Global characteristics of the medium produced in ultra-high energy cosmic ray collisions

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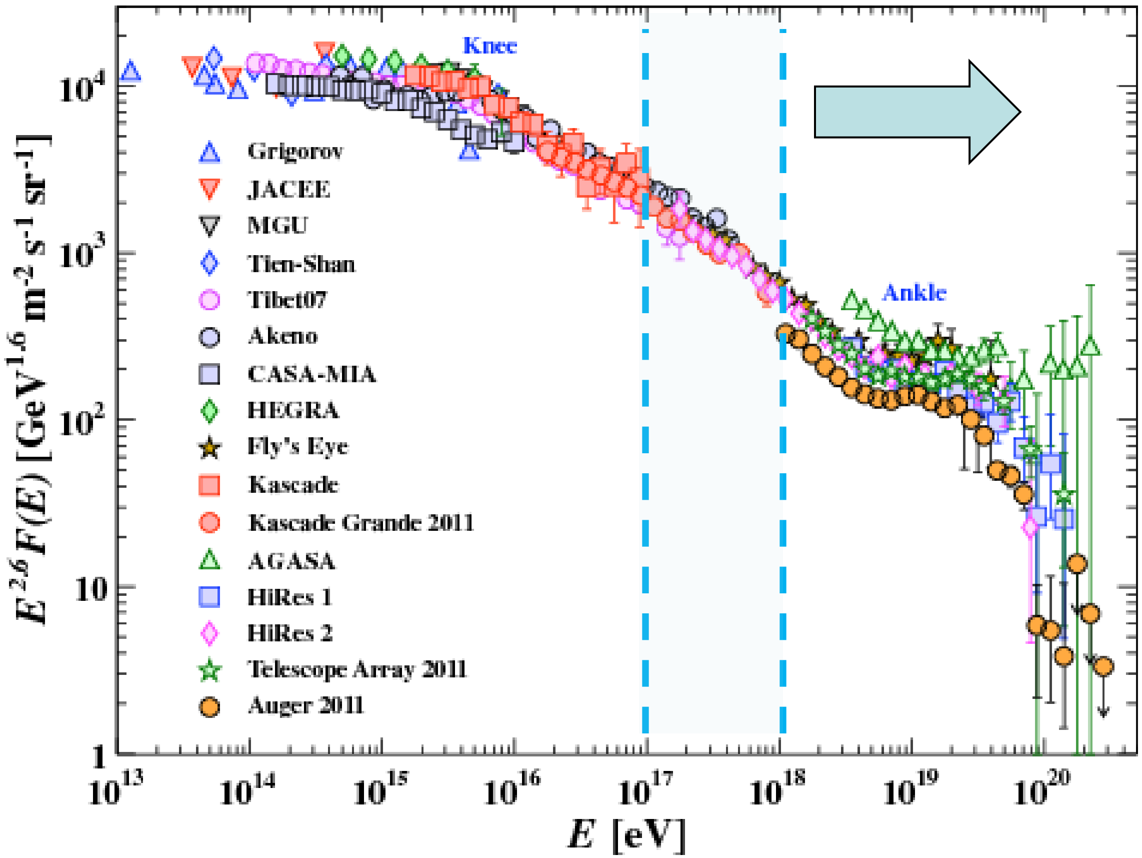
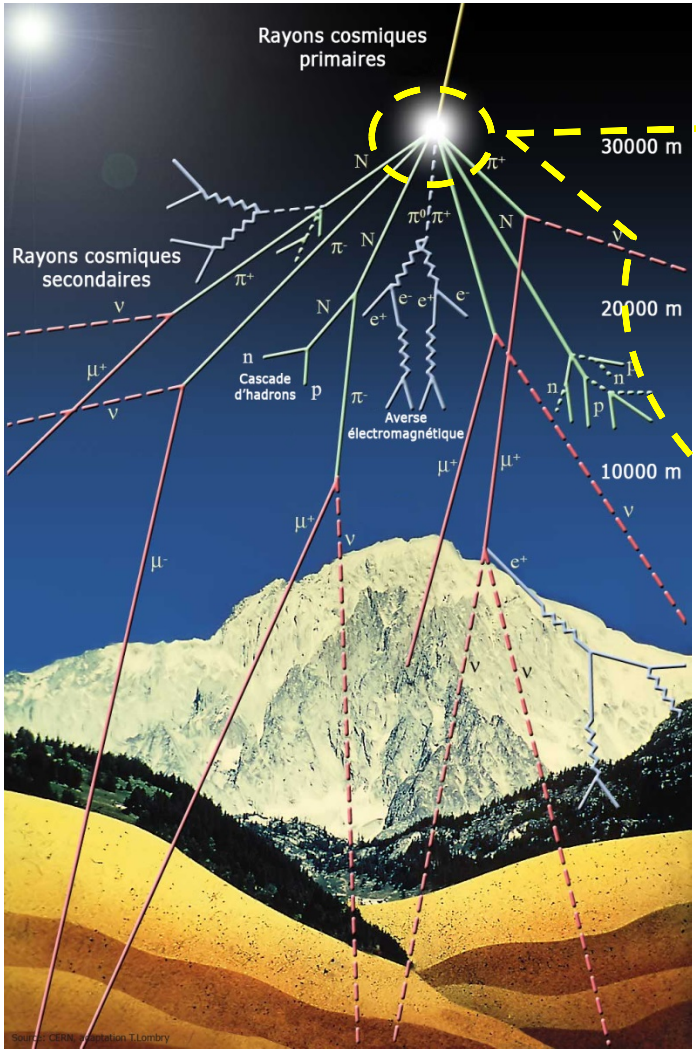
Uniqueness of the UHECR

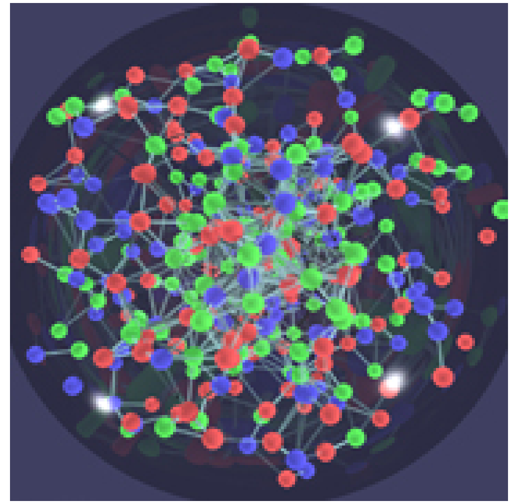


Measurements of interactions of ultra-high energy cosmic rays (UHECR), i.e. cosmic ray particles with initial laboratory energies larger than 10^{17} – 10^{18} eV, with nuclei in the atmosphere allow the new unique possibilities for study of multiparticle production processes at energies (well) above not only the Large Hadron Collider (LHC) range but future collider on Earth as well.

M. T. Dova, arXiv: 1604.07584 [astro-ph.HE]

Final-state matter





Collisions at ultra-high energies can lead to creation of a strongly interacting matter under extreme conditions called also quark-gluon plasma (QGP).

Due to the air composition and main components of the UHECR the passage of UHECR particles through atmosphere can be considered as collision mostly small systems.

Why study the UHECR collisions

- Among the most challenging problems for collider experiments is the study of the quark-gluon matter created in small system collisions.

- The investigation of main properties of the final-state matter for UHECR particle collisions with atmosphere can be useful for better understanding of the origin and features of UHECR itself.

Therefore the estimations of global characteristics of the matter produced in ultra-high energy cosmic ray collisions seems important for both the experiments at present and, possibly, even more for future colliders and the physics of cosmic rays.

Energy domain under study: proton

The energy range for protons in laboratory reference system considered here is

$$E_p = 10^{17} - 10^{21} \text{ eV}.$$

This range includes the energy domain corresponded to the Greisen – Zatsepin – Kuzmin (GZK) limit and somewhat expands it, taking into account,

- on the one side, both possible uncertainties of theoretical estimations for the limit values for UHECR and important experimental results, namely, measurements of several events with $E_p > 10^{20}$ eV and the absence of UHECR particle flux attenuation up to $E_p \sim 10^{20.5}$ eV

and,

- on the other hand, the energies corresponding to the nominal value $\sqrt{s_{pp}}$ = 14 TeV of the present LHC as well as to the parameters for the main international projects HE–LHC ($\sqrt{s_{pp}}$ = 27 TeV) and Future Circular Collider – FCC ($\sqrt{s_{pp}}$ = 100 TeV).

Therefore the estimations below can be useful for both the UHECR physics and the collider experiments.

Energy for nuclear interactions

It seems reasonably to suggest the same acceleration mechanism for protons and heavier components of the UHECR which affects on the charged component of the nuclei. The some electromagnetic fields can be such mechanism but not the shock waves from explosion processes.

The nucleus-nucleus collisions

$$(\mathrm{A}_1, \mathrm{Z}_1) + (\mathrm{A}_2, \mathrm{Z}_2)$$

are considered within this approach, where A_i and $\mathrm{Z}_i e$ is the nucleon number and charge for beam particle (i = 1) and for target nucleus at rest (i =2). Therefore in conditions with electromagnetic field set for protons of laboratory momentum p_p, the nuclear collision will be characterized by the following momentum per nucleon of the incoming particle in laboratory reference system and the center-of-mass energy per nucleon-nucleon pair

$$p_N = (\mathrm{Z}_1/\mathrm{A}_1)\,p_p, \quad \sqrt{s_{NN}}\Big|_{m_N \approx m_p \ll E_p} \approx \sqrt{(\mathrm{Z}_1/\mathrm{A}_1)s_{pp}},$$

$$s_{NN/pp} = 2m_{N/p}(E_{N/p} + m_{N/p}).$$

Here $s_{NN/pp}$ is the standard Mandelstam variable, $E_{N/p}$ and $m_{N/p}$ is the energy in the laboratory frame and mass of nucleon / proton.

Nuclear species

Here the following set of nuclei is considered

$$G_Y \equiv \{G_Y^i\}_{i=1}^4 = \{{}^1p^{1+},\ {}^4He^{2+},\ {}^{14}N^{7+},\ {}^{56}Fe^{26+}\}.$$

The nuclei correspond to the four groups of elements which are the main components of cosmic rays within studied energy domain.

Some collision energies are shown in Table 1 for particle types and proton energy range in laboratory frame under consideration.

Table 1. Center-of-mass energies for collisions with various incoming nuclei

E_p, TeV	**$\sqrt{s_{NN}}$, TeV**			
	${}^1p^{1+}$	${}^4He^{2+}$	${}^{14}N^{7+}$	${}^{56}Fe^{26+}$
10^5	13.70	9.686	9.686	9.334
10^7	137.0	96.86	96.86	93.34
10^9	1370	968.6	968.6	933.4

Multiplicity parameters

The energy dependence of the pseudorapidity (η) density of secondary charged particles produced at $\eta = 0$ per nucleon-nucleon pair can be approximated in particular by universal power expression

$$\rho^{\eta} \equiv \xi^{-1} (dN_{ch} / d\eta)\big|_{\eta=0} = a_1 \varepsilon^{a_2}, \;\; \varepsilon \equiv s / s_0, \;\; \xi \equiv 0.5 \left\langle N_{part} \right\rangle .$$

Here $s_0 \equiv 1$ GeV^2, $\langle N_{part} \rangle$ is the average number of participant and $\langle N_{part} \rangle = 2$ for $p+p$ collisions, $\forall\, i = 1, 2$: a_i are free parameters which values are driven by the collision type.

The approximating function for the total multiplicity of charged particles produced in nuclear collisions depended on s is following

$$\xi^{-1} N_{ch} = a_1 + a_2 \varepsilon^{a_3} .$$

The free parameter values are from

G. Alexander and V. A.O., arXiv: 1606.08665 [hep-ph].
ALICE Coll., EPJC 79, 307 (2019); PRL 116, 222302 (2016); PLB 790, 35 (2019).
E. K. G. Sarkisyan et al., PRD 93, 054046 (2016).

Energy densities

The following approximation for energy dependence of the transverse energy (E_{T}) density at $\eta = 0$ normalized by participant pairs is used

$$\rho_{\mathrm{T}}^{E} \equiv \xi^{-1} (dE_{\mathrm{T}} / d\eta)\Big|_{\eta=0} = (0.46 \pm 0.16)\varepsilon^{0.200\pm0.005},$$

where values of the free parameters are derived within the present work based on the experimental data at RHIC and LHC energies [*PHENIX Coll., PRC 71, 034908 (2005), CMS Coll., PRL 109, 152303 (2012)*].

The Bjorken energy density at time τ after collision moment $\tau = 0$ for the most central events is

$$\rho_{\mathrm{Bj}}^{E}(\tau) = (\pi R^{2} \tau) \times (dE_{\mathrm{T}} / d\eta)\Big|_{\eta=0},$$

where the radius for incoming nucleus is estimated as the radius of spherically-symmetric object $\forall\, A > 1 : R = r_0 A^{1/3}$ with r_0 = (1.25 0.05) fm and for $p+p$ collisions R = (0.875 0.006) fm [*V.A. Petrov and V.A.O., IJMPA 33, 1850077 (2018)*].

Temperature and decoupling time

The temperature of the medium produced in the interactions of relativistic particles can be estimated with help of the relation

$$T(\tau) = \left[30\rho_{\text{Bj}}^{E}(\tau) / \pi^2 n_{df}\right]^{1/4},$$

where n_{df} is the number degrees of freedom for created matter.

The time duration since the collision moment until kinetic freeze-out stage called also (Bose–Einstein) decoupling time and characterized the total duration of the longitudinal expansion of final-state matter is evaluated as follows [*ALICE Coll., PLB 696, 328 (2011)*]

$$\tau_{kin} \approx 0.875[(dN_{ch} / d\eta)|_{\eta=0}]^{1/3}.$$

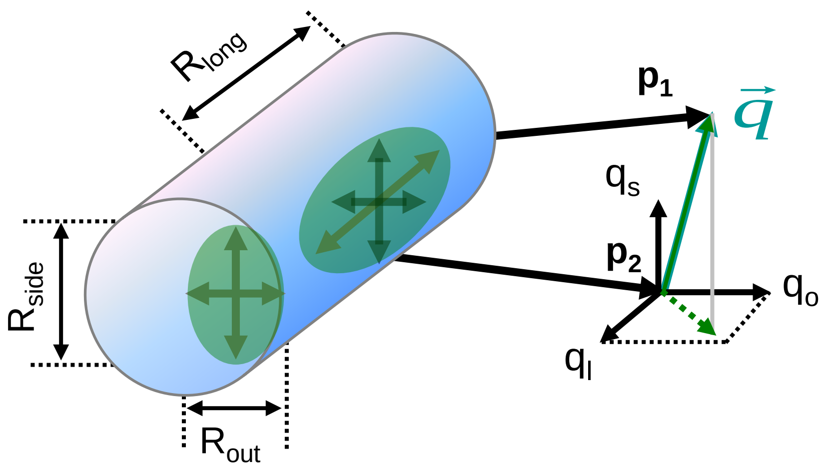
Bose–Einstein (BE) correlations

At present, the Bose–Einstein correlations is a unique experimental method for determination of sizes and lifetime of particle source in high energy and nuclear physics.

The correlation function (CF) for two secondary particles with momenta p_1 and p_2 is defined as the following ratio of the two- and single-particle cross sections

$$C_2^i(p_1, p_2) = \sigma_{\text{in}} \frac{d^2\sigma^i(p_1, p_2)\big/dp_1 dp_2}{d\sigma^i\big/dp_1 \times d\sigma^i\big/dp_2}.$$

The space-time geometry of the emission region can be considered in the Pratt–Bertsch coordinate system



$$\{p_1, p_2\} \to \{q, k\},$$

$$q = p_1 - p_2,\ k = (p_1 + p_2)/2,$$

$$\vec{q} = \{q_s, q_o, q_l\},\ \vec{k} = \{k_{||}, k_{\perp}\},$$

$$C_2(p_1, p_2) \to C_2(q, k);$$

$$\{q_s, q_o, q_l\} \Leftrightarrow \{R_s, R_o, R_l\}.$$

Space-time extents of the source

The smooth energy dependences of the BE correlation parameters allow the study of the geometry and space-time extent of the emission region of secondary particles produced in UHECR collisions. The linear scales (radii) of the homogeneity region for the 3D Gaussian source of the charged pion pairs with low relative momentum can be parameterized by the universal function [*V.A.O., AHEP 2015, 790646 (2015)*]

$$f_i(\varepsilon) = a_1^i \left[1 + a_2^i (\ln \varepsilon)^{a_3^i} \right], \quad i = s, o, l$$

with the appropriate set of parameters for each direction *i* of the Pratt–Bertsch coordinate system. The volume of the homogeneity region is calculated as follows

$$V = (2\pi)^{3/2} R_s^2 R_l .$$

Multiplicity estimations

The values for multiplicity density at midrapidity and for scaled total charged particle multiplisity are shown in Table 2 and first lines correspond to the symmetric (A + A) collisions while second lines – to the p + A interactions.

Table 2. Multiplicity values in some UHECR collisions.

Parameter	E_p, TeV	${}^{1}p^{1+}$	${}^{4}He^{2+}$	${}^{14}N^{7+}$	${}^{56}Fe^{26+}$
ρ^{η}	10^5	6.6 ± 0.7 -	46.5 ± 1.7 13.8 ± 0.6	46.5 ± 1.7 -	45.9 ± 1.7 -
	10^7	11.1 ± 1.4 -	95 ± 4 22.2 ± 1.1	95 ± 4 -	94 ± 4 -
	10^9	18.8 ± 2.6 -	194 ± 9 35.6 ± 1.8	194 ± 9 -	191 ± 9 -
$\xi^{-1}N_{ch}$	10^5	80.5 ± 2.2	141 ± 20	141 ± 20	139 ± 20
	10^7	154.7 ± 2.3	331 ± 20	331 ± 20	327 ± 20
	10^9	291.6 ± 2.4	768 ± 21	768 ± 21	758 ± 21

The multiplicity density in p + p interactions at E_p =10^{19} eV is already equal to the value of this parameter in most central Pb + Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [*ALICE Coll., PRL 116, 222302 (2016)*] .

Energy density estimations

The values for transverse energy density at midrapidity and for scaled Bjorken energy density at the time moment $\tau = 1$ fm/c are shown in Table 3 for nuclear collisions.

Table 3. Energy density values in nuclear collisions for UHECR.

Parameter	E_p, **TeV**	${}^{1}p^{1+}$	${}^{4}He^{2+}$	${}^{14}N^{7+}$	${}^{56}Fe^{26+}$
ρ_{T}^{E}, GeV	10^5	-	18 ± 7	18 ± 7	18 ± 7
	10^7	-	45 ± 19	45 ± 19	45 ± 19
	10^9	-	110 ± 50	110 ± 50	110 ± 50
$\xi^{-1} \rho_{\mathrm{Bj}}^{E}\big\vert_{\tau=1}$, GeV/fm^3	10^5	-	1.5 ± 0.6	0.63 ± 0.26	0.24 ± 0.10
	10^7	-	3.7 ± 1.6	1.6 ± 0.7	0.62 ± 0.27
	10^9	-	9 ± 4	4.0 ± 1.9	1.6 ± 0.7

The Bjorken energy density is well above than the estimation for the critical value (0.34 ± 0.16 GeV/fm^3) with taking into account the scale factor for any nuclei and energies under study.

The scaled Bjorken energy densities in small system collisions exceed significantly the value of this parameter in *Pb*+*Pb* collisions at $\sqrt{s_{NN}}$ = 2.76 TeV which is ≈ 0.07 GeV/fm^3 [*CMS Coll.*, *PRL 109, 152303 (2012)*].

Estimations for T and τ_{kin}

The values for temperature at the time $\tau = 1$ fm/c after collision moment and for decoupling time multiplied for the appropriate scale factors are shown in Table 4 for nuclear collisions.

Table 4. Values for scaled temperature and decoupling time in some UHECR collisions.

Parameter	E_p, TeV	${}^{1}p^{1+}$	${}^{4}He^{2+}$	${}^{14}N^{7+}$	${}^{56}Fe^{26+}$
$\xi^{-1/4} T\big\vert_{\tau=1}$, GeV	10^5	-	0.55 ± 0.06	0.45 ± 0.05	0.35 ± 0.04
	10^7	-	0.70 ± 0.08	0.57 ± 0.06	0.45 ± 0.05
	10^9	-	0.88 ± 0.10	0.71 ± 0.08	0.56 ± 0.07
$\xi^{-1/3}\tau_{kin}$, fm/c	10^5	-	13.55 ± 0.17	13.55 ± 0.17	13.40 ± 0.17
	10^7	-	27.7 ± 0.4	27.7 ± 0.4	27.7 ± 0.4
	10^9	-	56.5 ± 0.9	56.5 ± 0.9	55.8 ± 0.9

The matter created in the collisions of UHECR particles with air is characterized by the temperature larger significantly than the critical one (≈ 0.16 GeV) and long lifetime until kinetic freeze-out. Therefore one can expect that the long-lived quark-gluon matter is created in small system collisions at any considered energies.

Estimations for source geometry

Table 5. Values for radii and volume of the source in some UHECR collisions.

Parameter	E_p, **TeV**	$^{1}p^{1+}$	$^{4}He^{2+}$	$^{14}N^{7+}$	$^{56}Fe^{26+}$
R_s, fm	10^5	1.7 ± 0.7	1.60 ± 0.07	2.43 ± 0.10	3.86 ± 0.16
	10^7	2.1 ± 0.7	1.71 ± 0.07	2.60 ± 0.11	4.11 ± 0.18
	10^9	2.5 ± 0.9	1.81 ± 0.08	2.75 ± 0.12	4.36 ± 0.19
R_o, fm	10^5	1.4 ± 0.7	1.72 ± 0.07	2.62 ± 0.11	4.16 ± 0.18
	10^7	1.7 ± 0.9	1.78 ± 0.08	2.70 ± 0.12	4.29 ± 0.19
	10^9	1.9 ± 1.1	1.84 ± 0.08	2.79 ± 0.13	4.42 ± 0.20
R_l, fm	10^5	1.82 ± 0.17	2.25 ± 0.09	3.42 ± 0.14	5.42 ± 0.23
	10^7	1.98 ± 0.20	2.50 ± 0.11	3.80 ± 0.16	6.01 ± 0.25
	10^9	2.14 ± 0.24	2.75 ± 0.12	4.17 ± 0.18	6.62 ± 0.28
V, fm^3	10^5	80 ± 60	91 ± 9	320 ± 30	1270 ± 120
	10^7	130 ± 90	115 ± 11	400 ± 40	1600 ± 150
	10^9	210 ± 140	142 ± 14	500 ± 50	1900 ± 190

Space-time shape of source

Estimations evaluated for the linear scales (radii) and volume of the pion emission region allow the following conclusions.

- The proton-proton interactions produce the quasi-spherical source with equal radii within large errors while the cylindrical shape of the emission region is clearly seen for nucleus-nucleus collisions.

- Source radii in the nitrogen nucleus collisions are comparable in order of magnitude with the space-time extents of the emission region in *Cu* + *Cu* collisions at RHIC energies $\sqrt{s_{NN}}$ = 62.4 – 200 GeV especially for longitudinal axis. The similar relations are valid for the radii in *Fe* + *Fe* collisions for ultra-high energy cosmic rays and heavy ion (*Au* + *Au*) collisions at RHIC energies $\sqrt{s_{NN}}$ = 62.4 – 200 GeV.

- The final-state matter in collisions of UHECR particles with atmosphere occupies a noticeable volume at freeze-out even for lightest system interactions (*p* + *p*, *He* + *He*) at low boundary energy under consideration.

Summary

1. The collisions of UHECR with atmosphere is the unique tool which allows the study of strong interaction processes up to the ultra-high center-of-mass energies $O(1\ \mathrm{PeV})$.

2. The medium produced in the collisions of the UHECR particles with air is characterized by high energy density at midrapidity and temperature well above the critical one for the creation of the quark-gluon matter already at $\sqrt{s_{NN}}$ corresponded to the $E_p = 10^{17}$ eV.

3. The particle source created in small system collisions at $E_p \geq 10^{19}$ eV is characterized by the large space-time extents which support the hypothesis of the creation of blobs of the quark-gluon matter under extreme conditions in UHECR interactions. BE decoupling time is about 10 fm/c on order of value even in helium collisions.

Therefore for the first time the quantitative analysis of the wide set of global and geometric characteristics strongly indicates that the long-lived medium in quark-gluon phase can be produced in light nuclei collisions at ultra-high energies of cosmic rays.

Thanks for you attention