Research Article Open Access

Simulating and Modeling the Extensive Air Showers Development through the Estimating the Energy of some Created Particles

Itab F. Hussein*, Ahmed. A. Al-Rubaiee

Department of Physics, College of Science, Mustansiriyah University, Baghdad, IRAQ.

*Correspondent contact: itabfadhil@uomustansiriyah.edu.iq

Article Info

Received
08/03/2022

Accepted
29/05/2022

Published
25/09/2022

ABSTRACT

Using the AIRES code and three hadronic interaction models, a simulation study of the energy of created particles due to the development of an extensive air shower was carried out (EPOS-LHC, QGSJET-II-04, and Sibyll2.3c). The main focus is put on the energy of the create particles as a function of depth for (^{12}C,^{56}Fe, p, and ^{28}Si) primary particles with high primary energies (10^{17},10^{18},10^{19}, and 10^{20}) eV with two zenith angles 0° and 30°. The New parameters were obtained by fitting the energy of created particles curves using Gaussian and linear functions for created particles, initiated by primary particles at the energy 10^{20} eV. Good agreement was obtained by comparing the present results with results simulated by CORSIKA simulation for primary proton at the energy 10^{19} eV

KEYWORDS: EAS; energy of created particle; AIRES; created particles.

INTRODUCTION

In general, only a small fraction of the initial energy reaches the earth as high-energy created particles during the showering process initiated by a primary cosmic ray in the atmosphere. Instead, the ionization and excitation of air molecules release the majority of the primary energy in the atmosphere. Fluorescence light is emitted by a tiny fraction of order 10^4 [1]. Extensive air shower (EAS) is a cascade started by primary cosmic rays in the atmosphere. As such, they serve as a connection to the highest particle energies in nature is offering, especially at energies exceeding 10^{15} eV where direct measurements of cosmic rays are hampered by the low primary flux [2]. Use can be made, however, of the fact that an EAS consists of different shower components. At higher energies, rely on EAS to supply feedback indirect information, meaning that do not straightly identify mass and energy elementary cosmic particles. The fact sought is deduced from secondary effects, as the energy of the created particle as a function of the depth and longitudinal evolution of the chain of particles initiated in the atmosphere by the primary cosmic particles. These techniques necessitate a thorough understanding of atmospheric evolution and high-energy particle interactions with air molecules. As reference patterns, used extensive Monte Carlo simulation (MC) techniques. More or less aggressive extrapolations of lower energies, formulated as theoretical models and parameters, for high-energy hadronic interactions [3]. In this work, several models of hadronic simulation, EPOS-LHC [4], QGSJetII-04 [5], and Sibyll2.3c [6] studied the energy of the created particle (Ecreated), as a function of depth (g/cm^2) for electrons, muons, and pions. [6]. Computer simulations utilizing the AIRES program are utilized to examine the different methodologies used in these codes to simulate the underlying physics. For initial energies ranging from 10^{17} eV to 10^{20} eV, the most important observables for both single collisions and air showers were investigated.

Energy of Created Particle ($E_{created}$)

A significant energy fraction is transferred to the electromagnetic component, which is further fed in the subsequent shower process. One can notice an exponential decrease of the energy left in the hadrons. This can be understood in a simple picture of a constant inelasticity k and a constant mean free path λ_h for hadronic interactions [7]. Based on the average fraction of $\frac{1}{3}k$ that is put into the electromagnetic channel per hadronic

Copyright © 2022 *Al-Mustansiriyah Journal of Science*. This work is licensed under a Creative Commons Attribution Noncommercial 4.0 International License.

interaction, the energy remaining in the hadronic component at depth x is:

$$E_h(x) = E_o(1 - \frac{1}{3}k)^{x/\lambda_h} \quad (1)$$

Adopting typical values used for modeling nucleon-air interactions at high energies of $\lambda_h \cong 55\ gcm^{-2}$ and $k \cong 0.6$, the hadronic scale depth Λ_h of the exponential fall-off thus amounts to

$$\Lambda_h = \frac{\lambda_h}{\left|ln(1 - \frac{1}{3}k)\right|} \cong 250 gcm^{-2} \quad (2)$$

The maximum of energy stored in electromagnetic particles $X_{elm}$is reached well before the so-called shower maximum X_{max}, i.e., the depth where the shower contains the largest electron multiplicity. This is due to the fact that at the early cascade stages, a large energy fraction is carried by high-energy particles. Only gradually, the energy is transformed into newly created particles [8]. The maximum of energy stored in electromagnetic particles $X_{elm}$is expected at the development stage where the gain from the hadron channel equals the loss by energy release,

$$-\frac{dE_{had}}{dX}(X_{elm}) \cong \frac{dE_{rel}}{dX}(X_{elm}) \quad (3)$$

where:

$$\frac{dE_{rel}}{dX}(X) \cong \alpha N(X) \quad (4)$$

α is specific ionization loss of relativistic electron (MeV/gcm^{-2}), using eq. (3) and differential eq. (1), obtain:

$$E_h(X_{elm}) = \alpha \Lambda_h N(X_{elm}) \quad (5)$$

Equations (3) and (4) indicate the connection between energy flow (of hadronic to electromagnetic channel) and particle multiplication (in the electromagnetic channel) [9].

SIMULATION USING AIRES SYSTEM

AIRES stands for "AIR-shower Extended Simulations," a suite of algorithms and subroutines that are used to simulate EAS particles that are created after high-energy primary cosmic rays interact with the atmosphere, as well as manage the associated output data [10]. For this work, primaries (^{12}C, ^{56}Fe, p, ^{28}Si), with energies (10^{17}, and 10^{20}) eV at zenith angles (0° and 30°). At the level of the ground 1400 m above the equivalent sea level to a slant depth of 1000 g/cm^2. Also, the energy of thinning algorithm was set to (ϵ_{th}=10^{-6}), in addition, the effect of three models of hadronic interaction was used, EPOS-LHC, QGSJetII.04, and Sibyll2.3c of the energy of created particles formed in the EAS are taken into consideration.

RESULT AND DISCUSSION

Created particles (e.g., e-, μ-,π-) are carry the most-majority of the energy in EAS. Figure 1 shows the $E_{created}$ (logarithmic scales) of the hadronic, muonic electromagnetic components as functions of the atmospheric depth (g/cm^2), which is obtained with the AIRES simulation of (C, Fe, p, and Si) primaries with various energies (10^{17}, 10^{18}, 10^{19}, and 10^{20}) eV and zenith angles of 0° and 30° simulated using QGSJET-II-04 hadronic model. Although the shower travels at the speed of light through the atmosphere, it does not have a flat shape. Particles deflected at large angles during the shower's development have longer path lengths, arriving slightly later and with more variations at the observation level. As a result, the shower front is relatively thin near the shower core and significantly thicker at greater distances from the core [11].

Figure 2 shows the energy spectra of electrons for primary particles (^{12}C, ^{56}Fe, p, and ^{28}Si) at the fixed primary energy 10^{17} eV and zenith angles of 0° and 30°, simulated using QGSJET-II-04, EPOS-LHC, and Sibyll2.3c hadronic models. From Figure 2, to reconstruct the mass and energy of the primary particle, at least two orthogonal observations are required. Because of the reduced resolution in the measurement of the primary mass, the majority of shower arrays traditionally separated events as "light" (proton) or "heavy" (iron), with results that are highly dependent on the primary mass. Because heavy primaries reach their shower maximum at lower depths than light primaries, proton and carbon are shifted down the Fe and Si curves, and because the inelastic cross-section of the nucleus of mass (A) is proportional to ($A^{2/3}$), this results in longer interaction mean free path (m.f.p.) for protons and short m.f.p. for nuclei [12, 13]. Figure 3 shows the simulation of $E_{created}$ (GeV) as a function of depth (g/cm^2) for primary particles (^{12}C, ^{56}Fe, p, and ^{28}Si), and muon created particles using three models of hadronic interaction (EPOS-LHC, QGSJetII.04, and Sibyll2.3c) at energies 10^{17} and 10^{20} eV with θ=30°. Each type of line represents simulations carried out using a particular

Al-Mustansiriyah Journal of Science
ISSN: 1814-635X (print), ISSN:2521-3520 (online) Volume 33, Issue 3, 2022 DOI: http://doi.org/10.23851/mjs.v33i3.1137

model of hadronic interaction regarding the energy distribution at the ground. The difference between the three models was minimal, and the quantity of created particles in each of the three hadronic interaction models was similar, not drastically different from the result data.

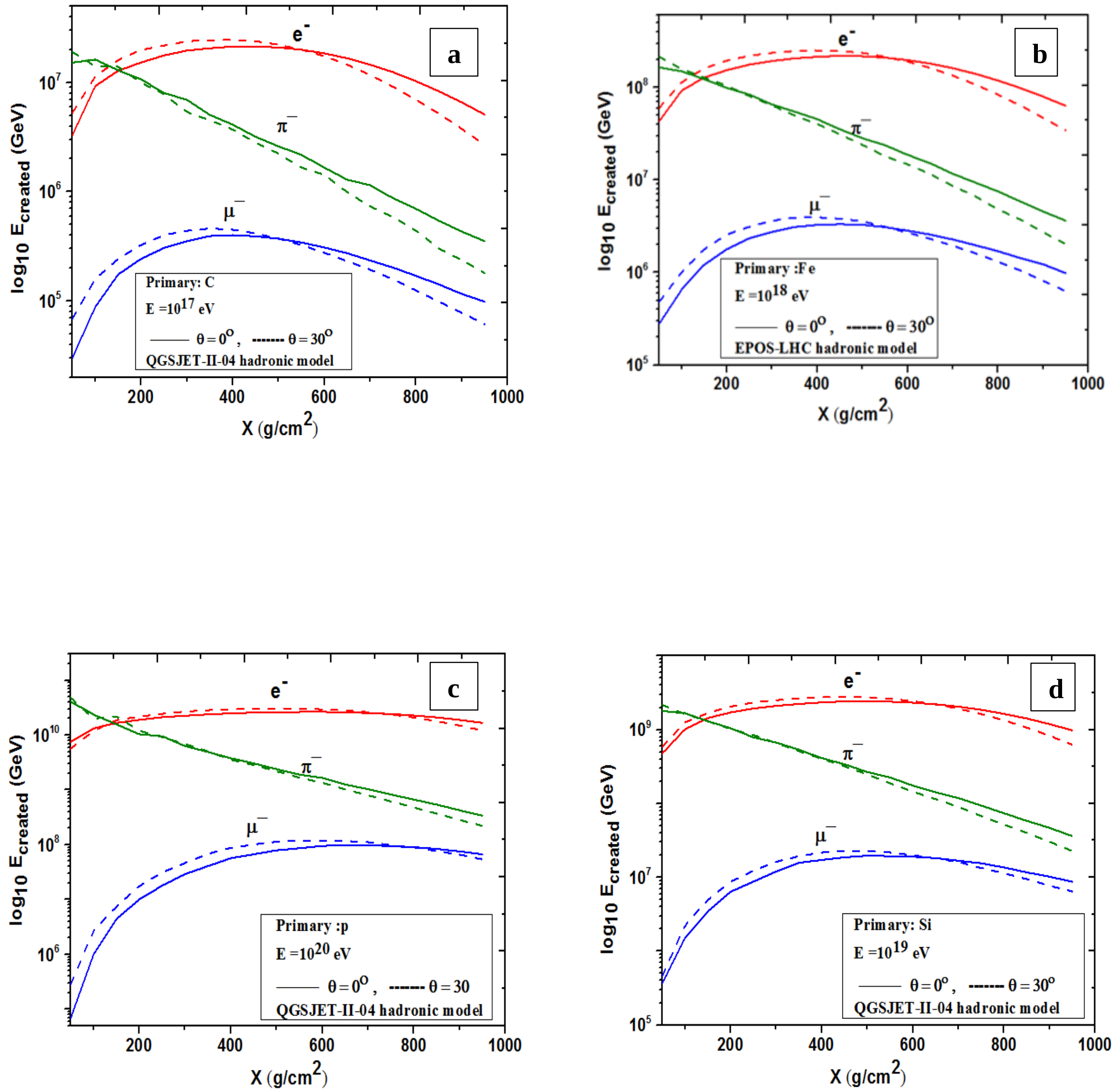

Figure 1. $E_{created}$ as a function of the depth (g/cm^2) for various primary particles and various energies (a)^{12}C at 10^{17}eV, (b)^{56}Fe at10^{18}eV, (c) p at 10^{20}eV, (d) ^{28}Si at10^{19}. for vertical showers (solid lines) and inclined showers (dashed lines) using QGSJET-II-04 hadronic model.

Copyright © 2022 *Al-Mustansiriyah Journal of Science*. This work is licensed under a Creative Commons Attribution Noncommercial 4.0 International License.

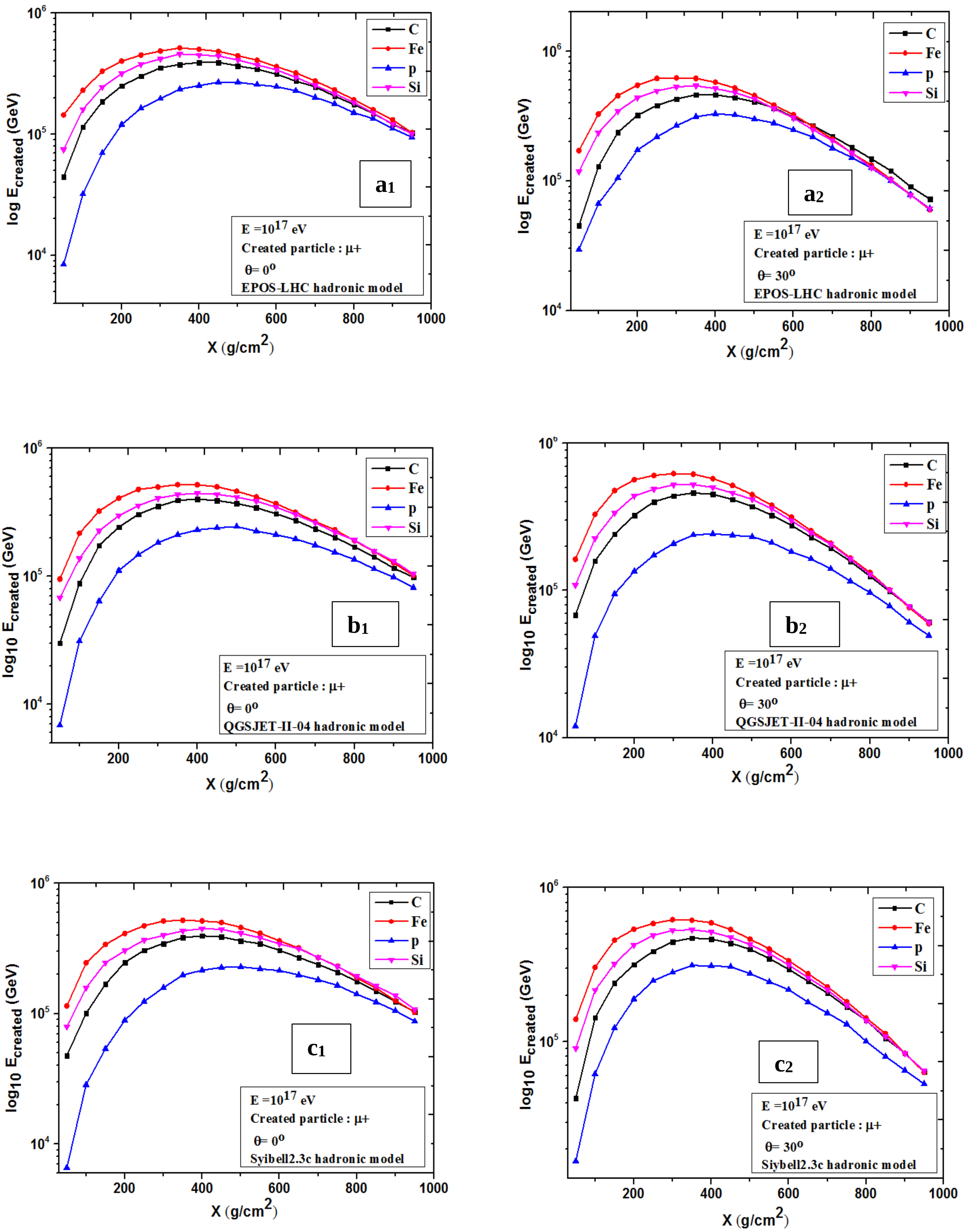

Figure 2. $E_{created}$ of (μ^+) for various primary particles (C, Fe, p and Si) respectively at primary energy (10^{17}eV) with zenith angles (0°and 30°) using three hadronic models,(a_1,a_2) EPOS-HLC model,(b_1,b_2) QGSJET-II-04model,(c_1,c_2) Siybell2.3c model

ISSN: 1814-635X (print), ISSN:2521-3520 (online) Volume 33, Issue 3, 2022 DOI: http://doi.org/10.23851/mjs.v33i3.1137

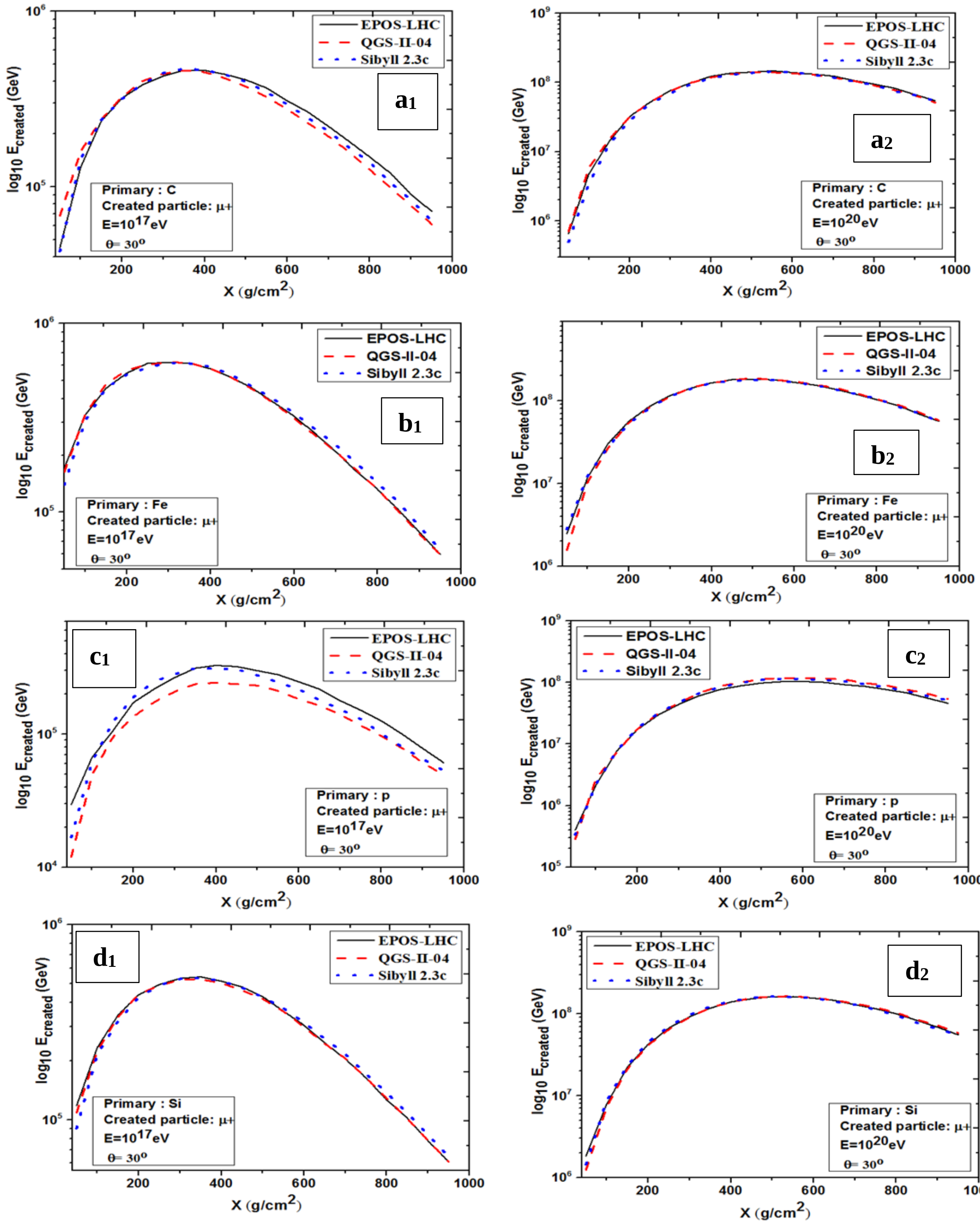

Figure 3. The simulation of $E_{Created}$ for various primary particles,(a_1,a_2) for ^{12}C,(b_1,b_2) for ^{56}Fe,(c_1,c_2) for p,(d_1,d_2) for ^{28}Si, with muon created particles using three models of hadronic interactions (EPOS-LHC, QGSJetII.04, and Sibyll2.3c) at the energies 10^{17} and 10^{20} eV with inclined showers (θ=30°).

$E_{Created}$ Parameterization

A Gaussian function was used for fitting the energy of created particles ($E_{Created}$) as a function of depth (g/cm^2), yielding four parameters for the various primary particles, depending on the type of primary and created particles that initiated in EAS. Several functions were obtained for (e+, μ+) at the same time. The Gaussian function is given as**:**

$$logE_{created} = \delta + \left(\frac{\alpha}{\lambda\sqrt{\frac{\pi}{2}}}\right)exp(-2((x-\varepsilon_c)/\lambda)^2) \quad (6)$$

Copyright © 2022 *Al-Mustansiriyah Journal of Science*. This work is licensed under a Creative Commons Attribution Noncommercial 4.0 International License.

Where ($E_{created}$) is the energy of created particles as a function of the shower depth (x); α, δ, λ and ε_c are the coefficients are given in Table 1.

For (π+) created particle in EAS, a linear function was obtained for fitting the ($E_{created}$) as a function of depth (g/cm^2), yielding two coefficients for the various primary particles. The linear function is given as:

$$E_{created} = a + b\,x \qquad (7)$$

a , *and* b, are the coefficients given in Table 2. Figure 4 shows the results of $E_{created}$ for vertical EAS that simulated with the AIRES system ((symbols)) comparison with the results obtained using Eq. (6) and Eq. (7), ((solid line)) for (e+, μ+ and π+) created particles which were initiated by (^{12}C,^{56}Fe, p, and ^{28}Si) primary particles at (10^{17}) eV, simulated using QGSJET-II-04 hadronic model.

Table 1. Coefficients of the Gaussian function Eq. (6) that obtained to parameterize the AIRES simulation for (^{12}C,^{56}Fe, p, and ^{28}Si) primary particles at the energy (10^{17}) eV with 0° and 30°zenith angles.

Primary particles	θ°	Created particles	values of coefficients				R^2
			δ	ε_c	λ	α	
^{12}C	0°	e^+	1.02669×10^6	431.00009	518.54428	1.24441×10^{10}	0.95509
		μ^+	4.3153×10^4	454.81923	441.74494	1.97743×10^8	0.91778
	30°	e^+	1.53369×10^6	381.46335	446.75788	1.20012×10^{10}	0.97416
		μ^+	6.6415×10^4	389.41734	377.70901	1.8613×10^8	0.95687
^{56}Fe	0°	e^+	1.81186×10^6	404.23651	470.47169	9.73294×10^9	0.97577
		μ^+	8.7556×10^4	402.68579	426.63426	2.36746×10^8	0.94198
	30°	e^+	1.51208×10^6	360.75329	413.63582	1.02214×10^{10}	0.97819
		μ^+	7.9190×10^4	335.60463	393.15877	2.71285×10^8	0.96244
P	0°	e^+	-3.07045×10^5	435.13083	582.6006	1.70904×10^{10}	0.96568
		μ^+	-2.08970×10^5	526.8443	818.46635	4.53414×10^8	0.94306
	30°	e^+	1.29003×10^6	381.27186	474.36996	1.46318×10^{10}	0.98188
		μ^+	1.7396×10^4	457.93929	435.24022	1.23717×10^8	0.93628
^{28}Si	0°	e^+	8.94803×10^4	436.38285	498.59611	1.15566×10^{10}	0.95415
		μ^+	$6.3282.\times 10^4$	442.12905	444.44238	2.14817×10^8	0.94336
	30°	e^+	1.56115×10^6	369.09275	424.5809	1.09471×10^{10}	0.97169
		μ^+	$6.9640.\times 10^4$	365.74729	393.40423	2.26869×10^8	0.95992

Table 2. Coefficients of the Linear function Eq. 7 that obtained parameterize the AIRES simulation for (^{12}C,^{56}Fe, p, and ^{28}Si) primary particles at the energy (10^{17}) eV with 0° and 30° zenith angles.

Primary particles	θ°	Created particles	values of coefficients (E=10^{17}eV)		R^2
			a	b	
^{12}C	0°	π^+	7.38032	-0.00192	0.99682
	30°		7.44569	-0.00226	0.99643
^{56}Fe	0°	π^+	7.36604	-0.00191	0.99587
	30°		7.4503	-0.00229	0.99705
P	0°	π^+	7.36601	-0.00197	0.98235
	30°		7.32998	-0.00217	0.98267
^{28}Si	0°	π^+	7.36245	-0.00187	0.99157
	30°		7.45597	-0.00229	0.99609

Al-Mustansiriyah Journal of Science
ISSN: 1814-635X (print), ISSN:2521-3520 (online) Volume 33, Issue 3, 2022 DOI: http://doi.org/10.23851/mjs.v33i3.1137

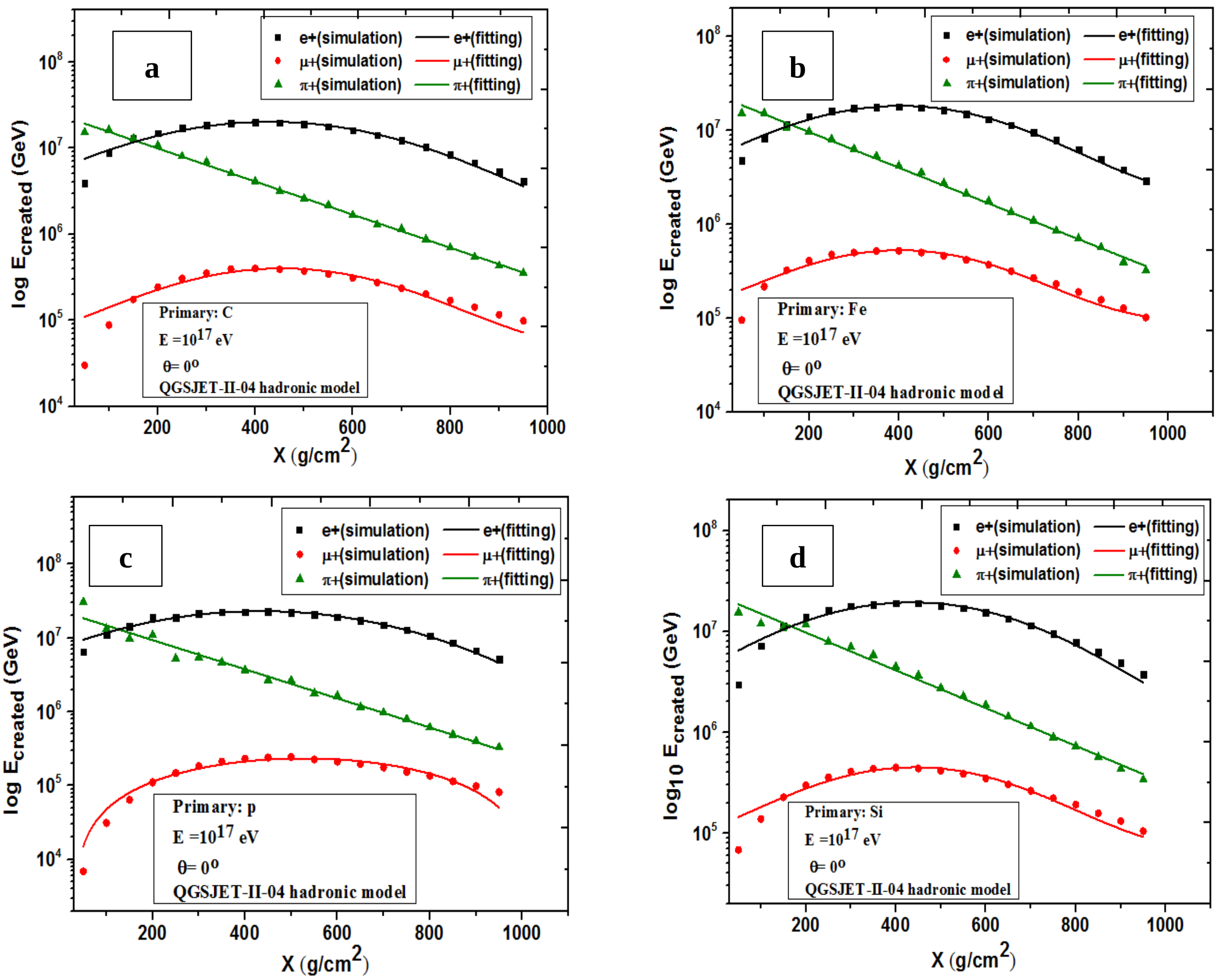

Figure 4. $E_{created}$ of vertical EAS that simulated with the AIRES system ((symbol)) comparison with the results obtained using Eq. (6) and Eq. (7) ((solid line)) for the primaries (a)^{12}C, (b)^{56}Fe , (c) p, (d) ^{28}Si with energy (10^{17}) eV.

Figure 5 displays the comparison between the present results of ($E_{created}$) performed by AIRES simulation (dash lines) with the CORSIKA (COsmic Ray Simulation for KAscade) simulation result (solid lines) [14]. In addition, it displays the muon-created particles initiated by the proton primary particle at energy (10^{19}) eV with a vertical zenith angle. AIRES and CORSIKA predict the energy of the created particle (muon), which is consistent with each other, and the difference between them is noticeable but small. This difference is also due to the different treatment of upward going particles. In general, agreement between AIRES and CORSIKA simulations is good. Most of all, should point out that the simulation results of CORSIKA and AIRES agree well with each other.

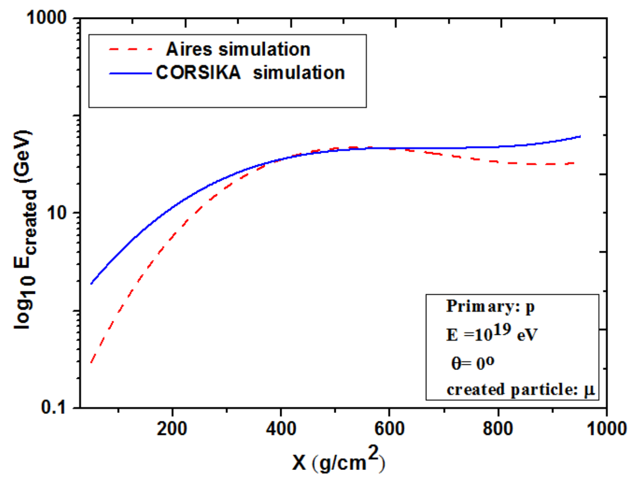

Figure 5. Comparison between the present results of $E_{created}$ performed by AIRES simulation (dash lines) and the CORSIKA simulation result (solid lines). For proton primary particle at energy (10^{19}) eV of muon created particle.

Copyright © 2022 *Al-Mustansiriyah Journal of Science*. This work is licensed under a Creative Commons Attribution Noncommercial 4.0 International License.

CONCLUSIONS

We use AIRES program to simulate the energy of created particle produced in EAS using the three hadronic interaction models for primary (carbon, iron, proton & silicon), this simulation was obtained for two zenith angles (0^o and 30^o) and four high energies (10^{17},10^{18}, 10^{19}, and 10^{20}) eV. The results demonstrated that for low zenith angles, the density of the particles generated decreases as the distance from the shower axis increases. Additionally, the density of produced particles increases with the primary particle's energy and decreases with the zenith angle. Its noticed that there is a small difference between the results of the used hadronic models. The results show that there is a good agreement between the hadronic interaction model and a good comparison was obtained of the result of the energy of created particle with results simulated by CORSIKA simulation result for the proton.

ACKNOWLEDGMENTS

The authors are grateful for help from the Mustansiriyah University at in Baghdad-Iraq, and the designers of the Aires system.

REFERENCES

[1] R.M. Baltrusaitis et al. The Utah Fly's Eye detector, Nucl. Instr. Meth. Volume 240, Issue 2, pp. 410-428, (1985). https://doi.org/10.1016/0168-9002(85)90658-8

[2] J. Knapp et al, Extensive Air Shower Simulations at the Highest Energies Astropart.Phys. 19,pp. 77-99 (2003). https://doi.org/10.1016/S0927-6505(02)00187-1

[3] T.K. Gaisser, Cosmic Rays and Particle Physics, Cambridge University Press, Cambridge (1990).

[4] T. Pierog, Iu. Karpenko, et al., EPOS LHC: test of collective hadronization with LHC data, Phys. Rev. C. 92, 034906(2015). https://doi.org/10.1103/PhysRevC.92.034906

[5] S. Ostapchenko., Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: I. QGSJET-II model, Phys. Rev. D. 83, 014018 (2011). https://doi.org/10.1103/PhysRevD.83.014018

[6] E. Ahn, R.Engel,, et al., Cosmic ray interaction event generator Sibyll 2.1, Phys. Rev. D 80, 094003 (2009). https://doi.org/10.1103/PhysRevD.80.094003

[7] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, and T. Thouw, FZKA 6019, Forschungszentrum Karlsruhe (1998).

[8] J. Knapp, D. Heck, et al, Extensive Air Shower Simulations at the Highest Energies, Astropart. Phys. Astropart.Phys. 19,pp. 77-99,(2003). https://doi.org/10.1016/S0927-6505(02)00187-1

[9] M. Risse and D. Heck, Energy Release in Air Showers, Astropart. Phys. 20 - 661, (2004). https://doi.org/10.1016/j.astropartphys.2003.10.006

[10] S. Sciutto, AIRES: a system for air shower simulations. User's guide and reference manual. Version 2.2. 0, in, 1999.

[11] T. Antoni et al, KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems, stropart.Phys.24:1-25, (2005). https://doi.org/10.1016/j.astropartphys.2005.04.001

[12] A. Haungs, H. Rebel1, et al, Energy spectrum and mass composition of high-energy cosmic rays, Rep. Prog. Phys. 66, pp. 1145-1206, (2003). https://doi.org/10.1088/0034-4885/66/7/202

[13] K.H. Kampert, Measurements of the cosmic ray composition with air shower experiments, Astroparticle Physics, Volume 35, Issue 10, pp. 660-678(2012). https://doi.org/10.1016/j.astropartphys.2012.02.004

[14] S.Y. Roh, et al, A comparison study of CORSIKA and COSMOS simulations for extensive air showers, Astroparticle Physics, Vol. 44, pp. 1-8, (2013). https://doi.org/10.1016/j.astropartphys.2013.01.013

How to Cite

I. Fadhil and Al-Rubaiee A. A., “Simulating and Modeling the Extensive Air Showers Development through the Estimating the Energy of some Created Particles ”, *Al-Mustansiriyah Journal of Science*, vol. 33, no. 3, pp. 74–81, Sep. 2022.