Kaon oscillations and baryon asymmetry of the universe

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Abstract

Baryon asymmetry of the universe (BAU) is naturally explained with $K^0 - K^0$ oscillations of a newly developed mirror-matter model and new understanding of quantum chromodynamics (QCD) phase transitions. The global symmetry breaking transitions in QCD are proposed to be staged depending on condensation temperatures of strange, charm, bottom, and top quarks in the early universe. The long-standing BAU puzzle can then be understood with $K^0 - K^0$ oscillations that occur at the stage of strange quark condensation and baryon number violation via a non-perturbative instanton-like (coined "quarkiton") process. Similar processes at charm, bottom, and top quark condensation stages are also discussed including an interesting idea for top quark condensation to break both the QCD global $U(1)_A$ symmetry and the electroweak gauge symmetry at the same time. Meanwhile, the $U(1)_A$ or strong CP problem of particle physics is simply solved under the same framework.
INTRODUCTION

The matter-antimatter imbalance or baryon asymmetry of the universe (BAU) has been a long standing puzzle in the study of cosmology. Such an asymmetry can be quantified in various ways. The Cosmic Microwave Background (CMB) data by Planck set a very precise observed baryon density of the universe at $\Omega_b h^2 = 0.02242 \pm 0.00014$ [1]. This corresponds to today’s baryon-to-photon number density ratio of $n_B/n_\gamma = 6.1 \times 10^{-10}$. For an adiabatically expanding universe, it would be better to use the baryon-number-to-entropy density ratio of $n_B/s = 8.7 \times 10^{-11}$ to quantify the BAU, which unfortunately is not true under the new understanding of the neutrino history in the early universe [2]. It turns out that the ratio of $n_B/n_\gamma$ is still better for tracking the BAU in the history of the universe [2].

From known physics, it is difficult to explain the observed BAU. For example, for an initially baryon-symmetric universe, the surviving relic baryon density from the annihilation process is about nine orders of magnitude lower than the observed one [3]. Therefore, an asymmetry is needed in the early universe and the BAU has to exist before the temperature of the universe drops below $T = 38$ MeV [3] to avoid the annihilation catastrophe between baryons and anti-baryons.

Sakharov proposed three criteria to generate the initial BAU: (i) baryon number (B-) violation (ii) C and CP violation (iii) departure from thermal equilibrium [4]. The Standard Model (SM) is known to violate both C and CP and it does not conserve baryon number only although it does $B - L$ (difference of baryon and lepton numbers). Coupled with possible non-equilibrium in the thermal history of the early universe, it seems to be easy to solve the BAU problem. Unfortunately, the violations in SM without new physics are too small to explain the observed fairly large BAU. The only known B-violation processes in SM are non-perturbative, for example, via the so-called sphaleron [5] which involves nine quarks and three leptons from each of the three generations. It was also found out that the sphaleron process can be much faster around or above the temperature of the electroweak symmetry breaking or phase transition $T_{EW} \sim 100$ GeV [6]. This essentially washes out any BAU generated early or around $T_{EW}$ since the electroweak transition is most likely just a smooth cross-over instead of ”desired” strong first order [7]. It makes the appealing electroweak baryogenesis models [6, 8] ineffective and new physics often involving the Higgs have to be added in the models [9–11]. Recently lower energy baryogenesis typically using
particle oscillations stimulated some interesting ideas \cite{12,13}. Other types of models such as leptogenesis \cite{14} are typically less testable or have other difficulties.

Here we present a simple picture for baryogenesis at energies around quantum chromodynamics (QCD) phase transition with $K^0 - K^{0'}$ oscillations based on a newly developed mirror matter model \cite{15}. $K^0 - K^{0'}$ oscillations and the new mirror matter model will be first introduced to demonstrate how to generate the "potential" amount of BAU as observed. Then the QCD phase transition will be reviewed and the sphaleron-like non-perturbative processes are proposed to provide B-violation and realize the "potential" BAU created by $K^0 - K^{0'}$ oscillations. In the end, the observed BAU is generated right before the $n - n'$ oscillations that determines the final normal-to-mirror(dark) matter ratio of the universe \cite{15}. Meanwhile, the long-standing $U(1)_A$ and strong CP problems in particle physics are also naturally resolved under the same framework.

$K^0 - K^{0'}$ OSCILLATIONS AND THE NEW MODEL

To understand the observed BAU, we need to apply the newly developed particle-mirror particle oscillation model \cite{15}. It is based on the mirror matter theory \cite{16–23}, that is, two sectors of particles have identical interactions within their own sector but share the same gravitational force. Such a mirror matter theory has appealing theoretical features. For example, it can be embedded in the $E_8 \otimes E_8'$ superstring theory \cite{18,24,25} and it can also be a natural extension of recently developed twin Higgs models \cite{26,27} that protect the Higgs mass from quadratic divergences and hence solve the hierarchy or fine-tuning problem. The mirror symmetry or twin Higgs mechanism is particularly intriguing as the Large Hadron Collider has found no evidence of supersymmetry so far and we may not need supersymmetry, at least not below energies of 10 TeV. Such a mirror matter theory can explain various observations in the universe including the neutron lifetime puzzle and dark-to-baryon matter ratio \cite{15}, evolution and nucleosynthesis in stars \cite{28}, ultrahigh energy cosmic rays \cite{29}, and a requirement of strongly self-interacting dark matter to address numerous discrepancies on the galactic scale \cite{30}.

In this new mirror matter model \cite{15}, no cross-sector interaction is introduced, unlike other particle oscillation type models. The critical assumption of this model is that the mirror symmetry is spontaneously broken by the uneven Higgs vacuum in the two sectors,
i.e., $< \phi > \neq < \phi ' >$, although very slightly (on the order of $10^{-15}$) [15]. When fermion particles obtain their mass from the Yukawa coupling, it automatically leads to the mirror mixing for neutral particles, i.e., the basis of mass eigenstates is not the same as that of mirror eigenstates, similar to the case of ordinary neutrino oscillations due to the family or generation mixing. Further details of the model can be found in Ref. [15].

The immediate result of this model for this study is the probability of $K^0 - K^{0'}$ oscillations in vacuum [15],

$$P_{K^0 K^{0'}}(t) = \sin^2(2\theta) \sin^2\left(\frac{1}{2} \Delta_{K^0 K^{0'}} t\right)$$

(1)

where $\theta$ is the $K^0 - K^{0'}$ mixing angle and $\sin^2(2\theta)$ denotes the mixing strength of about $10^{-4}$, $t$ is the propagation time, $\Delta_{K^0 K^{0'}} = m_{K^0_2} - m_{K^0_1}$ is the small mass difference of the two mass eigenstates of about $10^{-6}$ eV [15], and natural units ($\hbar = c = 1$) are used for simplicity. Note that the equation is valid even for relativistic kaons and in this case $t$ is the proper time in the particle’s rest frame. There are actually two weak eigenstates of $K^0$ in each sector, i.e., $K^0_S$ and $K^0_L$ with lifetimes of $9 \times 10^{-11}$ s and $5 \times 10^{-8}$ s, respectively. Their mass difference is about $3.5 \times 10^{-6}$ eV very similar to $\Delta_{K^0 K^{0'}}$, which makes one wonder if the two mass differences and even CP violation may originate from the same source.

For kaons travel in the thermal bath of the early universe, each collision or interaction with another particle will collapse the oscillating wave function into a mirror eigenstate, in other words, during mean free flight time $\tau_f$ the $K^0 - K^{0'}$ transition probability is $P_{K^0 K^{0'}}(\tau_f)$. The number of such collisions will be $1/\tau_f$ in a unit time. Therefore, the transition rate of $K^0 - K^{0'}$ with interaction is [15],

$$\lambda_{K^0 K^{0'}} = \frac{1}{\tau_f} \sin^2(2\theta) \sin^2\left(\frac{1}{2} \Delta_{K^0 K^{0'}} \tau_f\right).$$

(2)

Note that the Mikheyev-Smirnov-Wolfenstein (MSW) matter effect [31, 32], i.e., coherent forward scattering that could affect the oscillations is negligible as the meson density is very low when kaons start to condensate from the QCD plasma (see more details for in-medium particle oscillations from Ref. [28]).

It is not very well understood how the QCD symmetry breaking or phase transition occur in the early universe, which will be discussed in detail in the next section. Let us suppose that the temperature of QCD phase transition $T_c$ is about 150 MeV and a different value (e.g., 200 MeV) here does not affect the following discussions and results. At this time only up, down, and strange quarks are free. It is natural to assume that strange quarks become
confined first during the transition, i.e., forming kaon particles first instead of pions and nucleons. A better understanding of this process is shown in the next section. As a matter of fact, even if they all form at the same time, the equilibrium makes the ratio of nucleon number to kaon number

$$\frac{n_N}{n_K} \simeq \left( \frac{m_N}{m_K} \right)^{3/2} \exp\left(-\frac{(m_N - m_K)}{T_c}\right) \sim 0.1$$

very small due to the fact of kaons much lighter than nucleons.

Once neutral kaons are formed, they start to oscillate by participating in weak interaction with cross section of

$$\sigma_{EW} \sim G_F^2 T^2$$

where

$$G_F = 1.17 \times 10^{-5} \text{ GeV}^{-2}$$

is the Fermi coupling constant. Then one can estimate $K^0$'s thermally averaged reaction rate over the Bose-Einstein distribution,

$$\Gamma = \frac{g}{(2\pi)^2} \int_0^\infty d^3p f(p) \sigma_{EW} \frac{p}{m}$$

$$= \frac{g}{2\pi^2} \frac{G_F^2 T^2}{m} \int_0^\infty dp \frac{p^3}{\exp(\sqrt{p^2 + m^2}/T)} - 1$$

where $g = 2$ for both $K^0_S$ and $K^0_L$, $m$ is the mass of kaons, and $T$ is the temperature. The expansion rate of the universe at this time can be estimated to be $H \sim T_{\text{MeV}}^2 \text{s}^{-1}$ where $T_{\text{MeV}}$ is the temperature in unit of MeV. The condition for $K^0$ to decouple from the interaction or freeze out is $\Gamma/H < 1$. It can be easily calculated from Eq. 4 that the freezeout occurs at $T_{fo} = 100 \text{ MeV}$. This means that kaon oscillations have to operate between $T_c = 150 \text{ MeV}$ and $T_{fo} = 100 \text{ MeV}$. And fortunately the $K^0$ mesons have long enough lifetime (compared to the weak interaction rate) for such oscillations and BAU to occur during this temperature range.

For a typical mirror-to-normal matter temperature ratio of $x = T'/T \sim 0.3$ \cite{18,20},

the two oscillation steps of $K^0 \rightarrow K^{0'}$ and $K^{0'} \rightarrow K^0$ will be decoupled in a similar way as the $n - n'$ oscillations discussed in Ref. \cite{15}. Using a typical weak interaction rate

$$\lambda_{EW} = 1/\tau_f = G_F^2 T^5 \sim T_{\text{MeV}}^5 \text{s}^{-1}$$

and the age of the universe $t = 0.3/T_{\text{MeV}}^2$ s during this period of time, one can get the final-to-initial $K^0$ abundance ratio in the mirror sector for the first step,

$$\frac{X_{K^0}}{X_{K^{0'}}} = \exp\left(-\int P_{K^0 K^{0'}}(\tau_f) \lambda_{EW} dt\right)$$

$$= \exp\left(-10^{29} \sin^2(2\theta)\left(\frac{\Delta_{K^0 K^{0'}}}{2 \text{eV}}\right)^2 \int_{T_c}^{T_{fo}} d\left(\frac{1}{T_{\text{MeV}}}\right)\right)$$

$$= 1 - 0.025 \equiv 1 - \epsilon$$

(5)
and the second step is calculated similarly.

After the conversion of the two oscillation steps, the final-to-initial $K^0$ abundance ratio in the normal world is,

$$\frac{X_f}{X_i} = 1 - \epsilon^2. \quad (6)$$

The CP violation amplitude in SM is on the order of $\delta = 10^{-3}$ so that the oscillation probability ratio can be estimated as $P_{K^0\bar{K}^0}/P_{\bar{K}^0K^0} \sim 1 - \delta^2$. Then the net $K^0$ fraction can be obtained as follows,

$$\frac{\Delta X_{K^0\bar{K}^0}}{X_{K^0\bar{K}^0}} = \frac{X_{K^0} - X_{\bar{K}^0}}{X_{K^0} + X_{\bar{K}^0}} = \epsilon^2\delta^2 \sim 10^{-8}/16 \quad (7)$$

If the excess of $K^0(d\bar{s})$ generated above can survive by some B-violation process, i.e., dumping $\bar{s}$ quarks and leaving $d$ quarks to form nucleons in the end, then assuming half of strange quarks condensate into $K^0_{L,S}$ (with the other half in $K^\pm$) we will end up with a net baryon density of $n_B/n_\gamma = 5 \times 10^{-10}$ that is very close to the observed value. In the next section, we will demonstrate how such a B-violation process could occur in the QCD phase transition.

QCD SYMMETRY BREAKING TRANSITION AND OTHER OSCILLATIONS

A massless fermion particle’s chirality or helicity has to be preserved, i.e., its left- and right-handed states do not mix [33]. This is essentially also true for extremely relativistic massive particles as required by special relativity. Therefore the global flavor chiral symmetry of $SU(2)_L \otimes SU(2)_R$ for the family of up and down quarks is very good as their masses are so tiny compared to the QCD confinement energy scale.

Under strong interactions like QCD, the non-vanishing vacuum expectation value of quark condensates can lead to spontaneous symmetry breaking (SSB) by mixing left- and right-handed quarks in the mass terms. The resulting pseudo-Nambu-Goldstone bosons (pNGB) and Higgs-like field will manifest as light bound states of quark condensates. For example, the approximate $SU(2)_L \otimes SU(2)_R$ chiral symmetry is spontaneously broken into $SU(2)_V$, i.e., the isospin symmetry at low energies in QCD, which can be described under an effective theory of the so-called $\sigma$-model [33]. In this case, the lightest isoscalar scalar $\sigma$ or $f_0(500)$ meson with mass of $\sim 450$ MeV serves as the quark condensate for SSB [34], a similar role to Higgs in electroweak SSB. The resulting pNGB particles are the three lightest pseudoscalar
mesons ($\pi^\pm$ and $\pi^0$). The Lagrangian for the matter part with omission of gauge fields and Higgs-like parts can be written as,

$$L_{\text{matter}} = \bar{q}_L^a (i\gamma^\mu D_\mu) q_L^a + \bar{q}_R^a (i\gamma^\mu D_\mu) q_R^a - m_a (\bar{q}_L^a q_R^a + \bar{q}_R^a q_L^a)$$

(8)

where the left- and right-handed quark fields $q_{L/R}$ are summed over the flavor index $a$. The non-vanishing mass terms can mix left- and right-handed states and hence explicitly break the chiral symmetry.

There is actually an extra global symmetry of $U(1)_L \otimes U(1)_R$ in the above QCD system before the SSB, where the $U(1)_{L+R}$ symmetry is conserved and manifests as baryon conservation in QCD while the axial part $U(1)_{L-R}$ or $U(1)_A$ is explicitly broken by the axial current anomaly, resulting in a CP violating term in the Lagrangian involving gauge field $G$,

$$L_\theta = \frac{\theta g_s^2}{32\pi^2} G \cdot \tilde{G}$$

(9)

with $\theta$ modified by the Yukawa mass matrices for quarks as the physical strong CP phase $\tilde{\theta} = \theta - \arg \det(\prod_a m_a)$. This leads to the long-standing so-called $U(1)_A$ and strong CP puzzles in particle physics as the $\tilde{\theta}$ parameter has to be fine-tuned to zero or at least $\leq 10^{-9}$ to be consistent with measurements of neutron electric dipole moment.

In the scheme of $1/N$ expanded QCD, Witten using a heuristic method discovered an interesting connection to the $\eta'$ meson as a possible pNGB to solve the $U(1)_A$ or strong CP problem although the $\eta'$ mass (958 MeV) seems to be too high for the above chiral SSB. The good Witten-Veneziano relation for obtaining the $\eta'$ mass under such a approach indicates some validity of the idea. In addition, it gives the correct QCD transition scale of about 180 MeV and relates the $\eta'$ mass to the interesting topological properties of QCD.

At a little earlier time, Peccie and Quinn conjectured a so-called $U(1)_{PQ}$ axial symmetry to solve the $U(1)_A$ problem by dynamically canceling the axial anomaly with an imagined "axion" field. Here we could combine the two brilliant ideas and find the clue for solving the problem as shown below.

The key is to realize that the QCD symmetry breaking transition can be staged as shown in Table I. That is, we could have a strange quark condensation first leading to an SSB at a higher energy scale and then the normal $SU(2)$ chiral SSB at slightly lower energy. At the early stage, it is the strange $U(1)$ (i.e., $U_s(1)$) symmetry that gets spontaneously broken.
TABLE I. Possible stages of QCD spontaneous symmetry breaking or phase transitions are shown. Candidates of Higgs-like and pNGB/NGB particles are taken from the compilation of Particle Data Group [41]. The major oscillations of neutral condensates and non-perturbative processes at each stage are listed as well.

| SSB stages          | (u, d)       | s\bar{s} | c\bar{c} | b\bar{b} | t\bar{t} |
|---------------------|--------------|----------|----------|----------|----------|
| Higgs-like          | \sigma/f_0(500) | f_0(980) | \chi_c(1P) | \chi_b(1P) | Higgs    |
| Broken Symm. \(\text{SU}(3) \rightarrow \text{SU}(2)\) | \(U_s(1)_A\) and \(U_c(1)_A\) | \(U_b(1)_A\) | \(U_t(1)_A\) and SU(2) \(\otimes U(1)_Y\) |
| pNGB / NGB          | \(\pi^\pm, \pi^0\) | \(\eta_1(\eta')\) and \(\eta_c(1S)\) | \(\eta_b(1S)\) | \(\eta_b(1S)\)? and K\(\pm, K^0_{L,S}, \eta_b(\eta)\) |
| Oscillations        | \(n - n'\) | \(K^0 - K^{0'}\) | \(D^0 - D^{0'}\) | \(B^0 - B^{0'}\) | \(H - H'\) |
| Non-perturbative    | s-quarkiton  | c-quarkiton | b-quarkiton | t-quarkiton and sphaleron |

The \(U_s(1)_{L+R}\) is kept as strange number conservation in QCD that will then be broken by the electroweak force while the other global \(U_s(1)_{L-R}\) symmetry is broken by mixing left- and right-handed strange quarks in the mass term. At the same time the \(SU(3)\) flavor symmetry of \((u,d,s)\) quarks is broken into \(SU(2)\) of \((u,d)\) quarks with five pNGB particles of \(K^\pm, K^0_{L,S}, \eta\) (more exactly \(\eta_b\)). The broken \(U_s(1)_{L-R}\) or \(U_s(1)_A\) gives another pNGB, i.e., \(\eta'\) (more exactly \(\eta_1\) with quark configuration of \(u\bar{u} + d\bar{d} + s\bar{s}\)), as Witten suspected. The Higgs-like particle leading to this SSB is the scalar singlet \(f_0(980)\) meson with mass of 990 MeV [41] that is perfectly compatible with the seemingly heavy \(\eta'\).

The \(U_s(1)_A\) symmetry has all the desired necessary features of the arbitrary \(U(1)_{PQ}\) axial symmetry conjectured by Pecce and Quinn [39, 40]. That is, SSB of \(U_s(1)_A\) due to strange quark condensates provides a Higgs-like field \((f_0(980))\) and a pNGB \((\eta_1)\) that can dynamically drive the \(U(1)_A\) axial anomaly and the \(\bar{\theta}\) parameter to zero and therefore solving the strong CP problem. The imagined "axion" from SSB of the Pecce-Quinn symmetry [42] is not needed and the problem can be solved within the framework of SM without new particles.

However, such a solution does not seem to provide a B-violation mechanism for solving the BAU problem as \(U_s(1)_{L+R}\) or strange number is conserved. Another key insight related
to the non-perturbative effects and topological structures of QCD and SM will be discussed below.

The work of ’t Hooft \[43, 44\] interpreted the $U(1)_A$ anomaly in the chiral SSB as the topological effects in QCD and introduced the so-called $\theta$-vacua between which tunneling occurs via instantons non-perturbatively although such quantum tunneling effects are extremely suppressed. It is actually this kind of non-trivial $\theta$-vacuum structure and instanton-like gauge field solutions leading to the desired $B$-violation in SM.

A saddle-point gauge field solution called ’’sphaleron’’ in the electroweak interaction of $SU(2)_L \otimes U(1)_Y$ was first discovered in 1984 by Klinkhamer and Manton \[5\] that inspired various electroweak baryogenesis models later. Such a process involves nine quarks and three leptons (all left-handed) from each generation and therefore violates $B$ and $L$ numbers by three units while conserving $B - L$ at the same time \[3\]. Finite temperature effects considered by Ref. \[6\] make the sphaleron-like process rate high enough for $B$-violation around or above the electroweak phase transition energy scale.

Now the question becomes if there is a similar sphaleron-like process that could occur at the energy scale of the QCD phase transition. The answer is very likely. There could be a similar saddle-point solution when the QCD gauge fields are included, we will call it ’’quarkiton’’ to distinguish from sphaleron for the electroweak interaction only. At the stage of strange quark condensation, it is natural to assume that it is a $B$ and $L$ violating process (by one unit for each) involving three strange quarks and three leptons in the same generation like the following,

$$sss + \mu^+ \nu_\mu \nu_\mu \leftrightarrow \text{Quarkiton} \leftrightarrow \bar{s}s\bar{s} + \mu^- \bar{\nu}_\mu \bar{\nu}_\mu$$ \hspace{1cm} (10)

where all of quarks and leptons are left-handed, three strange quarks ensure a color singlet, and the overall $B - L$ is conserved. In particular, a quarkiton is configured to be a neutral singlet under the SM gauge symmetry of $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$.

Such a quarkiton process can help solve the BAU problem under the scenario of $K^0 - K^{0'}$ oscillations discussed in the previous section. That is, the extra down quarks from $K^0$ with a quark configuration of $(d\bar{s})$ can be saved once all the extra anti-strange quarks are converted to strange quarks via the quarkiton process and then condensate into mesons. Half of the saved down quarks are subsequently transitioned to up quarks by the electroweak interaction. When the next stage QCD phase transition (i.e., the chiral $SU(2)$ SSB) occurs at possibly
around $T = 100$ MeV, these extra up and down quarks will condensate into protons and neutrons forming the initial baryon content of the universe. The net effect after all these processes for one $K^0$ ($d\bar{s}$) excess is,

$$d + \bar{s} \rightarrow \frac{1}{6}p + \frac{1}{6}n + \frac{1}{6}e^- + \frac{1}{6}\bar{\nu}_e + \frac{1}{3}\nu_\mu.$$ (11)

During the strange quark condensation, kaons are the lightest strange mesons. So it is safe to assume that about half of strange quarks condensate into $K^0$ while the other half into $K^\pm$. Before condensation the strange quark to photon number density ratio is $n_s/n_\gamma = 4.5$. Taking into account the oscillation result from Eq. (7) one can obtain a net baryon-to-photon number density ratio of $n_B/n_\gamma = 5 \times 10^{-10}$ that is very close to the observed value.

Note that $B - L$ is conserved at the end of net baryon generation from (11) with extra amount of $\nu_\mu$ equal to net baryon number. The fate of these and other neutrinos and their effects on thermal evolution of the universe will be discussed in a separate paper.[2]

Now one may wonder if such a quarkiton process and SSB could also operate earlier at higher temperatures for charm, bottom, and even top quark condensation. Interestingly, similar to the strange quarkiton process, the following could be conceived to occur at different condensation stages for c-, b-, and t- quarks, respectively,

\begin{align*}
ccc + \mu^-\mu^-\nu_\mu &\leftrightarrow \text{Quarkiton} \Leftrightarrow \bar{c}\bar{c}\bar{c} + \mu^+\mu^+\nu_\mu \quad (12) \\
bbb + \tau^+\nu_\tau\nu_\tau &\leftrightarrow \text{Quarkiton} \Leftrightarrow \bar{b}\bar{b}\bar{b} + \tau^-\bar{\nu}_\tau\bar{\nu}_\tau \quad (13) \\
ttt + \tau^-\tau^-\bar{\nu}_\tau &\leftrightarrow \text{Quarkiton} \Leftrightarrow \bar{t}\bar{t}\bar{t} + \tau^+\tau^+\nu_\tau \quad (14)
\end{align*}

where the SM gauge singlet configuration is required for all quarkitons. The Higgs-like candidates could be $\chi_{c0}(1P)$ for c-quark condensation and $\chi_{b0}(1P)$ for b-quark condensation with the possible pNGB particles of $\eta_c(1S)$ and $\eta_b(1S)$ for breaking the corresponding $U_c(1)_A$ and $U_b(1)_A$ symmetries, respectively, as shown in Table [II].

Another interesting idea could be conceived from the coincident energy scale of t-quark condensation and electroweak phase transition. That is, the actual Higgs could be a bound state of top quark condensate that breaks both the global QCD top flavor $U_t(1)_A$ and the electroweak gauge symmetries at the same time by giving mass to all the fermion particles and defining the SM vacuum structure. The subsequent b-, c-, s- quark condensation and SSB transitions just modify the QCD vacuum structure further. Together with evidence of similar $K^0$ mass differences due to CP violation and mirror splitting as discussed earlier,
one may wonder if at the scale of $T_{\text{EW}}$ the top quark condensation could also break the degeneracy of normal and mirror worlds and cause the CP violation at the same time.

These phase transition processes can lead to more particle oscillations between the normal and mirror sectors from $D^0$, $B^0$, and Higgs during the $c$-, $b$-, and $t$-quark condensation phases, respectively. For Higgs with $\Delta_{HH'} \sim 10^{-4}$ eV and $\sin^2(2\theta) \sim 1$, one can get a small oscillation parameter of $\epsilon(HH') \sim 10^{-14}$ at $T_c = 100$ GeV from Eq. 5. For $D^0$ with $\Delta_{D^0D'^0} \sim 10^{-6}$ eV and $\sin^2(2\theta) \sim 10^{-4}$, we can estimate $\epsilon(D^0D'^0) \sim 10^{-8}$ at $T_c = 1$ GeV from Eq. 5. Similarly, $\epsilon(B^0B'^0) \sim 10^{-13}$ at $T_c = 10$ GeV for $B^0$ with $\Delta_{B^0B'^0} \sim 10^{-5}$ eV and $\sin^2(2\theta) \sim 10^{-4}$. These oscillations are much weaker compared to the $K^0 - K'^0$ oscillations and therefore they are negligible for the generation of BAU.

**CONCLUSION**

Under the new mirror-matter model and new understanding of possibly staged QCD symmetry breaking phase transitions, the long-standing BAU puzzle can be naturally explained with $K^0 - K'^0$ oscillations that occur at the stage of strange quark condensation. Meanwhile, the $U(1)_A$ or strong CP problem in studies of particle physics is understood under the same framework. Non-perturbative processes via quarkitons at different quark condensation stages are proposed for B-violation and could be verified and further understood with calculations using the lattice QCD technique. More accurate studies on $K^0_{L,S}$ at the kaon production facilities, in particular, on the branching fractions of their invisible decays that surprisingly are not constrained experimentally, will better quantify the generation of baryon matter in the early universe. Future experiments at the Large Hadron Collider may provide more clues for such topological quarkiton processes and reveal more secrets in the SM gauge structure, the Higgs mechanism, and the amazing oscillations between the normal and mirror worlds.

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