ElectroWeak BaryoGenesis via Top Transport

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We study electroweak baryogenesis driven by the top quark in two Higgs doublet model that allows flavor-changing neutral Higgs couplings. Taking Higgs sector couplings and the additional top Yukawa coupling ρ_{tt} to be $\mathcal{O}(1)$, one naturally has first order electroweak phase transition and sufficient *CP* violation to fuel the cosmic baryon asymmetry. Even if ρ_{tt} vanishes, the favor-changing coupling ρ_{tc} can still achieve baryogenesis. Phenomenological consequences such as $t \to ch$, $\tau \to \mu\gamma$, electron electric dipole moment, $h \to \gamma\gamma$, and *hhh* coupling are discussed. The extra scalars H^0, A^0 and $H^\pm$ are sub-TeV in mass, and can be searched for at the LHC.

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1. Introduction: "General" 2HDM

Remarkably, the Standard Model (SM) carries all ingredients of the Sakharov conditions for generating baryon asymmetry of the Universe (BAU), albeit falling short on order of electroweak phase transition (EWPT), and strength of *CP* violation (CPV): the weak interaction is too weak to make EWPT 1st order, while the Jarlskog invariant is too meager a source for CPV. Involving all three generations, the latter is suppressed by both small masses and mixing angles.

If one adds a second Higgs doublet (2HDM), it is known that one could have 1st order EWPT if Higgs sector couplings are $\mathscr{O}(1)$. For CPV, while some have tried complex couplings in Higgs sector, it may be prudent to keep the Higgs potential *CP* invariant to avoid trouble with neutron edm, d_n. Recalling that known CPV arises from the CKM matrix, i.e. from Yukawa couplings, one naturally asks whether there can be extra Yukawa couplings in 2HDMs. Alas, such couplings were eliminated by the Natural Flavor Conservation (NFC) condition of Glashow and Weinberg [1] 40 years ago. NFC is usually implemented by imposing a Z_2 symmetry on the two Higgs fields Φ_1 and Φ_2 to forbid flavor-changing neutral Higgs (FCNH) couplings. Admittedly, such discrete symmetries may seem *ad hoc*, and indeed deemed perhaps unnecessary [2], given the observed trickle-down pattern or mass suppression of far off-diagonal quark mixings.

Here, we drop Z_2 symmetry (or NFC) and utilize extra Yukawa couplings ρ_{tt} and ρ_{tc}, which are naturally $\mathscr{O}(1)$ and complex, to drive [3] EWBG. We note that, recently, many authors have taken a data-driven approach to these FCNH couplings, not just in the old suggestion [4] of $t \to ch$ decay, but applying also to the so-called $B \to D^{(*)}$ anomaly, as well as $h \to \tau\mu$ decay.

2. Model

The Yukawa interaction for up-type quarks in a general 2HDM without Z_2 is

$$-\mathscr{L}_Y = \bar{q}_{iL} \left(Y^u_{1ij}\tilde{\Phi}_1 + Y^u_{2ij}\tilde{\Phi}_2 \right) u_{jR} + \text{h.c.}, \tag{2.1}$$

where i, j are flavor indices and $\tilde{\Phi}_b = i\tau_2\Phi^*_b$ ($b = 1, 2$). With $\Phi_{1,2}$ each acquiring a vacuum expectation value (VEV) $\upsilon_{1,2}$, and defining the usual $\upsilon_1 = \upsilon c_\beta$, $\upsilon_2 = \upsilon s_\beta$ (hence $\upsilon^2 = \upsilon^2_1 + \upsilon^2_2$), the matrix $Y^{\text{SM}} = Y_1 c_\beta + Y_2 s_\beta$ is diagonalized by a biunitary transform $V^{u\dagger}_L Y^{\text{SM}} V^u_R$ to Y_D, with diagonal elements $y_i \equiv \sqrt{2}m_i/\upsilon$. However, the orthogonal combination

$$\rho = V^{u\dagger}_L \left(-Y_1 s_\beta + Y_2 c_\beta \right) V^u_R, \tag{2.2}$$

cannot be simultaneously diagonalized, and the exotic neutral Higgs bosons H and A possess FCNH couplings in general, including extra diagonal couplings ρ_{ii},

$$-\sqrt{2}\mathscr{L}_Y = \bar{u}_{iL} \left[(y_i\delta_{ij}s_{\beta-\alpha} + \rho_{ij}c_{\beta-\alpha})h + (y_i\delta_{ij}c_{\beta-\alpha} - \rho_{ij}s_{\beta-\alpha})H - i\rho_{ij}\gamma_5 A \right] u_{jR} + \text{h.c.} \tag{2.3}$$

The ρ_{ij}s are complex, i.e. $\arg \rho_{ij} \equiv \phi_{ij} \neq 0$, and we have introduced the mixing angle $c_{\beta-\alpha}$ between the two *CP*-even Higgs bosons h and H. It is known that the discovered 125 GeV boson h is rather close to the SM-Higgs boson, i.e. we are close to the *alignment* limit [5] of $c_{\beta-\alpha} \to 0$ (hence $|s_{\beta-\alpha}| \to 1$). In this limit, the Yukawa couplings of h are diagonal, while H and A have FCNH couplings ρ_{ij}. In the following, we largely adopt the alignment limit to simplify.

3. EWBG

Let us first give a heuristic account of EWBG. Baryon number violation is facilitated by sphaleron processes in the symmetric phase. As temperature cools, one has an expanding "bubble" of the broken phase. But to avoid "washout" of the generated baryon number n_B through the bubble wall, one needs $\Gamma_B^{(br)}(T_C) < H(T_C)$, i.e. the n_B changing rate $\Gamma_B^{(br)}(T_C)$ is less than the Hubble parameter $H(T_C)$ at critical temperature T_C. This can be satisfied if the EWPT is first order such that $\upsilon_C/T_C \gtrsim 1$, where $\upsilon_C^2 = \upsilon_1^2(T_C) + \upsilon_2^2(T_C)$. This is where the $\mathcal{O}(1)$ Higgs couplings in 2HDM differ from the rather weak Higgs self-coupling in SM, that a strongly 1st order EWPT can be achieved through thermal loops involving extra Higgs bosons.

BAU, or $n_B/s \equiv Y_B \neq 0$, arises via

$$Y_B \equiv \frac{n_B}{s} = \frac{-3\Gamma_B^{(sym)}}{2D_q\lambda_+ s} \int_{-\infty}^0 dz' n_L(z') e^{-\lambda_- z'}, \tag{3.1}$$

where $\Gamma_B^{(sym)} = 120\alpha_W^5 T$ is the n_B-changing rate in symmetric phase, $D_q \simeq 8.9/T$ is the quark diffusion constant, s is the entropy density, $\lambda_\pm \sim \upsilon_w$ is the bubble wall velocity, and n_L is the total left-handed fermion number density. The integration is over z', the coordinate opposite bubble expansion direction. We use the Planck value $Y_B^{obs} = 8.59 \times 10^{-11}$ [6] in our numerical analysis.
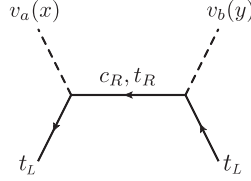

Figure 1: Leading CPV process for BAU, with bubble wall denoted symbolically as $\upsilon_a(x)$ and $\upsilon_b(y)$.

CPV Top Interactions

Nonvanishing n_L is needed for Y_B, which in our case is from the l.h. top density. CPV interactions of (anti)top with the bubble wall is illustrated symbolically in Fig. 1, where vertices can be read off from Eq. (2.1). The detailed "transport" problem is rather elaborate, which we cannot possibly give full account here. Suffice it to say that, with the closed time path formalism in the VEV insertion approximation, the CPV source term S_{ij} for left-handed fermion f_{iL} induced by right-handed fermion f_{jR} takes the form

$$S_{i_L j_R}(Z) = N_C F \operatorname{Im}\left[(Y_1)_{ij}(Y_2)_{ij}^*\right] v^2(Z) \partial_{t_Z}\beta(Z), \tag{3.2}$$

where $Z = (t_Z, 0, 0, z)$ is position in heat bath (very early Universe), $N_C = 3$ is number of color, F is a function[1] of complex energies of f_{iL} and f_{jR}, and $\partial_{t_Z}\beta(Z)$ is the variation in $\beta(Z)$. Note that, even though β is basis-dependent in the general 2HDM, its variation is physical and plays an essential role in generating the CPV source term. In our numerics, we take $\Delta\beta = 0.015$.

If bubble wall expansion and $\partial_{t_Z}\beta(Z)$ reflect departure from equilibrium, the essence of CPV for BAU is in the $\operatorname{Im}\left[(Y_1)_{ij}(Y_2)_{ij}^*\right]$ factor in Eq. (3.2). Let us see how it depends on the couplings

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[1]See Ref. [7] for explicit form, as well as more details on the transport equations.

ρ_{ij}. From Eq. (2.2) and the relation between Y^{SM} and Y_D, one has

$$\text{Im}\big[(Y_1)_{ij}(Y_2)_{ij}^*\big] = \text{Im}\big[(V_L^u Y_{\text{diag}} V_R^{u\dagger})_{ij}(V_L^u \rho V_R^{u\dagger})_{ij}^*\big]. \tag{3.3}$$

To understand the result presented in the plot below, suppose [8] $(Y_1)_{tc} \neq 0$, $(Y_2)_{tc} \neq 0$, and $(Y_1)_{tt} = (Y_2)_{tt} \neq 0$, while all else vanish (we take $\tan\beta = 1$ throughout for convenience). Then $\sqrt{2}Y^{\text{SM}} = Y_1 + Y_2$ can be diagonalized by just V_R^u to a single nonvanishing 33 element y_t, the SM Yukawa coupling, while the combination $-Y_1 + Y_2$ is not diagonalized. Solving for V_R^u in terms of nonvanishing elements in Y_1 and Y_2, one finds

$$\text{Im}\big[(Y_1)_{tc}(Y_2)_{tc}^*\big] = -y_t \,\text{Im}(\rho_{tt}), \quad \rho_{ct} = 0, \tag{3.4}$$

with ρ_{tc} basically a free parameter. Note that both doublets are involved for EWBG.

$T_C \cong 119\,\text{GeV}$	$\upsilon_C \cong 177\,\text{GeV}$	$\upsilon_w \cong 0.4$	$\Delta\beta \cong 0.015$	$D_q \cong 8.9/T$	$D_H \cong 102/T$
$m_{t_L} \cong 0.59T$	$m_{t_R} \cong 0.62T$	$m_{c_R} \cong 0.50T$	$\Gamma_{q_{L,R}} \cong 0.22T$	$\Gamma_B^{(s)} \cong 120\alpha_W^5 T$	$\Gamma_{ss} = 16\alpha_s^4 T$

Table 1: Input parameters for the Y_B calculation.

To calculate n_L in Eq. (3.1), one has a set of transport equations that are diffusion equations fed by various density combinations weighted by mass (hence T) dependent statistical factors, as well as CPV source terms such as in Eq. (3.2). Following a relatively standard path, we reduce the coupled equations to a single equation for n_H, controlled by a diffusion time $D_H \simeq 101.9/T$ modulated by $1/\upsilon_w^2$ (see Ref. [7] for more discussion and references). For experts, we list the important parameters in Table 1, where one can see that $\upsilon_C/T_C \gtrsim 1$ is satisfied.

Scanning over $|\rho_{tc}|$, ϕ_{tt} and ϕ_{tc}, we plot Y_B/Y_B^{obs} vs $|\rho_{tt}| \in (0.01, 1)$ in Fig. 2[left], with ρ_{tt} and ρ_{tc} satisfying [9] B_d, B_s mixing as well as $b \to s\gamma$ constraints. We have taken $m_H = m_A = m_{H^\pm} = 500$ GeV to simplify. Though perhaps too restrictive, it illustrates the charm of EWBG: the exotic Higgs masses are sub-TeV. We separate $0.1 \leq |\rho_{tc}| \leq 0.5$ and $0.5 \leq |\rho_{tc}| \leq 1.0$, which are plotted as purple
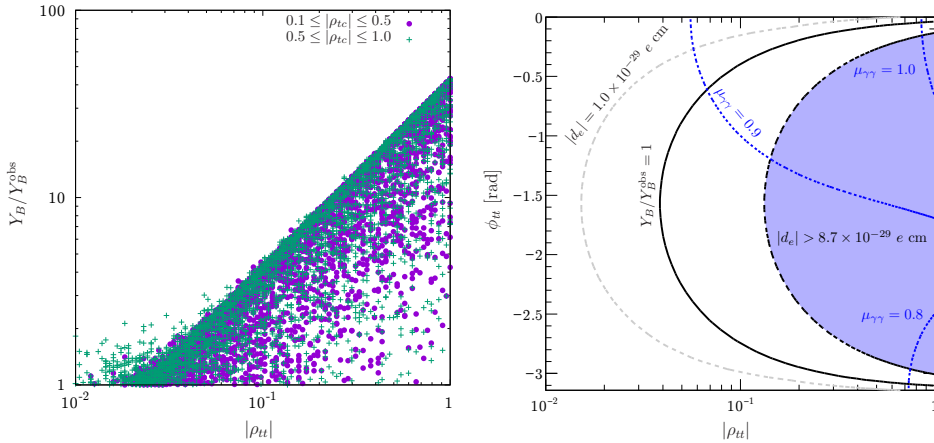

Figure 2: [left] Y_B/Y_B^{obs} vs $|\rho_{tt}|$, where purple dots (green crosses) are for $0.1 \leq |\rho_{tc}| \leq 0.5$ ($0.5 \leq |\rho_{tc}| \leq 1.0$); [right] $Y_B/Y_B^{\text{obs}} = 1$ (solid) and $|d_e|$ (dashed) in the $|\rho_{tt}|$–ϕ_{tt} plane for $c_{\beta-\alpha} = 0.1$, where shaded region is excluded, while dotted curves are for $h \to \gamma\gamma$ with $\mu_{\gamma\gamma}$ as marked.

dots and green crosses, respectively. It is clear that sufficient Y_B can be generated handsomely, even for $|\rho_{tt}|$ considerably below 0.1. Since no obvious difference is seen between lower and higher $|\rho_{tc}|$ for the bulk of the plot, we infer that Y_B is driven by ρ_{tt}. However, note that for small $|\rho_{tt}|$, the green crosses populate $Y_B/Y_B^{\text{obs}} \gtrsim 1$ much more than the purple dots, which means that $|\rho_{tc}| \sim \mathscr{O}(1)$ could take over EWBG for low ρ_{tt}, but it would demand near maximal ϕ_{tc}.

Thus, we have two mechanisms for BAU: ρ_{tt} as main driver, with ρ_{tc} at $\mathscr{O}(1)$ as backup.

4. Phenomenology

As already mentioned, a leading effect is $t \to ch$ decay, which demands $c_{\beta-\alpha} \neq 0$. Taking $c_{\beta-\alpha} = 0.1$ and $|\rho_{tc}| = 1$, we find $\mathscr{B}(t \to ch) = 0.15\%$, which satisfies the latest ATLAS bound [10] of 0.22% using 36.1 fb^{-1} data at 13 TeV. One recent motivation for FCNH was a hint for $h \to \tau\mu$ in 8 TeV data by CMS. Unfortunately, the hint disappeared with more data, and CMS sets a new bound [11] of $\mathscr{B}(h \to \tau\mu) < 0.25\%$ based on 35.9 fb^{-1} at 13 TeV. Taking $c_{\beta-\alpha} = 0.1$, this still allows $\mathscr{B}(\tau \to \mu\gamma)$ up to 10^{-8}, which can be probed by Belle II.

It is of interest to test CPV, as it links with EWBG. Recent progress in the electron edm, d_e, by the ACME experiment is rather astounding [12], which is shown ($c_{\beta-\alpha} = 0.1$) as the dashed curve in Fig. 2[right] with excluded region shaded, and $Y_B/Y_B^{\text{obs}} = 1$ given as the solid curve. ACME projects an improvement by factor of 9 (gray dashed curve), which could probe our EWBG mechanism. The effect of ρ_{tt} on d_e given in Fig. 2[right], which is through the two-loop mechanism, assumes $\rho_{ee} = 0$. For $|\rho_{ee}| \sim y_e = \sqrt{2}m_e/\upsilon$ but purely imaginary, cancellation between one- and two-loop effects could occur, allowing one to evade ACME. What may be more exasperating is that the flavor or *CP* violating effects mentioned so far would all vanish with $c_{\beta-\alpha} \to 0$, i.e. alignment. What does not vanish with $c_{\beta-\alpha}$ is EWBG itself. Nature seems skilled at producing the Universe, but hides the flavor and CPV traces.

EWBG in 2HDM needs both $\rho_{tt} \sim \mathscr{O}(1)$ and Higgs couplings $\sim \mathscr{O}(1)$. We have also plotted in Fig. 2[right] possible reductions[2] to $h \to \gamma\gamma$ width (dotted curves) due to H^+ effect, which does not vanish with $c_{\beta-\alpha}$. Another effect that does not vanish with alignment is extra Higgs correction to λ_{hhh}, or triple-h coupling, which could receive 60% enhancement with our benchmark, $m_H = m_A = m_{H^\pm} = 500$ GeV. The "charm of EWBG", as mentioned, is of sub-TeV exotic scalars, which can be probed directly at LHC. This is a consequence of $\mathscr{O}(1)$ self-couplings in the Higgs sector. Of course, full degeneracy is clearly too restrictive, and the actual parameter space should be much broader. Together with the notion that H^0 and A^0 detection may be hampered by interference effects in $t\bar{t}$ decay final state, search strategy for heavy Higgs should be readjusted.

5. Conclusion

We have studied [3] EWBG induced by the top quark in 2HDM with FCNH couplings. The leading effect arises from extra *top* Yukawa coupling ρ_{tt}, where BAU can be in the right ballpark for $\rho_{tt} \gtrsim 0.01$ with moderate CPV phase ϕ_{tt}. Even if $|\rho_{tt}| \ll 0.1$, sufficient BAU can still be generated by $|\rho_{tc}| \simeq 1$ with large CPV phase ϕ_{tc}. These scenarios are testable in the future with new flavor parameters that have rich implications, and extra Higgs bosons below the TeV scale.

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[2]Loop effect from top via ρ_{tt} could compensate [13] this reduction.

Nature may opt for a second Higgs doublet for generating the matter asymmetry of the Universe, through a new CPV phase associated with the top quark. As a bonus, it is found that alignment emerges naturally from such 2HDM without discrete symmetry [14].

References

[1] S.L. Glashow and S. Weinberg, Phys. Rev. D **15**, 1958 (1977).

[2] T.-P. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987).

[3] K. Fuyuto, W.-S. Hou and E. Senaha, arXiv:1705.05034 [hep-ph].

[4] W.-S. Hou, Phys. Lett. B **296**, 179 (1992).

[5] J.F. Gunion and H.E. Haber, Phys. Rev. D **67**, 075019 (2003).

[6] P.A.R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. **571**, A16 (2014).

[7] C.-W. Chiang, K. Fuyuto and E. Senaha, Phys. Lett. B **762**, 315 (2016).

[8] H.-K. Guo *et al.*, arXiv:1609.09849 [hep-ph].

[9] B. Altunkaynak *et al.*, Phys. Lett. B **751**, 135 (2015).

[10] M. Aaboud *et al.* [ATLAS Collaboration], arXiv:1707.01404 [hep-ex].

[11] The CMS Collaboration, CMS-PAS-HIG-17-001.

[12] J. Baron *et al.* [ACME Collaboration], Science **343**, 269 (2014).

[13] W.-S. Hou and M. Kikuchi, Phys. Rev. D **96**, 015033 (2017).

[14] W.-S. Hou and M. Kikuchi, arXiv:1706.07694 [hep-ph].