ON THE POSSIBLE ROLE OF SUPERHEAVY PARTICLES
IN THE EARLY UNIVERSE*

A. A. GRIB
A.Friedmann Laboratory for Theoretical Physics,
Institute of Gravitation and Cosmology, PFUR.
30/32 Gribedov kanal, St.Petersburg, 191023, Russia
Email: andrei_grib@mail.su

YU. V. PAVLOV
Institute of Mechanical Engineering, Russian Academy of Sciences,
61 Bolshoy pr., V.O., St.Petersburg, 199178, Russia
Email: yuri.pavlov@mail.ru

Different models of the role of creation of superheavy particles in the early Friedmann Universe with their subsequent decay on light particles are investigated. The observable numbers of baryon and entropy are predicted. The possible role of superheavy particles in creation of cold dark matter is discussed.

1. Introduction
It is known\(^1\)\(^2\)\(^3\) that the number of particles with mass of the order of the Grand Unification scale created by gravitation in the early Universe described by the radiation dominated Friedmann metric is of the Dirac-Eddington order, i.e. of the observable order for the visible mass. Euristic considerations for particle creation in the early Friedmann Universe leading to the prediction that the number of created pairs of particles and antiparticles qualitatively is estimated as the number of causally disconnected parts of space expanding to the present size of horizon\(^2\) say that in spite of difficulties of exact calculations for the case different from the radiation dominated regime the result must be of the same order. On the other side it is clear that if superheavy particles after their creation continued to be stable for large enough time they will lead to the collapse of the Universe.

*This work is supported by Min. of Education of Russia, grant E02-3.1-198.
governed by the radiation dominated metric in the short on the cosmolog-
ical scale time for closed Friedmann space or lead to the unrealistic scale
factor for the open space. So the idea was proposed that these superheavy
particles must decay on quarks and leptons with $CP$-noninvariance lead-
ing to the observable baryon charge of the Universe before the time when
the energy density of the created superheavy particles will become equal to
that creating the background metric. If superheavy particles have nonzero
baryon charge then their decay in analogy with decay of neutral $K$-mesons
will go as decay of some short living and long living components. Supposing
that the lifetime of long living components is of the cosmological order but
their number was diminished in comparison with the number of the short
living components due to their interaction with the baryon charge created
previously similar to the well known regeneration mechanism for $K$-mesons
one can speculate about their existence today as cold dark matter. Rare
events of their decays can be identified as experimental observations of high
energetic cosmic rays with the energy higher than the Greisen-Zatsepin-
Kuzmin limit. Here we shall discuss different possibilities of the role of
superheavy particles with the mass of the Grand Unification scale in the
early Universe.

1) It is natural to think that some inflation era took place before the
Friedmann stage. Some inflaton field which may be is manifesting itself as
the quintessence in the modern epoch after the quasi de Sitter stage led to
the dust like or to the radiation dominated Friedmann Universe. Usually it
is supposed that the inflaton field does not interact with ordinary particles
and can be some manifestation of the non Einsteinian gravity for example
due to high order corrections. So even if it decayed on some light “inflaton”
particles the primordial inflaton field can form hot dark matter but not the
visible matter and entropy present in background radiation. Our idea is
that inflaton field was the source of Friedmann metric with some small
inhomogeneities, but visible matter and the entropy of the Universe were
created not by the inflaton field itself but by the gravitation of this inflaton
field. That gravitation created pairs of superheavy particles. Short living
components decayed in time of the Grand Unification scale and led to the
nonzero baryon charge observed today as visible matter. If long living
components had the lifetime of the order of the “early recombination era”
then the energy density of created long living particles soon became equal
to that of the background inflaton field (hot dark matter). Then the decay
of all long living components led to the observable entropy of the Universe.
Here it is supposed that the energy density of the inflaton field led to the
observed cosmological scale factor, so it is evident that the created entropy due to our mechanism will be of the observable order.

2) The other possibility is to put the hypothesis discussed by us earlier[6,7] that not all long living components decayed and formed the entropy but some part of them survived up to modern time as cold dark matter and superheavy particles are observed in cosmic rays events. Then it is natural to suppose that the lifetime of the long living component is of the cosmological order but the large part of them regenerated into short living components due to interaction with the baryon charge in time shorter or equal to that of the “early recombination era” and entropy appeared due to this decay.

Now let us give some numerical estimates.

2. Model and Numerical Estimates

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[4]

$$N = n^{(s)}(t) a^3(t) = b^{(s)} M^{3/2} a_0^3,$$  \hspace{1cm} (1)

where $b^{(0)} \approx 5.3 \cdot 10^{-4}$ for scalar and $b^{(1/2)} \approx 3.9 \cdot 10^{-3}$ for spinor particles ($N \sim 10^{60}$ for $M \sim 10^{14}$ Gev, see Ref.[4]). 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

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

If $M \sim 10^{14}$ Gev, $t_X \sim 10^{-15}$ sec for scalar and $t_X \sim 10^{-17}$ sec for spinor particles. Let us call $t_X$ — “early recombination era”.

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 $d \varepsilon_X(t_{rec}) = \varepsilon_{crit}(t_{rec})$, where $\varepsilon_{crit}$ is the critical density for the time $t_{rec}$. It leads to

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

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 life time of 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 $\tau_q \sim t_C \approx 10^{-38} - 10^{-35}$ sec, i.e. Compton time for $X$-particles) b) long living particles decay with $\tau_l \approx t_X$. 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 nonhermitean matrix.

For the matrix of the effective Hamiltonian $H = \{H_{ij}\}$, $i, j = 1, 2$ let

$$H_{11} = H_{22}$$

due to $CP T$-invariance. Denote

$$\varepsilon = \left( \sqrt{H_{12}} - \sqrt{H_{21}} \right) / \left( \sqrt{H_{12}} + \sqrt{H_{21}} \right).$$

The eigenvalues $\lambda_{1,2}$ and eigenvectors $|\Psi_{1,2}\rangle$ of matrix $H$ are

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

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

In particular

$$H = \begin{pmatrix}
E - \frac{i}{2} (\tau_q^{-1} + \tau_l^{-1}) & \frac{1 + i\varepsilon}{2} \left[ A - \frac{i}{2} (\tau_q^{-1} - \tau_l^{-1}) \right] \\
\frac{1 + i\varepsilon}{2} \left[ A - \frac{i}{2} (\tau_q^{-1} - \tau_l^{-1}) \right] & E - \frac{i}{2} (\tau_q^{-1} + \tau_l^{-1})
\end{pmatrix}. \quad (6)$$

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

So for the scenario 1) it is sufficient to take $\tau_l \approx t_X$.

In scenario 2) the small $d \sim 10^{-15} - 10^{-12}$ part of long living $X$-particles with $\tau_l > t_U \approx 10^{18}$ sec ($t_U$ is the age of the Universe) is forming the dark matter. The decay of these superheavy particles in modern epoch can give observed ultra high energy cosmic rays. Using the estimate for the velocity of change of the concentration of long living superheavy particles\cite{8} $|\dot{n}_{x}| \sim 10^{-42} \text{ cm}^{-3} \text{ sec}^{-1}$, and taking the life time $\tau_l$ of long living particles as $2 \cdot 10^{22}$ sec, we obtain concentration $n_{x} \approx 2 \cdot 10^{-20} \text{ cm}^{-3}$ at the modern epoch, corresponding to the critical density for $M = 10^{14}$ Gev.

Let us use the model with effective Hamiltonian (6) where $\tau_l > t_U$ and take into account transformations of the long living component into the short living one due to the presence of baryon substance created by decays of the short living particles in analogy with the regeneration mechanism for $K^0$-mesons.
Let us investigate the model with the interaction which in the basis $|1\rangle, |2\rangle$ is described by the matrix

$$H^d = \begin{pmatrix} 0 & 0 \\ 0 & -i\gamma \end{pmatrix}. \quad (7)$$

The eigenvalues of the Hamiltonian $H + H^d$ are

$$\lambda_{1,2}^d = E - \frac{i}{4}(\tau_q^{-1} + \tau_l^{-1}) - i\frac{\gamma}{2} \pm \sqrt{\left(A - \frac{i}{4}(\tau_q^{-1} - \tau_l^{-1})\right)^2 - \frac{\gamma^2}{4}}. \quad (8)$$

In case when $\gamma \ll \tau_q^{-1}$ for the long living component one obtains

$$\lambda_2^d \approx E - A - i\frac{\tau_l^{-1}}{2} - i\frac{\gamma}{2}, \quad (9)$$

$$\|\Psi_2(t)\|^2 = \|\Psi_2(t_0)\|^2 \exp\left[\frac{t_0 - t}{\tau_l} - \int_{t_0}^t \gamma(t) \, dt\right]. \quad (10)$$

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: $\gamma = \alpha n^{(0)}(t)$. Putting $\tau_l = 2 \cdot 10^{22} \text{sec}, t \leq t_U, a(t) = a_0\sqrt{t}$ by (11) one obtains

$$\|\Psi_2(t)\|^2 = \|\Psi_2(t_0)\|^2 \exp\left[\alpha 2b^{(s)} M^{3/2} \left(\frac{1}{\sqrt{t}} - \frac{1}{\sqrt{t_0}}\right)\right]. \quad (11)$$

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 $X_q$. This temperature is defined from $M n^{(s)}(\tau_q) \approx \sigma T^4$ and is given by

$$T(t) = \left(\frac{30 b^{(s)}}{\pi^2 N_l}\right)^{1/4} \frac{M^{5/8}}{k_B \sqrt{T}}, \quad (12)$$

where $k_B$ is Boltzmann constant, $N_l$ is defined by the number of boson $N_B$ and fermion $N_F$ degrees of freedom of all kinds of light particles: $N_l = N_B + \frac{7}{8} N_F$ (see Ref. 11). At time $t_X$ this temperature is equal to

$$T(t_X) = \frac{64\sqrt{\pi}}{3} \left(\frac{30}{N_l}\right)^{1/4} \left(b^{(s)}\right)^{5/4} \left(\frac{M}{M_{Pl}}\right)^{1/8} \frac{M^3}{k_B M_{Pl}}. \quad (13)$$
If \( \tau_q = 1/M \) and \( N_l \sim 10^2 - 10^4 \), then for spinor \( X \)-particles \( T(t_X) \approx 300 - 100 \text{ Gev} \), i.e. the electroweak scale for created particles (which is however different from that for the background).

So let us suppose \( t_0 \approx t_X \). If \( d \) is the part of long living particles surviving up to the time \( t \) \((t_U \geq t \gg t_C)\) then from (3) and (11) one obtains the evaluation for the parameter \( \alpha \)

\[
\alpha = \frac{-3 \ln d}{128 \pi (\hbar s)^2} \frac{M^2}{M^4}. \tag{14}
\]

For \( M = 10^{14} \text{ Gev} \) and \( d = 10^{-15} \) one obtains \( \alpha \approx 10^{-30} \text{ sm}^3/\text{sec} \). If \( \tau_q \sim 10^{-38} - 10^{-35} \text{ sec} \) then the condition \( \gamma(t) \ll \tau_q^{-1} \) used in Eq. (9) is valid for \( t > t_X \). For this value \( \alpha \) we have \( \gamma(t_U) \approx 10^{-36} \text{ sec}^{-1} \ll t^{-1} \). So one can neglect this mechanism for the decay of the long living component of \( X \)-particles for the modern epoch while for early universe at \( t_0 \approx t_X \) it was important. The entropy in this scenario is created due to decay of \( X_1 \) on quarks and antiquarks at the time \( t_X \) when the Grand Unification symmetry is totally broken. Baryon charge is created at \( t_q \) which can be equal to Compton time for \( X \)-particles \( t_C \sim 10^{-38} - 10^{-35} \text{ sec} \).

Our scheme is the same for the scalar particles and the fermions. The superheavy fermions are used, for example, in some models of neutrino mass generation (the see-saw mechanism) in Grand Unification theories. New experiments on high energetic particles in cosmic rays surely will give us more information on their structure and origin.

References

1. A. A. Grib, S. G. Mamayev and V. M. Mostepanenko, Vacuum Quantum Effects in Strong Fields (Friedmann Laboratory Publishing, St.Petersburg, 1994).
2. A. A. Grib, Early Expanding Universe and Elementary Particles (Friedmann Laboratory Publishing, St.Petersburg, 1995).
3. A. A. Grib and V. Yu. Dorofeev, Int. J. Mod. Phys. D3, 731 (1994).
4. M. Takeda et al., Phys. Rev. Lett. 81, 1163 (1998).
5. K. Greisen, Phys. Rev. Lett. 16, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, Pis’ma Zh. Exp. Teor. Fiz. 4, 114 (1966) [JETP Lett. 4, 78 (1966)].
6. A. A. Grib and Yu. V. Pavlov, Int. J. Mod. Phys. D11, 433 (2002); Int. J. Mod. Phys. A17, 4435 (2002).
7. A. A. Grib and Yu. V. Pavlov, Gravitation & Cosmology 8, Suppl., 148 (2002); Gravitation & Cosmology 8, Suppl. II, 50 (2002).
8. V. Berezinsky, P. Blasi and A. Vilenkin, Phys. Rev. D58, 103515 (1998).
9. H. V. Klapdor-Kleingrothaus and K. Zuber, Teilchenastrophysik, (Teubner, Stuttgart, 1997).
10. M. Gell-Mann, P. Ramond and S. Slansky, in *Supergravity*, eds. P. van Niewenhuizen and D. Z. Freedmann, (North Holland, Amsterdam, 1979) pp. 315–321.

11. K. Oda, E. Takasugi, M. Tanaka and M. Yoshimura, *Phys. Rev.* **D59**, 055001 (1999).