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Ultra-High Energy Cosmic Rays, Superheavy Long-Living Particles, and Matter Creation after Inflation

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Abstract

The highest energy cosmic rays, above the Greisen–Zatsepin–Kuzmin cut-off of cosmic ray spectrum, may be produced in decays of superheavy long-living X-particles. We conjecture that these particles may be produced *naturally* in the early Universe from *vacuum fluctuations* during inflation and may constitute a considerable fraction of Cold Dark Matter. We predict a new cut-off in the UHE cosmic ray spectrum $E_{\rm cut-off} < m_{\rm inflaton} \approx 10^{13}$ GeV, the exact position of the cut-off and the shape of the cosmic ray spectrum beyond the GZK cut-off being determined by the QCD quark/gluon fragmentation. The Pierre Auger Project installation might discover this phenomenon.

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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

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

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]

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

for the radiation dominated Universe, and $n_X \propto m_X^3 \, (m_X t)^{-3q}$ 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. (1). 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 produsedby 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 $m_X \ll H(0)$ [13,14]. For massless self-interacting field $\langle X^2 \rangle \approx 0.132 H(0)^2/\sqrt{\lambda}$ [15]. C is expected to decrease exponentially when $m_X > m_\phi$. Particle creation in the case of Hubble dependent effective mass, $m_X(t) \propto H(t)$, was considered in Ref. [16].

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 $m_\phi^2 M_{\rm Pl}^2$ [9,10]. 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

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

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

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

For $m_X \sim$ (a few) $\cdot$ m$_\phi$ 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 [17] 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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