Pis'ma v ZhETF, vol. 77, iss. 7, pp. 403 – 406

Primordial pairing and binding of superheavy charged particles in the Early Universe

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Submitted 10 July 2002

Resubmitted 18 February 2003

Primordial superheavy particles, considered as the source of Ultra High Energy Cosmic Rays (UHECR) and produced in local processes in the early Universe, should bear some strictly or approximately conserved charge to be sufficiently stable to survive to the present time. Charge conservation makes them to be produced in pairs, and the estimated separation of particle and antiparticle in such pair is shown to be in some cases much smaller than the average separation determined by the averaged number density of considered particles. If the new $U(1)$ charge is the source of a long range field similar to electromagnetic field, the particle and antiparticle, possessing that charge, can form primordial bound system with annihilation timescale, which can satisfy the conditions, assumed for this type of UHECR sources. These conditions severely constrain the possible properties of considered particles.

PACS:

The origin of cosmic rays with energies, exceeding the GZK cut off energy [1], is widely discussed, and one of popular approaches is related with decays or annihilation in the Galaxy of primordial superheavy particles [2 – 5] (see [5] for review and references where in). The mass of such particles is assumed to be higher than the reheating temperature of inflationary Universe, so it is assumed that the particles are created in some nonequilibrium processes, such as inflaton decay [6] at the stage of preheating after inflation [7].

The problems, related with this approach, are as follows. If the source of ultra high energy cosmic rays (UHECR) is related with particle decay in the Galaxy, the timescale scale of this decay, which is necessary to reproduce the UHECR data, needs special nontrivial explanation. Indeed, the relic unstable particle should survive to the present time, and having the mass m of the order of 10^{14} GeV or larger it should have the lifetime τ, exceeding the age of the Universe. On the other hand, even, if particle decay is due to gravitational interaction, and its probability is of the order of $1/\tau = (m/m_{Pl})^4 m$, where $m_{Pl} = 10^{19}$ GeV is the Planck mass, the estimated lifetime would be by many orders of magnitude smaller. It implies some specific additional suppression factors in the probability of decay, which need rather nontrivial physical realisation [2, 5], e.g. in the model of cryptons [8] (see [9] for review).

If the considered particles are absolutely stable, the source of UHECRs is related with their annihilation in the Galaxy. But their averaged number density, constrained by the upper limit on their total density, is so low, that strongly inhomogeneous distribution is needed to enhance the effect of annihilation to the level, desired to explain the origin of UHECR by this mechanism.

In the present note, we offer new approach to the solution of the latter problem. If superheavy particles possess new $U(1)$ gauge charge, related to the hidden sector of particle theory, they are created in pairs. The Coulomb-like attraction (mediated by the massless $U(1)$ gauge boson) between particles and antiparticles in these pairs can lead to their primordial binding, so that the annihilation in the bound system provides the mechanism for UHECR origin.

Note, first of all, that in quantum theory particle stability reflects the conservation law, which according to Noether's theorem is related with the existence of a conserved charge, possessed by the considered particle. Charge conservation implies that particle should be created together with its antiparticle. It means that, being stable, the considered superheavy particles should bear

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a conserved charge, and such charged particles should be created in pairs with their antiparticles at the stage of preheating.

Being created in the local process of inflaton field decay the pair is localised within the cosmological horizon in the period of creation. If the momentum distribution of created particles is peaked below $p \sim mc$, they don't spread beyond the proper region of their original localization, being in the period of creation $l \sim c/H$, where the Hubble constant H at the preheating stage is in the range $H_r \leq H \leq H_{end}$. Here H_{end} is the Hubble constant in the end of inflation and H_r is the Hubble constant in the period of reheating. For relativistic pairs the region of localization is determined by the size of cosmological horizon in the period of their derelativization. In the course of successive expansion the distance l between particles and antiparticles grows with the scale factor, so that after reheating at the temperature T it is equal to (here and further, if not indicated otherwise, we use the units $\hbar = c = k = 1$)

$$l(T) = \left(\frac{m_{Pl}}{H}\right)^{1/2} \frac{1}{T}. \qquad (1)$$

The averaged number density of superheavy particles n is constrained by the upper limit on their modern density. Say, if we take their maximal possible contribution in the units of critical density, Ω_X, not to exceed 0.3, the modern cosmological average number density should be

$$n = 4 \cdot 10^{-22} \frac{10^{14}\,\mathrm{GeV}}{m} \frac{\Omega_X}{0.3} T^3 \mathrm{cm}^{-3}.$$

It corresponds at the temperature T to the mean distance ($l_s \sim n^{-1/3}$) equal to

$$l_s \approx 1.6 \cdot 10^7 \left(\frac{m}{10^{14}\,\mathrm{GeV}}\right)^{1/3} \left(\frac{0.3}{\Omega_X}\right)^{1/3} \frac{1}{T}\,\mathrm{cm}. \qquad (2)$$

One finds that superheavy nonrelativistic particles, created just after the end of inflation, when $H \sim H_{end} \sim 10^{13}$ GeV, are separated from their antiparticles at distances more than 4 orders of magnitude smaller, than the average distance between these pairs. On the other hand, if the nonequilibrium processes of superheavy particles creation (such as decay of inflaton) take place in the end of preheating stage, and the reheating temperature is as low as it is constrained from the effects of gravitino decays on ^{6}Li abundance ($T_r < 4 \cdot 10^6$ GeV [10, 11]), the primordial separation of pairs, given by Eq.(1), can even exceed the value, given by Eq.(2). It means that the separation between particles and antiparticles can be determined in this case by their averaged density, if they were created at

$$H \leq H_s \sim 10^{-15} \cdot m_{Pl} \left(\frac{10^{14}\,\mathrm{GeV}}{m}\right)^{2/3} \left(\frac{\Omega_X}{0.3}\right)^{2/3} \sim$$
$$\sim 10^4 \left(\frac{\Omega_X}{0.3}\right)^{2/3} \mathrm{GeV}.$$

If the considered charge is the source of a long range field, similar to the electromagnetic field, which can bind particle and antiparticle into the atom-like system, analogous to positronium, it may have important practical implications for UHECR problem. The annihilation timescale of such bound system can provide the rate of UHE particle sources, corresponding to UHECR data.

The pair of particle and antiparticle with opposite gauge charges forms bound system, when in the course of expansion the absolute magnitude of potential energy of pair $V = \alpha_y/l$ exceeds the kinetic energy of particle relative motion $T_k = p^2/2m$. The mechanism is similar to the proposed in [12] for binding of magnetic monopole-antimonopole pairs. It is not a recombination one. The binding of two opositely charged particles is caused just by their Coulomb-like attraction, once it exceeds the kinetic energy of their relative motion.

In case, plasma interactions do not heat superheavy particles, created with relative momentum $p \leq mc$ in the period, corresponding to Hubble constant $H \geq H_s$, their initial separation, being of the order of

$$l(H) = \left(\frac{p}{mH}\right), \qquad (3)$$

experiences only the effect of general expansion, proportional to the inverse first power of the scale factor, while the initial kinetic energy decreases as the square of the scale factor. Thus, the binding condition is fulfilled in the period, corresponding to the Hubble constant H_c, determined by the equation

$$\left(\frac{H}{H_c}\right)^{1/2} = \frac{p^3}{2m^2\alpha_y H}, \qquad (4)$$

where H is the Hubble constant in the period of particle creation and α_y is the "running constant" of the long range $U(1)$ interaction, possessed by the superheavy particles. If the local process of pair creation does not involve nonzero orbital momentum, due to the primordial pairing the bound system is formed in the state with zero orbital momentum. The size of bound system strongly depends on the initial momentum distribution and for $p \leq mc$ equals

$$l_c = \frac{p^4}{2\alpha_y m^3 H^2} = 2\frac{\alpha_y}{m\beta^2}, \qquad (5)$$

where

$$\beta = \frac{2\alpha_y m H}{p^2}. \quad (6)$$

The annihilation timescale of this bound system can be estimated from the annihilation rate, given by

$$w_{\rm ann} = |\Psi(0)|^2 (\sigma v)_{\rm ann} \sim l_c^{-3} \frac{\alpha_y^2}{m^2} C_y, \quad (7)$$

where the "Coulomb" factor C_y arises similar to the case of a pair of electrically charged particle and antiparticle. For the relative velocity $v/c \ll 1$ it is given by [13] $C_y = 2\pi\alpha_y c/v$. Finally, taking $v/c \sim \beta$, one obtains for the annihilation timescale

$$\tau_{\rm ann} \sim \frac{1}{8\pi\alpha_y^5} \left(\frac{p}{mc}\right)^{10} \left(\frac{m}{H}\right)^5 \frac{1}{m} = \frac{4}{\pi m \beta^5}. \quad (8)$$

For $H_{end} \geq H \geq H_s$, the annihilation timescale equals

$$\tau_{\rm ann} = 2\cdot 10^{19} \left(\frac{1}{50\alpha_y}\right)^5 \left(\frac{p}{mc}\right)^{10} \times \times \left(\frac{10^4\,{\rm GeV}}{H}\right)^5 \left(\frac{m}{10^{14}\,{\rm GeV}}\right)^4 {\rm s}, \quad (9)$$

being for $p \sim mc$, $\alpha_y = 1/50$ and $m = 10^{14}$ GeV in the range from 10^{-26}s up to $2\cdot 10^{19}(0.3/\Omega_X)^{10/3}$ s. The size of a bound system is given by

$$l_c = 5\cdot 10^{-7} \left(\frac{p}{mc}\right)^4 \frac{m}{10^{14}\,{\rm GeV}} \left(\frac{10^4\,{\rm GeV}}{H}\right)^2 {\rm cm}, \quad (10)$$

ranging for $2\cdot 10^{-10} \leq \Omega_X/0.3 \leq 1$ from $7\cdot 10^{-7}$ cm to $6\cdot 10^{-3}$ cm.

Provided that the primordial abundance of superheavy particles, created on preheating stage corresponds to the appropriate modern density $\Omega_X \leq 0.3$, and the annihilation timescale exceeds the age of the Universe $t_U = 4\cdot 10^{17}$ s, owing to strong dependence on initial momentum p, the magnitude $r_X = \frac{\Omega_X}{0.3}\frac{t_U}{\tau_X}$ can reach the value $r_X = 2\cdot 10^{-10}$, which was found in [2] to fit the UHECR data by superheavy particle decays in the halo of our Galaxy.

In the case of late particle production (i.e. at $H \leq \leq H_s$) the binding condition can retain the form (4), if $l(H) \leq l_s$. In the opposite case, when $l(H) \geq l_s$, the primordial pairing is lost and even being produced with zero orbital momentum particles and antiparticles, originated from different pairs, in general, form bound systems with nonzero orbital momentum. The size of the bound system is in this case obtained from the binding condition for the initial separation, determined by Eq.(2), and it is equal to

$$l_c \approx \frac{10^{15}}{2\alpha_y m_{Pl}} \left(\frac{m}{10^{14}\,{\rm GeV}}\right)^{2/3} \left(\frac{0.3}{\Omega_X}\right)^{2/3} \left(\frac{p}{mc}\right)^2 \left(\frac{m}{H}\right). \quad (11)$$

The lifetime of the bound system can be reasonably estimated in this case with the use of the well known results of classical problem of the falling down the center due to radiation in the bound system of massive particles with opposite electric charges. The corresponding timescale is given by (see [14] for details)

$$\tau = \frac{l_c^3}{64\pi} \frac{m^2}{\alpha_y^2}. \quad (12)$$

Using the Eq.(11) and the condition $l(H) \geq l_s$, one obtains for this case the following restriction

$$r_X = \frac{\Omega_X}{0.3}\frac{t_U}{\tau_X} \leq 3\cdot 10^{-10} \left(\frac{\Omega_X}{0.3}\right)^5 \left(\frac{10^{14}\,{\rm GeV}}{m}\right)^9. \quad (13)$$

The gauge $U(1)$ nature of the charge, possessed by superheavy particles, assumes the existence of massless $U(1)$ gauge bosons (y-photons) mediating this interaction. Since the considered superheavy particles are the lightest particles bearing this charge, and they are not in thermodynamical equilibrium, one can expect that there should be no thermal background of y-photons and that their non equilibrium fluxes can not heat significantly the superheavy particles.

The situation changes drastically, if the superheavy particles possess not only new $U(1)$ charge but also some ordinary (weak, strong or electric) charge. Due to this charge superheavy particles interact with the equilibrium relativistic plasma (with the number density $n \sim T^3$) and for the mass of particles $m \leq \alpha^2 m_{Pl}$ the rate of heating $n\sigma v \Delta E \sim \alpha^2 T^3/m$ is sufficiently high to bring the particles into thermal equilibrium with this plasma. Here α is the running constant of the considered (weak, strong or electromagnetic) interaction.

Plasma heating causes the thermal motion of superheavy particles. At $T \leq m(\frac{m}{\alpha^2 m_{Pl}})^2$ their mean free path relative to scattering with plasma exceeds the free thermal motion path, so it is not diffusion, but free motion with thermal velocity v_T that leads to complete loss of initial pairing, since $v_T t$ formally exceeds l_s at

$$T \leq 10^{-10} m_{Pl} \left(\frac{\Omega_X}{0.3}\right)^{2/3} \left(\frac{10^{14}\,{\rm GeV}}{m}\right)^{5/3}.$$

While plasma heating keeps superheavy particles in thermal equilibium the binding condition $V \geq T_{\rm kin}$ can not take place. At $T < T_N$, (where $N = e$, QCD, w respectively, and $T_e \sim 100\,\mathrm{keV}$ for electrically charged particles; $T_{\mathrm{QCD}} \sim 300\,\mathrm{MeV}$ for coloured particles and $T_w \approx 20\,\mathrm{GeV}$ for weakly interacting particles, see [14] for details) the plasma heating is suppressed and superheavy particles go out of thermal equilibrium.

In the course of successive expansion the binding condition is formally reached at T_c, given by

$$T_c = T_N \alpha_y 3 \cdot 10^{-8} \left(\frac{\Omega_X}{0.3}\right)^{1/3} \left(\frac{10^{14}\,\mathrm{GeV}}{m}\right)^{1/3}. \quad (14)$$

However, for electrically charged particles, the binding in fact does not take place to the present time, since one gets from Eq.(14) $T_c \le 1\,\mathrm{K}$. Bound systems of hadronic and weakly interacting superheavy particles can form, respectively, at $T_c \sim 0.3\,\mathrm{eV}$ and $T_c \approx 20\,\mathrm{eV}$, but even for weakly interacting particles the size of such bound systems approaches a half of meter (30 m for hadronic particles!). It leads to extremely long annihilation timescale of these bound systems, that can not fit UHECR data. It makes impossible to realise the considered mechanism of UHECR origin, if the superheavy $U(1)$ charged particles share ordinary weak, strong or electromagnetic interactions.

Disruption of primordial bound systems in their collisions and by tidal forces in the Galaxy reduces their concentration in the regions of enhanced density. Such spatial distribution, specific for these UHECR sources, makes possible to distinguish them from other possible mechanisms [4, 9, 15] in the future AUGER and EUSO experiments.

The crucial physical condition for the formation of primordial bound systems of superheavy particles is the existence of new strictly conserved local $U(1)$ gauge symmetry, ascribed to the hidden sector of particle theory. Such symmetry can arise in the extended variants of GUT models (see e.g. [10] for review), in heterotic string phenomenology (see [13] and references wherein) and in D-brane phenomenology [16]. Note, that in such models the strictly conserved $SU(2)$ symmetry can also arise in the hidden sector, what leads to a nontrivial mechanism of primordial binding of superheavy particles due to macroscopic size $SU(2)$ confinement, as it was the case for "tetons" [17].

The proposed mechanism offers the link between the observed UHECRs and the predictions of particle theory, which can not be tested by any other means and on which the analysis of primordial pairing and binding can put severe constraints. If viable, the considered mechanism makes UHECR the unique source of detailed information on the possible properties of the hidden sector of particle theory and on the physics of very early Universe.

The work was partially performed in the framework of State Contract # 40.022.1.1.1106 and supported in part by RFBR grant # 02-02-17490 and grant UR.02.01.026. One of us (MYuKh) expresses his gratitude to IHES, LUTH (Observatory Paris-Meudon) for hospitality and the both authors are grateful for support of their visit to College de France (Paris, April 2002). We are grateful to D.Fargion and S.Sarkar for useful comments.

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