Production of matter in the universe via after-GUT interaction

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Abstract

In this paper we propose a model of the dark energy decay into ordinary and dark matter via the action of some interaction, dubbed as the after-GUT interaction, with the mass scale between the electroweak and grand unification. The dark energy decay rate Γ_ϕ is expressed through the three parameters - the coupling constant α_X, the mass scale M_X which defines the mass of X-boson as the mediator of after-GUT interaction, and the energy imparted to the decay products. We show that the masses of dark matter particle m_χ and dark energy quasiparticle m_ϕ can be extracted from the astrophysical data about the contributions of baryon, dark matter, and dark energy densities to the total matter-energy density budget in our universe. For this purpose we use the quantum cosmological model in which dark energy is a condensate of quantum oscillations (the ϕ-quanta) of the primordial scalar field ϕ. We find that the dark energy quasiparticle with the mass $m_\phi \approx 15$ GeV and the dark matter particle with the mass $m_\chi \approx 5$ GeV are consistent with the 7-year WMAP and other data on matter-energy density constituents. Such a mass of light WIMP dark matter agrees with the recent observations of CoGeNT, DAMA, and CDMS. The obtained masses of dark energy quasiparticle and dark matter particle are concordant with the parameters of after-GUT interaction $\alpha_X \sim \frac{1}{70}$, $M_X \sim 6 \times 10^{10}$ GeV, and the decay rate $\Gamma_\phi \approx 2 \times 10^{-18}\,\mathrm{s}^{-1}$. We find the value $n_\phi \sim 10^{73}\,\mathrm{cm}^{-3}$ for the density of the dark energy quasiparticles considered as the ϕ-quanta surrounded by virtual X-boson cloud. The cross-section of the $\bar{\nu}\phi$-scattering via virtual X-boson exchange is very small, but finite, $\sigma(\bar{\nu}\phi) \sim 0.5 \times 10^{-74}\,\mathrm{GeV}^{-2}$.

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1. Introduction

The present data of modern cosmology pose the principle question about the origin and nature of mass-energy constituents of our universe. The WMAP7-year and other data [1] indicate that: observed part of our universe is practically spatially flat; the expansion of the universe is accelerating due to the action of dominating substance called dark energy; the universe is now comprised of one third dark matter which provides the formation of observed structures composed of baryons and leptons. It is remarkable that observed mass of stars is negligibly small (it accounts for $\lesssim 0.5\%$ from the total amount of mass-energy in the universe [2, 3]). In view of the current dominance of dark energy over all other forms of matter it is reasonable to consider an assumption that ordinary and dark matter can be decay products of a portion of dark energy (in the form of a condensate of some primordial field) under the action of some interaction, dubbed as the after-GUT interaction, with gauge coupling between the electroweak and grand unification scales. This interaction leads to the violation of CP-invariance which can cause the baryon asymmetry of the universe.

According to the quantum cosmological model developed in Refs. [4], dark energy itself can be identified with a condensate of quantized primordial scalar field (denoted as ϕ) filling the homogeneous, isotropic, and closed universe. It was shown that a condensate is a quantum medium which consists of excitations of the spatially coherent oscillations of a primordial scalar field about an equilibrium state corresponding to (true, $\Lambda = 0$, or false, $\Lambda \neq 0$) vacuum. According to the quantum model, the state vector of the universe is the superposition of all possible masses of a condensate (numbers of zero-momentum ϕ-quanta). For the states with the mass of a condensate which exceeds significantly the Planck mass, a condensate acquires the properties of an antigravitating medium with the vacuum-type equation of state. If one discards the contribution from the transition amplitudes between the quantum states with different masses of a condensate, a condensate turns into an aggregate of separate macroscopic bodies with zero pressure (known as dust which is used to model ordinary matter in general relativity). The existence of this limit argues, first of all, in favour of reliability of proposed quantum model [4] and, secondly, exhibits the quantum nature of antigravitating property of dark energy.

In this paper we consider the nonstationary universe in which a condensate of a primordial scalar field is a source of matter in the form of baryons, leptons, and dark matter, while observed dark energy is a portion of a condensate which has not decayed up to the instant of observation. In Section 2 the decay rate Γ_ϕ of ϕ-quantum is derived under assumption of the existence of a new force mediated by new virtual massive X-bosons with the coupling at the mass scale M_X between the electroweak M_W and grand unification M_G. In Section 3 the numerical values of unknown parameters such as the mean decay rate $\overline{\Gamma}_\phi$, masses of ϕ-quantum and dark matter particle are calculated. In Section 4 these values are used to obtain the numerical estimation for the mass scale M_X and corresponding coupling constant α_X. The estimations for the density of the dark energy quasiparticles considered as the ϕ-quanta surrounded by virtual X-boson cloud and for the cross-section of the $\bar{\nu}\phi$-scattering via virtual X-boson exchange are given. In Section 5 the conclusions are drawn.

2. Concept of the after-GUT interaction

Let us suppose that baryons (n, p), leptons (e^-, ν_e), dark matter particle (χ) and their antiparticles ($\bar{n}$, $\bar{p}$, e^+, $\bar{\nu}_e$, $\bar{\chi}$) are produced via the decays of the ϕ-quantum in the processes

$$\phi \to \chi + \nu + n \quad \text{and} \quad n \to p + e^- + \bar{\nu}, \tag{1}$$

or

$$\phi = \bar{\phi} \to \bar{\chi} + \bar{\nu} + \bar{n} \quad \text{and} \quad \bar{n} \to \bar{p} + e^+ + \nu. \tag{2}$$

The particle χ is the quantum of the residual excitation of the oscillations of the field ϕ about an equilibrium state. The set of χ-particles forms dark matter. The neutrino takes away the spin and the dark matter particle χ may have spin 0 or 1. It follows from Ref. [5] that a dark matter particle may be a scalar particle with scalar interaction. Therefore one can accept that the spin of χ is equal to zero. Since the universe is a charge neutral system, then all charges of zero-momentum ϕ-quantum may be taken equal to zero. As it is assumed that dark matter has a non-baryonic nature, then the baryonic charge of χ is equal to zero.

Particles and antiparticles of the decays (1) and (2) can annihilate between themselves and contribute to the observed CMB. In the reactions (1) and (2) the ϕ-quantum decays into three particles or antiparticles with the subsequent decay of n or $\bar{n}$ into three more particles. The probability of inverse fusion reaction of three or more particles into the zero-momentum ϕ-quantum is negligibly small. As a result, the T-invariance breaks down in the decays (1) and (2), and the arrow of time arises. Supposing that this theory is CPT-invariant, one concludes that CP-invariance is violated as well. This may be connected with the existence of a new interaction which mediates the dark energy decay.

According to modern view, CP-violation can be caused by the baryon asymmetry of the universe. Therefore in this Section we consider only the reaction (1).

In the standard model (see, e.g., the review [6]) the decay of neutron is the result of weak interaction, mediated by virtual W-boson exchange,

$$n \to p + W^- \quad \text{and} \quad W^- \to e^- + \bar{\nu}. \tag{3}$$

The rate Γ_n of decay of a neutron into the final $pe\nu$-state is equal to

$$\Gamma_n = \frac{1}{\tau_n} = \alpha_W^2 \, \frac{\Delta m^5}{M_W^4} \tag{4}$$

(in units $\hbar = c = 1$), where τ_n is the mean life of neutron, $\Delta m = m_n - m_p$ is the energy imparted by the W-boson to the leptons $e\nu$, M_W is the mass of the W-boson,

m_n and m_p are the masses of neutron and proton, respectively. The quantity α_W^2 is dimensionless constant which characterises the strength of weak interaction and includes small radiative and other quantum corrections. This number is close to the value $G_F m_p^2 = 1.027 \times 10^{-5}$, where $G_F = 1.166 \times 10^{-5}$ GeV^{-2} is the Fermi coupling constant,

$$\alpha_W^2 = G_F m_p^2 \, (1 - \delta) \sim 10^{-5}, \tag{5}$$

where $\delta \sim O(10^{-1})$ is small correction.

In any grand unified theory (GUT) (see, e.g., the review [6]) the proton lifetime τ_p is given by the following relation

$$\Gamma_p = \frac{1}{\tau_p} = \alpha_G^2 \, \frac{m_p^5}{M_G^4}, \tag{6}$$

where Γ_p is the decay rate of proton, α_G and M_G are two independent parameters. Universal gauge coupling α_G is defined at the grand unification scale M_G. The values $\alpha_G = \frac{1}{25}$ (SUSY GUTs) and $M_G = 3 \times 10^{16}$ GeV lead to the proton lifetime equal to $\tau_p = 1.45 \times 10^{37}$ yrs. The other value $\alpha_G = \frac{1}{45}$ (non SUSY GUTs) and the same M_G give $\tau_p = 4.70 \times 10^{37}$ yrs. Comparing $\alpha_G^2 = (\frac{1}{25})^2 = 1.6 \times 10^{-3}$ and $\alpha_G^2 = (\frac{1}{45})^2 = 0.49 \times 10^{-3}$ we find that in any case

$$\alpha_G^2 \sim 10^{-3}. \tag{7}$$

It can be compared with α_W^2 from Eq. (5)

$$\alpha_W^2 \sim 10^{-5} < \alpha_G^2 \sim 10^{-3}. \tag{8}$$

This inequality shows that notwithstanding the fact that the mass scales $M_W \sim 10^2$ GeV and $M_G \sim 10^{16}$ GeV are terrifically different, the corresponding coupling constants α_W^2 and α_G^2 differ by two orders of magnitude only.

If one introduces the 'dimensional GUT coupling constant',

$$G_G \equiv \alpha_G^2 m_p^{-2}, \tag{9}$$

it appears that its numerical value is $G_G \sim 10^{-3}\,\mathrm{GeV}^{-2}$. It can be compared with $G_F \sim 10^{-5}\,\mathrm{GeV}^{-2}$.

Let us suppose that the decay of the ϕ-quantum in the process (1) is mediated by exchange of virtual X-bosons which are quanta of some new field with the mass scale

$$M_X \gg m_\chi > m_n \gg m_\nu, \tag{10}$$

where m_χ is the mass of dark matter particle. A few versions of such a decay are possible

$$\begin{aligned} \phi &\to \chi + X \quad \text{and} \quad X \to n + \nu, \\ \phi &\to n + X \quad \text{and} \quad X \to \chi + \nu, \\ \phi &\to \nu + X \quad \text{and} \quad X \to \chi + n. \end{aligned} \tag{11}$$

In Fig. 1, the diagram represents the first process in (11). The two other diagrams can be obtained by cyclic permutation of the particles χ, n, ν.

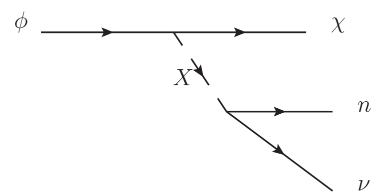

Figure 1: The diagram which corresponds to the first decay in (11).

Let us suppose that we can consider these processes by analogy to those described by Eqs. (4) and (6). We shall neglect the contribution from integration with respect to intermediate momentum of X-boson in corresponding transition amplitudes, as well as contributions into Γ_ϕ arising from all higher-order diagrams. Then the decay rate of the ϕ-quantum Γ_ϕ can be written as follows

$$\Gamma_\phi = \alpha_X^2 \frac{Q^5}{M_X^4}, \tag{12}$$

where

$$Q = m_\phi - (m_\chi + m_n + m_\nu) \tag{13}$$

is the energy imparted by the ϕ-quantum at rest to the decay products in (1). The dimensionless coupling constant α_X^2 takes into account the contributions into Γ_ϕ from all three pole diagrams in accordance with (11).

Using Eqs. (4), (6), and (12) one can write the expressions for the ratios of the decay rate of the ϕ-quantum to the neutron and proton decay rates

$$\frac{\Gamma_\phi}{\Gamma_n} = \frac{\alpha_X^2}{\alpha_W^2} \left(\frac{Q}{\Delta m}\right)^5 \left(\frac{M_W}{M_X}\right)^4 \tag{14}$$

and

$$\frac{\Gamma_\phi}{\Gamma_p} = \frac{\alpha_X^2}{\alpha_G^2} \left(\frac{Q}{m_p}\right)^5 \left(\frac{M_G}{M_X}\right)^4. \tag{15}$$

Here the quantities Γ_ϕ, α_X^2, Q and M_X are unknown. They can be calculated independently in the kinetic theory which considers two-step processes (1) and (2) as dynamical ones and uses the astrophysical data about the contributions of baryons, dark matter, and dark energy densities to the total matter-energy density budget in our universe.

3. Dark energy and light WIMP dark matter

According to the quantum model [4] the energy density of a condensate ρ_k is

$$\rho_k = \frac{2M_k}{a^3}, \tag{16}$$

where a is the cosmic scale factor taken in unit of the Planck length $l_P = \sqrt{\frac{2G}{3\pi}}$, $M_k = m_\phi \left(k + \frac{1}{2}\right)$ is an amount of matter (mass) in the universe related to the quantized scalar field, k is the number of ϕ-quanta with the mass $m_\phi = \left[\frac{d^2V(\phi)}{d\phi^2}\right]^{1/2}_{\phi=\sigma}$ in unit of the Planck mass $m_P = l_P^{-1}$, $V(\phi)$ is the potential of the scalar field in unit of the Planck density $\rho_P = \frac{3}{8\pi G l_P^2}$. At the point $\phi = \sigma$ we have $\left[\frac{dV(\phi)}{d\phi}\right]_{\phi=\sigma} = 0$, $V(\sigma) \equiv \frac{\Lambda}{3}$, where Λ is the cosmological constant. Since a condensate with the energy density (16) is governed by the vacuum-type equation of state, $p_k = -\rho_k$, where p_k is the pressure, then, generally speaking, there is no need for a cosmological constant to explain the observed accelerating expansion of the present-day universe.

On large spacetime scales at some fixed instant of the proper time t the total energy density of the universe relative to critical density Ω_{tot} can be represented by the sum of the terms

$$\Omega_{tot} = \Omega_B + \Omega_L + \Omega_{DM} + \Omega_{CMB} + \Omega_{DE}, \tag{17}$$

where Ω_B, Ω_L, Ω_{DM}, and Ω_{CMB} are the energy densities of baryons, leptons, dark matter particles, and the cosmic microwave background radiation (CMB) which includes here the contribution from other types of relativistic matter in the universe. The quantity Ω_{DE} is the density of residual (observed) dark energy (i.e. a portion of a condensate which has not decayed up to the instant of observation). According to the decays (1) and (2) these constituents can be written as follows

$$\Omega_B = \frac{2m_p \delta N_p(t)}{a^3(t)H^2(t)}, \quad \Omega_L = \frac{2m_l \delta N_l(t)}{a^3(t)H^2(t)}, \quad \Omega_{DM} = \frac{2m_\chi \delta N_\chi(t)}{a^3(t)H^2(t)}, \tag{18}$$

where m_l is the sum of masses of all leptons in the final state of reaction (1), and H is the dimensionless Hubble expansion rate (in unit of time $t_P = l_P$). The density of observed dark energy at the instant of time t is

$$\Omega_{DE} = \frac{2m_\phi \delta N_\phi(t)}{a^3(t)H^2(t)}. \tag{19}$$

Here

$$\delta N_p = N_p - N_{\bar{p}}, \quad \delta N_l = N_l - N_{\bar{l}}, \quad \delta N_\chi = N_\chi - N_{\bar{\chi}}, \tag{20}$$

are net amounts of protons, leptons, and dark matter particles, respectively, as the functions of t, and

$$\delta N_\phi = N_\phi - N_{\bar{\phi}} \tag{21}$$

is the difference between the quantities of the ϕ-quanta decayed into particles and antiparticles.

We suppose that the ϕ-quanta and neutrons decay independently with some decay rates $\Gamma_\phi = \Gamma_{\bar{\phi}}$ and $\Gamma_n = \Gamma_{\bar{n}}$. According to the quantum model description [4], when the universe expands, the following condition is realized at every instant of time for large enough number of the ϕ-quanta,

$$\langle a \rangle_k = M_k, \tag{22}$$

where $\langle a \rangle_k$ is the mean value of the scale factor a in the k-state of the universe with the mass of a condensate M_k. The equation (22) can be interpreted as a mathematical formulation of the Mach's principle proposed by Sciama [7, 8]. In the classical limit, the evolution of the mean value $\langle a \rangle_k$ in time is described by the Einstein-Friedmann equations. Denoting the number of the ϕ-quanta as a function of the proper time t by $N_\phi(t)$, we can write the condition (22) as follows

$$a(t) = m_\phi N_\phi(t). \tag{23}$$

Under the expansion of the universe in accordance with the Hubble law

$$\frac{da(t)}{dt} = H(t) a(t), \tag{24}$$

the number of the ϕ-quanta will change as follows

$$\frac{dN_\phi(t)}{dt} = H(t) N_\phi(t). \tag{25}$$

The same equation takes place for the number $N_{\bar{\phi}}$. For net amount δN_ϕ of the ϕ-quanta considered as stable particles we can write the equation

$$\frac{d\delta N_\phi(t)}{dt} = H(t) \delta N_\phi(t). \tag{26}$$

But the ϕ-quanta are supposed to be unstable ones, then taking into account two-channel ϕ-quantum decay as in the schemes (1) and (2), we can write the equations of the evolution of net amounts of unstable particles in the form

$$\frac{d\delta N_\phi(t)}{dt} = -\lambda(t)\delta N_\phi(t), \quad \frac{d\delta N_n(t)}{dt} = -\Gamma_n(t)\delta N_n(t) + \Gamma_\phi(t)\delta N_\phi(t),$$
$$\frac{d\delta N_p(t)}{dt} = -\Gamma_p(t)\delta N_p(t) + \Gamma_n(t)\delta N_n(t), \tag{27}$$

where

$$\lambda(t) = \Gamma_\phi(t) - H(t) \tag{28}$$

is an effective decay rate which takes into account the change in the number of the ϕ-quanta during the expansion of the universe. Taking $\Gamma_p = \Gamma_{\bar{p}} = 0$ and choosing the initial conditions as follows

$$\delta N_\phi(t') = N, \quad \delta N_n(t') = 0, \quad \delta N_p(t') = 0, \tag{29}$$

where N is the number of the ϕ-quanta at some arbitrary chosen initial instant of time t', we find the solution of the set (27)

$$\frac{\delta N_\phi(t)}{N} = e^{-\overline{\lambda}\Delta t}, \tag{30}$$

$$\frac{\delta N_n(t)}{N} = \int_{t'}^{t} dt_1 \Gamma_\phi(t_1)\, e^{-\int_{t'}^{t_1} dt_2 \lambda(t_2)}\, e^{-\int_{t_1}^{t} dt_2 \Gamma_n(t_2)}, \tag{31}$$

$$\frac{\delta N_p(t)}{N} = \int_{t'}^{t} dt_1 \Gamma_n(t_1) \int_{t'}^{t_1} dt_2 \Gamma_\phi(t_2)\, e^{-\int_{t'}^{t_2} dt_3 \lambda(t_3)}\, e^{-\int_{t_2}^{t_1} dt_3 \Gamma_n(t_3)}, \tag{32}$$

where $\overline{\lambda} = \overline{\Gamma}_\phi - \overline{H}$ and

$$\overline{\Gamma}_\phi = \frac{1}{\Delta t}\int_{t'}^{t} dt_1 \Gamma_\phi(t_1), \qquad \overline{H} = \frac{1}{\Delta t}\int_{t'}^{t} dt_1 H(t_1) \tag{33}$$

are the mean decay rate of the ϕ-quantum and the mean Hubble expansion rate on the time interval $\Delta t = t - t'$.

The decay rate of the ϕ-quantum $\Gamma_\phi(t)$ is unknown. We shall assume that this decay rate and the rate Γ_n depend very weakly on averaging interval Δt. Then from Eqs. (31) and (32) we obtain

$$\frac{\delta N_n(t)}{N} = \frac{\overline{\Gamma}_\phi}{\overline{\Gamma}_n - \overline{\lambda}} \left(e^{-\overline{\lambda}\Delta t} - e^{-\overline{\Gamma}_n \Delta t} \right), \tag{34}$$

$$\frac{\delta N_p(t)}{N} = \frac{\overline{\Gamma}_\phi}{\overline{\lambda}} \left[1 + \frac{1}{\overline{\Gamma}_n - \overline{\lambda}} \left(\overline{\lambda}\, e^{-\overline{\Gamma}_n \Delta t} - \overline{\Gamma}_n\, e^{-\overline{\lambda}\Delta t} \right) \right]. \tag{35}$$

The equations (30), (34) and (35) are consistent with the conservation law of particles,

$$\delta N_\phi(t) + \delta N_n(t) + \delta N_p(t) = N + \frac{\overline{H}}{\overline{\lambda}}\, N \left(1 - e^{-\overline{\lambda}\Delta t} \right), \tag{36}$$

where the second summand on the right-hand side takes into account the number of ϕ-quanta which have appeared in the universe under its expansion and then decayed.

For our universe today $\overline{\Gamma}_n = 1.12 \times 10^{-3}\ \mathrm{s}^{-1}$, $H_0 = 71.0 \pm 2.5\,\mathrm{km\,s^{-1}Mpc^{-1}}$ and the age $t_0 = 13.75 \pm 0.13$ Gyr [1]. Taking $\Delta t = t_0$ for estimation we find that

$$H_0 \Delta t = 0.999, \qquad \overline{\Gamma}_n \Delta t = 4.86 \times 10^{14}. \tag{37}$$

We have supposed that the decay of the ϕ-quantum is caused by the action of the after-GUT interaction with the mass scale M_X. Then the inequality $\overline{\Gamma}_\phi \ll \overline{\Gamma}_n$ must hold, and

$$\overline{\lambda} \ll \overline{\Gamma}_n. \tag{38}$$

Under this condition, the number of baryons δN_p in the expanding universe obeys the law

$$\frac{\delta N_p(t)}{N} = \frac{\overline{\Gamma}_\phi}{\overline{\lambda}} \left[1 - e^{-\overline{\lambda}\Delta t}\right]. \tag{39}$$

The ratio $\frac{\Omega_B}{\Omega_{DE}}$ can be written as follows

$$\frac{\Omega_B}{\Omega_{DE}} = \sqrt{\frac{g_p}{g_\phi}}\,\frac{\overline{\Gamma}_\phi}{\overline{\lambda}} \left[e^{\overline{\lambda}\Delta t} - 1\right], \tag{40}$$

where $g_p = G_N m_p^2 = 0.59 \times 10^{-38}$ and $g_\phi = G_N m_\phi^2$ are the dimensionless gravitational coupling constants for proton and the ϕ-quantum, respectively, $G_N = 6.707 \times 10^{-39}$ GeV^{-2} is the Newtonian gravitational constant.

If $\overline{\Gamma}_\phi \gg \overline{H}$, then $\overline{\lambda} \approx \overline{\Gamma}_\phi$ and

$$\frac{\Omega_B}{\Omega_{DE}} = \sqrt{\frac{g_p}{g_\phi}} \left[e^{\overline{\Gamma}_\phi\Delta t} - 1\right]. \tag{41}$$

This limit was considered in Ref. [9].

If $\overline{\Gamma}_\phi \ll \overline{H}$, then $\overline{\lambda} \approx -\overline{H}$ and

$$\frac{\Omega_B}{\Omega_{DE}} = 0. \tag{42}$$

It means that in this case baryons (and ordinary matter) will not be produced in the universe.

If $\overline{\Gamma}_\phi \approx \overline{H}$, and $\overline{\lambda}\Delta t \ll 1$, then

$$\frac{\Omega_B}{\Omega_{DE}} = \sqrt{\frac{g_p}{g_\phi}}\,\overline{\Gamma}_\phi\Delta t \left[1 + \frac{1}{2}\overline{\lambda}\Delta t + \ldots\right]. \tag{43}$$

The ratio (43) describes the case, when the number of the ϕ-quanta remains almost unchanged, $\delta N_\phi(t) \approx N = \text{const.}$. It means that the amount of a condensate in the universe is semipermanent, but its energy density diminishes during the expansion. Then the coupling constant g_ϕ is equal to

$$g_\phi = g_p \left(\frac{\Omega_{DE}}{\Omega_B}\,\overline{H}\Delta t\right)^2_{\overline{\lambda}=0}. \tag{44}$$

Using the WMAP and other data [1], $\Omega_B = 0.0456 \pm 0.0016$, $\Omega_{DE} = 0.728^{+0.015}_{-0.016}$, and Eq. (37), and setting $\overline{H}\Delta t \approx H_0\Delta t$, we obtain

$$g_\phi \approx 254\, g_p. \tag{45}$$

Under this assumption, the decay rate of the ϕ-quantum is very close to the Hubble expansion rate H_0 and it equals to

$$\overline{\Gamma}_\phi \approx 2.3 \times 10^{-18}\,\mathrm{s}^{-1}. \tag{46}$$

This value is close to the value found in Ref. [9], where Eq. (26) was not taken into account. That case is equivalent to the limit $\overline{\Gamma}_\phi \gg \overline{H}$. Therefore the values (45) and (46) may be considered as realistic, since they have changed very slightly and seem almost model-independent.

The coupling constant (45) corresponds to the mass

$$m_\phi \approx 16\, m_p. \tag{47}$$

Taking into account that the number of dark matter particles χ according to the decay schema (1) is almost equal to the number of baryons,

$$\delta N_\chi(t) \approx \delta N_p(t), \tag{48}$$

from Eq. (18) we find that

$$\frac{\Omega_B}{m_p} \approx \frac{\Omega_{DM}}{m_\chi}. \tag{49}$$

For the observed values of Ω_B and $\Omega_{DM} = 0.227 \pm 0.014$ [1] it follows that

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5. \tag{50}$$

With the regard for the errors of measurement of Ω_{DM} and Ω_B, one can take the value of the mass of the χ-particle equal to

$$m_\chi \approx 5\, m_p. \tag{51}$$

This value is in the range $m_\chi \sim 1 - 10$ GeV indicated in Ref. [5]. It agrees with the observations of CoGeNT [10], DAMA [11], and CDMS [12]. The equation (48) is a relationship between the dark matter and baryon chemical potentials with the precise value $c_1 = 1$ of the coefficient c_1 introduced in ADM models (cf. Ref. [5]).

The values of masses (47) and (51) show that the decay (1) occurs with the release of energy $Q \approx 10\, m_p$ in the form of kinetic energy of decay products.

From Eqs. (18) and (19) it follows

$$\frac{\Omega_{DE}}{\Omega_{DM}} = \frac{m_\phi \delta N_\phi}{m_\chi \delta N_\chi}. \tag{52}$$

Using the observed values of Ω_{DE} and Ω_{DM}, and the obtained values of the masses m_ϕ (47) and m_χ (51), we find that

$$\delta N_\phi \approx \delta N_\chi. \tag{53}$$

It means that the chemical potentials of dark energy and dark matter coincide. The equation (53) is a manifestation of the so-called coincidence problem, $\frac{\Omega_{DE}}{\Omega_{DM}} \approx 3.2$.

In conclusion to this Section, we note that the low mass dark matter problem can be analyzed, for instance, within the context of the standard model with scalar dark matter, ADM models, or the minimal supersymmetric standard model with neutralino dark matter (see, e.g., the bibliographies in Refs. [5, 10, 13, 14, 15]). A different model based on the quantum cosmological approach involving the available data on the abundances of baryons and dark matter in our universe was proposed in Ref. [9]. Obtained restriction on the mass of dark matter particle with zero spin $m_\chi < 15$ GeV, with the preference for $m_\chi \sim 5 - 10$ GeV, agrees with the values given in Refs. [5, 10] and in this paper.

4. Estimations of after-GUT coupling constant and mass scale

Let us suppose that the decay rate of the ϕ-quantum (12) is of the same order of magnitude as the mean decay rate (46). For the present epoch we have

$$\frac{\Gamma_\phi}{\Gamma_p} \sim 0.7 \times 10^{27}, \qquad \frac{\Gamma_\phi}{\Gamma_n} \sim 2 \times 10^{-15}. \tag{54}$$

It is interesting that the ratio

$$\frac{\Gamma_n}{\Gamma_p} \sim 3 \times 10^{41} \tag{55}$$

gives the value, which is of the same order of magnitude as the well-known Eddington's magic numbers. It can be used for a more precise definition of the proton lifetime.

Using the values of the masses (47) and (51) we find that $Q \approx 10\, m_p$ and according to Eqs. (12) and (46) we obtain

$$M_X \approx \sqrt{\alpha_X}\, 0.5 \times 10^{12}\, m_p. \tag{56}$$

The same formula follows from Eqs. (14) and (15). The coupling constant α_X^2 must satisfy the inequality

$$\alpha_W^2 \sim 10^{-5} < \alpha_X^2 < \alpha_G^2 \sim 10^{-3}. \tag{57}$$

It gives the value for the mass scale M_X which lies in the interval

$$0.3 < (M_X \times 10^{-11}\, m_p^{-1}) < 0.9, \tag{58}$$

and we can accept the following numerical values

$$\alpha_X \sim \frac{1}{70}, \quad \text{and} \quad M_X \sim 6 \times 10^{10}\,\text{GeV} \tag{59}$$

for the parameters of after-GUT interaction. The radius of action of the after-GUT force is

$$R_X = M_X^{-1} \sim 3 \times 10^{-25}\,\mathrm{cm}. \tag{60}$$

It gives the following value

$$n_\phi \sim M_X^3 \sim 10^{73}\,\mathrm{cm}^{-3} \tag{61}$$

for the density of the dark energy quasiparticles considered as the ϕ-quanta surrounded by virtual X-boson cloud. The ϕ-quantum is massive and it can, in principle, exhibit itself through the gravitational action. But its gravitational coupling constant $g_\phi \approx 1.5 \times 10^{-36}$ is very small, whereas the after-GUT coupling $\alpha_X \sim 10^{-2}$ has the same order of magnitude as the fine structure constant $\alpha \approx \frac{1}{137}$. This allows to consider the subtle processes such as the $\bar{\nu}\phi$-scattering which occurs via virtual X-boson exchange

$$\begin{aligned} \bar{\nu} + \phi \to \bar{\nu} + \chi + X \quad &\text{and} \quad \bar{\nu} + X \to n \\ \bar{\nu} + \phi \to \bar{\nu} + n + X \quad &\text{and} \quad \bar{\nu} + X \to \chi. \end{aligned} \tag{62}$$

In Fig. 2 the diagram of the first process from (62) is shown. The second diagram can be obtained by cyclic permutation of the particles χ and n.

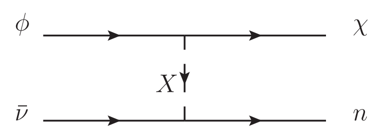

Figure 2: The diagram which describes the first process in Eq. (62).

The corresponding cross-section is equal to

$$\sigma(\bar{\nu}\phi) = \frac{2}{3}\,\frac{\Gamma_\phi}{vM_X^3}, \tag{63}$$

where v is the relative $\bar{\nu} - \phi$ motion velocity and the denominator is the incident flow of antineutrinos in the rest frame of the ϕ-quantum. The coefficient $\frac{2}{3}$ takes into account that only two pole diagrams should be taken into account when calculating the probability of the process, in accordance with (62). Since in this reference frame the velocity v is equal to the velocity of the incident antineutrino, we can take $v \approx c$, and for the decay rate (46) and the mass scale M_X from (59) we obtain

$$\sigma(\bar{\nu}\phi) \sim 0.5 \times 10^{-74}\,\mathrm{GeV}^{-2}. \tag{64}$$

It is very small number, but it is interesting that the cross section of such an exotic scattering process has finite value.

5. Conclusion

Thus, one can conclude that the observed values of the densities Ω_B, Ω_{DM}, and Ω_{DE} in the model of the decays (1) and (2) lead to the values of mass of dark energy quasiparticle ~ 15 GeV and mass of dark matter particle ~ 5 GeV. The obtained masses of dark energy quasiparticle and dark matter particle are consistent with the parameters of after-GUT interaction (59) and the decay rate Γ_ϕ (46). The parameters of after-GUT interaction are in so-called *gauge desert* - the domain between the electroweak and grand unification scales.

The density of the dark energy quasiparticles (61) shows that the volume $\sim 2\,\mathrm{m}^3$ contains the same number of dark energy quasiparticles as the number of equivalent baryons $N_B \sim 10^{80}$ in the observed part of our universe. The cross-section of the $\bar{\nu}\phi$-scattering via virtual X-boson exchange (64) is very small, but it is finite.

Within the framework of quark model of baryons, one may conclude that a condensate (and, hence, dark energy) can be a chargeless aggregate of point-like quarks and gluons, a kind of quark-gluon plasma, which can form the particle-like excitations of a primordial matter field called above the ϕ-quanta. The presence of virtual X-bosons gives the possibility for quasiparticles, formed by the ϕ-quanta and virtual X-bosons, to decay with a very small probability into the observed matter. As regards the after-GUT X-boson, it can be one of type of super-heavy Higgs boson or a supersymmetric particle [6].

Using the hypothesis about the existence of a new scale $M_X \sim 10^{10}$ GeV, a more general scheme of unification of now four (without gravitation) fundamental interactions into one single force with a scale $M_X \sim 10^{16}$ GeV may be proposed in the framework of quark model of baryons. In the simplest version of a new theory some new gauge group G' must be included formally into the scheme

$$G \xrightarrow{G} G' \xrightarrow{X} SU(3) \times SU(2) \times U(1) \xrightarrow{W} SU(3) \times U(1), \tag{65}$$

where G is some group which realizes the local symmetry principle and contains the group G' as a subgroup. The model with such a group G must have three mass scales - the masses of gauge bosons G, X, and W. The values of these masses M_G, M_X, and M_W characterize the spontaneous symmetry breaking of G to G', then to $SU(3) \times SU(2) \times U(1)$ and finally to $SU(3) \times U(1)$. Since $M_G \gg M_X \gg M_W$, then there is a vast hierarchy of gauge symmetries. In order to build a grand unification theory (GUT) which will realize the scheme (65), it is necessary to make the group G specific. In present paper we have tried, as far as possible, to avoid unnecessary specification of a model of decay of dark energy according to schemes (1) and (2), so that the obtained values of parameters of after-GUT interaction (59) be model-independent.

References

[1] N. Jarosik et al. (WMAP7), arXiv:1001.4744 [astro-ph] (2010).

[2] S.M.Cole et al. MNRAS 326 (2001) 255.

[3] M.Persic, P. Salucci, MNRAS 258 (1992) 14P; P. Salucci, M.Persic, MNRAS 309 (1999) 923.

[4] V.E. Kuzmichev, V.V. Kuzmichev, Acta Phys. Pol. B 39 (2008) 2003, [arXiv:0712.0465 [gr-qc]]; ibid. 39 (2008) 979, [arXiv:0712.0464 [gr-qc]]; ibid. 40 (2009) 2877, [arXiv:0905.4142 [gr-qc]]; Ukr. Phys. J. 55 (2010) 626.

[5] A.L. Fitzpatrick, D. Hooper, K.M. Zurek, arXiv:1003.0014 [hep-ph] (2010).

[6] K. Nakamura et al. (Particle Data Group), J. Phys. G37 (2010) 075021.

[7] R.H.Dicke, in: Gravitation and Relativity, eds. Hong-Yee Chiu, W.F. Hoffmann, Benjamin, New York 1964.

[8] V.E. Kuzmichev, V.V. Kuzmichev, Ukr. Phys. J. 50 (2005) 321, [arXiv:astro-ph/0510763].

[9] V.E. Kuzmichev, V.V. Kuzmichev, in: Trends in Dark Matter Research, ed. J.V. Blain, Nova Science, Hauppage 2005 [astro-ph/0405455]; Ukr. J. Phys. 48 (2003) 801, [arXiv:astro-ph/0301017]]; arXiv:astro-ph/0302173 (2003); in: Selected Topics in Theoretical Physics and Astrophysics, eds. A.K. Motovilov, F.M.Pen'kov, JINR, Dubna 2003.

[10] C.E. Aalseth et al. (CoGeNT), arXiv:1002.4703 [astro-ph.CO] (2010).

[11] R. Bernabei et al. (DAMA), Eur. Phys. J. C56 (2008) 333.

[12] Z. Ahmed et al. (CDMS), arXiv:0912.3592 [astro-ph.CO] (2009).

[13] S.Andreas et al, arXiv:1003.2595 [hep-ph] (2010).

[14] D. Feldman, Z. Liu, P. Nath, arXiv:1003.0437 [hep-ph] (2010).

[15] A. Bottino, F. Donato, N. Fornengo, S. Scopel, arXiv:0912.4025 [hep-ph] (2009); Phys. Rev. D78 (2008) 083520.