LETTERS TO PROGRESS IN PHYSICS

On the Ultimate Energy of Cosmic Rays

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It is established that the upper limit of cosmic-ray energy due to the Greisen-Zatsepin-Kuzmin effect is local. On the basis of the mechanistic interpretation of J. Wheeler's geometrodynamic concept, a more fundamental limitation on this limit was established, which, in the final analysis, depends on Planck's size $(\hbar\gamma/c^3)^{1/2}$ and for protons the limit is 4.51×10^{18} eV. The inflection in the spectrum curve, the "knee", corresponds to the mass-energy of the vortex tube of the limiting proton-electron contour, 1.46×10^{15} eV. For other nuclei these energies increase in proportion to the atomic number of the element.

Cosmic rays are a flow of nuclei of chemical elements — hydrogen (~ 90%), helium (~ 8%), and the nuclei of the heavier elements (~ 2%). The energy spectrum of cosmic rays or the dependence of the cosmic ray flux on energy extends from 10^3 to 10^{20} eV. The main sources of primary cosmic rays are supernova explosions (galactic cosmic rays) and the Sun, as well as extragalactic sources — radio galaxies and quasars. The protons and heavier nuclei emitted during supernova explosions are further accelerated in specific astrophysical processes. Falling into the earth's atmosphere, cosmic ray particles transmit their energy to a multitude of secondary particles. Thus, the particles cascade is formed; it is called an extensive air shower (EAS) and covers a large area.

Nature ultrahigh energy cosmic rays (more than 10^{17} eV) has not yet been unambiguously interpreted, their sources have not yet been identified, and there is no complete understanding of the mechanisms of their acceleration and even the nature of the accelerated particles [1]. There are reasons to assume that they are of extragalactic origin. It is believed that the upper limit of cosmic-ray energy is limited by a threshold of 5×10^{19} eV, because cosmic ray particles interact energetically with relic radiation, which leads to their absorption and reduction of their energy to a threshold value at distances of the order of several tens of megaparsecs (Greisen-Zatsepin-Kuzmin effect) [2, 3]. The presence of particles with energies exceeding this threshold does not yet find a satisfactory explanation, since within range of up to one hundred megaparsec powerful radiation sources are absent.

The question arises: what energy could be cosmic rays, if the distance between the source and the Earth would be much less than the Greisen-Zatsepin-Kuzmin limit, and could not microparticle produce a huge macroscopic effect? Here we see a paradox, since theoretically relativistic mass and energy of the particle can approach infinity. It seems that the Greisen-Zatsepin-Kuzmin effect is of local importance, and there are more fundamental causes that limit the energy of cosmic rays.

A fundamental limitation can be derived by considering a charged microparticle from the point of view of John Wheeler's geometrodynamic concept. Wheeler's concept assumes that charged microparticles are singular points on a topologically non-unitary coherent two-dimensional surface of our world, connected by a "wormhole", a vortex tube or a current line of the input-output kind in an additional dimension, generally forming a closed counter. According to the mechanistic interpretation of Wheeler's idea when the contour (proton-electronic, for example) is opened individual charged particles retain part of the contour vortex tube (boson mass) whose momentum is numerically equal to the charge [4, 5]. In these works formulas are derived for the vortex tube parameters: its boson mass m_y, the circulation velocity of the medium along the contour v, the radius r, and the length l_y:

$$m_y = (an)^2\, m_e\,, \tag{1}$$

$$v = \frac{c_0^{1/3}}{(an)^2}\, c\,, \tag{2}$$

$$r = \frac{c_0^{2/3}}{(an)^4}\, r_e\,, \tag{3}$$

$$l_y = (an)^2 r_e\,, \tag{4}$$

where n is the principal quantum number of the contour, a is the inverse of the fine structure constant, m_e and r_e are the mass and classical radius of the electron, c_0 is the dimensionless speed of light equal to $c/[\text{m/sec}]$. Depending on the size of the contour, i.e. from its quantum number, its parameters vary, but the momentum (charge equivalent) in a closed counter remains constant. At the same time, *both the contour size and the parameters of the vortex tube have their ultimate values*.

In [6], in determining the neutrino mass, it was shown that the Planck size $r_h = (\hbar\gamma/c^3)^{1/2}$ has a physical meaning and is the limiting size inherent in the neutrino, and, obviously, in general for the microcosm, i.e. $r_{\min} = r_h = 1.62 \times 10^{-35}$ m or $5.74 \times 10^{-21}\, r_e$. Then from (1) and (3) we get other ultimate values: $n = 21700$ and $m_y = 8.83 \times 10^{12}\, m_e$. The boson mass is compared with that of mass-energy in units of

$m_e c^2$, provided that $v \to c$ (here the boson mass can be considered as the mass of the excited or "associated" vacuum). It is this condition that is satisfied for cosmic rays whose particles relative to their source move with velocities close to the speed of light. Thus, the energy equivalent of the mass m_y is $E = 8.83 \times 10^{12} \times 511000 = 4.51 \times 10^{18}$ eV.

This quantity is the ultimate energy for cosmic-ray protons. Obviously, for heavier nuclei, the energy increases in proportion to the atomic number A. This conclusion agrees with the fact of "weight increasing" the primary cosmic ray component with increasing energy, and the heavy nuclei flux (most likely iron) in the region of $\sim 10^{18}$ eV is much larger than that of protons [7–9]. Consequently, the largest energy value for the heaviest nuclei can not exceed $E \sim 3.7 \times 10^{20}$ eV and even higher values, apparently, can not be. Indeed, during the entire time of observation on Earth, only a few dozen events with energies above 10^{20} eV were recorded in various installations (the maximum energy of the cosmic particle 3×10^{20} eV was registered in October 1991 on the "Fly's Eye" device [10]).

The figure adopted from [11] shows the observed spectrum of cosmic radiation, on which the energy limits for protons (II) and heavy nuclei (III) are noted (the values along the ordinate are reduced to the energy in GeV). The region of the graph is marked, where the intensity of cosmic rays is about 1 particle per square meter per year. A narrow scatter of the experimental data over the entire length of the spectrum, with the exception of the region of ultrahigh energies, gives grounds to assume that the intensity of cosmic rays depends slightly on the nature of their sources and the mechanism for their acceleration, and this can be shown.

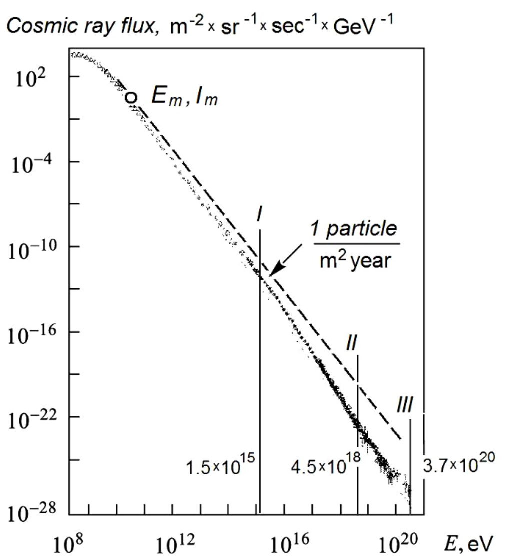

Fig. 1: The observed spectrum of cosmic radiation in the energy range 10^8–10^{20} eV.

Let us assume that the particle velocity increases proportionally to the distance from the source, and the number of particles falling per unit area of the receiver is inversely proportional to the cube of the distance from the source. This is true in the case of unimpeded particle propagation. Then, by simple computations, we obtain a relation that is independent of the distance:

$$I = (E_m/E)^{1.5}\, I_m\,, \qquad (5)$$

where E_m and I_m are the coordinates of some reference point on the $I(E)$ dependence in units of [eV] and [flux $\times$ m^{-2} $\times$ sr^{-1} $\times$ sec^{-1}]. When the ordinates are divided by energy in GeV, formula (5) becomes:

$$I = 10^9\, (E_m^{1.5}/E^{2.5})\, I_m \qquad (6)$$

and shown in the figure with a dashed line. The actual dependence is somewhat more steeply and approximated by the relation $dI/dE \sim E^{-2.7}$, which is explained by the presence of magnetic fields and other cosmogenic factors affecting charged particles. Nevertheless, it turns out that the shape of the energy spectrum is largely determined by the increase in the particles energy and the decrease in their number as radiation sources are removed from the Earth.

In the energy range 10^{15}–10^{16} eV, the dependence $I(E)$ undergoes an inflection increasing index at E, the so-called "knee". The energy value at the inflection point matches with the mass-energy of the contour corresponding to the *ultimate size of the hydrogen atom*. For this atom, the ultimate value of the quantum number $n = 390$ [5]. In general, detailed formula for the inflection point energy, given the results of [5], and assuming that the energy increases in proportion to the atomic number of nuclei can be represented as:

$$E_{\text{knee}} = 5.11 \times 10^5 \left(\frac{2\pi\gamma\rho_e m_p \times [\text{sec}^2]}{c_0^{1/3} \cos q_w} \right)^2 A = \\ = 1.46 \times 10^{15} \times A \text{ eV}, \qquad (7)$$

where γ is the gravitational constant, $\rho_e = m_e/r_e^3$ is the electron density equal to 4.07×10^{13} kg/m^3, m_p is the relative mass of the proton, and q_w is the Weinberg angle of 28.7°.

For protons, this energy value is indicated in the figure by the vertical (I), which matches with the beginning of the inflection of the energy spectrum. The removal of the inflection point towards higher energies for heavier nuclei is confirmed in [12].

One can propose the following explanation for the increase in the energy spectrum incline. At energies up to 1.46×10^{15} eV ($n < 390$), protons and electrons in cosmic rays can be in a bound state — either as atoms having a neutral charge or in some associations that have a total positive charge less than the protons total charge. It may reduce their interaction with magnetic fields.

At higher energies, protons are not accompanied by electrons, their total positive charge remains, and they are fully exposed to magnetic fields. Perhaps this is the reason for the abrupt decrease in the number of electrons in the EAS when primary particles have energies about 10^{15}–10^{16} eV [13].

As for the neutrinos, then, bearing in mind their inherent size limit of r_h, their maximum energy, possible, can reach the same value as that of the proton, 4.51×10^{18} eV. At the moment, the highest recorded neutrino energy is $2{\times}10^{15}$ eV [14].

Conclusion

The ultimate energy of cosmic rays is limited by the maximum mass-energy of the proton vortex tube, which in turn is determined by the fundamental parameter — the Planck size inherent in a neutrino. The reason for the inflection of the spectrum of cosmic rays (the "knee") is the obtaining by the proton of the energy at which a proton-electronic counter, having ultimate quantum number, opens. For other nuclei these energies increase in proportion to the atomic number of the element.

It is shown that, for all on a variety of radiation sources and the mechanism of acceleration of cosmic particles, the shape of the spectrum of cosmic rays, provided that they spread without interference, is largely determined by the most common factors — the increase in their particle energy and the decrease in their number — as the distance between the sources and the Earth is increasing.

Submitted on June 24, 2017

References

1. Kalashev O.E. Cosmic rays of ultrahigh and ultrahigh energies. Associated neutrino and photon radiation. 01.04.02 — theoretical physics. Thesis for the degree of Doctor of Physical and Mathematical Sciences. Moscow, 2016.
2. Greisen K. End to the cosmic ray spectrum? *Phys. Rev. Lett.*, 1966, v. 16, 748–750.
3. Zatsepin G.T., Kuzmin V.A. On the upper boundary of the spectrum of cosmic rays. JETP-Letters, 1966, v. 4, 78–80.
4. Belyakov A.V. Charge of the electron, and the constants of radiation according to J. A. Wheeler's geometrodynamic model. *Progress in Physics*, 2010, v. 4, 90–94.
5. Belyakov A.V. Macro-analogies and gravitation in the micro-world: further elaboration of Wheeler's model of geometrodynamics. *Progress in Physics*, 2012, v. 2, 47–57.
6. Belyakov A.V. Determination of the neutrino mass. *Progress in Physics*, 2016, v. 12, issue 1, 34–38.
7. Troitsky S.V. Cosmic rays of ultrahigh energies: composition and source problem. 01.04.16 — physics of the atomic nucleus and elementary particles. The dissertation author's abstract on competition of a scientific degree of the doctor of physical and mathematical sciences. Institute of Nuclear Research, Russian Academy of Sciences, Moscow, 2008.
8. Grigorov N.L. et al. In: *Proc. 12th Int. Cosmic Ray Conf.*, Hobart, 1971, v. 5, 1746.
9. Isaev P.S. Some problems of the physics of cosmic rays of ultrahigh energies. P2-99-33. Joint Institute for Nuclear Research, Dubna, 1999.
10. Bird D.J. et al. *Astrophys. J.*, 1994, v. 424, 491.
11. Bednyakov V.A. Why research of cosmic rays of ultrahigh energies should be produced in a near-earth orbit. *Physics of Elementary Particles and the Atomic Nucleus*, Joint Institute for Nuclear Research, Dubna, 2002, v. 33, no. 5.
12. Kalmykov V.N. Mass composition of primary cosmic radiation in the region of the break according to the data of the installation EAS of the MSU. The dissertation and the author's abstract on VAK 01.04.23 (Moscow, Russia), the candidate of physical and mathematical sciences.
13. Kulikov G.V., Christiansen G.B. *Journal of Experimental and Theoretical Physics*, 1958, v. 35, 635.
14. Aartsen et al. Evidence for astrophysical muon neutrinos from the Northern Sky with IceCube. *Physical Review Letters*, 2015, v. 115, 081102; arXiv: 1507.04005 [astro-ph.HE].