Impact of a complex singlet: From dark matter to baryogenesis

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With the assistance of a complex singlet, and an effective operator involving CP violations, the dark matter relic abundance and baryon asymmetry of the universe (BAU) are accommodated simultaneously. The mechanism Electroweak baryogenesis (EWBG) is studied systematically: from the necessary condition strong first order electroweak phase transition (SFOEWPT) to BAU generation. The SFOEWPT takes one step or two steps due to the dynamics of the energy gap of the Electroweak vacuum and the vacuum of the complex singlet with the temperature cooling down. Two steps case always give rise to higher magnitude of BAU.

I. INTRODUCTION

The Standard model (SM) has passed all experimental tests during the last 40 years, leaving us without any direct evidence for new physics beyond the SM. And the discovery of a 125 GeV Higgs-like particle by the ATLAS [1] and CMS [2] collaborations at the LHC seems to provide the last missing piece of the SM. However, it has long been known that the SM has two obviously shortcomings, i.e., the observed dark matter abundance and matter-anti-matter asymmetry of the universe couldn’t be accommodated.

Firstly, the observed dark matter abundance is another issue that couldn’t be addressed in the SM. The existence of dark matter (DM) has already been established by the observations of galaxy rotation curves and analysis of cosmic microwave background (CMB) etc. And the PLANCK [4] and WMAP [3] predict that about 26.5% of our Universe is constituted by DM. Secondly, the matter-anti-matter asymmetry of the universe, i.e., baryon asymmetry in the Universe (BAU) as a baryon to entropy ratio

\[ \frac{n_b}{s} \approx (0.7 - 0.9) \times 10^{-10} \]  

(1)
couldn’t be addressed and predicted in the framework of the SM. The dynamical generation of BAU requires three necessary ingredients [6]: (1) violation of baryon number; (2) violation of both C- and CP-symmetry; and (3) departure from equilibrium dynamics or CPT violation. Though the SM contains all these requirements, and the electroweak phase transition (EWPT) provides a natural mechanism for baryogenesis [6], the SM is unable to solve the problem for the reason listed below: Although the baryon number violation is provided in the SM by weak sphalerons [7,9], the departure from thermal equilibrium, provided by a strong first-order phase transition, proceeding by bubble nucleation which makes electroweak symmetry breaking (EWSB), does not occur in the SM [10]. In the SM, no first-order phase transition occurs for Higgs mass larger than about 80 GeV [11-13], which is far below the experimental bound of \( m_h > 114 \) GeV from LEP [13] and \( m_h \approx 126 \) GeV from [1-2]. And the CP violation in the CKM matrix is too small to produce a sufficiently large baryon number, new CP violations beyond the SM are required [14].

This work is aimed at accommodating the observed relic density and successful EWBG simultaneously. The observed DM relic density reported by CMB anisotropy probes suggests weakly interacting massive particle (WIMP) [17,18] and a feasible candidate for DM requires the extension of the SM. Based on C x S M [19], we consider one simple extension of the SM with one complex singlet (S) being supplemented, the singlet transforms trivially under the SM gauge groups and the imaginary part takes the responsibility of being DM. One very attractive mechanism, i.e., EWBG, wherein baryon number generation is driven by the generation of CP asymmetry at the time of the EWPT [20] is adopt. We take advantage of the S to get the CP-violation required for EWBG by introducing a dimension-6 operator. After which, the top quark mass at nonzero \( S \) is modified. The Lagrangian takes the form of

\[ y_t \bar{Q}_L H \left( 1 + \frac{a + ib}{\Lambda^2 S^2} \right) t_R + \text{h.c.} \]  

(2)

where \( a, b \) is real parameters and \( \Lambda \) is a new physics scale. During the EWPT, the top quark mass gets a spatially-varying complex phase along the bubble wall profile, which provides the source of CP violation needed to generate the baryon asymmetry [59]. Precision test, electric dipole moment (EDM) search, can probe directly CP violation relevant to EWBG. Using the polar molecule thorium monoxide (ThO), the ACME collaboration reported an upper limit on the electron EDM (eEDM) recently [16], at 90% confidence level, an order of magnitude stronger than the previous best limit,

\[ |d_e| < 8.7 \times 10^{-29} \text{e cm} \]  

(3)

This limit severely constrains the allowed magnitude of CP-phases in the Higgs couplings [20,23] via Barr-Zee
diagrams. We would like to mention that, one must take into account the tension between the CP-phase required for successfully implementing EWBG and constraints from the electron EDM. The preliminary results of the work are listed as follows:

- The imaginary part of the complex singlet serve as the DM candidate. Relic abundance in different parameter spaces are studied, and the direct detection of DM gives rise to very strong constraints on parameter spaces.
- The EWPT are explored in two parameter spaces: triple couplings ($c_2$, $\delta_1$) and quartic couplings ($d_2$, $\delta_2$). The behavior of $v_c/T_c$ with respect to triple (quartic) couplings is inverse in compare with that of the energy gap $\Delta V$ (the energy barrier of the Electroweak vacuum and the vacuum of the complex singlet), a smaller $\Delta V$ corresponds to a bigger $v_c/T_c$. Two types of phase transition, i.e., one- and two-step are studied, and the two-step phase transition always give rise to bigger $v_c$.
- The BAU during the EWPT in the model is explored, the behaviors of BAU as functions of triple couplings and quartic couplings match well with that of EWPT, and the CP violation relevant to EWBG is below the limits of ACME.
- One benchmark scenario which accommodates DM and EWBG is presented.

II. THE MODEL

The tree-level potential of the model is given by,

$$V (H, S) = \frac{1}{2} m^2 H^\dagger H + \frac{\lambda}{4} (H^\dagger H)^2 + \frac{\delta_1}{2} H^\dagger H |S|^2 + (\frac{\delta_1 e^{i\phi_1}}{4} H^\dagger H S \text{ c.c.)} +  \frac{b_2}{2} |S|^2 + \frac{d_2}{4} |S|^4 + (\frac{1}{4} b_1 e^{i\phi_1} S^2 + \frac{c_2 e^{i\phi_2}}{6} S |S|^2 \text{ c.c.)},$$

where $H$ and $S$ are the $SU(2)$ doublet and complex singlet fields. For simplicity, phases are chosen as: $\phi_{h_1} = \pi$, $\phi_{h_2} = 0$ (\pi\), and $\phi_{c_2} = 0$ (\pi\). To get the minimization conditions of the potential, it is convenient to represent the $SU(2)$ doublet and complex singlet as $H = (0, h/\sqrt{2})$ and $S = (S + iA)$. Thus Eq. (4) recasts the form of

$$V_0 (h, S, A) = \frac{m^2}{4} h^2 + \frac{\lambda}{16} h^4 + \frac{\sqrt{2}}{8} \delta_1 h^2 S + \frac{\delta_2}{8} h^2 (S^2 + A^2) + \frac{1}{4} (b_2 + b_1) A^2 + \frac{1}{2} (b_2 - b_1) S^2 + \frac{\sqrt{2}}{12} c_2 S (S^2 + A^2) + \frac{d_2}{8} S^2 A^2 + \frac{d_2}{16} (S^4 + A^4),$$

in which, $\delta_1$ and $c_2$ can be both positive and negative. As could be seen from Eq. (5), the breaking of the global $U(1)$ indicates one $Z_2$ symmetry for the imaginary part of $S$, i.e. $A$, thus makes a feasible DM candidate.

The three minimization conditions of the potential,

$$(\delta V_0/\partial h)|_{h=v_s=x, A=0} = 0, \quad (\delta V_0/\partial S)|_{h=v_s=x, A=0} = 0, \quad (\delta V_0/\partial A)|_{h=v_s=x, A=0} = 0,$$

with $v = 246.2$ GeV and $x$ being the VEVs of the SM and $S$, implies that,

$$m^2 = -\frac{\sqrt{2} \delta_1}{2} x - \frac{\delta_2}{2} x^2 - \frac{\lambda}{4} v^2,$$

$$b_2 = b_1 - \frac{\sqrt{2} \delta_1}{4} v^2 + \frac{\sqrt{2} \delta_1}{2} x - \frac{b_2}{2} x^2 - \frac{\delta_2}{2} v^2.$$

At the minima, the mass matrix is,

$$\begin{bmatrix}
    m^2_{h} & m^2_{hS} & m^2_{hA} \\
    m^2_{hS} & m^2_S & m^2_{SA} \\
    m^2_{hA} & m^2_{SA} & m^2_A
\end{bmatrix} = \begin{bmatrix}
    M & 0 \\
    0 & m^2_A
\end{bmatrix},$$

in which, the DM candidate $A$ with mass given by $m^2_A = b_1 - \frac{\sqrt{2}}{12} c_2 x - \frac{\sqrt{2} \delta_1}{4} v^2/x$ does not mix with $h$ or $S$. And the mass matrix of $h$ and $S$ being,

$$M = \begin{bmatrix}
    \frac{1}{2} \lambda v^2 & \frac{1}{2} \delta_1 v^2 + \frac{\sqrt{2}}{4} v \delta_1 \\
    \frac{1}{2} \delta_2 v \delta_1 & \frac{1}{2} d_2 v^2 + \frac{2}{4} c_2 x - \frac{\sqrt{2}}{4} \delta_1 v^2/x
\end{bmatrix}.$$

The non-zero entry for $m^2_{hS}$ induces mixing between the SM Higgs and the real component of the singlet(S). The masses of the resulting mass eigenstates, denoted by $h_1$ and $h_2$, are given by the eigenvalues of $M$,

$$m^2_{\pm} = \frac{1}{2} \left[ \text{Tr} (M) \pm \sqrt{\text{Tr} (M)^2 - 4 \text{Det} (M)} \right].$$

with $m_+ > m_-$. Here, $m_{\pm}$ could be $m_{h_1}$ or $m_{h_2}$. In order for these masses to be positive real numbers, the condition $\text{Det} (M) > 0$ needs to hold. The mass square of the “Higgs-like” particle $h_1$, i.e., $m^2_{h_1}$ is given by:
The mass eigenstates $h_1, h_2$ couple to the fermions and gauge bosons via SM Higgs couplings reduced by a factor of $\cos \phi, \sin \phi$, respectively. We take the mixing angle to be $-\pi/4 < \phi < \pi/4$ so that $h_1$ is always the “Higgs-like” eigenstate and $h_2$ is always “singlet-like”. Using this convention, the mass matrix entries of Eq. (8) could be expressed as,

$$m_h^2 = \cos^2 \phi m_{h_1}^2 + \sin^2 \phi m_{h_2}^2,$$

$$m_{h_s}^2 = \sin^2 \phi m_{h_1}^2 + \cos^2 \phi m_{h_2}^2,$$

$$m_{h_s}^2 = \cos \phi \sin \phi (m_{h_1}^2 - m_{h_2}^2),$$

which allows us to replace $\lambda, d_2$ and $\delta_1$ with $m_{h_1}, m_{h_2}$ and $\phi$, as what we have taken advantage in the next section. In fact, the global fit on the current Higgs measurements at the LHC requires $|\cos \phi| \geq 0.84$ at 95% C.L. limit [24], which we use to constrain parameter spaces in EWPT and BAU analysis.

### III. Dark Matter

In the model, the thermal relic density $\Omega_A h^2$ is mainly controlled by the annihilation cross section of pairs of $A$ ($\langle \sigma v \rangle$, i.e., $\Omega_A h^2 \sim 1/\langle \sigma v \rangle$, in which $\langle \sigma v \rangle$ is the thermal average of the product of annihilation cross section and relative velocity, with relevant Feynman diagrams being shown in Fig. 3.

![FIG. 3: Annihilation channels of dark matter particle pairs.](image)

Taking $m_A = 40$ GeV, the dark matter $A$ pairs annihilates only to $bb$, and the annihilation cross section cast the form of $\langle \sigma v \rangle \sim (c_2 + k\delta_2)^2$ (with $k$ being a constant), which makes the contours of $\Omega_A h^2$ with respect to $c_2$ and $\delta_2$ straight lines, and parameters region that satisfy the WMAP 1$\sigma$ measurement $\Omega_{DM} h^2 = 0.092 - 0.118$ falls to two separated bands, as depicted in Fig. 4. In Fig. 5 the two $s$-channel resonances of $\langle \sigma v \rangle$ mediated by $m_{h_1,2}$ display themselves at $m_A = 62.5$ GeV(100 GeV). The region that satisfies the WMAP 1$\sigma$ measurement [25], i.e., $\Omega_{DM} h^2 = 0.092 - 0.118$, is given by $m_A < 50$ GeV or $m_A > 150$ GeV. For $m_A = 300$ GeV, the contours in Fig. 6 are mostly circles, because of $\langle \sigma v \rangle$ depends quadratically on $c_2$ and $\delta_2$.

Direct detection experiments are searching for dark
FIG. 4: The contour of $\Omega_\chi h^2$ with respect to $c_2$ and $\delta_2$ (purple contours), with $x = 200$ GeV, $m_{h_1} = 125$ GeV, $m_A = 30$ GeV, $\phi = \pi/8$, and $m_{h_2} = 200 \pm (70)$ GeV for the top(bottom) panel. The green shade represents the region of $d_2 < 0$ or $\delta_2 < -\sqrt{\lambda d_2}$ required by the tree level vacuum stability \[19, 27\]. Regions excluded by the XENON100 are shown by the orange shade. The blue lines in the bottom panel is the contours of $\langle |\sigma v| \rangle_d^8$ in units of $10^{-26}$ cm$^2$. Branch ratio of invisible decay are shown by dark contours.

FIG. 5: The contour of $\Omega_\chi h^2$ with $x = 200$ GeV, $\phi = \pi/8$, $m_{h_2} = 200$ GeV, and $c_2 = 400$ GeV ($\delta_2 = 0$) for top(bottom) panel. The green shade represents the region of $d_2 < 0$ or $\delta_2 < -\sqrt{\lambda d_2}$. Regions excluded by the XENON100 are shown by the orange shade. Top: $\Omega_\chi h^2$ with respect to $m_A$ and $\delta_2$; Bottom: $\Omega_\chi h^2$ with respect to $m_A$ and $c_2$.

which is the same with Eq. (25) in \[24\] except for the couplings $g_{A Ah_1}$ and $g_{A Ah_2}$ are different as shown in the Appendix. B.

Constraints from XENON100 experiment \[26\], as shown by the orange shading in Fig. 4, Fig. 5, and Fig. 6, give raise to severely bounds on $m_A$. This mainly because that, when the dark matter mass is small, $\sigma_{dd}$ depends on the couplings $g_{A Ah_1}$ and $g_{A Ah_2}$ in a similar way with $\langle |\sigma v| \rangle$. The small $\sigma_{dd}$ corresponds to a small annihilation cross section in general, thus an over saturation of the relic abundance appears. When the dark matter mass is larger, the constraint tends to be much weaker for the highly suppressed effects of $m_A$ in $\sigma_{dd}$, as shown in

matter scattering off atomic nuclei, and the spin-independent scattering cross section as a function of the dark matter mass constrains on our parameter choices. The scattering cross section of $A$ with a proton for our model casts the form of,

$$
\sigma_{dd} = \frac{m_p^4}{2\pi v^2 (m_p + m_A)^2} \times \left( \frac{g_{AAh} \cos \phi + g_{AAh} \sin \phi}{m_{h_1}^2} \right)^2 \times \left( f_{pu} + f_{pd} + f_{ps} + \frac{2}{27} (3f_G) \right)^2 ,
$$

(15)
IV. EWBG

Before the EWBG is triggered, the early Universe is assumed to be hot and radiation-dominated, containing zero net baryon charge, and the $SU(2)\times U(1)_Y$ electroweak symmetry is manifest\,[29,32]. With the universe cooling to temperatures below the electroweak scale, the Higgs field acquires a non-zero expectation value and thus spontaneously breaks the $SU(2)_L \times U(1)_Y$ symmetry down to $U(1)_{EM}$. During this phase transition process, the EWBG takes place.

Bubble (of the broken phase) formation and growth begin at nucleation temperature $T_N (< T_C$, the critical temperature of the strong first-order EWPT (SFOPT)). Baryon creation in EWBG takes place in the front (and vicinity) of the expanding bubble walls\,[33]. With CP violation implemented, particles in the plasma (symmetry phase) scatter with the bubble walls and generate CP (and C) asymmetries in particle number densities; and these asymmetries diffuse into the symmetric phase ahead of the bubble wall and they bias electroweak sphaleron transitions\,[15,16] to produce more baryons than antibaryons; and some of the net baryon charge being created is then captured by the expanding wall into the broken phase; at last, inside the bubbles (broken phase), the rate of sphaleron transitions, that provides $(B + L)$-violating processes will wash out the baryons being created, should be strongly suppressed, i.e., SFOEWPT.

A. SFOEWPT

The dynamic of the EWPT is governed by the effective potential at finite temperature, i.e., $V_{eff}(h,S,A,T)$ in our model. After minimizing $V_{eff}(h,S,A,T)$, the VEVs of three scalar fields $h,$ $S,$ and $A$ at each temperature could be obtained. For a first order phase transition there develops a local minimum with $\langle h \rangle \neq 0$, which become degenerate with the electroweak symmetric minimum when the temperature decreased to the critical temperature $T_C$ as the temperature decreases, and the two minima are separated by an energy barrier. To protect the BAU generated by EWBG, the strong first order condition,

$$\frac{v_c}{T_c} > 1,$$  \hspace{1cm} (16)

with $v_c$ being the higgs VEV of the symmetry broken minimum, is necessary.

The standard analysis of $V_{eff}(h,S,A,T)$ involves tree level scalar potential ($V_0(h,S,A)$) and Coleman-Weinberg one-loop effective potential ($V_1(h,S,A)$) at $T = 0$, the leading thermal corrections $\Delta V$, and the $V_{ct}$ being the counter terms choosing to maintain the tree

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FIG. 6: The contour of $\Omega_A h^2$ with respect to $c_2$ and $\delta_2$, other parameters are fixed as $x = 200\text{GeV}$, $m_A = 300 \text{GeV}$, $m_{h_1} = 125 \text{GeV}$, $\theta = \pi/8$; and $m_{h_2} = 200(70) \text{GeV}$ for top(bottom) panel. The green shade represents the region of $d_2 < 0$ or $\delta_2 < -\sqrt{\lambda d_2}$. Regions excluded by the XENON100 are shown by the orange shade.

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the two plots of Fig.\,[4] And for the $m_A$ suppress effects in $\sigma_{dd}$ is not very strong at smaller $m_A$, the magnitude of $\sigma_{dd}$ is always bigger than the experiment constraints. This can be partially verified by the two plots of Fig.\,[4]

As shown in Fig.\,[4] $\langle \sigma v \rangle_{c\rightarrow 0} \sim 10^{-26} \text{cm}^3/s$ is founded live in the ballpark of right relic abundance, which might be used to explain the galactic center excess (GCE), while this door is closed because of the big invisible decay branch ration being excluded by LHC\,[28].
level relations of the parameters in the $V_0 (h, S, A)$,

$$V_{\text{eff}} (h, S, A, T) = V_0 (h, S, A) + V_1 (h, S, A) + \Delta V (h, S, A, T) + V_{ct} (h, S, A) . \quad (17)$$

Here, $V_0$ is the same as the tree level potential Eq. [3], $V_1$ is the Coleman-Weinberg one-loop effective potential at $T = 0$ and could be expressed in terms of the field-dependent masses $m_i (h, s, A)$:

$$V_1 (h, S, A) = \sum_i n_i \frac{m_i^4 (h, S, A)}{64 \pi^2} \left[ \ln \left( \frac{m_i^2 (h, S, A)}{Q^2} \right) - C_i \right] \quad (18)$$

in $\overline{MS}$ scheme and Landau gauge. Here, the sum $i$ runs over the scalar, fermion, and vector boson contributions. $n_i$ is the number of degrees of freedom for the $i$-th particle, with a minus sign for fermionic particles. $Q$ is a renormalization scale which we fix to $Q = v$. $C_i = \frac{1}{2}$ for the transverse polarizations of gauge bosons, and $C_i = \frac{3}{2}$ for their longitudinal polarizations and for all other particles. The field-dependent masses are given in the Appendix. B. With $V_1$ being entailed in the potential, the minimization conditions Eq. [6] will be shifted slightly, and the relations Eq. [7] as well as the mass matrix Eq. [8] will not hold as well. To maintain these relations, the counter terms $V_{ct}$ should be added [34, 35], and cast the form of,

$$V_{ct} = \delta m_1^2 h^2 + \delta m_2^2 S^2 + \delta m_3^2 A^2 , \quad (19)$$

in which, the relevant coefficients are determined by:

$$\delta m_1^2 = - \frac{1}{2v} \frac{\partial V_1}{\partial h} \big|_{h=v, s=x, A=0} , \quad (20)$$

$$\delta m_2^2 = - \frac{1}{2x} \frac{\partial V_1}{\partial S} \big|_{h=v, s=x, A=0} , \quad (21)$$

$$\delta m_3^2 = - \frac{1}{2} \frac{\partial^2 V_1}{\partial A^2} \big|_{h=v, s=x, A=0} . \quad (22)$$

Thus, the VEVs of $h$ and $S$ as well as the dark matter mass will not be shifted. We have not include more complicate terms to compensate the shift of mass matrix of $S$ and $h$, because these shift effects are basically small.

The finite temperature component $\Delta V (h, S, A, T)$ is obtained as

$$\Delta V (h, S, A, T) = \frac{T^4}{2 \pi^2} \sum_i n_i J_{B,F} (M_i^2 (h, A, S, T) / T^2) , \quad (23)$$

where the functions $J_{B,F} (y^2)$ are given by

$$J_{B,F} (y) = \int_0^\infty dx \, x^2 \ln \left[ 1 + \exp \left( -\sqrt{x^2 + y} \right) \right] \quad (24)$$

with the upper (lower) sign corresponds to bosonic (fermionic) contributions. And $M_i^2 (h, S, A, T)$ is given in terms of the masses at $T = 0$ and the finite temperature mass functions $\Pi_k$:

$$M^2_k (h, S, A, T) = M^2_k (h, S, A) + \Pi_k \quad , \quad (25)$$

with $\Pi_k$ being listed in Appendix. B.

The behaviour of EWPT depends strongly on the shape of the potential at zero temperature. Fig. [7] shows contours of $V_0$ in the $h - S$ plane in two typical situations. Since the $V_0$ does not develop a minimum at $A \neq 0$, especially when the dark matter mass is large which is demanded by the research in Sec. [11], we do the analysis in the $A = 0$ plane. In the top panel, the electroweak vacuum is the only local minimum of the potential $V_0$. For this situation, the universe might translate from the high-$T$ symmetric phase to the electroweak symmetry broken phase directly. In the bottom panel, an additional local
minimum besides the electroweak vacuum shows up in the direction of $S$ at $h = 0$. For this situation, there is a possibility that the universe translate to this phase at the first step and then to the electroweak symmetry broken phase at the second step. Since the potential at this additional minimum (in the direction of $S$) can be very close to that of the electroweak vacuum (in the direction of $h$), the second step can happen at a very low temperature, therefore a strong first order phase transition could be realized easily. Of course, the phase transition could also be the one-step case, since the energy gap between the minima in the direction of $S$ and $h$ is too large to be overcome by the $T$ dependent thermal correction at high temperature, as explored in 37, 38.

We take advantage of the CosmoTransitions package 39 to examine the phase transition numerically. Fig. 8 shows the results in the $c_2 - \delta_1$ plane. The first order and second order phase transition regions are separated by green points where no phase transition happens, up to our highest temperature setting $T_{\text{max}} = 1000$ GeV, means that the electroweak vacuum minimum is always the deepest one for $T < 1000$ GeV. The contour lines of $V_0$ are plotted to help better understanding of this pattern qualitatively: for regions below the green line, the electroweak vacuum is the only minimum of $V_0$, thus only one-step phase transition could happen. The contour $\Delta V = 0.6 \times 10^8$ GeV$^4$ divide the one-step from the two-step phase transition. When the difference between the two minima is bigger than that value, the $T$ dependent thermal corrections could only changes the magnitude of $\Delta V$ a bit thus one could only get the one-step phase transition. With the magnitude of $\Delta V$ gets smaller, the phase transition changes from a one-step to a two-step one. In the bottom plot, we find that, for a one-step phase transition, $v_c/T_c$ gets smaller with increasing of $c_2$ and $\delta_1$, and changes to a second order one at last. For the two-step cases, $v_c/T_c$ gets larger with $c_2$ and $\delta_1$ increasing and the SFOP condition $v_c/T_c > 1$ could always be satisfied. The shape of contours of $v_c/T_c$ is opposite to that of $\Delta V$, i.e., the smaller $\Delta V$ leads to the larger $v_c/T_c$.

Fig. 9 illustrates how does the quartic couplings $\delta_2$ and $d_2$ affect the behavior of phase transition. For the one-step phase transition, the magnitude of $v_c/T_c$ becomes higher and higher with decreasing of $\delta_2$ and increasing of $d_2$. For the two-step phase transition, the value of $v_c/T_c$ increases with the two couplings getting larger. Almost all one-step phase transition are excluded by the global fit constraint on mixing angle $\phi$ 24, i.e., $\cos \phi \geq 0.84$, while most two-step ones survive. The mass of the "Singlet-like" particle is appropriate in the range of about 220GeV-300GeV.

FIG. 8: EWPT with $x = 200$ GeV, $m_A = 300$ GeV, $\delta_2 = 0.2$, $d_2 = 1.4$, and $\lambda$ is solved from $m_{h_2} = 125$ GeV as shown in Fig. 1. The blue shade are regions where there is no solution of $m_{h_2} = 125$ GeV or the mass matrix is not positive definite.

The black points are those where the electroweak vacuum is local minimum but not a global minimum. The orange and red points are those with one-step and two-step first order phase transitions. The blue points are where second order phase transition happen. Top panel: The black contours in region above the green line are the contours of $\Delta V = V_S - V_h$ divided by $10^8$ GeV, the green is to divide the parameter regions into the region where $V_S$ exist (above) and $V_S = 0$ (below); Bottom panel: We show the contours of $v_c/T_c$ of first order phase transitions with dashed lines, the contours of $\cos \phi$ with pink lines and $m_{h_2}$ with brown lines. The grey shade represents the region that $h$ and $S$ are so mixed that should be exclude by a global fit on $\cos \phi$ 24. Green points are to display the situation no phase transition happens.

B. BAU

The SFOEWPT analyzed in the last section is for preventing the BAU being generated from washing out. To get a more comprehensive understanding of EWBG, we solve the transport equations as explored in Ref. 36 directly, in which the speed and profile of the walls are the core ingredients. With the nucleating bubbles reaching a sizable extent and expanding with a constant velocity, we could boost into the rest frame of the bubble wall.
and proceed all calculations with a planar wall. With $z$ being taken to be the coordinate transverse to the wall, $h(z)$, $x(z)$ and $a(z)$ are the expectation value of $h$, $S$ and $A$ inside the bubbles. To determine them precisely, one needs to minimize the Euclidean action $\mathcal{S}$:

$$S = \int_{-\infty}^{\infty} dz \left\{ \frac{1}{2} (\partial_z h)^2 + \frac{1}{2} (\partial_z S)^2 + \frac{1}{2} (\partial_z A)^2 + V_{\text{eff}}(h, S, A, T_c) \right\}. \quad (26)$$

As a good approximation we can estimate the bubble wall profile in the form of,

$$h(z) = \frac{1}{2} v_c (1 - \tanh(z/L_w)), \quad (27)$$

$$S(z) = x_c + \frac{1}{2} \Delta x_c (1 + \tanh(z/L_w)), \quad (28)$$

$$A(z) = a_c + \frac{1}{2} \Delta a_c (1 + \tanh(z/L_w)). \quad (29)$$

Here, $L_w$ is the width of the wall, $v_c$, $x_c$, and $a_c$ are the VEVs of the electroweak symmetry broken phase at $T_c$, and $\Delta x_c$ ($\Delta a_c$) is the total change of $\langle S \rangle$ ($\langle A \rangle$). For the scenario of this work, $A$ hardly gets VEV during the whole phase transition process, therefore, $A(z)$ is almost zero. The wall width is approximated with $L_w \approx \sqrt{\left(\Delta v_c^2 + \Delta o_c^2 + v_c^2\right)/8V_w}$, in which $V_w$ is the height of the value of the potential barrier at $T_c$. And the bubble wall profiles are shown in Fig. 11.

As mentioned in Sec. I, we introduced the CP violating top quark mass term, and for definiteness we fix $a = 0$ to maximize the CP violation. Following Ref. [42, 43], the top quark acquires a spatially varying complex mass inside the bubble walls during the phase transition, obtained as

$$m_t(z) = \frac{\mu_t}{\sqrt{2}} h(z) \left( 1 + i \frac{S^2(z) + A^2(z)}{A^2} \right) \equiv |m_t(z)| e^{i\theta(z)}. \quad (30)$$

If the existence of the nontrivial phase $\theta(z)$ is sufficient to source the baryon asymmetry is to be verified in the following studies.

With the top quark profile for our model being obtained, we solve the transport equations to get the chemical potentials of left-handed SU(2) doublet top quark ($\mu_{t,2}$), left-handed SU(2) doublet bottoms ($\mu_{b,2}$), right-handed SU(2) singlet top quark ($\mu_{t,2}$), and Higgs bosons ($\mu_{h,2}$), and the corresponding plasma velocities. And, the chemical potential of left-handed quarks cast the form of:

$$\mu_{B_L} = \frac{1}{2} (1 + 4K_{1,t}) \mu_{t,2} + \frac{1}{2} (1 + 4K_{1,b}) \mu_{b,2} - 2K_{1,t} \mu_{r,2} . \quad (31)$$

Finally, The baryon asymmetry is obtained using

$$\eta_B = \frac{\eta_B}{s} = \frac{45\Gamma_{ws}}{4\pi^2v_w g_s T \int_0^\infty dz \mu_{B_L}(z)e^{-\nu z}}, \quad (32)$$

where $\Gamma_{ws}$ is the weak sphaleron rate and $\nu = 45\Gamma_{ws}/(4v_w)$. The effective number of degrees of freedom in the plasma is $g^* = 106.75$.

In order to figure out how does the value of baryon asymmetry correlates to the parameters during EWPT (i.e., the critical temperature $T_c$ and the field expectation values ($v_c$)), we input these parameters directly and calculate the magnitude of BAU, instead of using...
FIG. 11: The correlation between baryon asymmetry and the parameters of EWPT. Top: \( v_c = 150 \) GeV, \( a_h = 0 \), and \( T_C = 100 \) GeV; Bottom: \( x_c = 150 \) GeV, \( x_h = 0 \), and \( a_h = 100 \) GeV.

The results obtained from the EWPT as in the last section. The top panel in Fig. 11 illustrates how does the expectation values of \( S \) affect the magnitude of BAU, with \( x_c \) and \( x_h \) denoting the VEV of \( S \) at electroweak symmetry broken phase and symmetric phase. It depicts that \( \eta_B \) gets larger with \( x_h \) getting smaller for \( x_c > 0 \), and the situation changes to be opposite when \( x_c < 0 \). \( \eta_B \) changes its sign near \( x_h = x_c \). And \( \eta_B \) relies on \( x_c \) more than on \( x_h \), especially when \( |x_c| \) is small. The bottom panel indicates how does \( \eta_B \) depend on \( v_c \) and \( T_c \). The dependence of \( \eta_B \) on \( v_c \) is simple and obvious: the larger \( \eta_B \) is correlated with larger \( v_c \), as expected, because the source of CP violation depends partly upon the amount by which \( |m_1| \sim v_c \) changes inside the bubble wall. The dependence of \( \eta_B \) on \( T_c \) is more complicated. When \( T_c > 80 \) GeV, \( \eta_B \) increases almost linearly with \( T_c \) getting smaller. While, for \( T_C < 50 \) GeV, the sign of \( \eta_B \) flips when \( T_C \) gets small enough. The inner mechanism is very interesting and left for further research.

FIG. 12: BAU from strong first order phase transitions with \( x = 200 \) GeV, \( m_A = 300 \) GeV, \( \delta_2 = 0.2 \), and \( d_2 = 1.4 \). Top panel: the contours of \( \eta_B \) corresponding to Fig. 8; the orange and red contours are magnitudes of the BAU for one- and two-step phase transition, and yellow points represent the situation that \( \eta_B \) falls into the range of \( 7 \times 10^{-11} - 9 \times 10^{-11} \), magenta lines are plotted as the contours of eEDM in unit of \( 10^{-29} \) cm; Bottom panel: \( \eta_B \) as function of \( v_c/T_c \), with orange band depicts the one-step case and red point to illustrate the two-step case.

Then, we calculated the BAU generated during SFOPT with input parameter using the results obtained in the previous section. The results are shown in Fig. 12 and Fig. 13. For the one-step phase transitions, the critical temperature is relatively high as being explored by us, the contours of \( \eta_B \) are very regular and indicates one good correspondence with the behavior of \( v_c/T_c \). For two-step phase transitions, the contours becomes tangled because of the lower critical temperature. And, \( 7 \times 10^{-11} < \eta_B < 9 \times 10^{-11} \) turns out to lives in the two-step region in Fig. 13 and one- and two-step regions in Fig. 12. The correlation between \( \eta_B \) and \( v_c/T_c \), as shown in the two bottom panels of Fig. 12 and Fig. 13 indicate a simple linear correlation for the one-step cases and a more complicated correlation for the two-step cases.
where, the two scalar mass eigenstates \( h \) by the Barr-Zee diagram \([44]\), as illustrated in Fig. 14. The eEDM contribution is dominated by \( \frac{16 \alpha}{3} \frac{m_e}{v^2} \left( \frac{B}{2A^2} \right) \), being expressed as:

\[
Z = \cos \phi \sin \phi = \frac{m_{e,h}^2}{\sqrt{(m_h^2 - m_S^2)^2 + 4m_{S,h}^4}},
\]

and the function \( G(z) \),

\[
G(z) \equiv z \int_0^1 dx \frac{1}{x(1-x) - z} \log \left[ \frac{x(1-x)}{z} \right],
\]

here, the angle \( \phi \) measures the mixing between the gauge eigenstates \((h, s)\) and mass eigenstates \((h_1, h_2)\). The exist, the sign of \( \eta_B \) flips and flips again with increasing of \( v_e/T_e \). With the two-step phase transitions a larger baryon asymmetry can be generated. As could be observed in the bottom two panels of Fig. 12 and Fig. 13.

**C. EDM**

In this section, we use the electron EDM (eEDM) search to detect the CP violation, which based the charge transport during the bubble expand and thus the generation of BAU. The eEDM contribution is dominated by the Barr-Zee diagram \([44]\), as illustrated in Fig. 14. Where, the two scalar mass eigenstates \((h_1, h_2)\) give two opposite sign contributions, obtained using

\[
\frac{d_{ee}}{e} = \frac{16 \alpha}{3} \frac{m_e}{v^2} \left( \frac{B}{2A^2} \right) \left[ G \left( \frac{m_e^2}{m_1^2} \right) - G \left( \frac{m_e^2}{m_2^2} \right) \right],
\]

with \( m_{e,1} \) are the electron (top quark) masses, and \( Z \) is the mixing between \( h \) and \( S \), being given by the experimental results of ACME \([16]\).

**V. DM AND EWBG**

With the dark matter mass \( m_A \sim 1000 \text{ GeV} \) and “Singlet-like” particle mass \( m_{h_2} \sim 250 \text{ GeV} \), the consistent result of EWBG and DM relic density could be obtained. We present in Fig. 15 the composite result of EWBG and DM relic density, and the direct detection constraint is satisfied for all regions in this plot. Fig. 15 indicates that the behaviors of one- and two-step phase transitions (and the corresponding BAU) are dominated by \( \delta_2 \) and \( c_2 \) respectively. The magnitude of eEDM is obtained to be \( |d_{ee}| = 4 \times 10^{-29} \text{ ecm} \), below the limit given by ACME.

**VI. DISCUSSIONS AND CONCLUSION**

With supplementing of a complex singlet to the SM, the model in which DM and BAU could be accommo-
d2 simultaneously is studied. The imaginary part of the complex singlet (A) makes the DM candidate for the reduced $Z_2$ symmetry from a global $U(1)$ symmetry. We analyze DM relic density and the direct detection numerically in parameters space of ($\delta_2$, $c_2$, $m_A$) and ($c_2$, $\delta_2$). Small DM mass regions are severely constrained by direct detection experimental results. The phase transition could be one- and two-step as found by the study of energy gap $\Delta V$. The dynamic of EWPT is studied numerically using CosmoTransitions package in the parameter spaces of ($c_2$, $\delta_1$) and ($\delta_2$, $\delta_2$), both one- and two-steps first order phase transition are obtained, and the two-step case favors SFOEWPT more than that of one-step case. And this study is consistent with the analysis of $\Delta V$, i.e., a lower magnitude of $\Delta V$ favors a larger value of $v_\nu/T$. The newly introduced CP violation makes the EWBG mechanism viable. The BAU is explored numerically as a function of $v_\nu$ and $\Delta v_{\nu}$, i.e., a lower magnitude of $\Delta V$ is found to be allowed by the ACME limit. At last, we present a scenario in which both right DM relic density and successful EWBG could by achieved in the parameter spaces of $\delta_2$ and $d_2$.

There is a possibility that baryogenesis and dark matter generated at EWPT simultaneously with the dark matter sector being asymmetric dark matter [46, 48], thus shed light on the path to explain the ratio between the observed abundance of DM and baryons in the present day: $\Omega_{DM}/\Omega_{B} = 5.4 \pm 2$. The key ingredient for the test of this kind of model is the colliders search of the Higgs triple coupling [24, 49–52] and the introduced CP violation $\delta_2$ [53–57], which will be postponed to the future work.

Appendix A: Field dependent masses

Field dependent masses matrix is given by,

$$m_{h,S,A}^2 = \text{eigenvalues} \left( M^2 \right),$$

(A1)

with

$$M^2 = \begin{pmatrix}
m_{h,h}(h,S,A) & m_{h,S}(h,S,A) & m_{h,A}(h,S,A) \\
m_{h,S}(h,S,A) & m_{S,h}(h,S,A) & m_{S,A}(h,S,A) \\
m_{h,A}(h,S,A) & m_{S,A}(h,S,A) & m_{A,h}(h,S,A)
\end{pmatrix},$$

and matrix entries are given by

$$m_{h,h}^2 = \frac{m^2}{2} + \frac{\sqrt{2} g_1}{4} S + \frac{\delta_2}{4} \left( S^2 + A^2 \right) + \frac{3}{4} \lambda h^2,$$

(A2)

$$m_{h,S}^2 = \frac{\sqrt{2} g_1}{4} h + \frac{\delta_2}{2} h S,$$

(A3)

$$m_{S,S}^2 = \frac{-b_1 + b_2}{2} + \frac{d_2}{4} A^2 + \frac{\sqrt{2} c_2}{6} S + \frac{3}{4} d_2 S^2 + \frac{\delta_2}{4} h^2,$$

(A4)

$$m_{h,A}^2 = \frac{\delta_2}{2} h A,$$

(A5)

$$m_{S,A}^2 = \frac{\sqrt{2} c_2}{6} A + \frac{d_2}{2} A S,$$

(A6)

$$m_{A,A}^2 = \frac{b_1 + b_2}{2} + \frac{3}{4} d_2 A^2 + \frac{\sqrt{2} c_2}{6} S + \frac{d_2}{4} S^2 + \frac{\delta_2}{4} h^2,$$

(A7)

and other field dependent masses given by,

$$m_{t,C}^2 = \frac{m^2}{2} + \frac{\sqrt{2} g_1}{4} S + \frac{\delta_1}{4} \left( S^2 + A^2 \right) + \frac{\lambda}{4} h^2,$$

(A8)

$$m_{t,fermion}^2 = \frac{1}{2} g_1 h^2,$$

(A9)

$$m_{W,\pm}^2 = \frac{1}{2} g_1 h^2,$$

(A10)

$$m_{Z}^2 = \frac{1}{2} (g^2 + g'^2) h^2,$$

(A11)

with $G$ being goldstone fields.
Appendix B: Scalar triple and quartic couplings

\[ g_{A Ah_1} = -2i(\delta_2v \cos \phi/4 + (\sqrt{2}c_2/12 + d_2x/4) \sin \phi), \]

\[ g_{h_1h_1h_1} = -6i(\lambda v \cos \phi^3/4 + (d_2x/4 + \sqrt{2}c_2/12) \sin \phi^3 + (\delta_2x/4 + \sqrt{2}\delta_1/8) \cos \phi^2 \sin \phi + \delta_2v/2 \sin \phi \cos \phi^2), \]

\[ g_{AAh_2} = -2i(\delta_2v \sin \phi/4 + (\sqrt{2}c_2/12 + d_2x/4) \cos \phi), \]

\[ g_{h_1h_1h_2} = -2i(-3\lambda v \cos \phi^2 \sin \phi/4 + 3 \sin \phi^2 \cos \phi d_2x/4 + \sqrt{2}c_2/12) - (\delta_2x/2 + \sqrt{2}\delta_1/4) \cos \phi \sin \phi^2 + \delta_2v/2 \sin \phi \cos \phi^2, \]

\[ g_{A Ah_2} = -4i(\delta_2 \cos \phi^2/8 + d_2 \sin \phi^2/8), \]

\[ g_{h_2h_2h_2} = -6i(-\lambda v \sin \phi^3/4 + (d_2x/4 + \sqrt{2}c_2/12) \cos \phi^3 + (\delta_2x/4 + \sqrt{2}\delta_1/8) \cos \phi \sin \phi^2 - \delta_2v \sin \phi \cos \phi^2/4), \]

\[ g_{AAh_2} = -4i(\delta_2 \sin \phi^2/8 + d_2 \cos \phi^2/8), \]

\[ g_{h_2h_2h_1} = -2i(3 \cos \phi^2 \sin \phi(d_2x/4 + \sqrt{2}c_2/12) + 3 \sin \phi^2 \cos \phi \lambda v/4 - (\delta_2x/2 + \sqrt{2}\delta_1/4) \cos \phi^2 \sin \phi - \delta_2v \sin \phi \cos \phi^2 \cos \phi/2), \]

\[ g_{A Ah_1h_2} = -2i(\sin \phi \cos \phi(d_2 - \delta_2)/4). \]

(C1)

Appendix C: Thermal masses used in EWPT analysis

Thermal masses of bosonic field relevant to EWPT study are listed bellow,

\[ \Pi_G = (3g_2/16 + g^2/16 + \lambda/8 + y_f^2/4 + \delta_2/4)T^2, \]

\[ \Pi_{hh} = (3g_2^2/16 + g^2(16 + \lambda/8 + y_f^2/4 + \delta_2/24))T^2, \]

\[ \Pi_{SS} = (d_2/12 + \delta_2/48)T^2, \]

\[ \Pi_{AA} = (d_2/12 + \delta_2/48)T^2. \]

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[58] which should be the strong first-order EWPT to protect the generated baryon asymmetry from washout and suppress the sphaleron after the process is ended.
[59] Ref. [42] considered the analogous dimension-5 operator involving $S/\Lambda$, and Ref. [43] use $S^2/\Lambda^2$ because of the $Z_2$ symmetry $S \rightarrow -S$ needed to prevent decay of $S$, as befits a dark matter candidate. In our case, we consider the complex scalar $S$, thus we have $S^2/\Lambda^2$, which ensures that the dark matter candidate preserves $Z_2$ symmetry and the CP violation source survive through $\eta S(1+i\gamma_5)t$ after symmetry breaking .
[60] The global $U(1)$ symmetry respect by $V(H,S)$ is broken softly by $b_1$ term and spontaneously when $S$ gets a VEV.