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ULTRA HIGH ENERGY COSMIC RAYS, SUPERHEAVY LONG-LIVING PARTICLES, AND MATTER CREATION AFTER INFLATION

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Cosmic rays of the highest energy, above the Greisen – Zatsepin – Kuzmin (GZK) cut-off of the spectrum, may originate in decays of superheavy long-living 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 Ultra High Energy cosmic ray spectrum $E_{cut-off} < m_{inflaton} \approx 10^{13}$ 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 may in principle observe this phenomenon.

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According to the Greisen – Zatsepin – Kuzmin [1] (GZK) observation , the energy spectrum of Ultra High Energy (UHE) cosmic rays produced at far extragalactic distances should exhibit an exponential cut-off at energy $E \sim 5 \cdot 10^{10}$ GeV. However, a number of cosmic ray events with energies well beyond the predicted GZK cut-off were observed recently by the various experimental groups [2]. This is an obvious contradiction with the standard cosmological and particle physics models and clearly requires some new physics beyond the Standard Model.

A number of possible solutions to the problem were suggested. One solution to the problem might be provided, for example, by the existence of some exotic particles which are able to propagate (evading the GZK bound) from cosmological distances and yet interact in the Earth's atmosphere like a hadron. A particle with such conflicting properties

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was found in a class of supersymmetric theories [3]. Alternatively, high energy cosmic rays may have been produced locally within the GZK distance. One possibility is connected with the destruction of topological defects [4], while another one is connected with decays of primordial heavy long-living particles [5, 6]. The candidate X-particle must obviously obey constraints on mass, density and lifetime.

In order to produce cosmic rays in the energy range $E \gtrsim 10^{11}$ 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, $\tau \approx 10^{10}$ yr. With such a short lifetime, the observed flux of UHE cosmic rays will be generated with the rather low density of X-particles, $\Omega_X \sim 10^{-12}$, where $\Omega_X \equiv m_X n_X / \rho_{crit}$, n_X is the number density of X-particles and ρ_{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 the exotic side, which may give rise to some 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 X-particles 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 estimated as $\tau_X \sim m_X^{-1} \cdot \exp(4\pi/\alpha_X)$, where α_X is the coupling constant of the relevant gauge interaction. The lifetime will fit the allowed window if the coupling constant (at the scale m_X) is $\alpha_X \approx 0.1$ [5].

The X-particles might be produced in the proper amount by collision and decay processes in cosmological plasma if the reheating temperature after inflation never exceeds 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, which may lead to the gravitino problem in generic supersymmetric models [7].

In the present paper we propose a quite different mechanism of X-particle creation, namely, their direct production by 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 may have the strength and the power spectrum suitable for generation of the large scale structure. This fixes the range of parameters of the inflaton effective 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 becomes smaller than the kinetic energy. Coherent oscillations of the inflaton field contained all the energy of the Universe at that time. It is possible that a significant fraction of this energy was released to other boson species after only a dozen oscillations of the inflaton field, in the regime of a broad parametric resonance [9]. This process was studied in detail [10, 11]. It was shown that even rather heavy particles with masses by an order of magnitude larger than the inflaton mass can be produced quite copiously. Applying these results to the case of our interest, we find that the stable very heavy particles, $m_\phi \lesssim m_X \lesssim 10\, m_\phi$, will be generally produced in excess and will overclose the Universe.

However, if the parametric resonance is ineffective for some reason, and one estimates the particle number density after inflation at the level of initial conditions used in Refs. [10], one finds that Ω_X might prove to be of the acceptable 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 perturbations. Parametric resonance for X particles is turned off if X field is either a fermion field or its coupling to inflaton is small, $g^2 \ll 10^4 (m_X/m_\phi)^4 (m_\phi/M_{Pl})^2$ [10].

At the epoch close to the end of inflation, the metric of the Universe is conformally flat, $ds^2 = a(\eta)^2 (d\eta^2 - d\mathbf{x}^2)$. We normalize the scale factor by the condition $a(0) = 1$, with $\eta = 0$ corresponding to the end of inflation. The number density of particles created in a time varying cosmological background may 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 co-moving momentum. Massless conformally coupled quanta (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-law (e.g., matter or radiation dominated) period of expansion of the Universe, one expects on dimensional grounds that $n_X \propto m_X^3/a^3$ 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 occurs at $mt \simeq qm/H \lesssim 1$. When $mt \ll 1$, the number density of created particles remains on the constant level $n_X = m_X^3/24\pi^2$ independently of q [12] while at $qm/H \gg 1$ the particle creation is negligible. Here H is the Hubble constant, $H \equiv \dot{a}/a$.

For the radiation dominated Universe one finds, $\Omega_X \sim (m_X^2/M_{Pl}^2)\sqrt{m_X t_e}$, where t_e is the 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 the regular Friedmann radiation dominated stage of the evolution. (It is possible to separate the vacuum creation from the creation in collisions in plasma since X-particles may be effectively sterile.)

However, this restriction will not be valid if the evolution of the Universe, as it is believed, was more complicated than the simple radiation dominated expansion from a singularity. The Hubble constant may have never exceeded m_X, which is the case of inflationary cosmology, $H(0) \approx m_\phi$. Moreover, compared to the case considered above, the density of X-particles created during inflation is additionally diluted by the late entropy release in reheating processes after inflation.

Particle creation from vacuum fluctuations during inflation (or in the de Sitter space) was extensively studied, see e.g. Refs [13, 14]. The characteristic quantity which is usually cited, namely 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 reduces to 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 $m_X \sim H(0) \approx m_\phi$, we find using dimensional arguments $n_X = C m_\phi^3 / 2\pi^2 a^3$, where the coefficient C is expected to be somewhat smaller than unity. Both fermions and bosons are produced by this mechanism, the exact numerical value of C being dependent on the spin-statistics. In general, C is the function of the ratio $H(0)/m_X$, of the self-coupling of X and the coupling constant ξ, and depends on details of the transition between inflationary and matter (or radiation) dominated phases, etc. For example, for the scalar Bose field with the minimal coupling to the curvature, $\langle X^2 \rangle = 3H(0)^4/8\pi^2 m_X^2$ 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 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 dominated stage. If there are light bosons in a theory, $m_B \ll m_\phi$, even relatively weakly coupled to the inflaton, $g^2 \gtrsim 10^4 m_\phi^2/M_{Pl}^2 \sim 10^{-8}$, this matter dominated stage will not last long: the inflaton will decay via parametric resonance and radiation domination will follow. This happens typically when the energy density in the inflaton oscillations is red-shifted by a factor $r \approx 10^{-6}$ compared to the value $m_\phi^2 M_{Pl}^2$ [9, 10]. Matter is still far from being in thermal equilibrium, but it is nevertheless convenient to characterize this radiation dominated stage by an equivalent temperature, $T_* \sim r^{1/4}\sqrt{m_\phi M_{Pl}}$. At this moment the ratio of the energy density in X-particles to the total energy density retains its value reached at the end of inflation, $\rho_X/\rho_R \approx C m_\phi m_X/2\pi^2 M_{Pl}^2$. Later on this ratio grows as $\propto T/T_*$ and reaches unity at $T = T_{eq}$, where

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

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

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

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 the equivalent reheating temperature) might be small, too.

Our hypothesis has unique observational consequences. If UHE cosmic rays are indeed due to the 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 energies somewhat smaller than m_X. Since the number density n_X depends exponentially upon m_X/m_ϕ, the position of this cut-off is fixed and can be predicted to be near $m_\phi \approx 10^{13}$ 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] may prove to be able to discover this fundamental phenomenon.

We conclude that the observations of UHE cosmic rays can probe the spectrum of elementary particles in the superheavy range and can give an unique opportunity for investigation of the earliest epoch of evolution of the Universe, starting with the amplification of vacuum fluctuations during inflation through fine details of gravitational interaction and down to the 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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