Dark Matter in the Standard Model Extension
with Singlet Quark

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Abstract

We analyze the possibility of hadron Dark Matter carriers consisting of singlet quark and the light standard one. It is shown that stable singlet quarks generate effects of new physics which do not contradict to restrictions from precision electroweak data. The neutral and charged pseudoscalar low-lying states are interpreted as the Dark Matter particle and its mass-degenerated partner. We evaluated their masses and lifetime of the charged component, and describe asymptotics of the potential of low-energy interactions of these particles with nucleons and with each other. Some peculiarities of Sommerfeld enhancement effect in the annihilation process are also discussed.

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I. INTRODUCTION

The problem of Dark Matter (DM) explanation has been in the center of fundamental physics attention for a long time. The existence of the DM is followed from astrophysical data and remains the essential phenomenological evidences of New Physics’ manifestations beyond the Standard Model (SM) [1, 2]. An appropriate candidates as DM carriers should be stable particles which weakly interact with ordinary matter (so called, WIMPs). Such particles usually are considered in the framework of supersymmetric, hypercolor or other extensions of the SM (see, for instance, review [3]). The last experimental rigid restrictions on cross section of spin-independent WIMP-nucleon interaction [4] exclude many variants of WIMPs as the DM carriers. So, another candidates are discussed in literature, such as quarks from fourth generation, hyper-colour quarks, dark atoms, axions and so on [3]. In spite of some theoretical peculiarities, the possibility of hadronic DM is not excluded and considered, for example, in Refs. [5]-[10]. For instance, the possibility of existence of new hadrons which can be interpreted as carriers of the DM, was analyzed in detail within the framework of the SM chiral-symmetric extension [10].

Principal feature of the hadronic structure of the DM is that the strong interaction of new stable quarks with standard ones leads to the formation of neutral stable meson or baryon heavy states. Such scenario can be realized in the extensions of the SM with extra generation [5]-[9], in mirror and chiral-symmetric models [10, 11] or in extensions with singlet quark [12]-[16]. The second variant was detailed considered in Ref. [10], where the quark structure and low-energy phenomenology of new heavy hadrons were described. It was shown that the scenario does not contradict to cosmochemical data, cosmological tests and known restrictions for new physics effects. However, the explicit realization of the chiral-symmetric scenario faces with some theoretical troubles, which can be eliminated with the help of artificial assumptions. The extensions of SM with fourth generation and their phenomenology were considered during last decades in spite of strong experimental restrictions which, for instance, follows from invisible Z-decay channel, unitary condition for CM-matrix, FCNC etc. The main problem of 4th generation is the contribution of new heavy quarks to the Higgs boson decays [17]. The contribution of new heavy quarks to vector boson coupling may be compensated by the contribution of 50 GeV neutrino [18–20], however, such assumption looks as artificial. In this paper, we analyze the hypothesis of hadronic Dark Matter which follows from the SM extension with singlet quark.

The paper is organised as follows. In the second section we describe the extension of the SM with singlet quark and consider the restrictions on its phenomenology, following from precision electroweak data. Quark composition and interaction of new hadrons with the standard ones at low energies is analyzed in the third section. The masses of new hadrons, decay properties of charged partner of the DM carrier and annihilation cross section are analyzed in the fourth section.

II. STANDARD MODEL EXTENSION WITH SINGLET QUARK

There is a wide class of high-energy extensions of the SM with singlet quarks which are discussed during many decades. Here, we consider the simplest extension of the SM with singlet quarks as the framework for description of the DM carrier. Singlet (or vector-like) quark is defined as fermion with standard $U_Y(1)$ and $SU_C(3)$ gauge interactions but it is singlet under $SU_W(2)$ transformations. The low-energy phenomenology of both down-
and up-type quarks (D and U) was considered in detail in large number of works (see, for instance, [21], [22], [23] and references therein). As a rule, singlet quark is supposed as unstable due to the mixing with the ordinary ones. This mixing leads to the FCNC appearing at the tree level. As a consequence, we get an additional contributions into rare processes, such as rare lepton and semi-lepton decays, and mixing in the systems of neutral mesons ($M^0 - \bar{M}^0$ oscillations). The current experimental data on New Physics phenomena give rigid restrictions for the angles of ordinary-singlet quark mixing. In this work, we consider alternative aspect of the extensions with singlet quark $Q_A$, namely, the scenario with the absence of such mixing. As a result, we get stable singlet quark which have no the decay channels due to absence of non-diagonal $Q$-quark currents. More exactly, due to confinement the singlet quark forms bound states with the ordinary ones, for instance ($Qq$), and the lightest state is stable. In this work, we consider some properties of such particles and analyze the possibility to interpret the stable neutral meson $M^0 = (\bar{Q}q)$ as the DM carrier.

Now, we examine the minimal variants of the SM extension with singlet quark $Q_A$, where subscript $A = U, D$ denotes up- or down-type with charge $q = 2/3, -1/3$. According to the definition, the field $Q$ is singlet with respect to $SU(2)$ group and has standard transformations under abelian $U_Y(1)$ and color $SU_C(3)$ groups. So, the minimal additional gauge-invariant Lagrangian has the form:

$$L_Q = i\bar{Q}\gamma^\mu(\partial_\mu - ig_1\frac{Y}{2}V_\mu - ig_s\frac{\lambda_a}{2}G^a_\mu)Q - M_Q\bar{Q}Q,$$ (2.1)

where $Y/2 = q$ is charge in the case of singlet $Q$, and $M_Q$ denotes phenomenological mass of quark. Note, singlet quark (SQ) can not get mass term from the standard Higgs mechanism because the Higgs doublet is fundamental representation of $SU(2)$ group. Abelian part of the interaction Lagrangian (2.1), which will be used in further considerations, includes the interactions with physical photon $A$ and $Z$ boson:

$$L_{Q}^{int} = g_1qV_\mu\bar{Q}\gamma_\mu Q = g_q(c_wA_\mu - s_wZ_\mu)\bar{Q}\gamma^\mu Q,$$ (2.2)

where $c_w = \cos \theta_w$, $s_w = \sin \theta_w$ and $\theta_w$ is Weinberg angle of mixing. Note, the left and right parts of the singlet field $Q$ have the same transformation properties and interaction (2.2) has vector-like (chiral-symmetric) form.

First of all, we should take into account direct and indirect restrictions on New Physics (NF) manifestations which follow from the precision experimental data. The additional chiral quarks, for instance from standard fourth generation, are excluded at the $5 \sigma$ level by LHC data on Higgs searches [21]. As the vector-like (non-chiral) singlet fermions do not receive their masses from a Higgs doublet, they are allowed by existing experimental data on Higgs physics. The last limits on new colored fermions follow from the jets data from the LHC [24]. The corresponding limits for effective colored factors $n_{eff} = 2, 3, 6$ are about 200 GeV, 300 GeV, 400 GeV. Note, these limits are much less then the estimation of quark mass which follows from the DM analysis (see the fourth section). Indirect limits follow from precision electroweak measurements of the effects such as flavor-changing neutral currents (FCNC) and vector boson polarizations which take place at the loop level in the SM. Because we consider the case of stable singlet quark, there are no mixing with ordinary quarks and, consequently, FCNC effects are absent. The NF manifestations in polarization effects of gauge bosons $\gamma, Z, W$ are usually described by oblique parameters (Peskin-Takeuchi parameters [25]). From Eq. (2.2), it follows that the singlet quark gives non-zero contributions
into polarizations of $\gamma$ and $Z$-bosons which are described by the values of $\Pi_{\gamma\gamma}, \Pi_{\gamma Z}, \Pi_{ZZ}$. As $W$-boson does not interact with the SQ, corresponding contribution into polarizaton operator is zero, $\Pi_{WW} = 0$. Taking into account the last fact, oblique parameters can be represented by the following expressions:

$$\alpha S = 4s_w^2c_w^2\left[\frac{\Pi_{ZZ}(M_Z^2)}{M_Z^2} - \frac{c_w^2 - s_w^2\Pi'_{\gamma Z}(0) - \Pi_{\gamma\gamma}(0)}{s_w c_w}\right];$$

$$\alpha U = -4s_w^2\left[c_w^2\frac{\Pi_{ZZ}(M_Z^2)}{M_Z^2} + 2s_w c_w \Pi'_{\gamma Z}(0) + s_w^2\Pi'_{\gamma\gamma}(0)\right];$$

$$\alpha T = -\frac{\Pi_{ZZ}(0)}{M_Z^2}; \quad \alpha V = \Pi'_{ZZ}(M_Z^2) - \frac{\Pi_{ZZ}(M_Z^2)}{M_Z^2};$$

$$\alpha W = 0 (W \sim \Pi_{WW} = 0); \quad \alpha X = -s_w c_w\left[\frac{\Pi_{\gamma Z}(M_Z^2)}{M_Z^2} - \Pi'_{\gamma Z}(0)\right]. \quad (2.3)$$

Note, parameters $V$, $W$, $X$ describe the contributions of new fermions with masses close to the electroweak scale. In (2.3) polarizations $\Pi_{ab}(p^2, M_U^2)$, where $a, b = \gamma, Z$, in one-loop approach can be represented in simple form (for the case of SQ with $q = 2/3$):

$$\Pi_{ab}(p^2, M_U^2) = \frac{g^2}{9\pi^2}k_{ab}F(p^2); \quad k_{\gamma Z} = s_w^2, \quad k_{\gamma\gamma} = c_w^2, \quad k_{\gamma Z} = -s_w c_w;$$

$$F(p^2) = -\frac{1}{3}p^2 + 2M_U^2 + 2A_0(M_U^2) + (p^2 + 2M_U^2)B_0(p^2, M_U^2). \quad (2.4)$$

In Eqs. (2.4) function $F(p^2)$ contains divergent terms in the one-point, $A_0(M_U^2)$, and two-point, $B_0(p^2, M_U^2)$, Veltman functions which are exactly compensated in (2.3). Using standard definition of the functions $A_0(M_U^2)$ and $B_0(p^2, M_U^2)$ and the equality $B_0(0, M_U^2) = M_U^2/6$, by straightforward calculations we get a simple expressions for oblique parameters:

$$-S = U = \frac{8s_w^4}{27\pi} \approx 4.2 \cdot 10^{-3}, \quad T = 0. \quad (2.5)$$

These values significantly less the experimental limits [26]: $S = 0.00 \pm 0.11(-010), \quad U = 0.08 \pm 0.11, \quad T = 0.02 \pm 0.11(-012)$, that is the scenario with up-type singlet quark satisfy to the restrictions on indirect manifestations of heavy new fermion. In the case of down-type singlet quark having charge $q = -1/3$ contributions into polarization and, consequently, into PT-parameters are four times smaller.

In the quark-gluon phase (QGP) of the Universe evolution, stable SQ interacts with standard quarks through exchanges by gluons $g, \gamma, Z$ according to Eq. (2.2). So, we have large cross-section for annihilation into gluons and quarks, $QQ \rightarrow gg$ and $QQ \rightarrow q\bar{q}$ correspondingly, and also small additional contributions in electroweak channels $QQ \rightarrow \gamma\gamma, ZZ$. These cross sections can be simply derived from the known expressions for the processes $gg \rightarrow QQ$ and $q\bar{q} \rightarrow QQ$ (see review in Ref. [26]) by time inversion. Two-gluon cross section in the low-energy limit looks like:

$$\sigma(U\bar{U} \rightarrow gg) = \frac{14\pi}{3} \frac{\alpha_s^2}{v_r M_U^2}, \quad (2.6)$$

where $M_U$ is $U$-quark mass and $\alpha_s = \alpha_s(M_U)$ is strong coupling at the corresponding scale. Two-quark channel in the massless limit $m_q \rightarrow 0$ is as follows:

$$\sigma(U\bar{U} \rightarrow q\bar{q}) = \frac{2\pi}{9} \frac{\alpha_s^2}{v_r M_U^2}. \quad (2.7)$$
So, the two-gluon channel dominates. We should note, that the cross section of SQ-annihilation is suppressed by large $M$ in comparison with the annihilation of standard quarks.

After the transition from quark-gluon plasma to hadronization stage, the singlet quarks having standard strong interactions (gluon exchange), form coupled states with ordinary quarks. New heavy hadrons can be constructed as coupled states which consist of heavy stable quark $Q$ and a light quark from the SM quark sector. Here, we consider the simplest two-quark states, neutral and charged mesons. The lightest of them, for instance neutral meson $M = (\bar{Q}q)$, is stable and can be considered as the carrier of cold Dark Matter. Possibility of existence of heavy stable hadron was carefully analyzed in \[10\], where it was shown that this hypothesis does not contradict to cosmochemical data and cosmological test. This conclusion was based on the important property of new hadron, namely, repulsive strong interaction with nucleons at large distances. The effect will be qualitatively analyzed for the case of $MM$ and $MN$ interactions in the next section.

III. QUARK COMPOSITION OF NEW HADRONS AND THEIR INTERACTIONS WITH NUCLEONS

At the hadronization stage, heavy SQ form the coupled states with the ordinary light quarks. Classification of these new heavy hadrons was considered in Ref. \[10\], where quark composition of two-quark (meson) and three-quark (fermion) states was represented for the case of up- and down-types of quark $Q$. Stable and long-lived new hadrons are divided into three families of particles with characteristic values of masses $M$, $2M$ and $3M$, where $M$ is the mass of $Q$-quark. Quantum numbers and quark content of these particles for the case of up-type quark $Q = U$ are represented in Table 1.

| $J^P$ | $T$ | $M = (M^0 M^-)$ | $M^0 = \bar{U}u$, $M^- = \bar{U}d$ |
|-------|-----|----------------|--------------------------|
| $J = \frac{1}{2}$ | $T = \frac{1}{2}$ | $B_1 = (B_1^{++} B_1^+ B_1^0)$ | $B_1^{++} = Uuu$, $B_1^+ = Uud$, $B_1^0 = Udd$ |
| $J = \frac{1}{2}$ | $T = 1$ | $B_2 = (B_2^{++} B_2^+ B_2^0)$ | $B_2^{++} = UUU$, $B_2^+ = UUd$ |
| $J = \frac{3}{2}$ | $T = 0$ | $(B_3^{++})$ | $B_3^{++} = UUU$ |

Some states in Table 1 were also considered in Ref. \[27\], where $U$-type quark belong to the sequential 4-th generation. In Ref. \[28\], there were considered an important property of suppression of hadronic interaction of heavy quark systems containing three new quarks, like $(UUU)$ states. This model has $SU(3) \times SU(2) \times SU(2) \times U(1)$ symmetry and offers a novel alternative for the DM carriers — they can be an electromagnetically bound states made of terafermions. The charged $M^-$ and neutral $M^0$ particles can manifest themselves in cosmic rays and as carrier of the DM. In Refs. \[7–9\] a possibility is discussed that new stable charged hadrons exist but are hidden from detection, being bounded inside neutral dark atoms. For instance, stable particles with charge $Q = -2$ can be bound with primordial helium atoms.

Interactions of the baryon-type particles $B_1$ and $B_2$ (the second and third line in Table 1) are similar to the nucleonic ones, and they may compose atomic nuclei together with nucleons. As it was demonstrated in Ref. \[10\], this circumstance does not prevent the $B_1$ and $B_2$ burn out in the course of cosmochemical evolution. There are no problems also
with interaction of $B_3$ isosinglet with nucleons which proceeds mainly through exchange by mesons, $\eta$ and $\eta'$. Constant of such interactions, as it follows from the quark model of the mesonic exchange (see Ref. [10]), is not a large one, i.e. $B_3N$ interaction is suppressed in comparison with the $NN$ interaction.

There is another type of hypothetical hadrons which possess analogous properties of strong interactions. They are constructed from stable quark of the down-type ($D$-quark) with $Q = -1/3$ electric charge. Quantum numbers and quark content of these particles are represented in Ref. [10] (Table 2).

Particles possessing a similar quark composition appear in various high-energy generalizations of SM, in which $D$-quark is a singlet with respect to weak interactions group. For example, each quark-lepton generation in $E(6) \times E(6)$-model contains two singlet $D$-type quarks; it is this quark appears from the Higgs sector in supersymmetric generalization of $SU(5)$ Great Unification model. As a rule, with a reference to cosmological restrictions it is assumed that new hadrons are unstable due to the mixing of singlet $D$-quarks with the standard quarks of the down type. Consequences for cosmochemical evolution existence of the hypothetical $U$- and $D$-types hadrons which can be supposed as stable, are very different.

Cosmochemical evolution of new hadrons at hadronization stage was qualitatively studied both for $U$ and $D$ cases in [10]. A very important conclusion was arrived from this analysis - baryon asymmetry in new quark sector must exist and has a sign opposite to asymmetry in standard quark sector (quarks $U$ disappear but antiquarks $\bar{U}$ remain). This conclusion follows from the strong cosmochemical restriction for the ratio “anomalous/natural” hydrogen $C \leq 10^{-28}$ for $M_Q \leq 1$ TeV [29] and anomalous helium $C \leq 10^{-12} - 10^{-17}$ for $M_Q \leq 10$ TeV [30]. In our case, the state $B_1^+ = (Uud)$ is heavy (anomalous) proton which can form anomalous hydrogen. At the stage of hadronization, $B_1^+$ can be formed by direct coupling of quarks and also as a result of reaction $\bar{M}_0 + N \rightarrow B_1^+ + X$, where $X$ is totality of leptons and photons in the final state. The antiparticles $\bar{B}_1^+$ are burning out due to the reaction $\bar{B}_1^+ + N \rightarrow M^0 + X$. The states like $(p M^0)$ can be also manifest itself as anomalous hydrogen, but as it was shown in [10], interaction of $p$ and $M^0$ has a potential barrier at large distances. So, formation of coupled states $(p M^0)$ at low energies is strongly suppressed. As it follows from the experimental restrictions on anomalous hydrogen and helium [29, 30], baryon symmetry in extra sector of quarks is not excluded for the case of super-heavy new quarks with masses $M_Q \gg 1$ TeV (see, also, the fourth section). Further, we consider the interaction of new hadrons with nucleons and their self-interaction in more detail.

At low energies the hadrons interactions can be approximately described by a model of meson exchange in terms of an effective lagrangian. It was shown in [31], low-energy baryon-meson interactions are effectively described by $U(1) \times SU(3)$ gauge theory, where $U(1)$ is the group of semi-strong interaction and $SU(3)$ is group of hadronic unitary symmetry. Effective physical lagrangian which was used for calculation of $MN$ interaction potential is represented in [10]. By straightforward calculations, it was demonstrated there that the dominant contribution is resulted from the exchanges by $\rho$ and $\omega$ mesons. This lagrangian at low energies can be applied for analysis both of $MN$ and $MM$ interactions. Here, we give the part of lagrangian with vector-meson exchange which will be used for evaluation of the potential:

\[
L_{int} = g_\omega \omega^\mu \bar{N} \gamma_\mu N + g_\rho \bar{\rho} \gamma_\mu \rho N + ig_\omega M \omega^\mu (M^+ \partial_\mu M - \partial_\mu M^+ M) + ig_\rho M (M^+ \partial_\mu M - \partial_\mu M^+ \bar{\rho}^\mu M). \tag{3.1}
\]
In (3.1) $N = (p, n)$, $M = (M^0, M^-)$ and coupling constants are the following [10]:

\[
\begin{align*}
g_\rho &= g_{\rho M} = g/2, \quad g_\omega = \sqrt{3}g/2 \cos \theta, \quad g_{\omega M} = g/4\sqrt{3} \cos \theta, \\
g^2/4\pi &\approx 3.16, \quad \cos \theta = 0.644.
\end{align*}
\]

Note, the one-pion exchange which is dominant in $NN$ interaction is forbidden in the $MM\pi$-vertex due to parity conservation.

In Born approximation, potential of the interaction and the non-relativistic amplitude of scattering for the case of non-polarized particles are connected by the relation:

\[
U(\vec{r}) = -\frac{1}{4\pi^2 \mu} \int f(q) \exp(i \vec{q} \cdot \vec{r}) \, dq,
\]

(3.3)

where $\mu$ is the reduced mass of scattering particles. For the case of $M$ scattering off nucleons, this potential was calculated in Ref. [10], where it was utilized the relation $f(q) = -2\pi i \mu F(q)$ between nonrelativistic amplitude, $f(q)$, and Feynman amplitude, $F(q)$. As it was shown, contributions of scalar and two-pion exchanges are suppressed by the factor $\sim m_N/m_M$.

Expressions for potentials of interaction of various pairs from doublets ($M^0, M^-$) and ($p, n$) have following form:

\[
\begin{align*}
U(M^0, p; r) &= U(M^-, n; r) \approx U_\omega(r) + U_\rho(r), \\
U(M^0, n; r) &= U(M^-, p; r) \approx U_\omega(r) - U_\rho(r).
\end{align*}
\]

(3.4)

In Eqs. (3.4) the terms $U_\omega(r)$ and $U_\rho(r)$ are defined by the following expressions:

\[
\begin{align*}
U_\omega &= \frac{g^2 K_\omega}{16\pi \cos^2 \theta} \frac{1}{r} \exp(-r/r_\omega), \\
U_\rho &= \frac{g^2 K_\rho}{16\pi} \frac{1}{r} \exp(-r/r_\rho),
\end{align*}
\]

(3.5)

where $K_\omega = K_\rho \approx 0.92$, $r_\omega = 1.04/m_\omega$, $r_\rho = 1.04/m_\rho$. Taking into account these values and $m_\omega \approx m_\rho$, we rewrite expressions (3.4) in a form:

\[
\begin{align*}
U(M^0, p; r) &= U(M^-, n; r) \approx 2.5 \frac{1}{r} \exp(-r/r_\rho), \\
U(M^0, n; r) &= U(M^-, p; r) \approx 1.0 \frac{1}{r} \exp(-r/r_\rho).
\end{align*}
\]

(3.6)

Two consequences can be deduced from the expressions (3.6). Firstly, all four pairs of particles have repulsive potential ($U > 0$) of interaction at long distances, where Born approximation is valid. Secondly, due to potential barrier the DM particles at low energies can not interact with nucleons, i.e. they can not form the coupled states ($pM^0$) which manifest itself as anomalous protons. So, they can not be directly detected. To overcome the barrier, nucleons should have energy $\sim 1\, \text{GeV}$ or more and this situation takes place in high energy cosmic rays.

Potential of $MM$ interaction can be also reconstructed with the help of above given method. Here, we determine only the sign of potential which define an asymptotics — attractive or repulsive — of interaction at long distances. This characteristic plays crucial role for low-energy collisions of the DM particles. To determine the sign of potential we use the definition of lagrangian in the non-relativistic limit:

\[
L = L_0 + L_{\text{int}} \longrightarrow W_k - U,
\]

(3.7)
where $W_k$ is kinetic part and $U$ is potential. There is a relation between effective $L_{\text{int}}$ and Feynman amplitude $M$: $M = ikL_{\text{int}}$, where $k > 0$ is real coefficient depending on the type of particles. As a result, we get equality $\text{signum}(U) = \text{signum}(iM)$, where amplitude of interaction is determined by one-particle exchange diagrams for the process $M_1M_2 \rightarrow M'_1M'_2$. Here, $M = (M^0, M^0)$ and vertexes are defined by the low-energy lagrangian (3.1). With the help of this simple approach, one can check previous conclusion about repulsive character of $MN$ interactions. First of all it should be noted, that low-energy effective lagrangians of $NM^0$ and $NM^0$ have opposite sign due to different sign of vertexes $\omega M^0 M^0$ and $\omega \bar{M}^0 M^0$. This effect can be seen from the differential structure of corresponding part of Lagrangian (3.1) and representation of field function of the $M$-particle in the form:

$$M(x) = \sum_p \hat{a}_p^-(M) \exp(-ipx) + \hat{a}_p^+(\bar{M}) \exp(ipx),$$

$$M^+(x) = \sum_p \hat{a}_p^+(M) \exp(ipx) + \hat{a}_p^-(\bar{M}) \exp(-ipx).$$

(3.8)

In Eqs. (3.8), $a_p^\pm(M)$ and $a_p^\pm(\bar{M})$ are the operators of creation and destruction of particles $M$ and antiparticles $\bar{M}$ with momentum $p$. As a result, we get the vertexes $\omega(q)M^0(p)M^0(p-q)$ and $\omega(q)\bar{M}^0(p)\bar{M}^0(p-q)$ in momenta representation with opposite signs, $L_{\text{int}} = \pm g_{\omega M}(2p-q)$, respectively. This leads to the repulsive and attractive potentials of $NM$ and $N\bar{M}$ low-energy effective interactions via $\omega$ exchange. Thus, the absence of potential barrier in the last cases give rise to the problem of coupled states $p\bar{M}^0$ (the problem of anomalous hydrogen). As it was noted earlier, to overcome this problem we make the suggestion that the hadronic DM is baryon asymmetric ($\bar{M}^0$ is absent at low-energy stage of hadronization) or particles $\bar{M}^0$ are superheavy. Properties of interactions of baryons type $B_1$ and $B_2$ are similar to nucleonic one (the main contribution give one-pion and vector meson exchanges) and together with nucleons they may compose an atomic nuclei. So, new baryons can form superheavy nuclei which in the process of evolution are concentrated due to gravitation in the center of massive planets or stars.

Further, we check that the potential of $M^0M^0$ and $\bar{M}^0\bar{M}^0$ interactions is attractive ($U < 0$) for the case of scalar meson exchange and repulsive for the case of vector meson exchange. Potential of $M^0\bar{M}^0$ scattering has attractive asymptotics both for scalar and vector meson exchanges. Thus, the presence of potential barrier in the processes of $M^0M^0$ and $\bar{M}^0\bar{M}^0$ scattering depends on the relative contribution of scalar and vector mesons. In the case of $M^0\bar{M}^0$ scattering the total potential is attractive and this property can lead to increasing of cross section in an analogy with Sommerfeld effect [32].

IV. MAIN PROPERTIES OF NEW HADRONS AS THE DM CARRIERS

The mass of heavy quark $M_Q$ and the mass splitting of the charged $M^-$ and neutral $M^0$ mesons, $\delta m = m^- - m^0$, are significant characteristics of these states both for their physical interpretation and for application in cosmology. In this analysis, we take into consideration standard electromagnetic and strong interactions only. So, some properties of new mesons doublet $M = (M^0, \bar{M}^-)$ are analogous to properties of standard mesons consisting of pairs of heavy and light quarks. From experimental data on mass splitting in neutral-charged meson pairs $K = (K^0, K^\pm)$, $D = (D^0, D^\pm)$ and $B = (B^0, B^\pm)$, it is seen that for down-type mesons $K$ and $B$ the mass-splitting $\delta m < 0$ while for up-type meson $D$ the value of $\delta m > 0$. 

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Such results can be explained by the experimental data on masses of quarks, \( m_d > m_u \), and binding energy of the systems \((Qu)\) and \((Qd)\), where Coulomb contributions have different signs. The absolute value of \( \delta m \) for the case of \( K^- \) and \( D^- \) mesons is \( O(\text{MeV}) \), but for \( B^- \) mesons it is less. Taking into account these data, for the case of up SQ we assume:

\[
\delta m = m(M^-) - m(M^0) > 0, \quad \text{and} \quad \delta m = O(\text{MeV}).
\] (4.1)

Then, we conclude that neutral state \( M^0 = (\bar{U}u) \) is stable and can play the role of the DM carrier. The charged partner \( M^- = (\bar{U}d) \) has only one decay channel with very small phase space:

\[
M^- \to M^0 e^- \bar{\nu}_e, \quad \text{if} \quad \delta m > m_e.
\] (4.2)

This semileptonic decay is resulted from the weak transition \( d \to u + W^- \to u + e^- \bar{\nu}_e \), where heavy quark \( \bar{U} \) is considered as spectator. The width of decay can be calculated in a standard way and final expression for differential width is as follows (see also review by R. Kowalski in [26]):

\[
\frac{d\Gamma}{d\omega} = \frac{G_F^2}{48\pi^3}|U_{ud}|^2(m_- + m_0)^2m_0^2(\omega^2 - 1)^{3/2}G^2(\omega). \] (4.3)

In the case under consideration \( m_- \approx m_0, \omega = k^0/m_0 \approx 1 \) and \( G(\omega) \approx 1 \) (HQS approximation). Here, \( G(\omega) \) is equivalent to normalized formfactor \( f_+(q) \), where \( q \) is the transferred momentum. In the vector dominance approach this formfactor \( f_+(q) = f_+(0)/(1 - q^2/m_v^2) \), where \( m_v \) is the mass of vector intermediate state. So, HQS approximation corresponds to the conditions \( q^2 \ll m_v^2 \) and \( f_+(0) \approx 1 \) for the case \( \omega = k^0/m_0 \approx 1 \). Using Eq.(4.3), for the total width we get:

\[
\Gamma \approx \frac{G_F^2|U_{ud}|^2m_0^5}{12\pi^3} \int_1^{\infty} (\omega^2 - 1)^{3/2}d\omega; \quad \omega_m = \frac{m_0^2 + m_-^2}{2m_0m_-}. \] (4.4)

After integration, the expression (4.4) can be written in the simple form:

\[
\Gamma \approx \frac{G_F^2}{60\pi^3}(\delta m)^5, \] (4.5)

where weak coupling constant is taking at a low-energy scale because of small transferred momentum in the process. From the expression (4.5) one can see that the width crucially depends on the mass splitting, \( \Gamma \sim (\delta m)^5 \) and does not depend on the mass of meson \( M \). For instance, in the interval \( \delta m = (1 - 10) \text{MeV} \) we get following estimations:

\[
\Gamma \sim (10^{-29} - 10^{-24}) \text{GeV}; \quad \tau \sim (10^5 - 10^6) \text{s}. \] (4.6)

Thus, charged partner of \( M^0 \), which is long-lived (metastable), can be directly detected in the processes of \( M^0N^- \) collisions with an energetic nucleons, \( N \). This conclusion is in accordance with the experimental evidence of heavy charged metastable particles presence in cosmic rays [10].

Experimental and theoretical premises of new heavy hadron existence were discussed in the Ref. [10]. With the help of low-energy model of baryon-meson interactions, it was shown that the potential of \( MN^- \) -interaction has repulsive asymptotics. So, the low-energy particles \( M \) do not form coupled states with nucleon and the hypothesis of their existence does not contradict to the cosmochemical data.
Now, we estimate the mass of new hadrons which are interpreted as carriers of the DM. The data on Dark Matter relic concentration result to value of the cross section of annihilation at the level:

$$\langle \sigma v_r \rangle^{exp} \approx 10^{-10} \text{ GeV}^{-2}. \quad (4.7)$$

Comparing the model annihilation cross section (which depends on the mass) to this value, we estimate the mass of the meson $M^0$. Note, the calculations are fulfilled for the case of hadron-symmetrical DM, that is, the relic abundance is suggested the same for $M^0$ and $\bar{M}^0$. To escape the contradiction with strong restriction on anomalous helium, we estimate the mass of $M^0$ above 10 TeV. Approximate evaluation of the model cross section $\sigma(M^0\bar{M}^0)$ can be fulfilled in spectator approach $\sigma(M^0\bar{M}^0) \sim \sigma(U\bar{U})$ considering the light $u$-quarks as spectators. Main contributions to this cross section result from sub-processes $U\bar{U} \to gg$ and $U\bar{U} \to q\bar{q}$, where $g$ and $q$ are standard gluon and quark. Corresponding cross sections are represented in the second section (Eqs. (2.6) and (2.7)) and their sum is used for approximate evaluation of the full annihilation cross section of the processes $M^0\bar{M}^0 \to$ hadrons. Thus, we can estimate $M_U$ mass from the following approximate equation:

$$\langle \sigma v_r \rangle^{exp} \approx \frac{44\pi}{9} \frac{\alpha^2_s}{M_U^2}. \quad (4.8)$$

Now, from (4.6) and (4.8) we get: $m(M^0) \approx M_U \approx 20 \text{ TeV}$ at $\alpha_s = \alpha_s(M_U)$.

As it was noted in the previous section, attractive potential of $M^0\bar{M}^0$ interaction at long distances can increase the cross section due to the light meson exchange. This effect leads to Sommerfeld enhancement [32] of the cross section:

$$\sigma v_r = (\sigma v_r)_0 S(\alpha/v), \quad (4.9)$$

where $(\sigma v_r)_0$ is initial cross section which is results from the left side of the expression (4.8), $\alpha = g^2/4\pi$ is defined by the effective coupling according to (3.2) and $v = v_r/2$. At $m \ll M \approx M_U$, where $m$ is mass of mesons (the light force carriers), Sommerfeld enhancement (SE) factor can be represented in the form [32]:

$$S(\alpha/v) = \frac{\pi \alpha/v}{1 - \exp(-\pi \alpha/v)}. \quad (4.10)$$

In our case, the light force carriers are $\omega$- and $\rho$-mesons and the value $\alpha \sim 1$ (see (3.1) and (3.2)), so from (4.10), we get $10^2 \lesssim S(\alpha/v)/\pi \lesssim 10^3$ in the interval $10^{-2} > v > 10^{-3}$. In this case, from (4.8)-(4.10) it follows that at $v \sim 10^{-2}$ the mass of new quark $M_U \sim 10^2 \text{ TeV}$. Thus, we get too heavy $M^0$ which can not be detected in the searching for signals of anomalous hydrogen ($M_{\text{max}} \lesssim 1 \text{ TeV}$) and anomalous helium ($M_{\text{max}} \lesssim 10 \text{ TeV}$). Note, however, that in these calculations we take into account the light mesons only, $(m \ll M_U)$, which act at long distances $r \sim m^{-1}_\rho$. At short distance, near the radius of coupling state $M^0 = (U\bar{u})$, i.e. at $r \sim M_U^{-1}$, it is possible the exchange by heavy mesons containing heavy quark $U$, for instance, by vector or scalar $M$-mesons. In this case, expression (4.10) is not valid because of $M_x \sim M_U$, where $M_x$ is the mass of heavy force carriers. To evaluate SE factor in this case, we use its numerical calculation from [33]. In this work, iso-contours of the SE corrections are presented on Fig. 1 as functions of $y = \alpha M/M_x$ and $x = \alpha/v$. Then $y \approx 1$, and from Fig. 1 in Ref. [33] it follows that $S \approx 10$ in the interval $10^{-1} > v > 10^{-3}$. As a result, from (4.8) and (4.10) it follows $M_U \approx 60 \text{ TeV}$ which does not change situation.
crucially. It should be noted, full description of SE requires an account of weak vector bosons $Z, W$ which interact with light quarks only. Thus, SE effect is formed at various energy regions corresponding to various distances and has very complicated and vague nature (see, also, Ref. [34]).

V. CONCLUSION

We have analyzed a scenario of the hadronic DM based on the simplest extension of the SM with singlet quark. It was shown in a previous work that the existence of new heavy hadrons does not contradict to cosmological constraints. Here, we demonstrate that the scenario is in accordance with the precision electroweak restrictions on manifestations of New Physics. With the help of effective model Lagrangian, we describe asymptotics of the potential at low energies for interactions of new hadrons with nucleons and with each other. Approximate value of the mass-splitting for charged and neutral components was evaluated and lifetime of charged meta-stable hadron component was calculated, it occurs rather large value $\tau \gg 1$ s. Using the value of the DM relic concentration and the expression for the model cross section of annihilation, mass of the hadronic DM carrier is estimated. The value of mass without account of SE effect is near 20 TeV and the SE increases it up to an order of $10^2$ TeV. So, superheavy new hadrons can not be generated in the LHC experiments and detected in the searching for anomalous hydrogen and helium. Some peculiarities of Sommerfeld enhancement effect in the process of annihilation are analyzed. It should be underlined, that the model annihilation cross section was evaluated at the level of sub-processes. So, for the description of the hadronic Dark Matter in more detail it is necessary to clarify the mechanism of annihilation process at various energy scales.

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