[9] E. Engels, Jr., T. Bowan, J. W. Cronin, R. L. McIlwain, and L. G. Pondrom, Phys. Rev. 129, 1858 (1963).

[10] A. Ashmore, A. N. Duddens, G. B. Huxtable, and K. Scarsvag, Proc. Phys. Soc. 72, 289 (1958).

[11] O. Chamberlain, G. Pettingill, E. Segre, and C. Wiegand, Phys. Rev. 93, 1424 (1954).

[12] A. J. Hartzler, R. T. Siegel, and A. Opitz, ibid. 95, 591 (1954); A. J. Hartzler and R. T. Siegel, ibid. 95, 185 (1954).

[13] R. T. Siegel, A. J. Hartzler, and W. A. Love, ibid. 101, 838 (1956).

[14] V. A. Nedzel, ibid. 94, 174 (1955).

[15] H. P. Stapp, T. Y. Ypsilantis, and N. Metropolis, ibid. 105, 302 (1957).

1) This means that the imaginary parts of the phase shifts of the ^3P and ^3F waves are identical.

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

Powerful isotropic thermal radiation of the Universe, having apparently a Planck distribution with temperature $T \approx 3°K$, has been observed in recent measurements [1,2]. The intensity of this radiation ($N \approx 550$ photons/cm^3, $kT \approx 2.5 \times 10^{-4}$ eV) is such that unique effects arise when cosmic rays of superhigh energy pass through it, specifically, cutoff of the cosmic-ray spectrum in the vicinity of 10^{20} eV.

At sufficiently high primary cosmic-ray proton energies $E_p \sim M_p c^2 (m_\pi c^2 / E_{ph,eff})$ [3], pion photoproduction processes occur when the protons interact with the photon gas, as a result of which the protons effectively lose energy ($\overline{\Delta E_p}/E_p \approx 20\%$) [4]. If the characteristic time for proton-phonon collision becomes sufficiently small compared with the lifetime of the cosmic rays with these energies in the Metagalaxy, as determined by other processes (for example, the expansion of the Universe), then effective cutoff of the cosmic-ray spectrum will take place. An exact analysis gives for the characteristic time of collision between a proton of energy $E_p \gg M_p c^2$ and a photon, at the photon-gas equilibrium temperature T,

$$\tau_{p\gamma} = \frac{2\pi^2 c^2 \hbar^3 \gamma^2}{kT\varphi} \text{ sec}, \quad \gamma = E_p / M_p c^2, \tag{1}$$

where

$$\varphi = \int_{E_{thr} \kappa m_\pi c^2}^{\infty} dE E \sigma_{p\gamma}(E) \sum_{n=1}^{\infty} \frac{1}{n} \exp(-nE/2\gamma kT) \left(1 + \frac{1}{n} \frac{2\gamma kT}{E}\right), \tag{2}$$

$\sigma(E)$ is the total cross section for the absorption of a photon of energy E by interaction with a proton; this is principally the cross section for the photoproduction of π^0 and π^+ mesons at $E \leq 1$ BeV; at higher energies, up to the highest ones, we can assume $\sigma_{p\gamma} = \text{const} \approx 1 \times 10^{-28}$ cm^2.

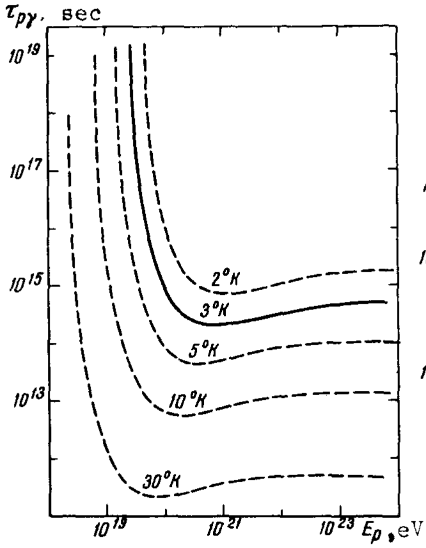

Fig. 1

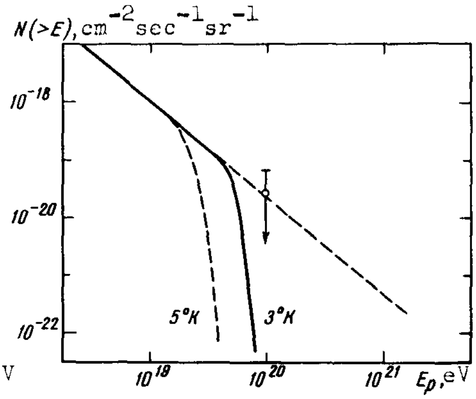

Fig. 2

The values of $\tau_{p\gamma}$ calculated by formula (1) for different proton energies are shown in Fig. 1 for several photon gas temperatures, T = 2, 3, 5, 10, and 30. We see that at proton energies $E_p \gtrsim 10^{20}$ eV, proton interactions with the photon gas become quite frequent, $\tau_{p\gamma} \approx 10^7$ years. This means that at the age $t \gtrsim 10^8$ of the cosmic rays with energies under consideration, their initial spectrum should be cut off in the high-energy region, even if the acceleration mechanism had been sufficiently effective in producing particles having these energies. The question of the exact form of the cosmic-ray spectrum in the energy region $E_p \gtrsim 10^{19}$ eV calls for a detailed analysis combined with allowance for their generation, the expansion of the Universe, and the interaction of the cosmic rays with the photon gas at each stage of evolution of the Universe. The form of the spectrum will, of course, depend here on which stage of evolution of the Universe the cosmic-ray particles of superhigh energy were generated, and how rapidly the generation took place.

A study of the energy spectrum of the cosmic rays near its upper limit yields information not only on the processes of their generation, but also on the evolution of the Universe. The influence of the change of the photon-gas temperature T on the position of the limit of the cosmic-ray spectrum is approximately shown in Fig. 2; for simplicity, we have assumed here that the cosmic rays were produced in the Metagalaxy $\approx 10^9$ years ago. The previously obtained experimental point [5] constitutes one registered event with energy' 10^{20} eV, with a probable error ~2 in the determination of the energy. The dashed curve corresponds to the case when the cosmic rays propagate during the 10^9 years in a photon gas having a temperature 5°K.

Notice should be taken of the disintegration of α particles and other nuclei [6] as they pass through metagalactic space. This occurs at an α-particle energy somewhat lower than the proton energy at which the pion photoproduction process begins. The rather large cross section of this process should lead to total disappearance of the nuclei from the cosmic rays at energies above 10^{19} eV.

Note. After writing this article, we received a preprint of a paper by K. Greisen, in which similar reasoning is presented and estimates agreeing with ours are obtained.

The authors take this opportunity to thank K. Greisen for communicating his unpublished results.

[1] A. A. Penzias and R. W. Wilson, Astrophys. J. 142, 420 (1965).
[2] P. G. Roll and D. T. Wilkinson, Phys. Rev. Lett. 16, 405 (1966).
[3] G. T. Zatsepin, DAN SSSR 80, 577 (1951).
[4] S. Hayakawa and Y. Yamamoto, Progr. Theor. Phys. 30, 71 (1963).
[5] J. Linsley, Phys. Rev. Lett. 10, 146 (1963); Proc. Int. Conf. Cosmic Rays, Bombay 4, 77 (1964).
[6] N. M. Gerasimova and I. L. Rozental', JETP 41, 488 (1961), Soviet Phys. JETP 14, 350 (1962).

CHARGE ASYMMETRY AND ENTROPY OF A HOT UNIVERSE

Ya. B. Zel'dovich and I. D. Novikov
Submitted 2 June 1966
ZhETF Pis'ma 4, No. 3, 117-120, 1 August 1966

Measurements of the cosmic background of radio emission at wavelengths 20, 7, 3, and 0.25 cm [1,2] have confirmed the theory of the hot Universe [3,4] 1). The dimensionless entropy (per baryon, in a system of units where the Boltzmann constant is $k = 1$), amounts to approximately 10^9. This means that there are approximately 10^8 quanta of electromagnetic radiation per baryon, and approximately as many electrons and muonic neutrinos.

From this it follows that for the earlier period $t < 10^{-6}$ sec (reckoning from the instant of singularity, $t = 10^{-6}$, corresponds to a temperature $T = 100$ MeV and a density $\rho = 5 \times 10^{17}$ g/cm^3) there are likewise approximately 10^8 baryon-antibaryon pairs per baryon. Thus, asymptotically as $t \to 0$ there are $\bar{N} = 99{,}999{,}999$ antibaryons and approximately as many mesons and leptons for each $N = 100{,}000{,}000$ baryons 2). The small but conserved difference $\Delta = N - \bar{N}$ (the composition is referred to $\Delta = 1$) plays the decisive role for the entire subsequent evolution of matter!

This almost-charge-symmetrical state seems quite unnatural. The alternative hypothesis of complete charge symmetry of the Universe [2,6] does not seem convincing to us. We shall attempt below to present a natural explanation of the aforementioned small charge asymmetry at high density.