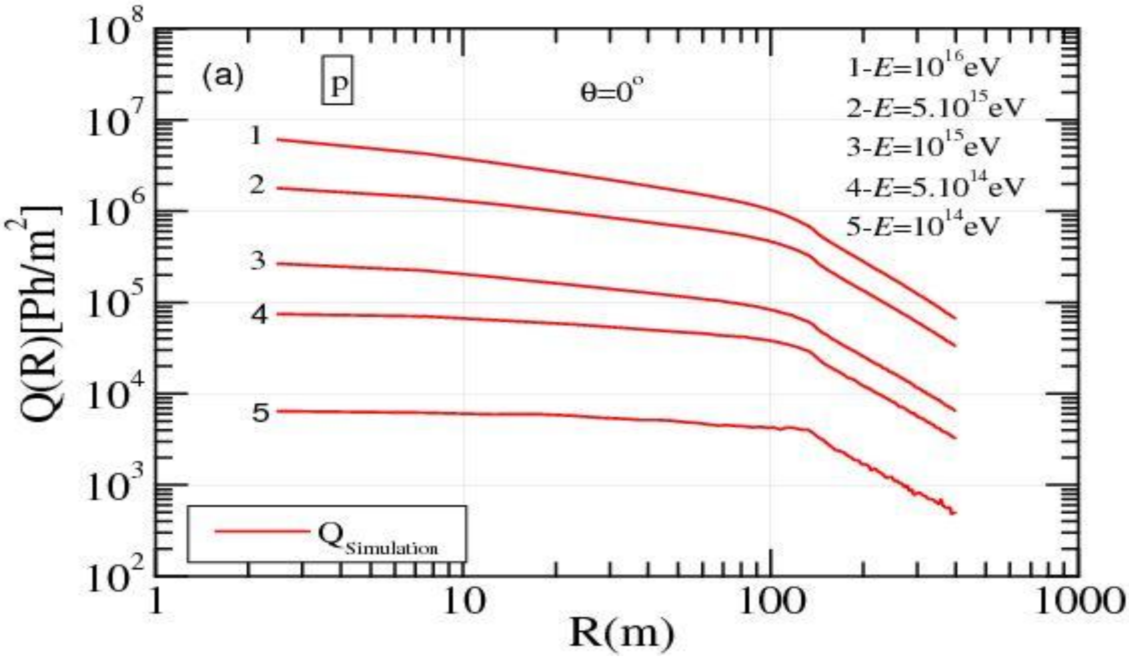


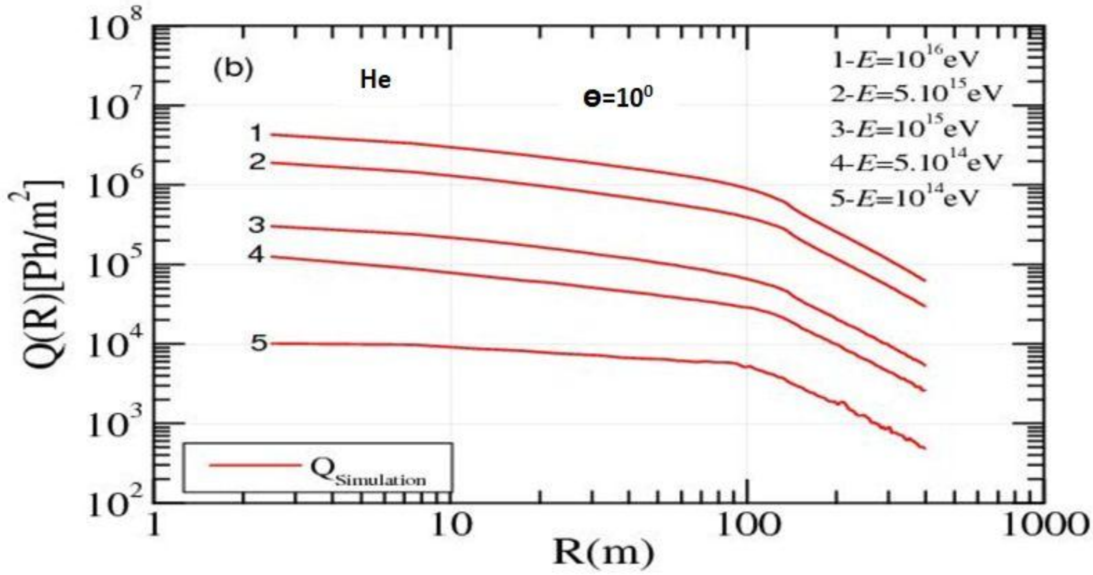
b)

Fig.1: The lateral Cherenkov light distribution function simulated by code of CORSIKA for (a) vertical shower at the 1016 eV energy for positron, electron, proton, and Iron nuclei particles and (b) primary lithium for different angles 0, 10o, and 30o at the energy 5x1014eV.

Particles with varied kinetic energies and azimuthal angles were used to kick off the simulations, which included positrons, electrons, protons, iron (Fe) nuclei, and lithium. Cherenkov light's lateral distribution function is shown to be directly related to primary particle energy in the above diagram. Cherenkov radiation has a wider lateral dispersion with higher primary particle energies. In addition, the angles were varied while maintaining a constant energy to determine their effect on the results. The essential properties of protons and helium particles at different angles and energies are shown in **Figure 2 (a and b).**



a)



b)

Fig. 2: Lateral distribution of Cherenkov light, which simulated with code of CORSIKA at the energies 1014,5x1014,1015,5x1015 and 1016eV for angle θ=0o for (a) primary proton for angle θ=0o; (b) primary Helium for angle θ=10o

The effect of changing the energy level while maintaining the same angle is being studied. For extensive air showers (EAS) produced by primary iron (Fe) nuclei at varying energies and angles within the Tunka-25 and Tunka-133 observatory, the Cherenkov light lateral distribution function (LDF) is shown in **Figure 3.**

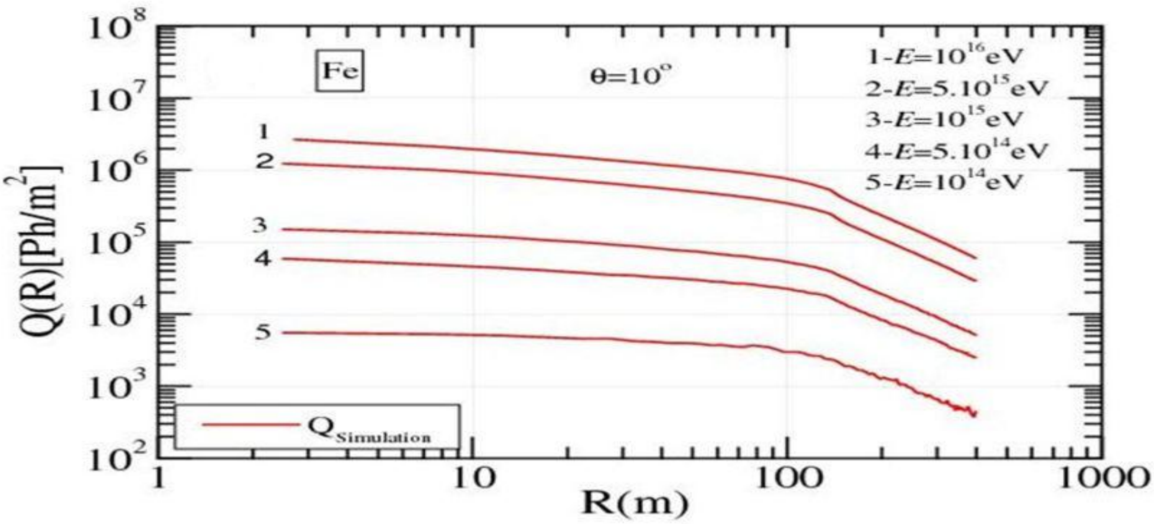


Fig. 3: Lateral distribution of Cherenkov light, which simulated with code of CORSIKA for primary Iron at the energies 1016,5x1015,1015,5x1014 and 1014eV for vertical showers.

Comparison of LDF with Tunka25 and Tunka-133 measurements

The method of EAS core location reconstruction is based on fitting of the Q_i data by LDF function with light density at the core distance i =190 m when :

$$Q_{(R)} = Q_{kn} f(R), \qquad (2)$$

Where Qkn is the light flux at the distance ,which is given as :

$$Q_{kn} = Q_{190}\left(\frac{R_{kn}}{175}\right)^{-2.2}, \qquad (3)$$

Where Q190 is the density of Cherenkov radiation at the distance 190m from the shower axis.

And:

$$f(R) = \begin{cases} exp\left(\frac{(R_{kn}-R)}{R_0}\left(1+\frac{3}{R+3}\right)\right), R < R_{kn} \\ \left(\frac{R_{kn}}{R}\right)^{2.2} \qquad 200 \geq R \geq R_{kn} \\ \left(\frac{R_{kn}}{200}\right)^{2.2}\left(\left(\frac{R}{200}+1\right)/2\right)^{-b}, R > 200 \end{cases} \qquad (4)$$

Where is the core distance (in meter), is a parameter of the first branch of LDF and is the distance of the first change of LDF given by:

$$R_o = exp(6.79 - 0.56P)$$
$$R_{kn} = 207 - 24.5P,$$

Where the steepness is given by:

$$P = 7.3 - (0.008 \times \Delta X)$$

and

$$\Delta X = \frac{X_o}{\cos\theta} - X_{max}$$

Where (The total vertical depth of the atmosphere); and is the depth of the shower maximum development which is given by:

$$X_{max} = 560 + 65\log\left(\frac{E_o}{10^{16} eV}\right)$$

The parameter   in eq. (4) can be defined as:

$$b = \begin{cases} 4.48 - 12.3\ln(6.5P), & P < 6 \\ 3.43, & P \geq 6 \end{cases}$$

The new EAS Cherenkov array Tunka-133 with about 1 km^2 geometric acceptance area, is installed in the Tunka Valley (50 km from Lake Baikal). The array permit a detailed study of cosmic ray energy spectrum and mass composition in the energy range of 10^{15} - 10^{18}eV with a uniform method. The array consists of 19 clusters, each composed of 7 optical detectors with 20 cm PMTs.

For primary Fe nuclei with energies of 10^{16}, $5x10^{15}$, 10^{15}, $5x10^{14}$, and 10^{14} electronvolts (eV) at a zenith angle of 10°, the simulated Cherenkov light LDF has been successfully compared with real data obtained by the Tunka-133 observatory

For different iron nuclei energies at a zenith angle of 10 degrees, the lateral distribution function (LDF) of Cherenkov light, as simulated by the CORSIKA algorithm, is compared with the LDF recorded by the Tunka-133 array shown in **Figure 4**.

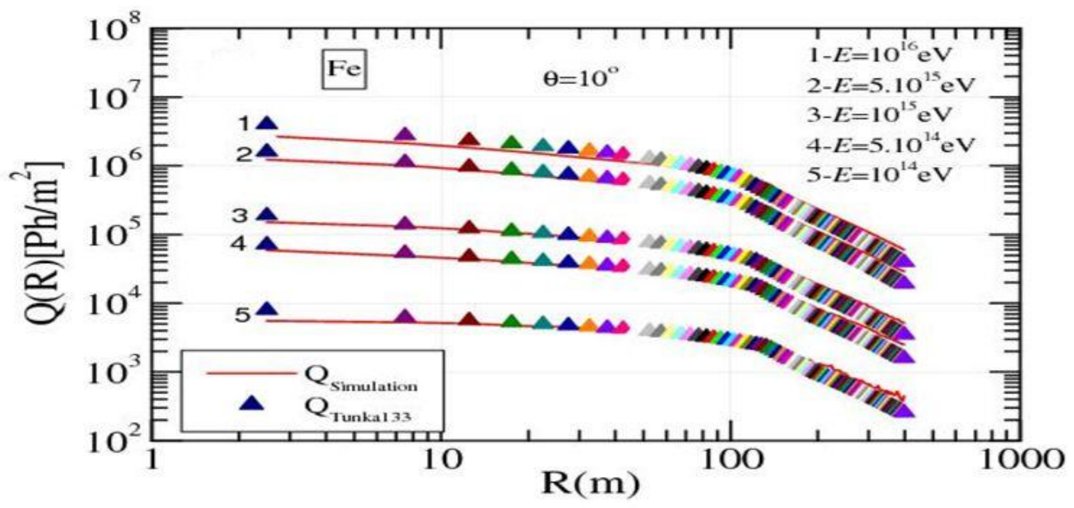


Fig. 4: Comparing the simulated light LDF of Cherenkov (solid lines) with the obtained data with Tunka-133 EAS array (symbol lines) for Iron nuclei at 1015, 2x1015 and 5x1015eV energies for angle θ=10o

For primary helium particles of varying energies, the lateral distribution function (LDF) of the Cherenkov light recorded by the Tunka-25 array is compared to the LDF simulated using the CORSIKA algorithm at a zenith angle of 10 degrees, as shown in **Figure 5.**

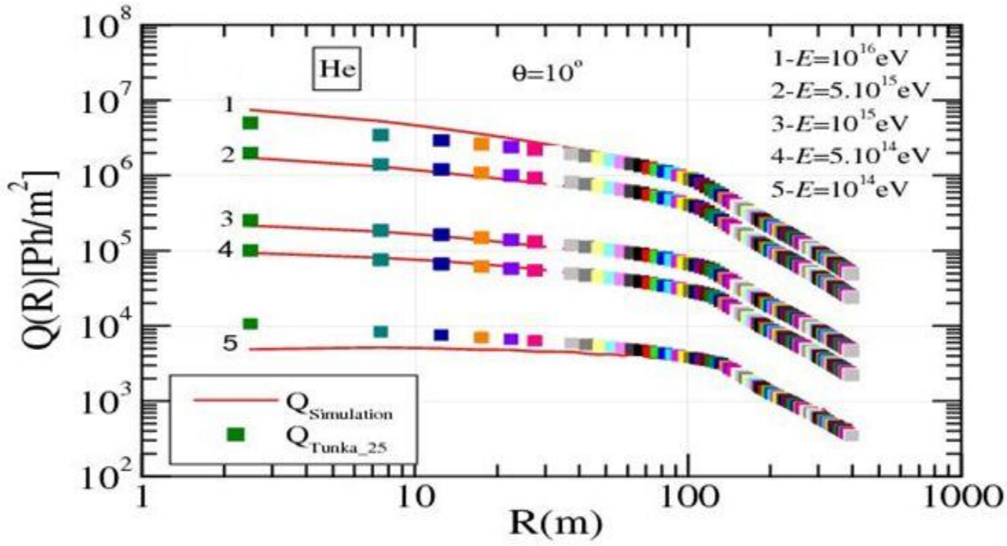


Figure 5: Lateral Cherenkov light distribution that is simulated with code of CORSIKA (solid lines) and 1 measured with Tunka-25 (symbols) at angle 10o for primary Helium at energies 1014,5x1014,1015,5x1015and 1016eV.

For primary lithium particles, the variations in Cherenkov light lateral distribution function (LDF) between the CORSIKA code simulation and the Tunka-25 array observations are shown in **Figure (6).**

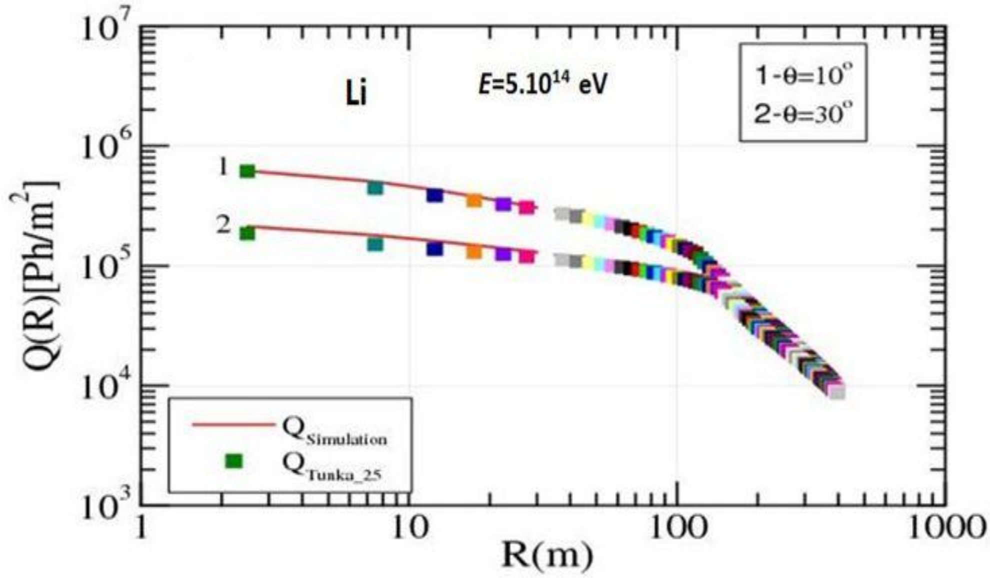


Figure 6: Lateral Cherenkov light distribution that is simulated with code of CORSIKA (solid lines) and 1 measured with Tunka-25 (symbols) for primary lithium at energy 5x1014eV for angles 10o and 30o.

In particular, it compares the LDF at an energy level of 2 x 10^{15} electronvolts (eV) for primary lithium particles at a zenith angle of 10 degrees (=10°) and the same particle at a zenith angle of 30 degrees (=30°) to the Tunka-25 array.

5. DISCUSSION AND RECOMMENDATIONS:

The findings of this study shed light on the behavior of Cherenkov light in extensive air showers and its relationship to primary particle energy and zenith angle (Bellido et al. 2018). This correlation between primary particle energy and the lateral dispersion of Cherenkov radiation provides a reliable way for determining the energy of primary cosmic rays using ground-based data (Grupen 2020). The relevance of the angle of incidence in our comprehension of Cherenkov radiation is shown by the effect of the zenith angle on this phenomenon.

By effectively comparing simulated data to actual observations, the study has validated the accuracy of the CORSIKA algorithm for simulating Cherenkov light lateral distribution functions (Abbasi et al. 2018). This demonstrates the power of simulation tools for cosmic ray study and the Tunka-25 observatory's capacity to precisely record Cherenkov light data (Kuzmichev et al. 2018).

To sum up, the findings of this study improve our understanding of Cherenkov light in the context of large-scale air showers, as well as its relationships to primary particle energy and zenith angle. Cherenkov radiation is highlighted as a promising way to determine the energy of primary cosmic rays, and the research also underlines the trustworthiness of both modelling methods and observational data for expanding our understanding of cosmic ray processes (Grupen 2020).

6. CONCLUSION

In this investigation, the Monte Carlo simulation code CORSIKA is used to simulate the evolution of large air showers in the Earth's atmosphere, triggered by a wide range of primary particles (including protons, iron nuclei, Helium, and lithium) within the energy range of 10^{14} to 10^{16} electronvolts (eV) and at a variety of zenith angles. Particularly interesting is the fact that our research uncovered a pattern in the electron and muon components' behavior, which shows promise as a differentiating feature among other basic particles. These correlations may be used to differentiate between fundamental particle masses that vary considerably within this energy range. Furthermore, our study shows that it is possible to identify primary particles and determine their energies in the range of 10^{14} to 10^{16} eV by comparing the calculated lateral Cherenkov light distribution function with data detected by the Tunka-25 and Tunka-133 arrays. The main benefit of this method is that it allows us to build a database of lateral distribution function examples that can be used to analyze data from large-scale air shower arrays. By doing such studies, the fundamental cosmic ray mass composition and energy spectrum may be reconstructed. The composition and energy distribution of primary cosmic rays is crucially important to the science of astroparticle physics, and this study adds to the improvement of detection and characterization techniques for these particles. Our capacity to differentiate between different primary particles and energies within the defined range is much improved. New insights are provided for the continuing study of high-energy particle interactions in Earth's atmosphere.

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