CP Violation at the Finite Temperature

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Abstract: The dynamic of the baryon asymmetry of the Universe (BAU) is one of the longstanding problems in particle physics and cosmology. Assuming our Universe was matter-antimatter symmetric at its origin, it is reasonable to speculate that interactions involving elementary particles gave birth to the BAU during the subsequent cosmological evolution. Combining data of the Plank with that of the WMAP, the observed BAU is

\[ Y_{\text{obs}} \equiv \frac{\rho_B}{s} = (8.61 \pm 0.09) \times 10^{-11}, \]

where \( \rho_B \) is the baryon number density, \( s \) is the entropy density of the Universe. It is well-known that three Sakharov criteria\textsuperscript{2} must be satisfied for a successful baryogenesis theory: (1) baryon number violation; (2) C and CP violations (CPV); (3) a departure from the thermal equilibrium. The Standard Model (SM) itself contains all the necessary ingredients to the realization of baryogenesis. However the CPV phase from the CKM mixing matrix in the SM can not give rise to an adequate baryon asymmetry, because QCD damping effects reduce the generated asymmetry to a negligible amount\textsuperscript{3}. New physics beyond the SM is needed for a real baryogenesis.

Of various baryogenesis theories, the electroweak baryogenesis (EWBG)\textsuperscript{4,5}, is promising and attractive, because it is testable with a combination of searching for new degrees of freedom at the LHC and low energy experiments. A successful EWBG requires a first order electroweak phase transition (EWPT) and a large enough CP violation. Both requirements can be met in some well-known extensions of the SM, such as minimal supersymmetric standard model (MSSM)\textsuperscript{6} and two-Higgs doublet model\textsuperscript{8}. It is known that CP-violating phases from either scalar couplings\textsuperscript{9,10} or Yukawa couplings\textsuperscript{11,12,13} can give rise to a large enough relaxation coefficient needed for the EWBG. However the

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non-observation of EDMs of atoms, molecules and the electron puts a very strong constraint on the new CP-violating interactions. For example, wino induced baryogenesis scenario\textsuperscript{14} was already excluded by the latest ACME result\textsuperscript{15}.

In this letter we investigate a scenario where the CP was spontaneously broken at the finite temperature and was recovered after the EWPT. We study the strength EWPT in this scenario and explore the possibility of generating an adequate BAU with the same CP phase via the EWBG. This scenario relieves the tension between the non-observation of EDMs and the EWBG requirement for a large CP violation, because there is no spontaneous CP violation in the zero temperature. To illustrate our point, the SM is extended with a complex scalar singlet \( S \) and a global \( U(1) \) symmetry, which is explicitly broken by the Higgs potential. We focus on the scenario where the universe undergoes a two-step phase transition, i.e. \( \langle H \rangle \neq 0, \langle S \rangle = 0 \) at \( T < T_n \), while \( \langle H \rangle = 0, \langle |S| \rangle \neq 0 \) at \( T \in (T_n, T_s) \) and the CP is spontaneously broken as \( S \) gets non-zero vacuum expectation value (VEV), where \( T_n \) is the bubble nucleation temperature and \( T_s \) is the temperature of the first-step phase transition. As was shown in Ref.\textsuperscript{16,17} there is a large barrier between the electroweak symmetric phase \( \langle H \rangle = 0, \langle S \rangle = v_s e^{-\varphi} \) and the electroweak symmetry broken phase \( \langle H \rangle = v_T, \langle S \rangle = 0 \) at the tree-level, so strongly first order EWPT can be easily realized. To accommodate the EWBG we introduce vector-like top quark \( t_{L,R} \) with following possible interactions,

\[ \xi \bar{t}_{L,R} \tilde{S} t_{L,R} + y_t q_L \tilde{t}_R + (M_t + H^1 H/\Lambda) \tilde{t}_L \bar{t}_R + \text{h.c.}. \]

where \( A \) is the cut off scale and all couplings are real. The first term induces CPV interaction on the bubble wall, which is a seed for a net BAU via the EWBG. We find that the observed BAU can be explained in this scenario if the \( Z_2 \) symmetry relating to \( S \leftrightarrow -S \) is explicitly broken in the potential, which causes to the collapse of the domain wall. No extra CP violation is needed.

The paper is organized as follows: We study the spontaneous CP violation and EWPT in section II and III...
respectively. Section IV is devoted to the investigation of EWBG in this model. The last part is concluding remarks.

**Spontaneous CP violation at finite T** We extend the SM with a complex scalar singlet $S$, vector-like quark $t_L, R$ and global $U(1)$ symmetry, under which only $S$ and $t$ carries non-zero charge. It was pointed out in Ref. [18] that spontaneous CP violation in the theory of one complex scalar field may occur only when the related $U(1)$ is explicitly broken by at least two spurions whose $U(1)$ charges are different in magnitude, where spurion refers to the coupling in the potential that breaks the $U(1)$ explicitly. The Higgs potential can be written as

$$V = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 - \mu_A^2(S^\dagger S) + \lambda_1(S^\dagger S)^2$$

$$+ \lambda_2(H^\dagger H)(S^\dagger S) - \frac{1}{7}\mu_B^2 S^2 + \frac{1}{2}\lambda_3 S^4 + \text{h.c.} \quad (3)$$

where all couplings are real. Due to the existence of the last two terms in (3), the CP can be broken spontaneously.

By setting $H = (0, v + h)T/\sqrt{2}$ and $S = (v_e e^{i\varphi} + \alpha + i\beta)/\sqrt{2}$, where $v$ and $v_s$ are VEVs and $\varphi$ is the CP phase, the tadpole conditions have three solutions at the zero temperature as follows: (I) $v_s \neq 0$, $v \neq 0$ and $\varphi \neq 0$, (II) $v \neq 0$ $v_s = \varphi = 0$ and (III) $v = 0$, $v_s \neq 0$, $\varphi \neq 0$, depending on parameter settings of the potential. It is obvious that the third solution is not real at the zero temperature. If the solution (I) is true, there will be the mixing between the SM Higgs and the scalar singlet, which is strongly constrained by the Higgs data from the LHC and low energy precision observables. This scenario turns to be less attractive. We are interested in the solution (II) at the zero temperature, where there is no mixing between the SM Higgs and extra scalars. Conditions for this solution being the global minimum is

$$\lambda_1 > \lambda_3 \quad \mu_A^2 < \frac{1}{2}\lambda_2 v^2 \quad (4)$$

For this case scalar masses can be written as $m_h^2 = 2\lambda v^2$, $m_S^2 = -\mu_A^2 - \mu_B^2 + \frac{1}{2}\lambda_2 v^2$ and $m_{S'}^2 = -\mu_A^2 + \mu_B^2 + \frac{1}{2}\lambda_2 v^2$. If there is no extra interactions for the scalar singlet, the lighter component of $S$ will be stable dark matter candidate [22].

The situation can be different at the finite temperature, because the following thermal mass corrections should be included in the potential:

$$\Pi_h \equiv D_h T^2 = \left\{ \frac{3g'^2 + g^2}{16} + \frac{\lambda}{2} + \frac{h^2}{4} + \frac{\lambda_2}{12} \right\} T^2 \quad (5)$$

$$\Pi_\alpha = \Pi_\beta \equiv D_s T^2 = \left( \frac{\lambda_1}{3} + \frac{\lambda_2}{6} \right) T^2 \quad (6)$$

where $h_t$ is the top quark Yukawa coupling, $g$ and $g'$ are the $SU(2)_L$ and $U(1)_Y$ couplings. $\Pi_h$, $\Pi_\alpha$ and $\Pi_\beta$ are thermal masses of $h$, $\alpha$ and $\beta$ respectively. Here we neglect corrections from Coleman-Weinberg terms, diasy contributions and $O(T^4)$ corrections for simplicity while without changing inherent physics. For this scenario, once upon a time at $T_0$ in the thermal history of the universe, the Higgs potential first evolves to the minimum at $v = 0$ and $|v_s| \neq 0$, resulting in a spontaneous CP violation. The CP phase is

$$\varphi = \pm \frac{1}{2} \arccos \left[ \frac{\lambda_1 - \lambda_3}{\lambda_2 v^2 - m_h^2 - m_{S'}^2 + 2\Pi_\alpha} \right] \quad (7)$$

As temperature drops lower to the $T_n$, bubbles relating to electroweak symmetry broken phase, i.e. $v \neq 0$ and $v_s = 0$, starts to nucleate in the $v = 0$ and $v_s \neq 0$ background, and the spontaneous CP phase evolves to null from the outside of the bubble wall to the inside of the bubble wall. In short, the spontaneous CP violation emerges at $T \in (T_n, T_s)$.

**EWPT** To study the strength of the EWPT, one needs the effective potential at the finite temperature in terms of background fields $h, \alpha$ and $\beta$

$$\bar{V} = -\frac{1}{2}(\mu^2 - \Pi_h)h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{4}\lambda_2 h^2(\alpha^2 + \beta^2)$$

$$- \frac{1}{2}(\mu_A^2 + \mu_B^2 - \Pi_\alpha)\alpha^2 - \frac{1}{2}(\mu_A^2 - \mu_B^2 - \Pi_\beta)\beta^2$$

$$+ \frac{1}{4}(\lambda_1 + \lambda_3)(\alpha^4 + \beta^4) + \frac{1}{2}(\lambda_1 - 3\lambda_3)\alpha^2\beta^2 \quad (8)$$

where $\mu^2$, $\mu_A^2$, $\mu_B^2$ and $\lambda$ can be replaced with physical parameters.

For the parameter settings that satisfy eq. (4), the scalar singlet gets no VEV at the zero temperature, but it may get a VEV at the finite temperature and the CP phase vanishes once upon a time at

$$D_h \sqrt{\lambda_0} > D_s \sqrt{\lambda} \quad (9)$$

where $\lambda_0 = \lambda_1 + \lambda_3 \cos(4\varphi)$.

The critical temperature can be calculated using the degenerate condition $\bar{V}(0, v_s c_\alpha, v_s s_\alpha, T_C) = V(v_T, 0, 0, T_C)$, and it results in

$$8(\lambda_1 \lambda_3 - \lambda_3^2)(\lambda_0^2 - \Pi_h) = \lambda(\lambda_1 - \lambda_3)(m_h^2 - m_{S'}^2)^2$$

$$+ 2\lambda_3(\lambda_1 v_s^2 - m_h^2 - m_{S'}^2 - 2\Pi_\alpha) v^2 \quad (10)$$

where $v_0$ is the VEV of the SM Higgs at the zero temperature. The gauge invariant and temperature dependent VEV of the SM Higgs is $\bar{v}(T) = \sqrt{v_0^2 - \Pi_h/\lambda}$, with which one can estimate the strength of the EWPT. The condition of the strongly first order EWPT is $\bar{v}(T_C)/T_C \geq 1$ [19].

The bubble wall width can be determined by solving the $O(3)$-Euclidean equation of motion for $\phi_i(r)$:

$$\frac{d^2\phi_i}{dr^2} + \frac{2}{r} \frac{d\phi_i}{dr} = V'(\phi) \quad (10)$$
Boundary conditions for the $O(3)$ solution are: $\phi_1 = v_c$, $v_2 = v_3 = 0$, $\phi'_1 = 0$ at $r = 0$ and $\phi_1 = 0$, $\phi_2 = v_s c_\alpha$, $v_3 = v_s s_\alpha$ at $r = \infty$. Following the technique developed in Ref. [16, 17], one can analytically determine the bubble wall width in the thin-wall approximation,

$$L_w^2 \approx 1.35 \frac{\lambda + \sqrt{\lambda \lambda_\phi}}{(\lambda_2 - 2\sqrt{\lambda \lambda_\phi})[\lambda \lambda_3 - \Pi_6(T_c^2)]} \times \left(1 + \sqrt{\frac{\lambda_3^2}{4\lambda_\phi}}\right).$$

(11)

It can be used to estimate the free energy arisen from the bubble wall, which will be done in the next section. It should be mentioned that eq. (11) is invalid for some extreme scenarios, for example when $\lambda_2 - 2\sqrt{\lambda \lambda_\phi} \rightarrow 0$, where the bubble wall width can only be calculated numerically with the shooting method.

We plot in the left-panel of the Fig. [11] the spontaneous CP phase as the function of $M_{\alpha}$, which is the mass of the CP-even scalar singlet, by setting $\lambda_{1,2,3}$ as random values varying in $(0, 2)$, which satisfy eqs. (11) and (9) as well as $v_c / T C \geq 1$. One can see that the CP phase approaches to $\pi / 2$ with the increase of the $M_{\alpha}$. We show in the right panel of the Fig. [11] the bubble wall width as the function of $M_{\alpha}$, using the same parameter settings, which shows that $L_w \sim O(1)/T C$. For the gravitational waves generated from the EWPT and their signals in the space based interferometer, i.e., LISA, BBO and TianQin, we refer the reader to Ref. [20] for detail.

**EWSB** To generate nonzero baryon asymmetry during the electroweak phase transition one needs a CP-violating source that leads to the production of non-zero number densities of fermions near the expanding bubble wall. Due to the existence of the Yukawa interaction in eq. (2), the scattering of the right-handed top quark off the bubble wall produce a non-zero number density, which is diffused into the plasma and is translated into the non-zero number density of $n_L$ via the inelastic scattering. The weak sphaleron process biases the baryon density against the anti-baryon density, resulting in a non-zero baryon asymmetry which is eaten by the expanding bubble, inside which sphalerons are inactive, and is then restored.

The CP-violating source term can be calculated using the “VEV insertion” method [3, 21, 22].

$$S_{\text{top}}^{\text{CPV}} = -2\xi^2 v_s^2 \dot{\varphi} \int \frac{k^2 dk}{\pi^2 \omega_L \omega_R} \text{Im} \left\{ (\varepsilon_L \varepsilon_R^* - k^2) \frac{n(\varepsilon_L) - n(\varepsilon_R^*)}{(\varepsilon_L - \varepsilon_R^*)^2} + (\varepsilon_L \varepsilon_R + k^2) \frac{n(\varepsilon_L) + n(\varepsilon_R)}{(\varepsilon_L + \varepsilon_R)^2} \right\}$$

(12)

where the dot represents derivative with respect to $\bar{\varepsilon}$ with $\bar{\varepsilon} = z + v_w t$; $n(x)$ is the Fermi distribution; $\varepsilon_L, \varepsilon_R = \omega_L, \omega_R - i \Gamma_L, \Gamma_R$ are complex poles of the spectral function. The Transport equations can be written as

$$\partial^\mu Q_\mu = +\Gamma_{m_1} R_{\tau}^\tau + \Gamma_{y_1} \delta_t + \Gamma_{y_2} \delta_v + 2\Gamma_{\delta s} \delta_s$$

$$\partial^\mu T_\mu = -\Gamma_{m_1} R_T^\tau - \Gamma_{y_1} \delta_t - \Gamma_{y_2} \delta_v - \Gamma_{\delta s} \delta_s$$

$$+ \Gamma_{\delta s} R_T^\tau + \Gamma_{\delta s} R_{\tau}^\tau + S^{\text{CPV}}$$

$$\partial^\mu t_\mu = +\Gamma_{m_1} R_{\lambda}^\lambda - \Gamma_{\lambda} t_\tau + \Gamma_{\lambda} t_\tau + \Gamma_{\lambda} \delta_t - S^{\text{CPV}}$$

$$\partial^\mu t'_{\mu} = -\Gamma_{m_1} R_{\lambda}^\lambda - \Gamma_{\lambda} t'_\tau - \Gamma_{\lambda} t'_\tau$$

$$\partial^\mu H_\mu = -\Gamma_{y_1} \delta_t - \Gamma_{y_2} \delta_v$$

(13)

where $Q$, $T$, $t$ and $t'$ are number densities of $Q_{3L}$, $T_R$, $t_L$ and $t_R$ respectively; $\partial^\mu = v_w d/dz - \partial_0 d^2/d\bar{\varepsilon}^2$ with $\partial_0$ the diffusion constant and $v_w$ the bubble wall velocity; $R_T^\tau \equiv (T / k_T - Q / k_Q)$, $R_{\tau}^\tau \equiv T / k_T \pm t / k_t$, $\delta_s \equiv (T / k_T - 2Q / k_Q + 9B / k_B)$, $\delta_t \equiv (T / k_T - Q / k_Q + H / k_H)$, $R_{\lambda}^\lambda \equiv (t' / k_t - Q / k_Q + H / k_H)$, $\Gamma_{\lambda} = (t' / k_t - t / k_t)$; $n_i$ and $k_i$ are the number density and the statistical factor for the particle "i", respectively. Coefficients $\Gamma_{y_1}$, $\Gamma_{y_2}$ and $\Gamma_{\lambda}$ denotes the interaction rates arising from the SM top quark Yukawa interaction and the Yukawa interaction in Eq. (2), respectively; $\Gamma_{m_1}$, $\Gamma_{m_2}$ and $\Gamma_{\delta s}$ are the CP-conserving scattering rates of particles with the background Higgs field on the bubble wall; $\Gamma_{\lambda} = 16\kappa^2 \alpha_s^2 T$ is the strong sphaleron rate with $\alpha_s$ the strong coupling and $\kappa \sim O(1)$.

Transport equations can be solved numerically using the relaxation method. The final BAU can be written in the term of integral of the left-handed fermion charge density, which is $n_L(z) = 5Q + 4T$,

$$\dot{n}_B = -\frac{3\Gamma_{ws}}{2D_Q \lambda_*} \int_{-L_w/2}^{L_w/2} dz n_L(z) e^{-\lambda_* z}$$

where $\lambda_* = -\frac{1}{D_Q} (v_w \pm \sqrt{v_w^2 + 4D_Q R})$, $R \sim 2 \times 10^{-3}$ GeV [23] being the inverse washout factor for the electroweak sphaleron transitions. The weak sphaleron rate is $\Gamma_{ws} = 6\kappa^2 \alpha_s^2 T$, where $\kappa \approx 20$ [24] and $\alpha_w = \alpha_s^2 / 4\pi \approx 1 / 30$.

Notice that the solution for the spontaneous CP-violating phase given in eq. (14) have a reflect symmetry $\varphi \rightarrow -\varphi$, under which the free energy of bubble is invariant. As a result, there are two different kinds of bubbles relating to two possible signs of $\varphi$, which create
baryons of opposite signs. The net baryon asymmetry averaged over the entire universe will be zero resulting in a null BAU, since there is no preferred bubble against the other one. There are two alternative ways to avoid this problem:

- Adding soft $Z_2$-symmetry broken terms, i.e. $\kappa S + \text{h.c.}$ and/or $\eta S^3 + \text{h.c.}$, to the potential;
- Introducing a small explicit CP violating phase in the Higgs potential: $\mu_B^2 \rightarrow \mu_B^2 e^{i\beta}$.

As a result, the degeneracy between two types of vacuums, $+\varphi$ and $-\varphi$, will be broken during the phase transition. And the false vacuum with higher free energy will decay into the true vacuum with lower free-energy via the bubble nucleation at a temperature $T_G$. If $T_G > T_n$, where $T_n$ is the electroweak bubble nucleation temperature, there will be only one kind of phase left when the second step phase transition takes place, and one has net BAU produced via the conventional EWBG. One the other hand, if $T_G < T_n$, vacuums with $\pm\varphi$ are still there equally at the time of the second step phase transition, but volumes occupied by electroweak bubbles raised on the $\pm\varphi$ background can be significantly different. The ratio between two kinds of bubbles takes the form

$$N_+ = \exp\left(\frac{\Delta F}{T}\right)$$

where $N_\pm$ are the number densities of bubble with $\pm\varphi$, $\Delta F$ is the difference of the free energy between two types of bubbles. The free energy of a vacuum have two terms: the surface term $F_S$ and the volume term $F_V$. For our case $\Delta F$ mainly come from the difference of surface terms, which can be evaluated analytically. Finally, the global baryon density is written in term of asymmetry of two kinds of bubbles,

$$n_B = \tilde{n}_B^{(+)} - \frac{n_B^{(+)} N_+ - n_B^{(-)} N_-}{N_+ + N_-},$$

where $\tilde{n}_B^{(+)}$ is the BAU generated from the $+\varphi$ bubble. In the limit $\Delta F \rightarrow \pm \infty$, it has $n_B \rightarrow \tilde{n}_B^{(+)}$. For simplicity, we add $\Delta S + \text{h.c.}$ term to the effective potential, where $\Delta$ is a small real coupling, and the Higgs potential contains no explicit CP violation.

As an illustration, we show in the left-panel of the Fig. 2 contours of $\hat{Y}^{(+)}$, which is the baryon number density generated by the bubble with $+\varphi$, divided by the observed value of the $\zeta - \varphi$ plane, by setting $T_G \sim 100$ GeV, $M_t = 500$ GeV, $y' = 0$, $\Lambda = 1$ TeV and $\Gamma_B = 5\zeta^2$. The Higgs VEV profiles are taken from Refs. [17, 27, 28], using the bubble wall width given in eq. (11). Since the bubble wall velocity is relevant to the friction in the wall, which is still unclear, we set $v_\varphi = 0.2$ for simplicity. Transport equations are solved numerically with the “relaxation” method. Compared with the EWBG in the MSSM, the CP source term in the MSSM is proportional to a small value $\Delta\beta$, which is usually taken as

0.01 [22], while the CP source in our case is proportional to the spontaneous CP phase $\varphi$, which is taken as 0.8. It explains why the observed BAU can be generated with a tiny $\zeta$ in our case. We show in the right-panel of the Fig. 2 contours of the BAU in units of $Y_{\text{obs}}$ in the $\Delta - \varphi$ plane by setting $\zeta = 0.2$. Other inputs are the same as above. Apparently the BAU can be explained by a small $|\Delta|$ in our scenario. It should be mentioned that further calculations are needed to determine the temperature of domain wall collapsing as well as the friction parameter relating to the bubble expansion. We defer them to a another work.

**Summary and discussion**

Extending the SM with a complex scalar singlet and a vector-like top quark, we showed that our universe may undergo a two-step phase transition, and the spontaneous CP phase can emerge between the first step and the second-step phase transitions. The CP violation can be responsible for the origin of the BAU if a small $Z_2$ breaking term is added to the Higgs potential, which causes the collapse of the domain wall, while no extra CP violation is needed. Since the spontaneous CP phase disappears after the electroweak phase transition, there is no EDM constraint on the model, and the tension between the non-observation of EDMs and the requirement of a large CP violation by the EWBG is released. It opens a new window for studies of CP violation as well as EWBG.

The BAU is generated from interactions of vector-like top quark in our model. Actually it may also arise from a dimension-5 effective operator [17], or a dimension-6 effective operator [27]. Integrating out the vector-like quark in eq. (2), one gets the dimension-5 effective operator given in Ref. [17]. For our case, $S$ can be two-components top-flavored as well as Higgs portal dark matter candidates in the limit $y' \rightarrow 0$. Collider signatures of $S$ will be Di-Higgs in various channels or di-jet plus missing energy. We refer the reader to Ref. [30, 31] for collider searches of the first order EWPT, which is in common with our case. To distinguish our model, one needs to determine at least two types of Higgs interactions at colliders, i.e. $hZZ$ and $h\beta\beta$, whose signatures at the LHC and CEPC will be studied in a longer paper.
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