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Horizontal Unification as the Phenomenology of the Theory of "Everything"

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Abstract – It is shown that the extension of the standard model of electroweak interaction and QCD, which includes spontaneously broken horizontal local gauge symmetry, provides a quantitatively definite phenomenological description for almost all phenomena in particle physics and modern cosmology. In this model, the predictions of the standard model are combined with a description of the mass spectrum and mixing of quarks and leptons, and with the predictions of the neutrino mass spectrum and parameters of an invisible axion. This model also gives a quantitatively definite physical basis for the theory of inflation, baryosynthesis, and dark matter of the Universe. A complex analysis of physical, cosmological, and astrophysical predictions of the model singles out a narrow range of allowed values of parameters corresponding to the "effective" mixed cold-hot version of the theory describing the formation of the structure of the Universe. The combination of experimental and astronomical tests of the model that ensure its unambiguous verification is indicated.

1. INTRODUCTION

The development of the theory of "everything" on the basis of superstring models [1] is promising with regard to the construction of a theoretical basis embracing, in a unified manner, the theories of microcosm and the theories of the Universe. With such an approach, the unified theory of fundamental forces of nature can be combined with a physically substantiated complete cosmological theory [2]. However, a comprehensive realistic description of "everything" is complicated by the existence of an enormous variety of versions reproducing both the standard model of electroweak interaction and QCD, and characterized by predictions in the range of high (sub-Planck) energies, which cannot be verified directly in experiments. On the contrary, a number of new hypothetical elements emerging when the symmetry of the standard model is supplemented to the complete symmetry of the theory of "everything" are found to be essential for improving the standard model and for eliminating its intrinsic problems such as the *CP* violation in QCD or the divergence of the Higgs boson mass. Similar elements of the hidden sector of the theory of "everything" are also essential in modern cosmology. It is the introduction of hypothetical elements of the hidden sector of the theory of elementary particles that provides physical grounds for generally adopted necessary components of the modern theory of the Universe such as inflation, baryosynthesis, or dark matter.

A new approach to the phenomenology of the theory of "everything", which has been proposed in [3, 4], ensures quantitative definiteness of various elements of the hidden sector of the theory of elementary particles in the framework of a unified theoretical model. The development of this approach must lead to quantitative phenomenology of the theory of "everything" in the sub-Planck energy range through the generalization of the standard model including the gauge model of the symmetry of fermion generations, the symmetry of grand unification, supersymmetry, and the dark world. In this paper, we will show that even the first step in the development of this approach can be regarded as a realistic quantitative phenomenology embracing, in a unified model, all basic concepts of the modern theory of elementary particles as well as the modern theory of the Universe.

2. MODEL OF HORIZONTAL UNIFICATION (MHU)

Because three known generations of quarks and leptons are indistinguishable in strong and electroweak interactions, it can be conjectured that a "horizontal" symmetry G_H between these generations, which was considered in [5], exists. According to [3] and [5], the model is based on the statement known as the hypothesis of "reflection." This hypothesis presumes that the form of mass matrices of quarks and leptons reflects the nature of "horizontal" symmetry breaking [i.e., the structure of vacuum expectation values (VEV) of "horizontal" scalars breaking G_H], while the mass hierarchy between generations is related to a certain hierarchy in this breaking [3]. It should be noted that masses of fermions in the standard model are obtained from the Yukawa couplings with the $SU(2) \times U(1)$ Higgs doublet $\phi = (\phi^0, \phi^-)$ of the standard model of electroweak interaction:

$$g^f_{\alpha\beta}\phi^{0}\bar{f}_{L\alpha}f^{\beta}_R + \text{h.c.}, \quad (1)$$

where $\alpha, \beta = 1, 2, 3$ are the generation indices; and the mass hierarchy of generations is associated with the

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difference between their Yukawa constants $g^f_{\alpha\beta}$. Therefore, quarks and leptons acquire masses only as a result of breaking the symmetry G_H of the "horizontal" interaction as well as the $SU(2) \times U(1)$ symmetry of electroweak interaction.

In the case of three generations, the "reflection" hypothesis leads to an almost unambiguous choice of G_H, which is reduced to the chiral (axial) local symmetry $SU(3)_H$ (introduced for the first time in [6]), in which the left-handed components of fermions are transformed as triplets $f_{L\alpha}$, while the right-handed components are transformed as antitriplets f_R^α in $SU(3)_H$ (see [3] for details). The masses of quarks and charged leptons in this case are generated by their "see-saw" mixing with hypothetical superheavy fermions. The choice of representation for these fermions in $SU(3)_H$ leads to two most natural realizations of the reflection [3] [$F_{L\alpha}$ and $F_{R\alpha}$ in the direct hierarchy model (DHM) and F_L^α and $F_{R\alpha}$ in the inverse hierarchy model (IHM)].

In the most general case, the mass term of quarks and charged leptons has the form

$$\hat{m}_f = \hat{g}\langle\phi^0\rangle, \tag{2}$$

where the structure of $\hat{g}$ matrices is determined by the choice of the model [3]:

$$\begin{aligned} \hat{g} &= g_f\langle g_{nf}\xi^{(n)}\rangle/M_F \text{ for the DHM and} \\ \hat{g} &= g_f\mu_f/\langle g_{nf}\xi^{(n)}\rangle \text{ for the IHM.} \end{aligned} \tag{3}$$

Here, $f = u$, d, and e; $F = U$, D, and E; and g_{nf} are the constants of Yukawa coupling between fermions F from different generations and "horizontal" scalars $\xi^{(n)}$ (see [3]). The generation of realistic mass matrices of quarks and leptons requires at least three "horizontal" scalars [3], one of which (with the maximum VEV) must be a sextet $\xi^{(0)}_{\{\alpha,\beta\}}$ (α, $\beta = 1, 2, 3$), while others may be either sextets or (anti)triplets $\xi^{(n)}_{[\alpha,\beta]} = \varepsilon_{\alpha\beta\gamma}\xi^{(n)\gamma}$ ($n = 1, 2$). Thus, the structure of mass matrices of quarks and leptons is determined (up to the corresponding Yukawa constants) by the structure of VEVs of scalars $\xi^{(n)}$ having the form [3]

$$\hat{V}_H = \sum_n \langle\xi^{(n)}\rangle = \begin{pmatrix} r_1 & p_1 & p_2 \\ \pm p_1 & r_2 & p_3 \\ \pm p_2 & \pm p_3 & r_3 \end{pmatrix}, \tag{4}$$

where $r_3 \gg p_2 \gg p_1$, $r_3 \gg p_2 \gg r_2 \gg p_1$, and $p_3 \gg r_1$ is the hierarchy (5 - 10 times). In this case, symmetry is broken according to the following scheme:

$$\begin{aligned} SU(3)_H \times U(1)_H &\xrightarrow{\xi^{(0)}} SU(2)_H \times U(1)'_H \\ &\xrightarrow{\xi^{(1)}} U(1)''_H \xrightarrow{\xi^{(2)}} I. \end{aligned} \tag{5}$$

Another scheme is possible in which $SU(3)_H \times U(1)_H \xrightarrow{\xi^{(0)}} SO(3)$ [3] is ruled out in the case of a supersymmetric generalization of the model [7].

The Dirac "see-saw" mechanism of generation of quark and lepton masses (2) and (3) involves the invariant mass parameter M_F in the DHM and μ_f in the IHM. The parameter μ_f can be explicitly connected with the VEV of the field η, which is invariant with respect to the vertical, as well as the horizontal, symmetry group.

Obviously, after the diagonalization of $\hat{m}_f$, the masses of quarks and leptons in DHM (IHM) are directly (inversely) proportional to VEVs of "horizontal" scalars.

The unambiguous prediction of the existence of neutrino mass in the MHU is associated with the existence of heavy neutral leptons that is required for cancellation of triangle anomalies in the $SU(3)_H$ group [5, 8]. In the DHM, the role of such particles can be played by right-handed $SU(3)_H$ triplets $N_{R\alpha}$ and the 15-plet $\Psi^\gamma_{R\{\alpha\beta\}}$ [the $SU(2) \times U(1)$ singlet]. In the IHM, only the $N_{R\alpha}$ triplets are sufficient. On the contrary, a ν_L neutrino acquires mass owing to "see-saw" mixing [8] with heavy neutral leptons $N_{R\alpha}$. In this case, the mass matrix of a neutrino in DHM and IHM has the form

$$\hat{m}_\nu = g_f\langle\phi_0\rangle g_f\langle\phi_0\rangle/(G_{fn}\langle\xi^{(n)}\rangle), \tag{6}$$

where g_f and G_{fn} are the corresponding Yukawa constants (see [2]), and the matrix $\hat{m}_\nu$ is nondiagonal only if $\xi^{(1)}$ and $\xi^{(2)}$ are sextets. According to relation (6), the hierarchy of neutrino masses is always inverse to the hierarchy of horizontal symmetry breaking. This gives

$$\begin{aligned} m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} &\simeq m_e^{-1} : m_\mu^{-1} : m_\tau^{-1} \text{ in the DHM and} \\ m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} &\simeq m_e : m_\mu : m_\tau \quad \text{ in the IHM.} \end{aligned} \tag{7}$$

The problem of CP violation in QCD is solved in the MHU in a natural way, namely, by identifying the global $U(1)''_H$ symmetry [3] with the Peccei–Quinn symmetry $U(1)_{PQ}$ [9]. The breaking of $U(1)''_H$ in (5) on the V''_H scale leads to the emergence in the DHM of an "invisible" axion similar to the standard DFSZ axion [10] for only the first generation ($x = 1$) with the mass

$$m_a = \frac{z^{1/2}}{1+z}\frac{m_\pi f_\pi}{V''_H}, \quad z = m_u/m_d. \tag{8}$$

The symmetry $U(1)''_H$ can be identified with $U(1)_{PQ}$ in the IHM only if there is a triangle anomaly in the interaction $aG\tilde{G}$ of the axial $U(1)_H$ current with gluons. This is natural for any extension of the model to the model based on the Grand Unification Theory (GUT). In this case, an axion in the IHM becomes similar to a hadronic axion [11] with a strongly suppressed coupling with leptons. The mass of such an axion is given by

$$m_a = A_c \frac{z^{1/2}}{1+z} \frac{m_\pi f_\pi}{2V_H^{\prime\prime}}, \tag{9}$$

where A_c is the color (QCD) anomaly.

In contrast to an invisible axion, the axion in the DHM and IHM has both diagonal and nondiagonal interactions with quarks and leptons [3]:

$$L_{\alpha\beta} = iag^f_{\alpha\beta}\bar{f}_\alpha (i \sin\phi_{\alpha\beta} + \gamma_5 \cos\phi_{\alpha\beta}) f_\beta + \text{h.c.} \tag{10}$$

On the contrary, the axion in the MHU is related to the mechanism of emergence of Majorana neutrino masses [3] and is, hence, a singlet-type majoron [12]. Thus, the axion in the MHU is simultaneously a majoron and a familon [13] of the singlet type and is called an archion [4].

3. PHENOMENOLOGY OF "EVERYTHING"

3.1. Flavor Structure of Particles

If the interaction constants for non-self-conjugate convolutions of "horizontal" scalars are small as compared to the constants of the self-conjugate polynomial, the VEV matrix $\hat{V}_H$ (4) in the DHM has a structure that ensures the Fritzsch configuration of the mass matrix of quarks and leptons [3]:

$$\hat{m}^f = \begin{pmatrix} 0 & m^f_{12} & 0 \\ m^f_{12} & 0 & m^f_{23} \\ 0 & m^f_{23} & m^f_{33} \end{pmatrix}, \quad f = u, d, c. \tag{11}$$

The solution of the secular equation $\det(\hat{m}^f - \lambda) = 0$ enables us to express the elements of mass matrices (11) and, hence, of the unitary matrices V_{fL}, diagonalizing them ($V^+_{fL}\hat{m}^f V_{fL} = \hat{m}^f_{diag}$, $V_{fL} = V_f = V^T_{fR}$) in terms of quark and lepton masses [3]. This model describes satisfactorily the values of weak mixing angles and the *CP* violation parameter ε in the system of K–$\bar{K}$ mesons. However, this version of the DHM is fraught with difficulties in the description of strong B_d–$\bar{B}_d$ mixing for $m_t \le 100$ GeV (see [3]).

The above conditions ensure in the IHM the inverse Fritzsch form of the mass matrix ($\sim \hat{V}_H^{-1}$) [14]

$$\hat{m}^f = \begin{pmatrix} (m^f_{13})^2/m^f_{33} & 0 & m^f_{13} \\ 0 & 0 & m^f_{23} \\ m^f_{13} & m^f_{23} & m^f_{33} \end{pmatrix}. \tag{12}$$

On the whole, this model describes (satisfactorily) *CP* violation in the system of K–$\bar{K}$ mesons and B_d–$\bar{B}_d$ oscillations for $m_t = 70$ - 80 GeV [3, 15].

The insufficiently correct description of the flavor structure by using the simplest ansätze for mass matrices, noted earlier, can be apparently improved for the mass of a t quark exceeding 100 GeV. This, however, does not eliminate grounds for a transition to a more general class of "mixed"-type models for mass matrices. The structure of mass matrices of quarks and leptons is found to be sensitive to the choice of the parameters of "horizontal" symmetry breaking. This makes it possible to rigidly fix these parameters as well as the form of the self-interaction potential for "horizontal" Higgs bosons.

3.2. Flavor Dynamics

The existence of a Goldstone boson a, namely, a "singlet" familon [13], allows us to predict two-particle familon decays:

(a) leptonic decays $\mu \longrightarrow ea$, $\tau \longrightarrow \mu a$, and $\tau \longrightarrow ea$ [3, 16] and

(b) mesonic decays $K^+ \longrightarrow \pi^+ a$ (transitions $s \longrightarrow da$); $D \longrightarrow \pi a$ and $D \longrightarrow \rho a$ (transitions $c \longrightarrow ud$); $B \longrightarrow Ka$, $B \longrightarrow \pi a$, $B \longrightarrow K^*a$, and $B \longrightarrow \rho a$ (transitions $b \longrightarrow sa$ and $b \longrightarrow da$) (see [16] for details).

The search for such familon decays becomes an important source of information on the structure of the mixing matrices V_u, V_d, and V_e for quarks and leptons and, hence, on the structure of their mass matrices. This, in turn, will make it possible to determine mixing in currents violating the baryonic number and to predict the expected lifetimes and partial widths of proton decay more reliably.

Because an archion is also a singlet-type majoron [2, 4] having interactions with a neutrino that are nondiagonal in flavors, the decays $\nu_H \longrightarrow \nu_L a$ of heavier neutrinos into lighter neutrinos and an archion are possible in the case of the sextet $\xi^{(n)}_{\alpha\beta}$ ($n = 1, 2$). The corresponding lifetime is [1, 4]

$$\tau(\nu_H \longrightarrow \nu_L a) = 16\pi/g^2_{HL}m_H, \tag{13}$$

where g_{HL} are the nondiagonal coupling constants [4]. In the case of the triplet $\xi^{(n)}_{\alpha\beta}$ ($n = 1, 2$), neutrino decays are absent [3].

3.3. Inflation

The theory of inflation, which forms the basis of modern cosmology of the early Universe, was developed for solving problems in the standard theory of the hot Universe [17]. We will prove here that, in the IHM, there are some physical grounds for the realization of the scenario of chaotic inflation, which is the most attractive at the moment and the least model-dependent mechanism of realization of exponential expansion of the Universe.

Indeed, the role of an inflaton can apparently be played by the field η, which is required for realization of the Dirac "see-saw" mechanism in the IHM and is a singlet both in $SU(3)_H$ and in $SU(2) \times U(1)$. The VEV of this field determines the neutrino mass suppression as compared to the mass of charged leptons and quarks:

$$\frac{m_\nu}{m_f} \propto \frac{g_f \langle \phi_0 \rangle}{g_{\eta f} \langle \eta \rangle}. \tag{14}$$

Here, $g_{\eta f} = \mu_f / \langle \eta \rangle \leq V_H'' / \langle \eta \rangle$, where V_H'' is the minimum scale of "horizontal" symmetry breaking [$U(1)_H''$ in (5)].

The main parameter characterizing the chaotic inflation process for a Higgs-type potential is the inflaton self-interaction constant λ_η whose value determines the amplitude of initial density perturbations $\delta\rho/\rho \cong 10^2 \lambda_\eta^{1/2}$ and is fixed by taking into account the results of the search for anisotropy in relic radiation [17]. The required value of λ_η can be obtained under the condition

$$\lambda_\eta > g_{\eta f}^4 / (8\pi^2). \tag{15}$$

This leads to the following constraint on the inflaton VEV for the typical value $\lambda_\eta \simeq 10^{-14}$:

$$\langle \eta \rangle > 10^3 V_H''. \tag{16}$$

Thus, the inflation of the Universe occurs during "rolling down" of the field η from $\eta \simeq \lambda_\eta^{-1/4} M_p$ to the minimum value of $V(\eta)$ for $\eta = \langle \eta \rangle$. After completion of the inflation, the field η develops oscillations in the vicinity of the minimum, realizing the postinflation dust-form stage of expansion with the equation of state $p = 0$ [18], which ultimately leads to heating of the Universe. The development of gravitational instability at this stage may lead to the formation of primary black holes (PBH) [18].

The temperature of heating of the Universe is given by the formula [17]

$$T_{RH} \leq 10^{-1} (\Gamma_{tot} M_p)^{1/2}, \tag{17}$$

where

$$\Gamma_{tot} = \Gamma_\psi + \Gamma_g, \tag{18}$$

$\Gamma_g = m_\eta^3 / M_p^2$ is the probability of the decay of the field η due to gravitational effects, and $\Gamma_\psi = \Gamma(\eta \longrightarrow \bar{F}f) = g_{\eta f}^2 m_\eta / (8\pi)$.

3.4. Baryosynthesis

Without going into details on the description of specific features of baryogenesis in the MHU (whose mechanism has been studied insufficiently in this model and requires a special analysis), we note, on the basis of the results obtained in [19], that a theory of the MHU type may apparently lead to a baryon-antibaryon asymmetry generation $n_B / n_\gamma \simeq 3 \times 10^{-10}$.

In the mechanism proposed in [19], the baryon-antibaryon asymmetry emerges as a result of combination of nonequilibrium processes with $\Delta L = 2$, which are associated with the "see-saw" mechanism of generation of the majoron mass of a neutrino, and nonconservation of $B + L$ at high temperatures in the standard model of electroweak interaction.

A supersymmetric generalization imparts to the MHU some additional possibilities of realization of baryosynthesis owing to the decay of the condensate of scalar supersymmetric particles with the nonzero value of B–L, which generalizes the Affleck–Dine–Linde mechanism [20] proposed in the framework of the supersymmetric $SU(5)$ GUT, and also owing to decays of superpartners of an archion in analogy with [21].

3.5. Dark Matter and Structure Formation of the Universe

The MHU combines various types of candidates for the role of dark matter particles (axion and unstable heavy neutrinos), which are considered in the theory of structure formation of the Universe, by using a unified approach. For a fixed modern total density ρ_{tot} and the baryon density ρ_B, the relation

$$\rho_a + \rho_{\nu_\tau} + \rho_{\nu_\mu} + \rho_{\nu_e} + \rho_B = \rho_{tot} \tag{19}$$

is an equation in the parameters of the model whose solutions fix a discrete set of cosmological models with various types of dark mater, thereby determining the relative contribution of heavy neutrinos and archions to the cosmological density.

The IHM is characterized by the most complete set of possible realizations of dark matter [4] in view of less stringent astrophysical limitations imposed on the interaction scale of an invisible axion [11]. Six cosmological scenarios of the IHM are consecutively reproduced by varying the parameters of V_H'' and the ratio g^2/G of the Yukawa constants in (6) [4, 22] and can be classified as follows [4]: (a) cold dark matter in the form of the energy of classical oscillation of the primary axion field and axions formed as a result of decays of cosmic strings, (b) hot dark matter in the form of stable neutrinos, and (c) four possibilities for unstable dark matter in the form of unstable neutrinos with dominating relativistic or nonrelativistic decay products in the modern Universe. Versions (a) and (b) are also possible in the DHM.

4. QUANTITATIVE SCHEMES OF MHU BASED ON A SYSTEM OF CONSTRAINTS ON FREE PARAMETERS

Like any gauge model with spontaneous symmetry breaking, the MHU involves various free parameters. Claiming to be a realistic phenomenology of "everything," however, the model under investigation is capable of giving various predictions whose combinations restrict the values of these parameters in the redefined system of relations and make it possible to work out a unified scheme of quantitative relations incorporating all of the phenomena described in Section 3. This system of relations can be obtained from the following predictions and restrictions.

(1) The three scalar fields $\xi^{(n)}$ $(n = 0, 1, 2)$ ensure complete breaking of the $SU(3)_H \times U(1)_H$ symmetry according to scheme (5). Each stage of this breaking is characterized by an energy scale. Therefore, the MHU contains at least three energy scales V_H, V'_H, and V''_H. According to relation (3), the structure of mass matrices of quarks and leptons is determined by matrix (4) of "horizontal" VEVs, while the hierarchy of masses between generations follows not from the drastic difference between Yukawa constants g_{nf}, $n = 0, 1, 2$ (which are assumed to be on the same order of magnitude), but from the hierarchy between the VEVs of "horizontal" scalars. In order to estimate this hierarchy, we consider the case when the mass matrices of quarks and leptons have the Fritzsch structure in the DHM and the inverse Fritzsch structure in the IHM. In this case, if $r_3 = V_H$, $p_2 = V'_H$, and $p_1 = V''_H$ in (4), the following estimates are possible [3]:

$$\begin{aligned} V''_H : V'_H : V_H &\simeq (m_d m_s)^{1/2} : (m_s m_b)^{1/2} : m_b \\ &\simeq 1 : 30 : 200 \text{ in the DHM,} \\ V''_H : V'_H : V_H &\simeq (m_s m_b)^{-1/2} : (m_d m_s)^{-1/2} : m_d^{-1} \\ &\simeq 1 : 30 : 200 \text{ in the IHM.} \end{aligned} \tag{20}$$

Thus, a strict hierarchy between the energy parameters of "horizontal" symmetry breaking, which is stable to radiative effects, exists. Consequently, the constraints obtained for one of the three scales of symmetry breaking can be automatically extended to all of the remaining scales.

(2) The data on the absence of the decays $\mu \longrightarrow ea$ lead, in the DHM, to the restriction $V_H > 10^8$ GeV [16], while the data on the absence of the decays $K \longrightarrow \pi a$ in the DHM yield $V''_H > 10^{10}$ GeV [16]. In the IHM, these constraints are abruptly relaxed ($V''_H > 4 \times 10^5$ GeV [16]) in view of the weakness of nondiagonal transitions between particles of the first two generations.

(3) An analysis of the influence of energy losses through emission of archions on the evolution rate of the stars yields, in the DHM, the restriction $V''_H > 3.7 \times 10^7$ GeV for stars from the main sequence [22] and $V''_H > 3.7 \times 10^9$ GeV for red giants [22]. In the IHM, these restrictions are relaxed to $V''_H \geq 10^6$ GeV [22] because the axion is of hadronic origin.

(4) An analysis of the admissible effect of the energy loss of a collapsing star through axion radiation on the neutrino signal of SN1987 rules out the interval $10^6 \leq V''_H \leq 3 \times 10^9$ GeV for a hadronic axion [23].

(5) An analysis of generation of density perturbations with a nonplanar spectrum in phase transitions with symmetry breaking (5) of generations at the inflation stage in the chaotic inflation model [24] leads to the constraint $V''_H < 10^{11}$ GeV if the restrictions on admissible large-scale inhomogeneities and the PBH concentration in the Universe are taken into account.

(6) The constraint on the emission of axions by cosmic strings formed at the postinflation stage and decaying after the QCD phase transition lowers the upper limit of the scale to $V''_H < 2 \times 10^{10}$ GeV [24, 4].

(7) An analysis of equation (18) in the phase space $(V''_H, g^2/G)$ leads to the restriction $g^2/G \leq 1.5 \times 10^{-4}$ following from the condition $\rho_{tot} \leq \rho_{cr}$ [22].

(8) The constraints $m_{\nu_e} \leq 3$ eV [25] on the Majorana mass of ν_e following from experiments on the $2\beta_{0\nu}$-decay lead to limitations on the combination of V_H (V''_H) and g^2/G because the Majorana mass of the electronic neutrino is given by the relation

$$\begin{aligned} m_{\nu_e} &= \frac{(g\langle\phi_0\rangle)^2}{GV_H} \text{ in the IHM,} \\ m_{\nu_e} &= \frac{(g\langle\phi_0\rangle)^2}{GV''_H} \text{ in the DHM.} \end{aligned} \tag{21}$$

Thus, the system of Restrictions 2 - 6 leads to the range of admissible values of the scale $V''_H = V_6 \simeq 10^6$ GeV and $V''_H = V_{10} \simeq 3 \times 10^9$ - 2×10^{10} GeV in the IHM and only $V''_H = V_{10}$ in the DHM. This permits the existence of two versions of realization of the dark matter model in the IHM and a single version in the DHM.

(a) The mixed stable dark matter (MSDM) is realized for V_{10} under the conditions of predominance of the density ρ_a of the primary archion field, archions formed as a result of decays of cosmic strings (cold dark matter), and ρ_ν ($\nu = \nu_\tau$ for the IHM and $\nu = \nu_e$ for the DHM) of heavy stable neutrinos (hot dark matter) with mass m_ν and the lifetime $\tau(\nu \longrightarrow \nu_\mu a)$ exceeding the age of the Universe $t_U = 4 \times 10^{17}$ s. The model of cold (CDM), hot (HDM), or mixed (CDM + HDM) stable dark matter is realized in the MSDM depending on the choice of g^2/G determining m_ν [22]:

$$\begin{aligned} \rho_\nu &= m_\nu n_\nu, \\ \rho_a &= (0.90 - m_\nu/28.9 \text{ eV})\rho_{cr}. \end{aligned} \tag{22}$$

Here, $n_\nu = (3/11)n_\gamma$ is the standard neutrino concentration.

(b) In the model of hierarchical decay scenario (HDS) realized for V_6 only in the IHM, the large-scale structure of the Universe is formed under the conditions when neutrinos and their relativistic decay products dominate alternatively. In the period from $t_0 = 10^6 (1 \text{ keV}/m_{\nu_\tau})^2$ s to the instant $\tau_{\nu_\tau}(\nu_\tau \longrightarrow \nu_\mu a) = 10^{10} (1 \text{ keV}/m_{\nu_\tau})^3$ s, ν_τ with mass $m_{\nu_\tau} = 1$ - 10 keV dominates in the Universe (depending on g^2/G). The decay of these neutrinos leads to the period of dominance of relativistic ν_μ neutrinos and a, followed by the dominance (for $t > \tau_{\nu_\tau}$) of ν_μ neutrinos with mass $m_{\nu_\mu} = 0.1 - 1$ keV to the instant $\tau_{\nu_\tau}(\nu_\mu \longrightarrow \nu_e a) = 10^{16}(1 \text{ keV}/m_{\nu_\tau})^3$ s.

The decay $\nu_\mu \longrightarrow \nu_e a$ slows down the evolution of the formed structure and ensures its conservation to the present time, thereby realizing the model of unstable dark matter [26]. As soon as primary neutrinos ν_μ become nonrelativistic, their perturbations become comparable with those of ν_τ and preserve their scales after the decays $\nu_\tau \longrightarrow \nu_\mu a$, while ν_μ, formed as a result of decays of ν_τ, enhance the long-wave component in the perturbation spectrum.

The admissibility of the low-energy scale of V_6 in the framework of the HDS model results in the establishment of equilibrium between archions and matter. This equilibrium sets in after the QCD phase transition owing to the reactions $\pi N \longrightarrow aN$ [22]. Thus, the dominating form of dark matter at present is relic archions [22] with mass $m_a \simeq 3$ eV and number density $n_a = 0.6 n_\nu$ as well as archions formed as a result of decays of ν_τ and ν_μ [22] having a nonthermal spectrum.

In addition to this, the decays of archions $a \longrightarrow 2\gamma$ with the lifetime

$$\tau(a \longrightarrow 2\gamma) = \xi^2 z^{-1}(m_\pi/m_a)^5 \tau(\pi^0 \longrightarrow 2\gamma), \quad (23)$$

where $\xi = 1, -z, -2z(z-1)^{-1}, \ldots$ (depending on the choice of representations of F), lead to the prediction of a nonthermal electromagnetic background in the framework of the HDS model [27]. For the red shift $z \le 10^3$, the existence of this background should hamper the recombination of matter, reducing the expected small-scale anisotropy of relic radiation. The presence of such a background in the modern Universe offers an additional possibility of verification of the theory in astronomical observations [27].

Together with Z.G. Berezhiani and A.G. Doroshkevich, we carried out a detailed analysis including the determination of transition functions for perturbation spectra in MSDM and HDS models as well as numerical calculations of these spectra and their characteristic scales and comparison of these scales with similar scales in the CDM model. The analysis revealed that Restriction (7) permits mixed forms of dark matter in the case of the IHM, while the MSDM scenario in the DHM degenerates to the CDM model in accordance with Restriction 8. The quantitative scheme of V_{10} can be fixed in final form only after the fixation of the scale in the search for cosmic axions in the halo of the Galaxy by using the axion haloscopy technique. Thereafter, according to Restriction 8, we can then specify the range of g^2/G in the interval $g^2/G < 1.5 \times 10^{-4}$. In the case of the HDS model, the best agreement with the observed parameters of the large-scale structure was reached for $m_\nu \simeq 1$ eV, which is in accord with Restriction 8. On the contrary, the rigid fixation of V_6 in the IHM on the basis of restrictions 2 - 4 makes it possible to determine unambiguously the upper value for the ratio of constants $g^2/G \le 10^{-6}$ according to formula (21) and the hierarchy (20).

The interpretation of the field η as an inflaton in the IHM leads, according to (16), to the following lower estimates of VEV $\langle\eta\rangle$ in both quantitative schemes for V_6 and V_{10}, respectively:

$$\langle\eta\rangle > 10^{-10} M_p = \langle\eta\rangle_{min},$$
$$\langle\eta\rangle > 10^{-6} M_p = \langle\eta\rangle_{min}. \quad (24)$$

It is natural to choose the single isolated scale of M_p, $\langle\eta\rangle_{max} \simeq M_p$ as the upper estimate for $\langle\eta\rangle$. In this case, the inflaton mass is $m_\eta = \lambda^{1/2}\langle\eta\rangle \le 10^{-7} M_p$. As a result, gravitation effects ($\Gamma_{tot} = \Gamma_g$) dominate in (18) because the following relation is valid both for V_6 and V_{10}:

$$\Gamma_g/\Gamma_\psi \ge 8\pi(m_\eta/V_H^2) \gg 1. \quad (25)$$

In this case, the temperature of heating of the Universe is $T_{RH} \le 3 \times 10^7$ GeV in accordance with (17), and a chaotic inflation may take place in which a transition to the next Friedmann stage of expansion is due to processes similar to those considered in the model from [28]. Relation (25) holds up to values $\langle\eta\rangle_{lim} = 4 \times 10^{-4} M_p$ and $\langle\eta\rangle_{lim} = 4 \times 10^{-2} M_p$ for V_6 and V_{10}, respectively. Thus, effects associated with the decay of η into fermions ($\Gamma_{tot} = \Gamma_\Psi$) dominate in the range $\langle\eta\rangle_{min} < \langle\eta\rangle < \langle\eta\rangle_{lim}$. In this case, the temperature of heating of the Universe is $T_{RH} \le 6 \times 10^5$ GeV for V_6 and $T_{RH} \le 6 \times 10^9$ GeV for V_{10} in accordance with (17). For supersymmetric generalization of the MHU, the constraints on relic gravitino concentration impose limitations $T_{RH} \le 10^8$ GeV on the heating temperature [29], which may lead to an additional constraint on $\langle\eta\rangle_{min}$ for V_{10}, namely, $\langle\eta\rangle_{min} = 6 \times 10^{-5} M_p$. The substitution of the value of $\langle\eta\rangle_{max}$ into (16) leads to a constraint on $V_H'' < 10^{16}$ GeV, i.e., $V_H'' < V_{GUT}$ (the GUT scale [30]). The upper limit obtained for V_H'' indicates that the last stage of $SU(3)_H$ breaking in (5) occurs after breaking of the GUT symmetry. In order to remain in the framework of self-consistence of the model, we must obviously require that the first two stages of symmetry breaking in scheme (5) occur after breaking of the GUT symmetry, i.e., $V_H < V_{GUT}$, thus justifying the elimination of scales above 10^{14} GeV in [2, 24].

5. CONCLUSION

The MHU is associated with a high energy scale of symmetry breaking, which is inaccessible for a direct investigation on operating or planned accelerators. However, it can be verified in laboratory experiments combined with astronomical observations. For example, a consistent analysis of physical experiments aimed at the search for rare decays and $K-\bar{K}$, $B-\bar{B}$ oscillations, as well as astrophysical observations of evolution of stars and experiments on the search for neutrino mass, neutrino oscillations, and also the $a \longrightarrow 2\gamma$ decays, becomes an effective method of verification of the V_6 scheme, which takes place only in the IHM. In addition, axion haloscopy, which is most effective in the case of V_{10}, taking place both in the DHM and the IHM, is worthy of notice.

The interpretation of COBE data [31] for anisotropy in the relic radiation leads to a mixed model based on dark matter, which can provide arguments in favor of the IHM in the case of V_{10}.

Note that the V_6 model, and apparently the mixed HDM + CDM model based on V_{10}, cannot result in a significant resonance amplification of neutrino oscillations in the Sun (the MSW mechanism [32]), which can be reproduced only for the CDM model based on V_{10}. However, the emission of archions by the Sun in the V_6 model may ensure smoothing of the temperature distribution in the central region of the Sun and a decrease in its core temperature. This may provide a solution of the solar neutrino problem in the framework of the V_6 model, which is similar to the solution of the type from the "cooled" Sun model or cosmion models [33]. On the contrary, V_{10} models are fraught with a serious problem of archioles, namely, the problem associated with the fact that nonuniformities of the energy density of coherent oscillations of the axion field have large-scale Brownian structure [34], which reflects the large-scale structure of axion walls and strings formed during "switching on" of the axion mass in the early Universe at $T \simeq 1$ GeV. The prediction of such a large-scale structure of initial inhomogeneities of cold dark matter is in serious contradiction with the observed isotropy of the relic radiation. These considerations evidence in favor of the V_6 model as a realistic phenomenology of "everything."

Thus, the MHU leads to an abundance of indirect consequences accessible to laboratory and astronomical tests, whose number is larger than the number of independent parameters of the theory. Therefore, the verification of consequences can be reduced to a redefined system of equations in these parameters.

The model considered here is an initial stage in the construction of a realistic description of the unified fundamental structure of micro- and macrocosms. The difficulties encountered in the MHU, i.e., the problem of scale hierarchy in the case of V_{10} [22], which requires a supersymmetric extension, and the problem of cancellation of the color anomaly in the IHM, which requires an extension to the model based on the GUT, illustrate this statement. Nevertheless, a detailed analysis of the low-energy basis of the theory of "everything," i.e., the MHU, may provide a set of criteria for selection of models claiming to play the role of a comprehensive fundamental physical theory.

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