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Axion and almost massless quark as ingredients of quintessence

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Abstract: It is pointed out that a natural introduction of quintessence is an axion with an almost massless quark. With an appropriate gauge or discrete symmetry, one can obtain the quintessence potential height of order $(0.003\ \mathrm{eV})^4$. Even though the QCD axion with almost massless up quark is a possibility, we stress the almost massless quark in the hidden sector together with the QCD axion toward the quintessence.

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It has been a theoretical prejudice that the cosmological constant is zero. But the recent Type 1a Supernova data strongly suggest that the cosmological constant is nonzero at the level of $\Omega_\Lambda \simeq 0.6$ [1]. In view of no widely accepted theory for vanishing cosmological constant, this observation can be an experimental hint that there cannot be a theory of *presently* vanishing cosmological constant.

Nevertheless, it is widely believed that there will be a theory of vanishing cosmological constant where at the minimum of the potential the vacuum energy is zero. Then the present nonvanishing cosmological constant might be a temporary phenomenon in the sense that the present vacuum energy happens to be close to the present energy density. For the temporary nonvanishing cosmological constant, "quintessence" has been proposed [2]. For theoretical reasons, it is required for this field to be a pseudo-Goldstone boson. In this scenario, the vacuum energy density at the minimum of the potential is zero and it is of order $(0.003 \text{ eV})^4$ away from the minimum and the mass of the pseudo-Goldstone boson is of order 10^{-34} eV if the corresponding decay constant is the Planck scale. The most serious challenge toward this scenario is *the timing problem: Why at this particular cosmic time is the cosmological constant* Λ *comparable to the energy density of the universe?*

In this scenario, the understanding of extremely small cosmological constant starts from a symmetry. Of course, in the symmetric limit it is assumed for the vacuum energy to be zero. Then, if this symmetry is explicitly broken, a small cosmological constant can be generated. Since the observed cosmological constant is extremely small compared to the other fundamental mass scales, we must look for a mass parameter which has a potential to be exactly zero. There are two such mass scales among the observed particles: neutrino and up quark. Another possible zero mass particle is the hidden sector quarks (h-quarks) carrying hidden sector confining color (h-color).

In this paper, after pointing out the possibility of an extremely small up quark mass toward a general discussion, we present a scenario with an almost massless h-quark(s) with axion. It is very interesting to consider this scenario of the axion in the h-sector, since with the almost massless h-quark(s) the QCD axion can become a candidate for the cold dark matter.

A vanishing up quark mass is an attractive solution of the strong CP problem [3]. Phenomenologically, it is known that this possibility is not ruled out so far [4]. For $m_u = 0$, the chiral symmetry, $u_L \to e^{i\alpha} u_L, \quad u_R \to e^{-i\alpha} u_R$, is an exact symmetry of QCD Lagrangian and the instanton potential is not developed. θ is not a physical parameter, namely physical quantities should not depend on θ. For example, for $m_u = 0$ the neutron electric dipole moment (NEDM), d_n, does not depend on θ. In the θ vacuum, NEDM is calculated [6, 3] to

$$\frac{d_n}{e} = \xi \frac{m_u \sin\theta}{f_\pi^2 \sqrt{2Z\cos\theta + (1+Z^2)}}\,, \tag{1}$$

where e is the electron charge, $Z = m_u/m_d$ and ξ is a parameter of order 10^{-1} [3]. The standard limit of $|\theta| < 10^{-9}$ is obtained from $m_u/m_d \sim 0.6$ and $d_n^{\rm theory} \simeq (2-20)\times 10^{-16}\theta\ e$cm and the bound $d_n^{\rm exp} < 1.2\times 10^{-25}\ e$cm [7]. But if $m_u = 0$, θ is not bounded. It is in this sense that θ is not a physical parameter.

If m_u is nonzero but small, then θ is physical. Nevertheless, the NEDM bound $|d_n| < 1.2\times 10^{-25}\ e$cm can be satisfied for $\theta = {\rm O}(1)$ if

$$m_u < 2\times 10^{-13}\ {\rm GeV}\,. \tag{2}$$

The vacuum angle θ can be of order 1, but still the only experimental constraint is not strong enough to bound θ. It is in this framework that vacuum energy can be very small with very small up quark mass parameter.

To introduce massless up quark, a discrete R_F parity $R_F = (-1)^{3B-L+2S+2IF}$ [8] has been introduced in the supersymmetric standard model. Here, B, L, S, I are the baryon number, lepton number, spin, and the weak isospin, respectively, and F is 1 for the first family and 0 for the others, i.e. $F = \delta_{f1}$ where $f(=1,2,3)$ is the family number. The R_F parity distinguishes the first family from the second and the third families. In this model, if the R_F parity were not broken, the left-handed up quark and ν_{eL} is the lightest particle with $R_F = -1$. Therefore, there is no particle responsible for dark matter even in the R_F conserving model, in contrast to the theory with the conventional R parity. The axion, needed to make the height of the axion potential a tiny amount above the true ground state, does not develop a QCD scale potential but a potential suppressed by $m_u/m_d \equiv Z$,

$$V = \frac{Z}{(1+Z)^2} f_\pi^2 m_\pi^2 \left(1-\cos\frac{a}{F_a}\right). \tag{3}$$

Therefore, the axion resulting from this theory is truly invisible cosmologically except for the cosmological constant. But the astrophysical bound still applies due to the presence of Peccei-Quinn symmetry preserving derivative coupling $\partial^\mu a\cdot J^a_\mu$, and hence $F_a \geq 10^9$ GeV [3, 11]. Therefore, the upper bound of the axion mass is

$$m_a \simeq \sqrt{\frac{m_u}{m_d}} f_\pi m_\pi \frac{10^9\ {\rm GeV}}{F_a} \leq 4\times 10^{-44}\ {\rm GeV}. \tag{4}$$

This extremely light axion can be called quintessence, but cannot be the cold dark matter candidate. Furthermore, there still exists a dispute on the viability on $m_u = 0$ [5].

For the axion to be the cold dark matter candidate, the QCD axion with $F_a \simeq 10^{12}$ GeV which is the usual very light axion [12], must be saved. For this purpose, the up quark mass is assumed to be the usual value, 5 MeV [5]. Then the above mechanism, with an almost massless quark and the corresponding axion, should be placed in another sector. The hidden sector (h-sector), introduced to break supersymmetry, nicely fits to this scheme. With two nonabelian gauge groups, we must consider two vacuum angles: θ corresponding to QCD and θ_h corresponding to the h-color. We need two axions: a_1 with the decay constant F_1 and a_2 with the decay constant F_2. One combination is for the dark matter candidate and the other combination for the quintessence. Since the QCD axion is designed to be the dark matter candidate, the quintessence potential must result from the h-color and be very shallow. Suppose that a_1 and a_2 have the following couplings to the QCD and the h-color field strengths [13]

$$\mathcal{L}_{\text{eff}} = \left(\frac{a_1}{F_1} + \frac{a_2}{F_2}\right) \{F\tilde{F}\} + \left(n_1 \frac{a_1}{F_1} - n_2 \frac{a_2}{F_2}\right) \{F'\tilde{F}'\}\,, \tag{5}$$

where $\{F\tilde{F}\} \equiv (1/64\pi^2)\epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma}$ is the pseudoscalar density constructed from QCD gluon field strength F and similarly for the h-color with primed field strength F'. We have assumed the couplings to the QCD density as $1/F_1$ and $1/F_2$ just for a simple discussion. In fact, the string compactification example shows this behavior [13]. To have two independent pseudo-Goldstone bosons, $n_1 : n_2 \neq 1 : -1$ is assumed, otherwise one Goldstone boson remains to be exactly massless and cannot be a candidate for quintessence. The very light QCD axion is $a = a_1 \cos\gamma + a_2 \sin\gamma$ where $\tan\gamma = F_1/F_2$. The QCD axion decay constant is

$$F_a = \frac{2F_1 F_2}{\sqrt{F_1^2 + F_2^2}}\,. \tag{6}$$

The other combination is the quintessence, $a_q = -a_1 \sin\gamma + a_2 \cos\gamma$. Its decay constant is

$$F_q = \frac{\sqrt{F_1^2 + F_2^2}}{n_1 + n_2}\,. \tag{7}$$

Suppose two scales F_1 and F_2 have a hierarchy, e.g. $F_1 \ll F_2$, such as $F_2 = M_P$ and $F_1 = 10^{12}$ GeV. Then, $F_a \simeq 2F_1$ and $F_q \simeq F_2/(n_1 + n_2)$, fulfilling our motivation to introduce the light axion as the dark matter particle (QCD axion with $F_a \sim 10^{12}$ GeV) and the remaining quintessence with the decay constant $F_q \simeq M_P$. This becomes possible because the QCD potential is much larger than the h-color potential. Without the almost massless h-quark, the h-color potential is much larger than the QCD potential and the QCD axion decay constant is the larger one, which is the so-called "decay constant problem" of the model independent axion [14].

To make the h-color potential extremely shallow, we introduce an almost massless h-color quark. For definiteness, let us introduce the h-color gauge group $\mathrm{SU}(N)_h$ and six chiral h-quarks: $\tilde{U}, \tilde{M}, \tilde{D}$ which are weak SU(2) singlets and $\tilde{U}^c, \tilde{M}^c, \tilde{D}^c$ which form a lefthanded weak SU(2) triplet with $Y = 0$ denoted as $\tilde{Q}_L$,

$$\tilde{Q}_L = \begin{pmatrix} \tilde{D}^c \\ \tilde{M}^c \\ \tilde{U}^c \end{pmatrix}_L\,, \qquad \tilde{U}_L\,, \qquad \tilde{M}_L\,, \qquad \tilde{D}_L\,. \tag{8}$$

They transform as $(1, 3, 0, \bar{N})$ and $(1, 1, (Y = +1, 0, -1), N)$ under $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_w \times \mathrm{U}(1)_Y \times \mathrm{SU}(N)_h$. The scalar superpartners will be denoted without tilde and subscript. Since we do not introduce a triplet Higgs field, these h-quarks are massless at the level of the electroweak scale.

However, these h-quarks can obtain mass suppressed by powers of M_P. Three combinations for isospin triplet operators are the symmetric combinations of the doublet fields, $(H_2H_2)_{\rm sym}$, $(H_1H_2)_{\rm sym}$, $(H_1H_1)_{\rm sym}$ which carry $Y = +1, 0, -1$, respectively. Without any further symmetry imposed, therefore the h-quark masses are suppressed only by one power of the Planck mass, which is not enough for the quintessence. Therefore, we introduce the Z_4 symmetry. The Z_4 charges of H_1 and H_2 are 1. If the Z_4 charge of h-quarks is zero, then $d = 4$ term in the superpotential suppressed by one power of M_P cannot arise. However, the following nonrenormalizable terms can be present in the superpotential,

$$\frac{1}{M_P^3} Q M^{ij} (H_i H_j)_{\rm sym} (H_1 H_2)_{\rm anti} \,, \tag{9}$$

where the symmetric combinations of i, j are for $M^{11} = U,\ M^{12} = M,\ M^{22} = D$. Since this operator is suppressed by M_P^3 and mass parameters in the numerator are at the electroweak scale, we obtain sufficiently small h-quark masses of order 10^{-42} GeV. Since the h-quark mass is extremely small, the vacuum energy contributed by this chiral symmetry violating interaction is also extremely small. Its magnitude is a function of the h-quark condensate, $\langle \tilde{U}^c \tilde{U} \rangle$, $\langle \tilde{M}^c \tilde{M} \rangle$, and $\langle \tilde{D}^c \tilde{D} \rangle$. Since the fermion condensate breaks supersymmetry (being the coefficient of $\theta\theta$ term), the supersymmetric vacuum does not allow the condensate. Thus we can allow its value only below the SUSY breaking scale M_{SUSY}. The condensate breaks $\mathrm{SU}(2) \times \mathrm{U}(1)$ also. From the experimental bound on the ρ parameter [15], we require the condensation scale of these h-quarks to be less than 5% of the electroweak scale, $\langle \tilde{U}^c \tilde{U} \rangle \leq 7$ GeV, etc. For $\langle \tilde{U}^c \tilde{U} \rangle = \langle \tilde{M}^c \tilde{M} \rangle = \langle \tilde{D}^c \tilde{D} \rangle \simeq 5$ GeV, we can estimate the vacuum energy contributed by the explicit chiral symmetry breaking interaction (9) as

$$V \simeq f \times 10^{-43} \tan^2 \beta \cos^4 \beta \ \mathrm{GeV}^4 \,, \tag{10}$$

where f is a coupling constant potentially arising in this estimation. For $\tan \beta = 2$ and 30, f of order 10^{-3} and 1, respectively, give the vacuum energy of order 10^{-47} GeV^4.

The other chiral symmetry breaking h-color instanton potential is

$$V \sim \frac{1}{\Lambda_h^{N-1}} m_{\tilde{U}} m_{\tilde{M}} m_{\tilde{D}} M^N_{\rm h-gluino} \left(1 - \cos \frac{a_q}{F_q} \right) , \tag{11}$$

where $\Lambda_h \sim 10^{13}$ GeV is the confining scale of $\mathrm{SU}(N)_h$. Since eq. (11) gives much smaller contribution to the vacuum energy for any N, eq. (10) is the dominant vacuum energy. Because eq. (11) is not the dominant potential, $\theta_h \neq 0$ at the minimum of the potential. Nevertheless, the QCD vacuum angle θ is very close to zero since the QCD instanton interaction of order $F_\pi^2 m_\pi^2$ is the dominant one for θ.

For F_q of order 10^{16} GeV [16], the quintessence mass is estimated as 10^{-40} GeV. On the other hand, if we use $F_q = M_P$, the mass will be about 10^{-43} GeV.

In passing, we point out that in models without h-quarks [17] we consider only the chiral symmetry for the h-gluino of SU$(N)_h$. The instanton contribution to the potential is the form given by eq. (11) without h-quark mass terms and the corresponding suppression factor with Λ_h. Since the h-gluino mass scale is of order $M_{SUSY} \sim \Lambda_h^3/M_P^2$, the height of the potential is of order $\Lambda_h^{2N+4}/M_P^{2N}$. For a Z_D discrete symmetry subgroup of U$(1)_R$ [17] where D is a positive even integer, the explicit chiral symmetry breaking term is $(1/M_P^{3D/2-3}) \int d^2\theta (W^\alpha W_\alpha)^{D/2}$. This explicit chiral symmetry breaking term is more important than eq. (11) for $N > (1/4)(3D-2)$. It is known that $D \geq 6$ gives the height less than 10^{-13} GeV^4 [17]. To realize the quintessence from this h-gluino chiral symmetry, we need $D \sim 10$ and $N > (1/4)(3D-2)$. For example, it is satisfied[1] for Z_5 and $N \geq 8$. Then the quintessence is composite and arising from the h-gluino condensation. The other possibility that eq. (11) is more important than the explicit h-gluino chiral symmetry breaking term is not elaborated here.

If the h-quarks are responsible for the shallow potential as discussed above, the lightest supersymmetric particle (LSP) can be the cold dark matter candidate also. But to solve the strong CP problem, we need a QCD axion.

In conclusion, we have explored the possibility of the quintessence being an axion in the hidden sector. However, this h-sector axion has an extremely shallow potential due to almost massless h-quarks. Even being an axion, the hidden-sector vacuum angle θ_h at the minimum of the potential is nonzero due to the explicit breaking of the Peccei-Quinn symmetry of the h-sector. The timing problem is solved by the discrete Z_4 symmetry to produce a dominant effective superpotential suppressed by M_P^3. The cold dark matter needed for large scale structure formation is the conventional very light axion [12] or the LSP. The model presented in this paper is just one example among multitude of models fulfilling almost vanishing h-sector potentials.

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