Ultra-High Energy Cosmic Rays and Superheavy Particles in the Universe.

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Abstract

In this lecture we conjecture that the Ultra-High Energy Cosmic Rays (UHECR) with energies $E > E_{GZK}$, where $E_{GZK} \sim 5 \cdot 10^{19}$ eV is the Greisen–Zatsepin–Kuzmin cut-off energy of cosmic ray spectrum, may originate from decays of superheavy long-living X-particles populating the Universe thus providing a unique window into the very early epoch of the Universe, namely, that of preheating and reheating after inflation. These particles may constitute a considerable fraction of cold dark matter in the Universe. We argue that the unconventionally long lifetime of the superheavy particles, which should be in the range of $10^{10} - 10^{22}$ years, might require novel particle physics mechanisms of their decays, such as instantons. First of all I will describe a toy model illustrating the instanton scenario and then will describe the possible proper mechanism of creation of superheavy particles in the early Universe. It is my pleasure to emphasize that all I will talk about was done in collaboration with my friends V.A. Rubakov and I.I. Tkachev.

1. Among the top-down mechanisms attempting to explain the observations [2] of ultra-high energy (UHE) cosmic rays beyond the Greisen–Zatsepin–Kuzmin cut-off [1] , decays of primordial heavy particles are most obvious possibility. It is clearly more conventional — at least at first sight — than scenarios invoking topological or non-topological defects [19], though the latter may be a viable alternative. Heavy particles with lifetime of the order of the age of the Universe or greater may constitute (a substantial fraction of) cold dark matter, so the two observed features of the Universe — ultra-high energy cosmic rays and dark matter — may be related to each other.

To get an idea of the range of properties of decaying particles (X-particles) that supposedly produce UHE cosmic rays, let us make the following simple observations.

First, assuming sizeable hadronic component (jets) among the decay products, the flux of protons or gammas of energy E on the Earth is estimated as

$$\frac{dF}{d\ lnE} = \frac{1}{4\pi}\frac{n_X}{\tau_X} R_{p,\gamma} N_j \frac{dN_{p,\gamma}(E)}{d\ lnE}, \tag{1}$$

where N_j is the number of jets in a typical decay, $R_{p,\gamma}$ is the effective distance to X-particles, n_X is the number density of X-particles at the scale $R_{p,\gamma}$, τ_X is the X-particle lifetime and $dN/d\ lnE$ is the fragmentation function. In the following estimates we take $N_j \sim 1-10$ (we will soon see that large jet multiplicity may be favored in some decay scenarios) and $dN_{p,\gamma}/d\ lnE \sim$ (a few) $\cdot$ $(10 - 100)$ in the energy range of interest, $E >$ (a few) $\cdot\, 10^{10}$ GeV (the latter estimate comes from bold extrapolation of the fragmentation functions of ref.[20] to extremely high jet energies). For the effective distance we take $R \lesssim 100$ Mpc, with understanding that the actual value of R may be much smaller than 100 Mpc if X-particles are clumped. In fact, our conclusions will be fairly insensitive to the actual values of the above parameters.

The second relation is

$$m_X < n_X >= \Omega_X \rho_{crit}, \tag{2}$$

where $< n_X >$ is the average number density of X-particles and $\Omega_X \lesssim 1$. If X-particles are clumped, the density n_X entering Eq.(2) may be several orders of magnitude larger than $< n_X >$. Again, this uncertainty will not affect our main conclusions, and we set $n_X \sim\ < n_X >$ in what follows. In order to produce cosmic rays of energies $E \gtrsim$ (a few) $\cdot\, 10^{11}$ GeV, the mass of X-particles is to be very large, $m_X \gtrsim 10^{13}$ GeV.

Let us now estimate the range of X-particle densities required. From Eq.(2) we find a bound for the present X-particle density-to-entropy ratio

$$n_X/s \lesssim 10^{-21}. \tag{3}$$

On the other hand, to produce the observed flux of UHE cosmic rays, the density of X-particles should not be too small. Keeping in mind that their lifetime, τ_X, cannot be much smaller than the age of the Universe,

$$\tau \gtrsim 10^{10}\ yr, \tag{4}$$

we obtain from Eq.(3)

$$n_X/s \gtrsim 10^{-33}. \tag{5}$$

Even though the window for n_X is very wide, the estimates (3) and (5) raise the issue of the production of X-particles in the early Universe.

Alternatively, Eqs.(3) and (5) may be used to place an upper bound on the lifetime of X-particles,

$$\tau_X \lesssim 10^{22}\ yr. \tag{6}$$

Again, the window for τ_X is wide, but the estimates (5) and (6) indicate another problem, namely, that of the particle physics mechanism responsible for long but finite lifetime of very heavy particles.

In the rest of this paper we propose possible scenarios for i) generating the abundance of X-particles in the range (3), (5) by processes in the early Universe, and ii) explaining the lifetime of X-particles in the range (4), (6).

Before coming to our main points, let us stress that these two problems inherent in theories with very heavy and almost stable particles were realized long ago (see, e.g., ref.[21] and references therein) in different contexts. In ref.[21] it was proposed that the problem i) may be solved by large entropy generation in the Universe after the heavy particles freeze out of thermal equilibrium, while their long lifetime may be due to very large dimension of operators responsible for the decay. We leave for the reader to judge how exotic are alternative possibilities that we discuss below.

2. If the temperature in the early Universe at some epoch exceeded the mass of X-particles and then decreased smoothly without large entropy generation, the freeze-out density of X-particles would greatly exceed the bound (3). A way out of this problem is provided by inflation and subsequent reheating. To explain the small abundance of X-particles, the reheating temperature T_r must be much smaller than m_X, so that X-particles were never at thermal equilibrium after inflation. In that case X-particles-to-entropy ratio is exponentially small,

$$n_X/s = \text{const}\cdot\exp(-2m_X/T_r), \tag{7}$$

where the constant depends on a number of factors (the coupling constant responsible for pair production of X-particles, the effective number of degrees of freedom, the ratios m_X/T_r and M_{Pl}/m_X, etc.) and is of order 10^{-3} with several orders of magnitude uncertainty. As the dominant suppression comes from the exponential factor, the reheating temperature can be estimated from (3), (5) fairly precisely,

$$T_r = \left(\frac{1}{20} - \frac{1}{35}\right) m_X, \tag{8}$$

and should be in the range $10^{11} - 10^{15}$ GeV, depending on m_X. Note that this range is realistic in many scenarios of inflation.

Hence, inflationary scenario can easily explain small value of the present density of X-particles in the space. Conversely, the determination of m_X from measurements of the upper end of cosmic ray spectrum would allow for rather precise estimate of the reheating temperature. Ultra-high energy cosmic rays may indeed serve as a window to reheating epoch in the early Universe.

3. Explaining long lifetime of X-particles is much harder. Conventional perturbative mechanisms cannot be responsible for cosmologically large τ_X (unless very high dimension operators are involved [21]), so one turns naturally to non-perturbative phenomena. A well known example is instantons that produce exponentially small effects in weakly coupled theories. If instantons are responsible for X-particle decays, the lifetime is roughly estimated as

$$\tau_X \sim m_X^{-1} \cdot \exp(4\pi/\alpha_X), \tag{9}$$

where α_X is the coupling constant of the relevant (spontaneously broken) gauge symmetry. From Eqs.(4), (6) we find that the coupling constant (at the scale m_X) is

$$\alpha_X = \frac{1}{10} - \frac{1}{12}. \tag{10}$$

Hence, we are lead to introduce additional non-Abelian gauge interactions with fairly large coupling constant at high energy scale.

To illustrate this possibility let us consider a toy model with $SU(2)_X$ gauge interactions added to the Standard Model. The $SU(2)_X$ gauge symmetry is assumed to be broken at sufficiently high energy scale. Some conventional quarks and leptons carry non-trivial $SU(2)_X$ quantum numbers (say, $SU(2)_X$ may be right-handed subgroup of a left-right symmetric theory, or it may be a horizontal group with generations forming $SU(2)_X$ triplets). Let there be two[1] left-handed $SU(2)_X$ fermionic doublets X and Y and four right-handed singlets, all of which are singlets under $SU(2)_L \times SU(3)_c$ of the Standard Model. After $SU(2)_X$ breaks down, all X- and Y-particles acquire large masses in a manner similar to the Standard Model. We further assume that X and Y carry different global quantum numbers, so there is no mixing between them.

Under these assumptions the lightest of X-particles and the lightest of Y-particles (we call them X and Y at certain risk of confusing notations) are perturbatively stable. However, $SU(2)_X$ instantons induce effective interactions violating global quantum numbers of X and Y. Say, if X is heavier than Y, then $SU(2)_X$-instantons lead to the decay

$$X \to Y + quarks + leptons \tag{11}$$

with the rate estimate given by Eq.(9). It is this type of processes that may be responsible for the production of ultra-high energy cosmic rays.

Let us point out a few features of this scenario which seem generic.

i) Decays induced by instantons typically lead to multiparticle final states. The number of quarks (jets) produced in the process (11) should be rather large, of order 10, and their distribution in energy should be fairly flat. In principle, the spectrum of cosmic rays within this scenario should be distinguishable from the spectrum predicted by other mechanisms (like two-jet decays of heavy particles born in the interactions of topological defects). Also, there are necessarily hard leptons among the decay products in the process (11).

ii) If Y-particles are indeed perturbatively stable, they are also stable against instanton-induced interactions (because of energy conservation and instanton selection rules). Then the dark matter in the Universe may consist predominantly of Y-particles, while the admixture of X-particles is small. Since the abundance of Y-particles is given by the formula similar to Eq.(7), and since the density of X-particles is bounded from above, Eq.(5), the mass splitting between X- and Y-particles should not be large,

$$m_X < 2m_Y. \tag{12}$$

Alternatively, the Higgs sector and its interactions with fermions may be organized in such a way that Y-particles are in fact perturbatively unstable (while X-particles remain perturbatively stable). In that case the heavy candidates for dark matter are X-particles, and the approximate degeneracy (12) need not hold.

[1] The $SU(2)_X$ anomaly prevents the number of $SU(2)_X$ doublets from being odd.

iii) Because of the instanton selection rules, this scenario for the slow decay of heavy particles is rather restrictive. For example, X-particles cannot be colored (otherwise the $SU(2)_X$ instanton vertex would include at least three X-fields); if Y-particles are stable, they cannot be colored either. This fits nicely to the expectation that dark matter particles do not experience strong interactions. On the other hand, X-particles (and Y-particles, if stable) cannot be weak doublets for the same reason, so the heavy dark matter in this scenario does not have electroweak interactions, too.

To conclude, an explanation of ultra-high energy cosmic ray events beyond the GZK cut-off by decays of hypothetical heavy particles of cosmologically long lifetime is not unrealistic from both cosmological and particle physics points of view. Detailed study of the upper end of cosmic ray spectrum will provide insight into the decay mechanism involved, and allow for the determination of the mass of X-particles. As the latter has been argued to be related to the reheating temperature, the ultra-high energy cosmic rays may become a clue to the end-of-inflation epoch in the early Universe.

After this work was completed , we received a paper by Berezinsky, Kachelriess and Vilenkin [22] where the decays of heavy particles have been also considered as the origin of cosmic rays beyond the GZK cut-off. Their main point is that X-particles are expected to concentrate in the galactic halo, and in this way one easily avoids the constraints coming from the analysis of the cascade radiation [23]. Their proposal for long but finite lifetime of X-particles is that it is due to quantum gravity (wormhole) effects.

Now I would like to consider yet another problem concerning the population of the Universe with superheavy particles.

According to the Greisen-Zatsepin-Kuzmin [1] (GZK) bound, the Ultra High Energy (UHE) cosmic rays produced in any known candidate extra galactic source should have an exponential cut-off at energies $E \sim 5 \times 10^{10}$ GeV. On the other hand, the number of observed [2] cosmic rays events beyond the cut-off is growing and leads to a mounting paradox within standard frameworks of cosmological and particle physics models.

A wide variety of possible solutions were suggested. Resolution could be due to exotic particle which may be produced at cosmological distances were suitable conventional accelerators are found, be transmitted evading GZK bound, and yet which interact in the atmosphere like a hadron. A particle with correct properties was found in a class of supersymmetric theories [3]. Alternatively, high energy cosmic rays may have been produced locally. One possibility is connected to the events of destruction of (topological) defects [4], while another one to decays of primordial heavy long-living particles [5, 6]. The candidate particle must obviously obey constraints on the mass, density and lifetime.

In order to produce cosmic rays of energies $E \gtrsim 10^{11}$ GeV, the mass of X-particles has to be very large, $m_X \gtrsim 10^{13}$ GeV [5, 6]. The lifetime, τ_X, cannot be much smaller than the age of the Universe, $\tau \gtrsim 10^{10}$ yr. With this smallest value of the lifetime, the observed flux of UHE cosmic rays will be reproduced with rather low density of X-particles, $\Omega_X \sim 10^{-12}$, where $\Omega_X \equiv m_X n_X/\rho_{\rm crit}$, n_X is the number density of X-particles and $\rho_{\rm crit}$ is the critical density. On the other hand, X-particles must not overclose the Universe, $\Omega_X \lesssim 1$. With $\Omega_X \sim 1$, the X-particles may play the role of cold dark matter and the observed flux of UHE cosmic rays can be matched if $\tau_X \sim 10^{22}$ yr. The allowed windows are quite wide [5], but on exotic side, which may rise problems.

The problem of the particle physics mechanism responsible for a long but finite lifetime of very heavy particles can be solved in several ways. For example, otherwise conserved quantum number carried by the X-particle may be broken very weakly due to instanton transitions [5], or quantum gravity (wormhole) effects [6]. If instantons are responsible for X-particle decays, the lifetime is roughly estimated as $\tau_X \sim m_X^{-1} \cdot \exp(4\pi/\alpha_X)$, where α_X is the coupling constant of the relevant (spontaneously broken) gauge symmetry. Lifetime will fit the window if the coupling constant (at the scale m_X) is $\alpha_X \approx 0.1$ [5].

X-particles can be produced in the right amount by usual collision and decay processes if the reheating temperature after inflation never exceeded m_X, but the temperature should be in the range $10^{11} \lesssim T_r \lesssim 10^{15}$ GeV, depending on m_X, [5, 6]. This is a rather high value of reheating temperature and will lead to the gravitino problem in generic supersymmetric models [7].

In the present paper we investigate another process of X-particle creation, namely the direct production from vacuum fluctuations during inflation.

Any viable modern cosmological model invokes the hypothesis of inflation [8]. During inflation the Universe expands exponentially, which solves the horizon and flatness problems of the standard Big-Bang cosmology. Inflation is generally assumed to be driven by the special scalar field ϕ known as the *inflaton.* Fluctuations generated at inflationary stage can have strength and the power spectrum suitable for generation of the large scale structure. This fixes the range of parameters in the inflaton potential. For example, the mass of the inflaton field has to be $m_\phi \sim 10^{13}$ GeV. During inflation, the inflaton field slowly rolls down towards the minimum of its potential. Inflation ends when the potential energy associated with the inflaton field became smaller than the kinetic energy. At that time all the energy of the Universe is contained entirely in the form of coherent oscillations of the inflaton field around the minimum of its potential. It is possible that a significant fraction of this energy is released to other Boson species after only a dozen or so inflaton field oscillations, in the regime of a broad parametric resonance [9]. This process was studied in details [10, 11]. Even particles with masses of order of magnitude larger than the inflaton mass can be produced quite abundantly. Applying these results to the case of our interest here, we find that stable very heavy particles, $m_X \gtrsim m_\phi$, generally will be produced in excess and will overclose the Universe.

However, if the parametric resonance is ineffective for some reason, and we estimate particle number density after inflation at the level of initial conditions used in Refs. [10], we find that Ω_X might prove to be of about the right magnitude. This level is saturated by the fundamental process of particle creation during inflation from *vacuum fluctuations* and it is the same process which generated primordial large scale density fluctuations. Parametric resonance for X particles is turned-off if X is either a fermion field or its coupling to inflaton is small, $g^2 \ll 10^4 (m_X/m_\phi)^4 (m_\phi/M_{\rm Pl})^2$ [10].

At some early epoch the metric of the Universe is conformally flat to a high accuracy, $ds^2 = a(\eta)^2 (d\eta^2 - d\mathbf{x}^2)$. We normalize the scale factor by the condition $a(0) = 1$ at the end of inflation. Number density of particles created in time varying cosmological background can be written as

$$n_X = \frac{1}{2\pi^2 a^3} \int |\beta_k|^2 k^2 dk \ , \tag{13}$$

where β_k are the Bogoliubov coefficients which relate "in" and "out" mode functions, and k is the comoving momentum. Massles conformally coupled particles (for scalars this means that $\xi = 1/6$ in the direct coupling to the curvature) are not created. For massive particles conformal invariance is broken. Therefore, for the power low (e.g., matter or radiation dominated) period of expansion of the Universe, one expects on dimensional grounds, $n_X \propto m_X^3/a^3$ at late times.

Indeed, it was found in Ref. [12]

$$n_X \approx 5.3 \times 10^{-4} m_X^3 \left(m_X t\right)^{-3/2} , \tag{14}$$

for the radiation dominated Universe, and $n_X \propto m_X^3 \left(m_X t\right)^{-3q}$ for $a(t) \propto t^q$. Note that all particle creation occur in the region $mt = qm/H \lesssim 1$. When $mt \ll 1$, the number density of created particles remains on the constant level $n_X = m_X^3/24\pi^2$ independent of q [12]. At $qm/H \gg 1$ particle creation is negligible. Here H is the Hubble constant, $H \equiv \dot{a}/a$.

For the radiation dominated Universe one finds, $\Omega_X \sim (m_X^2/M_{\rm Pl}^2)\sqrt{m_X t_e}$, where t_e is time of equal densities of radiation and matter in $\Omega = 1$ Universe. This gives $\Omega_X \sim m_9^{5/2}$, where $m_9 \equiv m_X/10^9$ GeV. Stable particles with $m_X \gtrsim 10^9$ GeV will overclose the Universe even if they were created from the vacuum during regular Friedmann radiation dominated stage of the evolution. It is possible to separate vacuum creation from creation in collisions in plasma since X-particles may be effectively sterile.

This restriction can be overcomed if evolution of the Universe, as it is believed, was more complicated than simple radiation dominated expansion from singularity. Hubble constant may have never exceeded m_X, which is the case of inflation, $H(0) \approx m_\phi$. Moreover, compared to the case considered above, density of X-particles created during inflation is additionally diluted by late entropy release in reheating after inflation.

Particle creation from vacuum fluctuations during inflation (or in de Sitter space) was extensively studied [13, 14]. Characteristic quantity which is usually cited, the variance of the field $\langle X^2 \rangle$, is defined by an expression similar to Eq. (13). In the typical case $\alpha_k \approx -\beta_k$ the difference is given by the factor $2\sin^2(\omega_k\eta)/\omega_k$ in the integrand, where $\omega_k^2 = k^2 + a^2 m_X^2$. If $m_X \sim H(0) \approx m_\phi$, one has on dimensional grounds $n_X = C m_\phi^3/2\pi^2 a^3$ where the coefficient C is expected to be somewhat smaller than unity. Both Fermions and Bosons are prodused by this mechanism, exact numerical value of C being dependent on spin-statistics. In general, C is the function of the ratio $H(0)/m_X$, the function of self-coupling of X and the coupling ξ, depends on details of the transition between inflationary and matter (or radiation) dominated phases, etc. For example, for the scalar Bose-field, $\langle X^2 \rangle = 3H(0)^4/8\pi^2 m_X^2$ if $m_X \ll H(0)$. For massless self-interacting field $\langle X^2 \rangle \approx 0.132 H(0)^2/\sqrt{\lambda}$. C is expected to decrease exponentially when $m_X > m_\phi$.

Let us estimate the today's number density of X-particles. We consider massive inflaton, $V(\phi) = m_\phi^2 \phi^2/2$. In this case inflation is followed by the matter domination stage. If there are light Bosons in a theory, $m_B \ll m_\phi$, even relatively weakly coupled to the inflaton, $g^2 \gtrsim 10^4 m_\phi^2/M_{\rm Pl}^2 \sim 10^{-8}$, this matter domination stage will not last long: inflaton will decay via parametric resonance and the radiation domination follows. This happens typically when the energy density in inflaton oscillations is redshifted by a factor $r \approx 10^{-6}$ compared to a value $m_\phi^2 M_{\rm Pl}^2$. Matter is still far from being in the thermal equilibrium, but it is still convenient to characterize this radiation dominated stage by an equivalent temperature, $T_* \sim r^{1/4}\sqrt{m_\phi M_{\rm Pl}}$. At this moment the ratio of energy density in X-particles to the total energy density retains its value reached at the end of inflation, $\rho_X/\rho_R \approx C\, m_\phi m_X/2\pi^2 M_{\rm Pl}^2$. Later on this ratio grows as $\propto T/T_*$ and reaches unity at $T = T_{\rm eq}$, where

$$T_{\rm eq} = \frac{C r^{1/4}}{2\pi^2} \left(\frac{m_\phi}{M_{\rm Pl}}\right)^{3/2} m_X \, . \tag{15}$$

Using relation $T_{\rm eq} = 5.6\Omega_X h^2$ eV we find that $10^{-12} \lesssim \Omega_X \lesssim 1$ if

$$10^{-23} \lesssim Cr^{1/4} m_X/m_\phi \lesssim 10^{-11}\,. \tag{16}$$

For $m_X \sim$ (a few) $\cdot$ m_ϕ this condition can be easily satisfied since the coefficient C is exponentially small. This condition may be satisfied even for $m_X \sim m_\phi$ since the coefficient $r^{1/4}$ (or equivalent reheating temperature) can be small too.

Our hypothesis has unique observational consequences. If UHE cosmic rays are indeed due to decay of superheavy particles which were produced from vacuum fluctuations during inflation, there has to be a new sharp cut-off in the cosmic ray spectrum at energy somewhat smaller m_X. Since the number density n_X depends exponentially upon m_X/m_ϕ, the position of this cut-off might be well predicted and has to be near $E_{\rm cut-off} < m_\phi \approx 10^{13}$ GeV, the very shape of the cosmic ray spectrum beyond the GZK cut-off being of quite generic form following from the QCD quark/gluon fragmentation. The Pierre Auger Project installation, the OWL project, the Telescope Array project might prove to be able to discover this fundamental phenomenon.

We conclude, observation of Ultra High Energy cosmic rays can probe the spectrum of elementary particles in its superheavy range and can be an additional opportunity (alongside with fluctuations in cosmic microwave background) to study the earliest epoch of the Universe evolution, starting from amplification of vacuum fluctuations during inflation through fine details of gravitational interaction and down to physics of reheating.

When our paper was at the very end of completion we became aware of the quite recent paper by Chung, Kolb and Riotto [18] where similar problems of superheavy dark matter creation were considered.

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