POSSIBLE PRESENCE OF RELIC QUARKS IN COSMIC RAYS

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According to Maksimenko et al. [1], quarks can be generated, with noticeable cross section, in high-energy hadron collisions only if their interaction at large distances is much weaker than that of the hadrons. It can be noted in this connection that there is another source of quarks in cosmic rays (c.r.). "Cold" relic quarks ($T \sim 3 - 4^\circ K$) which remain, in accord with the analysis of [2], from the first stages of the expansion of the universe in the interstellar medium and in other cold media, and whose proportion can be estimated only very crudely (we assume $Q \sim 10^{-11}$ per stable baryon) can experience the same acceleration as ordinary protons and nuclei, and may also be present in the cosmic rays.

The mechanism of c.r. generation is still unknown. We shall therefore consider several possibilities.

1. It is quite probable [3] that the bulk of the c.r. are generated in explosions of supernovas and similar hot objects. In these, however, the quarks burn out [2]. Then the ratio of the fast-quark flux I_q to the cosmic-ray flux $I_{c.r.}$ is very small, $I_q/I_{c.r.} = \xi \ll 10^{-11}$. To be sure, it may be that the acceleration occurs in the cold shells of these objects, which experience no convection (at least in part). Then ξ can be close to Q.

2. Cosmic rays from the non-convective shells of the sun and other stationary stars yield a flux of $\sim(10^{-3} - 10^{-5})I_{c.r.}$ with energy $\lesssim 10^{10}$ eV. We can expect that they include a fraction $\sim 10^{-11}$ of quarks, $\xi \sim 10^{-14} - 10^{-16}$.

3. The acceleration of protons of the interstellar medium by the statistical Fermi mechanism is given by the formulas

$$\frac{dE}{dt} = \alpha \frac{v}{c} E, \quad \alpha = u^2/(c\ell) \quad \text{for } E_{kin} > E_{kin.i}, \tag{1}$$

where E_{kin} is the kinetic energy, v the particle velocity, u the velocity of the interstellar gas clouds, ℓ the particle mean free path between collisions with the clouds, c the velocity of light, and $E_{kin.i}$ the injection kinetic energy

$$E_{kin.i} = \frac{2\pi e^4 Z_q^2 n L}{\alpha m_e c} \sim 7 \times 10^{-9} \frac{Z^2 n}{c\alpha}. \tag{2}$$

Here Ze is the charge of the accelerated particle, $n(cm^{-3})$ is the number of hydrogen atoms in the medium, m_e the electron mass, and L a logarithmic factor ($L \sim 20$). This mechanism is of low efficacy for the acceleration of the bulk of the cosmic rays [3], for when $u/c \sim 10^{-4}$, $\ell \sim 3 \times 10^{19}$ cm, and $\alpha \sim 10^{-17}$ sec^{-1}, the value of E can increase, even during the entire lifetime of the universe $t_0 \sim 3 \times 10^{17}$ sec, only to $E = E_0 \exp(\alpha t_0)$, by a factor ~10, which does not explain the c.r. spectrum. In addition, it is difficult to explain the spectrum of the nuclei with $Z > 1$.

As applied to the quarks, however, this means that such a mechanism can yield only quarks of low energy

$$E_q \lesssim m_q c^2 \exp(\alpha t_{eff}),$$

where m_q is the mass of the quark and t_{eff} its lifetime. When $t_{eff} \sim t_0$, using the previous estimates for α, we have $\alpha t_{eff} \sim 1$ and ξ is determined by the injection efficiency. Its simplest mechanism is the transfer of the quarks into a region above the injection, $v_q > v_i = (2E_{min.i}/m_q)^{1/2}$, by means of Coulomb collision with the flux of ordinary cosmic rays. The cross section for such a collision, taking (1) and (2) into account, is

$$\sigma = \frac{4\pi Z^2 e^4}{v^2_{c.r.} v_i^2 m_q^2} \sim \left(\frac{u}{c}\right)^2 \frac{1}{n\ell L} \frac{m_e}{m_q}, \tag{3}$$

where the velocity of the cosmic ray proton is $v_{c.r.} \sim c$ ($v_{c.r.} \gg m_q v_i/m_N$). All these quarks are then accelerated. Let us multiply σ by the number nQ of cold quarks per cm^3, c, t, and $I_{c.r.}$. This yields I_q:

$$\xi \lesssim Q\left(\frac{u}{c}\right)^2 \frac{m_e}{m_q} \frac{ct}{\ell L} \sim Q \times 10^{-4} \frac{m_N}{m_q} \sim 10^{-15} \frac{m_N}{m_q}. \tag{4}$$

This apparently ensures a lower limit for I_q.

4. We see from (4) that in other media, with appreciably larger u^2/ℓ, even such a simple injection mechanism and statistical acceleration can yield $\xi \sim Q \sim 10^{-11}$. It is possible that there are regions with larger u^2/ℓ in operation in the interstellar medium, too. However, as is well known [3], the cosmic ray source must ensure predominant acceleration of heavy nuclei. It can be the consequence of non-injective statistical acceleration [3] if

$$\alpha > \alpha_k = \frac{4\pi n e^4 L}{m_e e v_e^2} \frac{Z^2}{m},$$

where Ze and m are the charge and mass of the accelerated particle. For quarks with $Z_q = 1/3$ and $m_q > 3m_N$ this parameter is at least 30 times smaller than for protons. Therefore in the case of noninjective statistical acceleration I_q should exceed the proton flux to a much higher degree than the flux of nuclei with the same Z^2/A of accelerated ions, i.e., $\xi > 10Q \sim 10^{-10}$.

5. It has become clear recently [4] that a very effective mechanism, especially in the nonrelativistic region, may be acceleration of particles in small-scale plasma turbulences. Assuming the velocity of the accelerated particle to be of the order of the phase velocity of the plasma wave, $v \sim v_{ph}$, we can obtain the estimate

$$\alpha_{plasma} \sim \frac{Z^2 e^2 nkTw}{m^2 c^2 \omega_0}, \tag{5}$$

where n is the number of plasma electrons per unit volume, $kT \sim 1 - 10$ eV is the thermal energy, $\omega_0 = (4\pi n e^2/m_e)^{1/2}$, and w is the ratio of the turbulence energy to the thermal energy of the plasma (w is very small). Thus, this mechanism ($\alpha_{plasma} \sim Z^2 m^2$) produces no preferred injection of heavy particles. The condition $\alpha_{\text{plasma}} > \alpha_k \sim Z^2/m$ shows that the quarks are non-injectively accelerated in such a medium only if the same is ensured (with a margin by a factor m_q/m_N) for the protons. However, α_{plasma} can be large: when $n \sim 10^{-2}$ we get $\alpha_{\text{plasma}} \sim Z^2(m_N/m)^2 \times 10^{-9}w\ \text{sec}^{-1}$, which can readily yield $\alpha_{\text{plasma}}t_0 \gg 1$. Therefore if the excess of heavy nuclei is connected not with the predominant injection for $Z^2/A > 1$ but with the increased abundance of heavy nuclei in c.r. sources, and if the acceleration is ensured by plasma waves, then the quarks will also be effectively accelerated by this mechanism, so that ξ may reach $\sim 10^{-11}$.

Let us summarize. We can expect the primary flux of cosmic rays to contain quarks, especially in the low energy region, $E_q/m_qc^2 \lesssim 10$. The ratio ξ of their flux to the proton flux can be smaller than the average relative concentration of cold quarks by several orders of magnitude, $\xi \sim 10^{-15}\ m_N/m_q$ (see items 2 and 3), but can also reach (or even exceed by one order of magnitude) $\xi \sim Q \sim 10^{-11}$, for example if the c.r. acceleration is by the statistical non-injective mechanism (items 4 and 5).

Experiment [5,6] has yielded so far $\xi < 10^{-8}$. The quarks can hardly be detected if $I_q < 10^{-11} - 10^{-12}\ \text{cm}^{-2}\text{sec}^{-1}$. It would be important to make further progress in the region of low intensities, paying particular attention to quarks having relatively low energies.

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ALLOWANCE FOR THE INFLUENCE OF ππ SCATTERING ANNIHILATION CHANNELS IN THE REACTION N(π,2π)N

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In calculating the pion production reaction in πN collisions in accord with the Chew-Low diagram, it is customary to take into account in the ππ scattering node only the direct channel [1], corresponding to the "coalescence" of the pions into a ρ meson and decay of the