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Research Article

Dark Matter in the Standard Model Extension with Singlet Quark

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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 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 evaluate their masses and lifetime of the charged component and describe the potential asymptotes 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.

1. 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 evidence of new physics' manifestations beyond the Standard Model (SM) [1, 2]. 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 scenarios are discussed in literature, such as quarks from fourth generation, hypercolor quarks, dark atoms, and axions [3]. In spite of some theoretical peculiarities, the possibility of hadronic DM is not excluded and considered, for example, in [5–11]. The possibility of new hadrons existence, which can be interpreted as carriers of the DM, was analyzed in detail within the framework of the SM chiral-symmetric extension [11].

Principal feature of the hadronic DM structure 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 [11, 12] or in extensions with singlet quark [13–17]. The second variant was considered in detail in [11], where the quark structure and low-energy phenomenology of new heavy hadrons were described. It was shown that the scenario does not contradict cosmochemical data, cosmological tests, and known restrictions for new physics effects. However, the explicit realization of the chiral-symmetric scenario faces 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, follow 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 [18]. The contribution of new heavy quarks to vector boson coupling may be compensated by the contribution of 50 GeV neutrino [19–21]; however, such assumption seems 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 are 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.

2. Standard Model Extension with Stable 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, [10, 22–24] and references therein). As a rule, singlet quark is supposed to be 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 additional contributions into rare processes, such as rare lepton and semileptonic decays, and mixing in the systems of neutral mesons ($M^0-\overline{M}^0$ 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, namely, the scenario with the absence of such mixing. As a result, we get stable singlet quark which has no decay channels due to absence of nondiagonal 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 of interpreting the stable neutral meson $M^0 = (\overline{Q}q)$ 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 $SU_W(2)$ 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

$$L_Q = i\overline{Q}\gamma^{\mu}\left(\partial_{\mu} - ig_1\frac{Y}{2}V_{\mu} - ig_s\frac{\lambda_a}{2}G^a_{\mu}\right)Q - M_Q\overline{Q}Q, \quad (1)$$

where $Y/2 = q$ is charge in the case of singlet Q, and M_Q denotes phenomenological mass of quark. Note, singlet quark (SQ) cannot 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 (1), which will be used in further considerations, includes the interactions with physical photon A and Z boson:

$$L^{int}_Q = g_1 q V_{\mu}\overline{Q}\gamma^{\mu}Q = qg_1\left(c_w A_{\mu} - s_w Z_{\mu}\right)\overline{Q}\gamma^{\mu}Q, \quad (2)$$

where $c_w = \cos\theta_w$, $s_w = \sin\theta_w$, $g_1 c_w = e$, and θ_w is Weinberg angle of mixing. Note, the left and right parts of the singlet field Q have the same transformation properties, interaction (2) has vector-like (chiral-symmetric) form, and singlet quark usually is named vector-like quark [23, 24].

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 σ level by LHC data on Higgs searches [22]. As the vector-like (nonchiral) 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 [25]. The corresponding limits for effective colored factors $n_{eff} = 2, 3, 6$ are about 200 GeV, 300 GeV, and 400 GeV. Note that these limits are much less than the estimation of quark mass which follows from the DM analysis (see the fourth section). Theoretical and experimental situation for long-lived heavy quarks were considerably discussed in the review [10], where it was noted that vector-like new heavy quarks can elude experimental constraints from LHC.

Indirect limits on new fermions follow from precision electroweak measurements of the effects, such as flavor-changing neutral currents (FCNC) and vector boson polarization, which take place at the loop level in the SM. Because we consider the case of stable singlet quark, there is no mixing with ordinary quarks and, consequently, FCNC effects are absent. The NF manifestations in polarization effects of gauge bosons γ, Z, W are usually described by oblique Peskin-Takeuchi parameters [26] (PT parameters). From (2), it follows that the singlet quark gives nonzero contributions into polarization of γ- 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 polarization operator is zero, $\Pi_{WW} = 0$. These parameters are expressed in terms of vector bosons polarization $\Pi_{ab}(p^2)$, where $a, b = W, Z, \gamma$. Here, we use the definition $\Pi_{\mu\nu}(p^2) = p_{\mu}p_{\nu}P(p^2) + g_{\mu\nu}\Pi(p^2)$ and the expressions for PT oblique parameters from [27]. In the case under consideration, $\Pi_{ab}(0) = 0$ and PT parameters can be represented by the following expressions:

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

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

$$\alpha T = -\frac{\Pi_{ZZ}\left(0, M_U^2\right)}{M_Z^2} = 0;$$

$$\alpha V = \Pi'_{ZZ}\left(M_Z^2, M_U^2\right) - \frac{\Pi_{ZZ}\left(M_Z^2, M_U^2\right)}{M_Z^2};$$
$$\alpha W = 0 \quad \left(W \sim \Pi_{WW} = 0\right);$$
$$\alpha X = -s_w c_w \left[\frac{\Pi_{\gamma Z}\left(M_Z^2, M_U^2\right)}{M_Z^2} - \Pi'_{\gamma Z}\left(0, M_U^2\right)\right]. \tag{3}$$

In (3) polarization $\Pi_{ab}(p^2, M_U^2)$, where $a, b = \gamma, Z$, in one-loop approach can be represented in simple form (for the case of SQ with $q = 2/3$):

$$\Pi_{ab}\left(p^2, M_U^2\right) = \frac{g_1^2}{9\pi^2} k_{ab} F\left(p^2, M_U^2\right);$$
$$k_{ZZ} = s_w^2,$$
$$k_{\gamma\gamma} = c_w^2,$$
$$k_{\gamma Z} = -s_w c_w; \tag{4}$$
$$F\left(p^2, M_U^2\right) = -\frac{1}{3}p^2 + 2M_U^2 + 2A_0\left(M_U^2\right) + \left(p^2 + 2M_U^2\right) B_0\left(p^2, M_U^2\right).$$

In (4) the function $F(p^2, M_U^2)$ 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 physical parameters (3). Using standard definitions 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 simple expressions for oblique parameters:

$$S = -U = \frac{16 s_w^4}{9\pi}\left[-\frac{1}{3} + 2\left(1 + 2\frac{M_Q^2}{M_Z^2}\right)\left(1 - \sqrt{\beta}\arctan\frac{1}{\sqrt{\beta}}\right)\right], \tag{5}$$

where $\beta = 4M_Q^2/M_Z^2 - 1$. We check that in the limit $M_Q^2/M_Z^2 \longrightarrow \infty$ the values of S and U go to zero as $\sim M_Z^2/M_Q^2$ in accordance with well-known results for the case of vector-like interactions [2, 27]. From (5) it follows that beginning from $M_Q = 500$ GeV the parameter $S < 10^{-2}$ and the remaining nonzero parameters have nearly the same values. These values are significantly less than the current experimental limits [28]: $S = 0.00 + 0.11(-0.10)$, $U = 0.08 \pm 0.11$, $T = 0.02 + 0.11(-0.12)$; that is, the scenario with up-type singlet quark satisfies the restrictions on indirect manifestations of heavy new fermions. Note that the parameters V, W, X describe the contributions of new fermions with masses close to the electroweak scale. In the case of down-type singlet quark, having charge $q = -1/3$, the contributions into all 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, γ, and Z according to (1). So, we have large cross section for annihilation into gluons and quarks, $Q\overline{Q} \longrightarrow gg$ and $Q\overline{Q} \longrightarrow q\overline{q}$ correspondingly, and also small additional contributions in electroweak channels $Q\overline{Q} \longrightarrow \gamma\gamma, ZZ$. These cross sections can be simply derived from the known expressions for the processes $gg \longrightarrow Q\overline{Q}$ and $q\overline{q} \longrightarrow Q\overline{Q}$ (see review in [28]) by time inversion. Two-gluon cross section in the low-energy limit looks like

$$\sigma\left(U\overline{U} \longrightarrow gg\right) = \frac{14\pi}{3}\frac{\alpha_s^2}{v_r M_U^2}, \tag{6}$$

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

$$\sigma\left(U\overline{U} \longrightarrow q\overline{q}\right) = \frac{2\pi}{9}\frac{\alpha_s^2}{v_r M_U^2}. \tag{7}$$

So, the two-gluon channel dominates. We should note that the cross section of SQ-annihilation is suppressed by large M_U 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 $M = (\overline{Q}q)$, is stable and can be considered as the carrier of cold Dark Matter. Possibility of existence of heavy stable hadrons was carefully analyzed in [11], where it was shown that this hypothesis does not contradict 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.

3. 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 [11], 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.

Some states in Table 1 were also considered in [10] for the case of long-lived vector-like heavy quark and in [29], where U-type quark belongs to the sequential 4th generation.

Table 1: Characteristics of U-type hadrons.

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

Table 2: Characteristics of D-type hadrons.

$J^P = 0^-$	$T = \frac{1}{2}$	$M_D = (M_D^+\ M_D^0)$	$M_D^+ = \overline{D}u$, $M_D^0 = \overline{D}d$
$J = \frac{1}{2}$	$T = 1$	$B_{1D} = (B_{1D}^{+}\ B_{1D}^{0}\ B_{1D}^{-})$	$B_{1D}^{+-} = Duu(Ddd)$, $B_{1D}^{0} = Dud$
$J = \frac{1}{2}$	$T = \frac{1}{2}$	$B_{2D} = (B_{2D}^{0}\ B_{2D}^{-})$	$B_{2D}^{0} = DDu$, $B_{2D}^{-} = DDd$
$J = \frac{3}{2}$	$T = 0$	(B_{3D}^{-})	$B_{3D}^{-} = DDD$

In [30], an important property of suppression of hadronic interaction of heavy quark systems containing three new quarks, like (UUU) states, was considered. 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 [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.

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 [11], this circumstance does not prevent the B_1 and B_2 burnout 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, η and η'. The constants of such interactions, as it follows from the quark model of the mesonic exchange (see [11]), are 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 Table 2 (see the corresponding analysis and comments in [11]).

In this table, the states $M_D^+, B_{1D}^0, B_{2D}^0, B_{3D}^-$ are stable. 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. This quark appears, also, from the Higgs sector in supersymmetric generalization of $SU(5)$ Great Unification model. As a rule, with 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. Note that the consequences for cosmochemical evolution, caused by existence of the hypothetical stable U- and D-types hadrons, are very different.

Cosmochemical evolution of new hadrons at hadronization stage was qualitatively studied both for U and D cases in [11]. 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 $\overline{U}$ remain). This conclusion follows from the strong cosmochemical restriction for the ratio "anomalous/natural" hydrogen $C \leqslant 10^{-28}$ for $M_Q \lesssim 1$ TeV [31] and anomalous helium $C \leqslant 10^{-12}$–10^{-17} for $M_Q \leq 10$ TeV [32]. 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 as a result of reaction $\overline{M}^0 + N \longrightarrow B_1^+ + X$, where X is totality of leptons and photons in the final state. The antiparticles $\overline{B}_1^+$ are burning out due to the reaction $\overline{B}_1^+ + N \longrightarrow M^0 + X$. The states like (pM^0) can also manifest themselves as anomalous hydrogens, but as it was shown in [11], interaction of p and M^0 has a potential barrier at large distances. So, formation of coupled states (pM^0) at low energies is strongly suppressed. As it follows from the experimental restrictions on anomalous hydrogen and helium [31, 32] that baryon symmetry in extra sector of quarks is not excluded for the case of superheavy 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 [33] that low-energy baryon-meson interactions are effectively described by $U(1) \times SU(3)$ gauge theory, where $U(1)$ is the group of semistrong 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 [11]. By straightforward calculations, it was demonstrated there that the dominant contribution resulted from the exchanges by ρ and ω mesons. This Lagrangian at low energies can be applied for analyzing both MN and MM interactions. Here, we give the part of Lagrangian with vector meson exchange which will be used for evaluation of the potential:

$$\begin{aligned} L_{int} &= g_\omega \omega^\mu \overline{N}\gamma_\mu N + g_\rho \overline{N}\gamma_\mu \hat{\rho}^\mu N \\ &+ i g_{\omega M}\omega^\mu \left(M^\dagger \partial_\mu M - \partial_\mu M^\dagger M\right) \\ &+ i g_{\rho M}\left(M^\dagger \hat{\rho}^\mu \partial_\mu M - \partial_\mu M^\dagger \hat{\rho}^\mu M\right). \end{aligned} \tag{8}$$

In (8) $N = (p,n), M = (M^0, M^-), M^\dagger = (\overline{M}^0, M^+)$, and coupling constants are the following [11]:

$$\begin{aligned} g_\rho &= g_{\rho M} = \frac{g}{2}, \\ g_\omega &= \frac{\sqrt{3}g}{2\cos\theta}, \\ g_{\omega M} &= \frac{g}{4\sqrt{3}\cos\theta}, \\ \frac{g^2}{4\pi} &\approx 3.16, \\ \cos\theta &= 0.644. \end{aligned} \tag{9}$$

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

In Born approximation, the potential of interaction and the nonrelativistic amplitude of scattering for the case of nonpolarized particles are connected by the relation:

$$U\left(\vec{r}\right) = -\frac{1}{4\pi^2\mu}\int f(q)\exp\left(i\vec{q}\vec{r}\right)d^3q, \tag{10}$$

where μ is the reduced mass of scattering particles. For the case of M scattering off nucleons, this potential was calculated in [11], where the relation $f(q) = -2\pi i\mu F(q)$ between nonrelativistic amplitude, $f(q)$, and Feynman amplitude, $F(q)$, was utilized. 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 the following form:

$$\begin{aligned} U\left(M^0, p; r\right) &= U\left(M^-, n; r\right) \approx U_\omega(r) + U_\rho(r), \\ U\left(M^0, n; r\right) &= U\left(M^-, p; r\right) \approx U_\omega(r) - U_\rho(r). \end{aligned} \tag{11}$$

In (11) the terms $U_\omega(r)$ and $U_\rho(r)$ are defined by the following expressions:

$$\begin{aligned} U_\omega &= \frac{g^2 K_\omega}{16\pi\cos^2\theta}\frac{1}{r}\exp\left(-\frac{r}{r_\omega}\right), \\ U_\rho &= \frac{g^2 K_\rho}{16\pi}\frac{1}{r}\exp\left(-\frac{r}{r_\rho}\right), \end{aligned} \tag{12}$$

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 (11) in the form

$$\begin{aligned} U\left(M^0, p; r\right) &= U\left(M^-, n; r\right) \approx 2.5\frac{1}{r}\exp\left(-\frac{r}{r_\rho}\right), \\ U\left(M^0, n; r\right) &= U\left(M^-, p; r\right) \approx 1.0\frac{1}{r}\exp\left(-\frac{r}{r_\rho}\right). \end{aligned} \tag{13}$$

Two consequences can be deduced from expressions (13). Firstly, all the 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 cannot interact with nucleons; i.e., they cannot form the coupled states (pM^0) which manifest themselves as anomalous protons. So, they cannot be directly detected. To overcome the barrier, nucleons should have energy $\sim 1\,GeV$ or more and this situation takes place in high-energy cosmic rays.

Potential of MM interaction can be also reconstructed with the help of the above given method. Here, we determine only the sign of potential which defines characteristic (attractive or repulsive) of interaction at long distances. This characteristic plays crucial role for low-energy collisions of the DM particles and nucleons. To determine the sign of potential we use the definition of Lagrangian in the nonrelativistic limit:

$$L = L_0 + L_{int} \longrightarrow W_k - U, \tag{14}$$

where W_k is kinetic part and U is potential. There is a relation between effective $L_{int}(q)$ and Feynman amplitude $F(q)$: $F(q) = ikL_{int}(q)$, where $k > 0$ is real coefficient depending on the type of particles. As a result, we get equality $signum(U) = signum(iF)$, where amplitude of interaction is determined by one-particle exchange diagrams for the process $M_1M_2 \longrightarrow M_1'M_2'$. Here, $M = (M^0, \overline{M^0})$ and vertexes are defined by the low-energy Lagrangian (8). 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 $N\overline{M}^0$ have opposite sign due to different sign of vertexes $\omega M^0 M^0$ and $\omega\overline{M}^0\overline{M}^0$. This effect can be seen from the differential structure of corresponding part of Lagrangian (8) and representation of field function of the M-particle in the form:

$$M(x) = \sum_p \hat{a}_p^-(M)\exp(-ipx) + \hat{a}_p^+(\overline{M})\exp(ipx),$$
$$M^\dagger(x) = \sum_p \hat{a}_p^+(M)\exp(ipx) + \hat{a}_p^-(\overline{M})\exp(-ipx). \quad (15)$$

In (15), $a_p^\pm(M)$ and $a_p^\pm(\overline{M})$ are the operators of creation and destruction of particles M and antiparticles $\overline{M}$ with momentum p. As a result, we get the vertexes $\omega(q)M^0(p)M^0(p-q)$ and $\omega(q)\overline{M}^0(p)\overline{M}^0(p-q)$ in momentum representation with opposite signs, $L_{int} = \pm g_{\omega M}(2p-q)$, respectively. This leads to the repulsive and attractive potentials of NM and $N\overline{M}$ low-energy effective interactions via ω exchange. Thus, the absence of potential barrier in the last cases gives rise to the problem of coupled states $p\overline{M}^0$ (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 ($\overline{M}^0$ is absent at low-energy stage of hadronization) or particles $\overline{M}^0$ are superheavy. Properties of interactions of baryons B_1 and B_2 are similar to nucleonic one (the main contribution gives one-pion and vector meson exchanges) and together with nucleons they may compose an atomic nuclei. So, new baryons can form superheavy nucleons which in the process of evolution are concentrated due to gravitation in the center of massive planets or stars.

Further, we have checked that the potential of M^0M^0 and $\overline{M}^0\overline{M}^0$ interactions is attractive ($U < 0$) for the case of scalar meson exchange and repulsive for the case of vector meson exchange. Potential of $M^0\overline{M}^0$ scattering has attractive asymptotes both for scalar and vector meson exchanges. Thus, the presence of potential barrier in the processes of M^0M^0 and $\overline{M}^0\overline{M}^0$ scattering depends on the relative contribution of scalar and vector mesons. In the case of $M^0\overline{M}^0$ scattering the total potential is attractive and this property can lead to increasing of annihilation cross section in an analogy with Sommerfeld effect [34].

4. 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 $M = (M^0, M^-)$ 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 $\delta m > 0$. Such results can be explained by the fitting data on current masses of quarks, $m_d > m_u$, and binding energy of the systems $(\overline{Q}u)$ and $(\overline{Q}d)$, where Coulomb contributions have different signs. The absolute value of δm for the case of $K-$ and $D-$ mesons is O(MeV), but for $B-$ mesons it is less. Taking into account these data, for the case of up SQ we assume

$$\delta m = m(M^-) - m(M^0) > 0,$$
$$\delta m = O(MeV). \quad (16)$$

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

$$M^- \longrightarrow M^0 e^- \overline{\nu}_e, \quad (\text{if } \delta m > m_e). \quad (17)$$

This semileptonic decay resulted from the weak transition $d \longrightarrow u + W^- \longrightarrow u + e^-\overline{\nu}_e$, where heavy quark $\overline{U}$ is considered as spectator. The width of decay can be calculated in a standard way and final expression for differential width as follows (see also review by R. Kowalski in [28]):

$$\frac{d\Gamma}{d\omega} = \frac{G_F^2}{48\pi^3}|U_{ud}|^2(m_- + m_0)^2 m_0^3(\omega^2-1)^{3/2}G^2(\omega). \quad (18)$$

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 form factor $f_+(q)$, where q is the transferred momentum. In the vector dominance approach this form factor is defined as $f_+(q) = f_+(0)/(1 - q^2/m_v^2)$, 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 (18), for the total width we get

$$\Gamma \approx \frac{G_F^2|U_{ud}|^2 m_0^5}{12\pi^3}\int_1^{\omega_m}(\omega^2-1)^{3/2}d\omega;$$
$$\omega_m = \frac{m_0^2 + m_-^2}{2m_0m_-}. \quad (19)$$

After integration, expression (19) can be written in the simple form:

$$\Gamma \approx \frac{G_F^2}{60\pi^3}(\delta m)^5, \quad (20)$$

where weak coupling constant is taken at a low-energy scale because of small transferred momentum in the process. From expression (20) 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 $\delta m = (1 - 10)$ MeV we get the following estimations:

$$\Gamma \sim (10^{-29} - 10^{-24})\,\text{GeV};$$
$$\tau \sim (10^5 - 10^0)\,\text{s}. \quad (21)$$

Thus, charged partner of M^0, which is long-lived (metastable), can be directly detected in the processes of M^0N- collisions with energetic nucleons, N. This conclusion is in accordance with the experimental evidence of heavy charged metastable particles presence in cosmic rays (see [11] and references therein). Note also that the models of DM with a long-lived coannihilation partner are discussed in literature (see, for instance, [10, 35]).

Experimental and theoretical premises of new heavy hadron existence were discussed in [11]. 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 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 in value of the cross section of annihilation at the level

$$(\sigma v_r)^{exp} \approx 10^{-10}\ GeV^{-2}. \tag{22}$$

Comparing the model annihilation cross section (which depends on the mass) to this value, we estimate the mass of the meson M^0. Note that the calculations are fulfilled for the case of hadron-symmetrical DM; that is, the relic abundance is suggested the same for M^0 and $\overline{M}^0$. To escape the contradiction with strong restriction on anomalous helium, we should expect the mass of M^0 above 10 TeV. Approximate evaluation of the model cross section $\sigma(M^0\overline{M}^0)$ can be fulfilled in spectator approach $\sigma(M^0\overline{M}^0) \sim \sigma(U\overline{U})$ considering the light u-quarks as spectators. Main contributions to this cross section result from subprocesses $U\overline{U} \longrightarrow gg$ and $U\overline{U} \longrightarrow q\overline{q}$, where g and q are standard gluon and quark. Corresponding cross sections are represented in the second section ((6) and (7)) and their sum is used for approximate evaluation of the full annihilation cross section of the processes $M^0\overline{M}^0 \longrightarrow$ hadrons. Thus, we can estimate M_U mass from the following approximate equation:

$$(\sigma v_r)^{exp} \approx \frac{44\pi}{9}\frac{\alpha_s^2}{M_U^2}. \tag{23}$$

Now, from (22) and (23) we get $m(M^0) \approx M_U \approx 20$ TeV at $\alpha_s = \alpha_s(M_U)$. Note that this value gets into the range (10–100) TeV which was declared for the case of heavy WIMPonium states in [36].

As it was noted in the previous section, attractive potential of $M^0\overline{M}^0$ interaction at long distances can increase the cross section due to the light meson exchange. This effect leads to Sommerfeld enhancement [34] of the cross section:

$$\sigma v_r = (\sigma v_r)_0\, S\left(\frac{\alpha}{v}\right), \tag{24}$$

where $(\sigma v_r)_0$ is initial cross section which results from the left side of the expression (23); $\alpha = g^2/4\pi$ is defined by the effective coupling according to (9) 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 [34]

$$S\left(\frac{\alpha}{v}\right) = \frac{\pi\alpha/v}{1-\exp(-\pi\alpha/v)}. \tag{25}$$

In our case, the light force carriers are ω- and ρ-mesons and $\alpha \sim 1$ (see (8) and (9)), so from (25), we get $10^2 \lesssim S(\alpha/v)/\pi \lesssim 10^3$ in the interval $10^{-2} > v > 10^{-3}$. In this case, from (23)-(25) it follows that at $v \sim 10^{-2}$ the mass of new quark $M_U \sim 10^2$ TeV, which agrees with the evaluation of the mass of baryonic DM in [37] ($M \sim 100$ TeV). Thus, we get too heavy M^0 which cannot be detected in the searching for signals of anomalous hydrogen ($M_{max} \lesssim 1$ TeV) and anomalous helium ($M_{max} \lesssim 10$ TeV). Note, however, that in these calculations we take into account the light mesons only, ($m \ll M_U$), which act at long distances $r \sim m_\rho^{-1}$. At short distance, near the radius of coupling state $M^0 = (\overline{U}u)$, i.e., at $r \sim M_U^{-1}$, the exchange by heavy mesons containing heavy quark U is possible, for instance, by vector or scalar M-mesons. In this case, expression (25) is not valid because of $M_\chi \sim M_U$, where M_χ is the mass of heavy force carriers. To evaluate SE factor in this case, we use its numerical calculation from [38], where isocontours of the SE corrections are presented as functions of $y = \alpha M/M_\chi$ and $x = \alpha/v$. Then $y \approx 1$, and from [38] (see Figure 1 there) it follows that $S \approx 10$ in the interval $10^{-1} > v > 10^{-3}$. As a result, from (23) and (25) it follows that $M_U \approx 60\ TeV$ which does not change the situation crucially. It should be noted that 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, [39]).

5. 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 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 the asymptotes of interaction potential at low energies for interactions of new hadrons with nucleons and with each other. These asymptotics, both attractive and repulsive, occur for different pairs of interacting particles N, M and their antiparticles. The cosmochemical constrictions on anomalous hydrogen and anomalous helium lead to the conclusion that abundance of particles M and antiparticles $\overline{M}$ is strongly asymmetrical, or new hadrons M are superheavy (with mass larger 10 TeV).

Approximate value of the mass splitting for charged and neutral components was evaluated and lifetime of charged metastable hadron component was calculated; it is rather large, $\tau \gg 1$ 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. These results agree with the evaluations of mass of baryonic DM, which are represented in literature (see previous section). So, superheavy new hadrons cannot 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 subprocesses. 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.

Data Availability

The graphic data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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