Do active galactic nuclei convert dark matter into visible particles?

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Abstract

The hypothesis that dark matter consists of superheavy particles with the mass close to the Grand Unification scale is investigated. These particles were created from vacuum by the gravitation of the expanding Universe and their decay led to the observable baryon charge. Some part of these particles with the lifetime larger than the time of breaking of the Grand Unification symmetry became metastable and survived up to the modern time as dark matter. However in active galactic nuclei due to large energies of dark matter particles swallowed by the black hole the opposite process can occur. Dark matter particles become interacting. Their decay on visible particles at the Grand Unification energies leads to the flow of ultra high energy cosmic rays observed by the Auger group. Numerical estimates of the effect leading to the observable numbers are given.

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1 Introduction

In our papers \cite{1} the hypothesis of superheavy dark matter was discussed. The main argument for this hypothesis is that calculation of particle creation from vacuum of the expanding Friedmann Universe gives finite numerical result for the number of particles coinciding with the observable baryon charge of the Universe (the Eddington-Dirac number) only for particles masses close to the Grand Unification (GU) scale. Supposing that at the GU energies these particles decayed on quarks and leptons with breaking of the \(CP\)-symmetry one obtains the observable baryon charge of the Universe. Superheavy \(X\)-particles with some charge are created by gravitation in particle-antiparticle pairs but they decay similar to \(K^0\)-meson decay as short living and long living components. It is short living component which decays on visible matter at the GU time, long living component particles survive and if their lifetime is larger than the time of breaking of the GU symmetry they become metastable and form dark matter observed today.

If similar to the \(K^0\)-meson theory these long living component particles can interact with the baryon charge then one finds that some part of \(X\)-particles disappeared in the early Universe and was transformed into light particles giving the entropy of the Universe. To get the observable density of dark matter one must have the cross-section of such interaction \(\sigma \approx 10^{-40} \text{sm}^2\), i.e. weak interaction.

Recently the Auger group published their results on observation of the ultra high energy cosmic rays (UHECR) coming from active galactic nuclei (AGN) of Galaxies close to our Galaxy \cite{2}. 27 events with energies \(E > 57 \cdot 10^{18} \text{eV}\) were registered.

So it seems that protons of such energies can be formed at AGN. What is the mechanism of creation of protons of such high energies at AGN? From our point of view the natural mechanism for this effect is conversion of superheavy dark matter into visible one near AGN.

The AGN is formed by the supermassive black hole. This black hole acts as a cosmic supercollider in which superheavy particles of dark matter are accelerated close to the horizon to the GU energies. For \(X\)-particles these energies are of the order of their mass and such energies are quickly obtained in a short time.

The difference of our mechanism from the usual acceleration of proton is important. Superheavy dark matter particles colliding close to the horizon are converted into light particles carrying the huge momenta so they can escape the vicinity of the black hole. The large mass of the \(X\)-particle is converted into energy. Colliding protons even in case of getting a large momentum due to the accelerating of the black hole in their back movement loose this momentum and cannot come to the Earth.

But due to our scenario of the creation of the vis-
ible matter at this energies dark matter particles are not WIMPS (weak interacting particles) and can be converted into visible particles. The probability of this conversion of long living components into decaying short living ones is defined by the nondiagonal terms of the effective Hamiltonian for the $X, \bar{X}$ system.

The situation in the vicinity of the black hole can be different from that in the early Universe. The expansion of the Universe led to the decreasing of the energy of the superheavy particles and the lifetime $\tau_7$ of the long living component occurred to be larger than the time of breaking of the GU symmetry. Near black hole the time when energy is of the GU scale can be larger than $\tau_7$.

Now let us give some numerical estimates for the decays and interaction of superheavy particles created by gravitation.

## 2 Superheavy particles in the early Universe

The total number of massive particles created in Friedmann radiation dominated Universe (scale factor $a(t) = a_0 t^{1/2}$) inside the horizon is, as it is known \[3\],

$$N = n(s) \left( \frac{a(t)}{a_0} \right)^3 = b(s) M^{3/2} a_0^3,$$  

where $b(0) \approx 5.3 \cdot 10^{-4}$ for scalar and $b(1/2) \approx 3.9 \cdot 10^{-3}$ for spinor particles. It occurs that $N \sim 10^{89}$ for $M \sim 10^{14}$ GeV \[3\]. The radiation dominance in the end of inflation era dark matter is important for our calculations. If it is dust-like, the results will be different (see further). However this radiation is formed not by our visible particles. It is quintessence or some mirror light particles not interacting with ordinary particles.

For the time $t \gg M^{-1}$ there is an era of going from the radiation dominated model to the dust model of superheavy particles,

$$t_X \approx \left( \frac{3}{64 \pi b(s)} \right)^2 \left( \frac{M_{Pl}}{M} \right)^4 \frac{1}{M},$$  

where $M_{Pl}$ is Planck mass. If $M \sim 10^{14}$ GeV, $t_X \sim 10^{-15}$ s for scalar and $t_X \sim 10^{-17}$ s for spinor particles.

Let us call $t_X$ the “early recombination era”.

The formula for created particles in the volume $a^3(t)$ can be written as

$$N(t) = \left( \frac{a(t_c)}{a_0} \right)^3 b(s),$$  

where $t_c = 1/M$ is Compton time, $b(s)$ depends on the form of $a(t)$. From \[3\] one can see the effect of connection of the number of created particles with the number of causally disconnected parts on the Friedmann Universe at the Compton time of its evolution.

For scale factor $a(t) = a_0 t^\alpha$ from Eq. \[3\] it follows that $N = b(s) M^{3(1 - \alpha)} a_0^3$. Therefore for a dust-like end of inflation era one has $N \sim M$, and the ratio of the $X$-particles energy density $\varepsilon_X$ to the critical density $\varepsilon_{crit}$ is time-independent ($\varepsilon_X < \varepsilon_{crit}$ for $M < M_{Pl}$).

Let us define $d$, the permitted part of long-living $X$-particles, from the condition: on the moment of recombination $t_{rec}$ in the observable Universe one has $d \varepsilon_X(t_{rec}) = \varepsilon_{crit}(t_{rec})$. It leads to

$$d = \frac{3}{64 \pi b(s)} \left( \frac{M_{Pl}}{M} \right)^2 \frac{1}{\sqrt{M t_{rec}}}.$$  

For $M = 10^{13} - 10^{14}$ GeV one has $d \approx 10^{-12} - 10^{-14}$ for scalar and $d \approx 10^{-13} - 10^{-15}$ for spinor particles. So the lifetime of the main part or all $X$-particles must be smaller or equal than $t_X$.

Now let us construct the model which can give: (a) short-living $X$-particles decay in time $\tau_q < t_X$ (more wishful is $\tau_q \sim 10^{-38} - 10^{-36}$ s, i.e., the Compton time for $X$-particles); (b) long-living particles decay with $\tau_7 > 1/M$. Baryon charge nonconservation with CP-nonconservation in full analogy with the $K^0$-meson theory with nonconserved hypercharge and CP-nonconservation leads to the effective Hamiltonian of the decaying $X, \bar{X}$ - particles with nonhermitian matrix.

For the matrix of the effective Hamiltonian $H = \{H_{ij}\}, \ i, j = 1, 2$ let $H_{11} = H_{22}$ due to CPT-invariance. Denote $\varepsilon = (\sqrt{H_{12} - \sqrt{H_{21}}} / (\sqrt{H_{12}} + \sqrt{H_{21}})$. The eigenvalues $\lambda_{1,2}$ and eigenvectors $|\Psi_{1,2}\rangle$ of matrix $H$ are

$$\lambda_{1,2} = H_{11} \pm \frac{H_{12} + H_{21}}{2} \frac{1 - \varepsilon^2}{1 + \varepsilon^2},$$  

$$|\Psi_{1,2}\rangle = \frac{1}{\sqrt{2(1 + |\varepsilon|^2)}} [(1 + \varepsilon)|1\rangle \pm (1 - \varepsilon)|2\rangle].$$

Let us choose matrix of effective Hamiltonian as

$$H = \left( E - \frac{1}{4} (\tau_q^{-1} + \tau_l^{-1}) \right) \mp \frac{i}{4} \varepsilon^2 [A - \frac{i}{4} (\tau_q^{-1} - \tau_l^{-1})].$$

Then the state $|\Psi_1\rangle$ describes short-living particles $X_q$ with the lifetime $\tau_q$ and mass $E + A$. The state $|\Psi_2\rangle$ is the state of long-living particles $X_l$ with lifetime $\tau_l$ and mass $E - A$. Here $A$ is the arbitrary parameter $-E < A < E$ and it can be zero, then $E = M$.

If $\tau_l$ is larger than the time of breaking of the Grand Unification symmetry it can be that the some quantum number can be conserved leading to some effective time $t_U \approx 4.3 \cdot 10^{17}$ s ($t_U$ is the age of...
the Universe). The small \( d \sim 10^{-15} - 10^{-12} \) part of long-living \( X \)-particles with \( \tau_1 > t_U \) forms the dark matter.

For \( t_{\text{eff}}^U \leq 10^{27} \) s one could have the observable flow of UHECR from the decay in our Galaxy \([7]\). But in this case one must get a strong anisotropy in the direction to the center of the Galaxy \([8]\). However, Auger experiments don’t show such an anisotropy and one must suppose \( t_{\text{eff}}^U > 10^{27} \) s.

Use a model with effective Hamiltonian \([7]\), where \( \tau_1 > t_U \) and now take into account vanishing of long-living component due to interaction with baryon matter. Consider a model with an interaction which in the basis \( \tau_1 \) one must suppose \( \gamma_1 \tau_1 \) is proportional to the concentration of particles:

\[
H = \begin{pmatrix}
0 & 0 \\
0 & -\gamma_1
\end{pmatrix}.
\]

(8)

The eigenvalues of the Hamiltonian \( H + H^d \) are

\[
\lambda_{1,2}^d = E - \frac{i}{4} \left( \tau_q^{-1} + \tau_l^{-1} \right) - \frac{i \gamma}{2} \pm \sqrt{\left( A - \frac{i}{4} \left( \tau_q^{-1} - \tau_l^{-1} \right) \right)^2 - \frac{\gamma^2}{4}}.
\]

(9)

In case \( \gamma \ll \tau_q^{-1} \), for the long-living component one obtains

\[
\lambda_2^d \approx E - \frac{i}{2} \tau_l^{-1} - \frac{i \gamma}{2},
\]

(10)

\[
||\Psi_2(t)||^2 = ||\Psi_2(t_0)||^2 \exp \left[ \frac{t_0 - t}{\tau_l} - \int_{t_0}^t \gamma(t) dt \right].
\]

(11)

The parameter \( \gamma \), describing the interaction with the substance of the baryon medium, is evidently dependent on its state and concentration of particles in it. For approximate evaluations take this parameter as proportional to the concentration of particles: \( \gamma = \alpha n^{(s)}(t) \). For \( \tau_l > t_U \), \( t < t_U \), \( a(t) = a_0 \sqrt{t} \), by Eq. (11), one obtains

\[
||\Psi_2(t)||^2 = ||\Psi_2(t_0)||^2 \exp \left[ \alpha 2 \frac{b^{(s)}}{M} \right] M^{5/2} \left( \frac{1}{\sqrt{t}} - \frac{1}{\sqrt{t_0}} \right).
\]

(12)

So the decay of the long-living component due to this mechanism takes place close to the time \( t_0 \).

One can think that this interaction of \( X_l \) with baryon charge is effective for times, when the baryon charge becomes strictly conserved, i.e., we take the time larger or equal to the electroweak time scale, defined by the temperature of the products of decay of \( X_q \). Supposing the great difference in masses of \( X_q \) and the products of its decay ("the great desert") one can assume the products as ultra relativistic gas with nonzero entropy. Its temperature is defined from \( M n^{(s)}(\tau_q) \approx \sigma T^4 \) and is given by

\[
T(t) = \left( \frac{30 b^{(s)}}{\pi^2 N_l} \right)^{1/4} \left( \frac{M^{5/8} \tau_q^{1/8}}{k_B \sqrt{t}} \right),
\]

(13)

where \( k_B \) is Boltzmann constant, and \( N_l \) is defined by the number of boson \( N_B \) and fermion \( N_F \) degrees of freedom of all kinds of light particles: \( N_l = N_B + \frac{2}{3} N_F \) (see Ref. \([7]\)). At time \( t_X \), this temperature is equal to

\[
T(t_X) = \frac{64 \sqrt{\pi}}{3 \left( \frac{30}{N_l} \right)^{1/4}} \left( \frac{\beta^{(s)}}{b^{(s)}} \right)^{5/4} \left( M \tau_q \right)^{1/8} \frac{M^3}{k_B M_{Pl}^2}.
\]

(14)

If \( \tau_q = 1/M \) and \( N_l \sim 10^2 - 10^4 \), then for spinor \( X \)-particles \( t(t_X) \approx 300 - 100 \) GeV, i.e., the electroweak scale for created particles (which is however different from that for the background). This unexpected coincidence shows consistency of our reasonings.

So let us suppose \( t_0 \approx t_X \). If \( d \) is the part of long-living particles surviving up to the time \( t (t_U > t > t_X) \), then from Eqs. (11) and (12) one obtains the evaluation for the parameter \( \alpha \):

\[
\alpha = \frac{3 \ln d}{128 \pi (b^{(s)})^2} \frac{M_{Pl}^2}{M^4}.
\]

(15)

For \( M = 10^{14} \) GeV and \( d = 10^{-14} \) one obtains \( \alpha \approx 10^{-40} \) cm. If \( \tau_q \sim 10^{-38} - 10^{-35} \) s then the condition \( \gamma(t) \ll \tau_q^{-1} \) used in Eq. (10) is valid for \( t > t_X \). Thus such a mechanism of the decay of the long-living component of \( X \)-particles was important in the early Universe at \( t_0 \approx t_X \).

The observed entropy in this scenario originates due to transformation of \( X \)-particles into light particles: quarks, antiquarks and some particle similar to \( \Lambda^0 \) in \( K^0 \)-meson theory, having the same quantum number as \( X \). Baryon charge is created close to the time \( t_q \), which can be equal to the Compton time of \( X \)-particles \( t_C \sim 10^{-38} - 10^{-35} \) s.

Our scheme can also work for spinor particles. Then it is possible to investigate some version of the seesaw mechanism \([8]\) for Majorana neutrinos in the Grand Unification theory, so that heavy sterile neutrinos form the dark matter.

3 Superheavy particles as source UHECR from active galaxy nuclei

Now let us give some numerical estimates of the conversion of superheavy particles into UHECR in active galactic nuclei. The Auger group registered 27 UHECR with energies higher than 57\,<\,10^{18} \) eV. The integrated exposure of Auger observatory for these data is \( 9.0 \times 10^{19} \) km\(^2\) sr year. The Auger group found the correlation of UHECR with nearby active extragalactic objects \([2]\). There are 318 AGN on the distance smaller than 75 Mpc. It is easy to see that if these AGN are distributed uniformly and have the same intensity of UHECR radiation, each of the AGN must
radiate approximately $j = 10^{39}$ UHECR in a year. The distance of propagation of UHECR is limited by the Greizen-Zatsepin-Kuzmin limit \[9\] and for proton with the energy higher than $8 \cdot 10^{19}$ eV this distance cannot be larger than 90 Mpc.

Due to Auger results the source of 2 particles of superheavy energy is the AGN Centaurus A located on 11 million of light years from the Earth. It is easy to calculate that for the integral exposure of Auger observatory this AGN must radiate approximately $3 \cdot 10^{37}$ UHECR in a year.

Our hypothesis is that these UHECR in AGN arise due to superheavy dark matter particles converted into quarks and leptons at high energies obtained by them close to the supermassive black hole horizon of the AGN. To understand the process of this conversion one must remember the consideration of parts 2 of this paper.

Superheavy dark matter particles with mass $M = 10^{14}$ GeV, fall on the black hole, so that if 100% of these particles are converted into UHECR than it’s mass must have the order of $10^{28}$ g. Even if only $\eta = 10^{-4}$ of the total mass of superheavy particles close to the horizon is converted into ordinary particles the whole mass of dark matter $m = M j/\eta$ is much lower than the mass of the ordinary matter accreted on the black hole leading to it’s observed light radiation.

The source of the energy of UHECR is the decay of superheavy particles at the GU energies on quarks and leptons which due to our reasoning at part 2 of our paper led to the origination of the baryon charge of the Universe. The mass of superheavy particle is converted into energy of light particles the flow of which can go from the black hole to the Earth similar to photons. The black hole plays the role of the cosmic accelerator or super collider creating the conditions for transforming the long living component of $X$-particles into short living and it’s decay. In any case if the time of existence of the $X$-particles with GU energies differently from the situation at the early Universe is larger than $\tau$, $X$ must decay.

Now let us evaluate the numerical density of dark matter accreted on the black hole leading to it’s observed light radiation.

Now let us discuss the possible physical mechanism of conversion of dark matter into visible matter at AGN. It is reasonable to think that AGN differently from other black holes are rapidly rotating supermassive black holes. Then one has the well known Penrose mechanism \[12\]. The incoming particle in ergosphere decays on two particles, one with negative energy goes inside the black hole while another particle with the opposite momentum and the energy larger than the incoming one goes to the outside space. The condition for the conversion of dark matter superheavy particles into quarks and leptons is great relative energy-momentum in interaction of these particles. This condition can be fulfilled for our Penrose process.

Then the particle with the energy greater than the GU scale going in opposite direction to AGN can collide with the other superheavy particle falling inside and so on. In the result macroscopic amount of dark matter can be "burned" close to the AGN. So AGN can work as a great cosmical collider.

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