Baryogenesis and CP violation in the K system

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Within a Left-Right Model with spontaneous CP violation it is possible to produce a baryon asymmetry which is related to other measured CP violating observables. We develop this relation for the parameter ε describing CP violating mixing in the K system.

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1. Introduction.

Since the seminal paper of Kuzmin, Rubakov and Shaposhnikov [1] on the possibility of creating the baryon asymmetry of the universe (BAU) at the electroweak (EW) scale, many efforts have been devoted to a better understanding of the underlying ingredients i.e. B number non-conservation, the emergence of non-equilibrium conditions and, last but not least, C and CP violation. Though we are far from a really satisfactory understanding of the behaviour of the universe at T around $100GeV$ it has nevertheless emerged that, if one insists on creating the BAU at the EW scale, the Standard Model has in some way or another to be extended. The main reason stands in the smallness of CP violation in the SM. A well-known parametrization of CP violation in the CKM picture [2] is given by

$$\mathcal{J} = \mathcal{I}m\ \mathcal{D}et(\lambda_U \lambda_U^\dagger, \lambda_D \lambda_D^\dagger) \approx 10^{-21} \tag{1.1}$$

where λ_U and λ_D are the up and down Yukawa matrices. In the neutral Kaon system an amplification is provided by the smallness of Δm_K and the measured CP violation is raised to

$$\varepsilon \approx 10^{-3} \tag{1.2}$$

It seems dubious that such an amplification mechanism could take place in the primordial plasma [3].

On the other hand, most of the popular (non-GUT) extensions of the SM are good canditates for the task of EW baryogenesis [4]. Many of them use, in addition to the usual complex Yukawa couplings, another source of CP violation, *i.e.* usually a non-trivial phase in the scalar sector. While this phase is used to produce the baryon asymmetry during the EW phase transition, the Yukawa couplings eventually lead to the unitary CKM matrix. Obviously the BAU and, for instance, ε are unrelated. Though there is no principle imposing that they should be related it is interesting to see to what extent they could be. As we will sketch below this can be achieved within a left-right symmetric model with spontaneous CP violation [5]

The basic reason is rather simple. In a two-Higgs extension of the SM the effects of the phase of the vacuum can be removed from the quark sector and its effects limited to a mixing between the neutral scalar and pseudo-scalar. This is achieved by redefining the right-handed quarks only. As these do not couple to the SM gauge bosons, the CKM matrix is orthogonal if the Yukawa couplings are real. In this case, to have CP violation in the K system one has to allow for flavour changing neutral current through the exchange of neutral scalars. These are constrained to be heavier than $O(1 - 10TeV)$ by the value of Δm_K, and finally can only give tiny CP violating effects in the K's.

Now, if the right handed quarks do couple to $SU(2)_R$ gauge bosons the vacuum phase cannot be removed from the quarks sector and, for not too heavy R-gauge bosons (typically $M_{W_R} \approx 10TeV$), this gives CP violation in the K system. In this case the very same phase can in principle be used to generate the BAU to an amount compatible with observation.

2. The Model

We consider here the $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ extension of the SM. As usual[6] the LR symmetry is broken through the *vev* of a (0,1,2) scalar field at a scale that we suppose to be rather low ($O(10 - 100TeV)$). This requirement is necessary in order to have a non trivial (*viz* SM-like) CP violation phenomenology in the $K^\circ - \bar{K}^\circ$. Then the electroweak symmetry is broken through the *vev* of a scalar bi-doublet *i.e.* a field in the $(1/2, 1/2, 0)$ representation of the gauge group. The quark Yukawa couplings read:

$$\mathcal{L}_{Yukawa} = -\Gamma_{ij}\, \bar{q}_{iL}\, \phi\, q_{jR} - \Delta_{ij}\, \bar{q}_{iL} \tilde{\phi}\, q_{jR} \quad , \tag{2.1}$$

where ϕ is the bi-doublet field, with *vev*:

$$\langle \phi \rangle = \begin{pmatrix} v & 0 \\ 0 & w \end{pmatrix} \tag{2.2}$$

and $\tilde{\phi} \equiv \sigma_2 \phi^* \sigma_2$. In order to deal with the sole vacuum phase as a source for CP violation, we further impose CP invariance of the lagrangian. The coupling matrices Δ and Γ are then real and symmetric. CP violation in the quark sector occurs if v and w^* are complex relative to each other. By making a $SU(2)_L$ or $SU(2)_R$ transformation it is possible to express this by one single phase α:

$$\langle \phi \rangle = e^{i\alpha/2} \begin{pmatrix} |v| & 0 \\ 0 & |w| \end{pmatrix} \tag{2.3}$$

In the chosen phase convention the mass matrices of the quarks are given by

$$\begin{aligned} M^{(u)} &= v\Gamma + w^* \Delta = |v| e^{i\alpha/2} (\Gamma + r e^{-i\alpha} \Delta) \\ M^{(d)} &= w\Gamma + v^* \Delta = |v| e^{i\alpha/2} (r\Gamma + e^{-i\alpha} \Delta) \end{aligned} \tag{2.4}$$

with $w/v^* = |w/v|\, e^{i\,\alpha} = r\, e^{i\,\alpha}$. These are complex symmetric matrices which can be diagonalized by two unitary matrices:

$$
\begin{aligned}
M^{(u)} &= e^{i\,\alpha/2} U D^{(u)} U^T \\
M^{(d)} &= e^{i\,\alpha/2} V D^{(d)} V^T
\end{aligned}
\tag{2.5}
$$

Contrary to the SM the L and R quarks are not rotated independently. This has as important consequence that the mixing matrices K_L and K_R (the generalisation of the CKM matrix) are not independent and in the chosen basis (phase convention) they are related by

$$
K_L = U^\dagger V = K_R^* \tag{2.6}
$$

For the case of N_f flavours, there are $(N_f^2 - N_f + 1)$ physical phases in the mixing matrices and so it is possible to have CP violation already with two generations. The nicety of the LR model with spontaneous CP violation is that all the phases are functions of α and that in the limit of small $r \sin\alpha$ they are analytically calculable [7]. Furthermore, an enhancement of the ΔS= 2 channel ensures a small value of ε'/ε for dynamical reasons [8].

3. The Mechanism of Baryogenesis

At the EWPT, the relevant degrees of freedom are essentially equivalent to those of the two Higgs-doublet extensions of the SM supplemented by the non-trivial LR structure of the Yukawa couplings.

The kind of baryogenesis mechanism will depend on the different time scales in the problem. These are:

i) the characteristic phase transition (PT) time $\tau_{\rm higgs}$ defined as

$$
\tau_{\rm higgs} \approx (\text{wall thickness})/(\text{wall velocity}) \tag{3.1}
$$

which is estimated to range from 1/T to about 100/T depending on the model.

ii) the thermalization time $\tau_{\rm therm} \equiv$ mean free path:

$$
\begin{aligned}
\tau_{quark} &\approx 4/\mathrm{T} \\
\tau_{lepton} &\approx 10/\mathrm{T}
\end{aligned}
\tag{3.2}
$$

iii) the time scale of B violating processes:

$$
\tau_{sphL} \geq (\kappa \alpha_W^4 \mathrm{T})^{-1} \approx 10^6/\mathrm{T} \tag{3.3}
$$

which is the symmetric phase estimate (clearly a lower bound)[1].
iv) the "age of the universe", *i.e.*

$$\tau_{\mathrm{U}} \equiv \mathrm{H}^{-1} \tag{3.4}$$

The expansion rate is relatively small at the EW scale and is only relevant when considering the effectiveness of B violation processes at the end of the PT [2].

In view of the above time scales two kinds of scenarios emerge:
I. If $\tau_{\mathrm{higgs}} \ll \tau_{\mathrm{therm}}$: the *Non-Adiabatic Regime.*

In this "thin wall" situation one uses reflection of (heavy) quarks on the bubble wall [9]. An asymmetry in the flux caused by CP violation can then bias B violating processes in the symmetric region.
II. If $\tau_{\mathrm{higgs}} \gg \tau_{\mathrm{therm}}$: the *Adiabatic Regime.*

In this "thick wall" case one considers the plasma to be in quasi-static thermal (but not chemical) equilibrium throughout the bubble wall (see *e.g.* [4]).

Here we will only consider the second situation which anyway is favored by the current understanding of the dynamic of the EWPT.

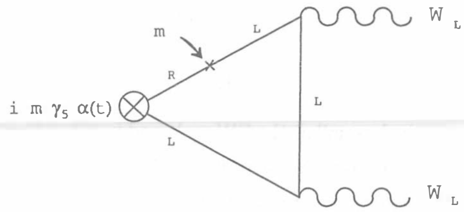
At this point one has to derive the effective CP violating action in the bubble wall. Starting from the Yukawa couplings of the phase to the quark fields, *i.e.* in the present case,

$$-\mathcal{L}_{yuk} = m_i \bar{q}_i q_i + i\bar{q}_i \gamma_5 q_j \{m_i \alpha \delta_{ij} + (M_{ij} r\alpha + O((r\alpha)^2))\} \tag{3.5}$$

two rather different approaches have been developed in the last few years. The first one, proposed by Cohen *et al* [4], consists in making a space-time dependent (non-anomalous if possible) rotation on the quark fields in order to have real Yukawa couplings for the heaviest quarks (the top). Then the kinetic terms induce effective chemical potentials in the rest frame of the plasma ($\alpha = \alpha(t)$) which can bias B violating processes. However this approach, as recently criticized by Dine and Thomas [10], can only be correct if the quarks may suffer many chirality flips (or equivalently if one has the right to use the massive Dirac equation) which even for the top can hardly be the case for typical τ_{higgs}. The second approach initiated by Turok and Zadrozny [11] simply consists in calculating the CP violating couplings of the phase to the $\mathrm{SU(2)_L}$ gauge field which occurs through the following Feynman diagrams:

[1] As R-gauge bosons are much more massive, R-sphaleron processes are completely negligible at the EW scale.

[2] This constraint can give an upper bound on the mass of the higgs particle



At zero temperature one finds using (3.5) to zero order in r:

$$\Delta\mathcal{L}_{eff} = \frac{g_W^2}{24\pi^2} N_f\ \alpha(t)\ W_L \tilde{W}_L \tag{3.6}$$

Note that all the flavours contribute ($\propto N_f$) at the same level as (3.6) is independent of the masses. Taking into account finite T effects, the results is:

$$\Delta\mathcal{L}_{eff} = \frac{7}{4}\zeta(3)(\frac{m_{\rm top}}{\pi \rm T})^2 N_f\ \alpha(t)\ W_L \tilde{W}_L \tag{3.7}$$

and, except for the top, the contribution of the quarks are strongly suppressed. This can be understood as a Fermi Blocking Effect or equivalently by noting that the IR cut-off in the diagram at zero T -the quark mass- is replaced by the temperature.

The simplest way to see how this effective coupling can lead to baryon asymmetry generation is to use the anomalous divergence of the baryon current:

$$\partial_\mu j^\mu_{\rm B} = -N_f \frac{g_W^2}{32\pi^2} W_L \tilde{W}_L \tag{3.8}$$

Inserting (3.8) in (3.7) and integrating by part gives

$$\begin{aligned}\Delta\mathcal{L}_{eff} &\propto (\frac{m_{\rm top}}{\rm T})^2 \dot{\alpha}(t)\ j^0_{\rm B} \\ &\equiv \mu_{\rm B} n_{\rm B},\end{aligned} \tag{3.9}$$

i.e. there is an induced chemical potential for the baryon number density. Now this would be without any effect if B was conserved. But, at least not too deep in the bubble wall, baryon number is slightly non-conserved due to sphaleron effects (note $\tau_{\rm sph} \gg \tau_{\rm higgs}$). If these processes are turned-off at some value of $<\phi>= \Phi_{\rm c.o.}$ while $\dot{\alpha}$ is still non-zero a net asymmetry is produced. Using detailed balance one can deduce that

$$\dot{n}_B = N_f \frac{\Gamma_{\rm EQ}}{\rm T} \frac{\Delta F}{\Delta B} \equiv N_f \frac{\Gamma_{\rm EQ}}{\rm T} \mu_B \tag{3.10}$$

where $\Gamma_{\rm EQ}$ is the rate for B violation at equilibrium. The simple minded approximation of sudden cut-off then gives:

$$\frac{n_B}{s} \leq \kappa\,(\frac{100}{g_*})\,(\frac{<\alpha>}{\pi})(\frac{\lambda_{\rm top}\Phi_{\rm c.o.}}{\rm T})^2 \times 10^{-7} \tag{3.11}$$

where $s = (\frac{2\pi}{45})g_*{\rm T}^3$, κ is largely unknown (O(.1-100)) and $\lambda_{\rm top}\phi_{\rm c.o.}/{\rm T} \leq m_{\rm top}/{\rm T} = O(1)$. This estimate has to be compared with

$$4 \times 10^{-11} \leq \left.\frac{n_B}{s}\right|_{\rm NUC} \leq 1.4 \times 10^{-10} \tag{3.12}$$

Some problem may arised in the present scenario. The most obvious one concerns the spontaneous breaking of discrete symmetries -in the present case LR and CP symmetry- in the early universe which lead to the formation of domain walls. Also, as there are domains with opposite phase sign, the global baryon number must be zero. As usually this problem can be circumvented by requiring that an inflationary period took place at, or after, the LR symmetry breaking scale. Within our horizon the "vacuum" is then such that R-gauge bosons are much more massive than L-ones and that one definite sign of α is selected. Another possibility simply consists of introducing soft symmetry breaking terms in the scalar potential. This may seems *ad hoc* but nevertheless put forward the incompatibility of *simultaneous* spontaneous CP breaking and baryogenesis. In the same spirit, one could remark that, in a region of the universe where R-gauge bosons are lighter than L-ones, R-sphalerons processes are the effective ones. As (compare with (3.8))

$$\partial_\mu j^\mu_{\rm B} = +N_f \frac{g_W^2}{32\pi^2}\, W_R \tilde{W}_R, \tag{3.13}$$

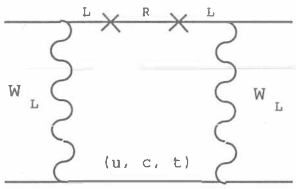
it is clear that with the same phase an anti-baryon excess is produced.

Another problem not considered here, is the possible existence of "rapid" chirality changing processes mediated by so-called strong-sphalerons [12], which have the tendency to reduce the baryon asymmetry. The relevance of their effect rests again on the characteristic time for chirality flips $\tau_{\rm strong}$ compared to $\tau_{\rm higgs}$. The current estimates give $\tau_{\rm strong} \ll \tau_{\rm higgs}$ and as such taking these effects into account only slightly modify the above estimate [10].

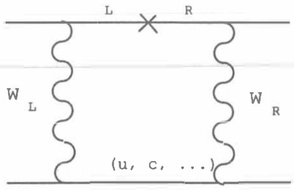
4. CP Phenomenology and Conclusions

For not too heavy R-gauge bosons, the model has an interesting phenomenology of CP violation at low energy. For instance it is a kind of superweak model due to an ampification of the $\Delta S = 2$ channel with respect to direct CP violation in the K decay, thus naturally ensuring $\varepsilon' \ll \varepsilon$.

We restrict ourself to the expectation for ε. As noted above only two generations are necessary to have CP violation in the flavour-changing charged-current couplings. Also less mass insertions (to prevent the GIM cancellation mechanism) than in the SM are necessary. For these reasons,the contribution of fig. IIb usually dominates the strict SM one of fig IIa.



IIa



IIb

Then

$$\varepsilon = \varepsilon_{SM} + \varepsilon_{LR} \approx \varepsilon_{LR} \tag{4.1}$$

where

$$\varepsilon_{LR} \approx \; e^{i\pi/4}\, 0.36\; r\; \sin\alpha\; f(\frac{M_{W_R}}{1.4\mathrm{TeV}}, m_q, ...) \tag{4.2}$$

which together with (3.11) shows the connection between the BAU and low energy CP violation. To our knowledge such a relation is impossible in any other model of EW baryogenesis. The price to pay is a low LR symmetry breaking scale (not very natural in a GUT context) and a rather sophisticated dynamic of the universe (late time inflation).

Is it possible to be more predictive ? Besides theoretical uncertainties in the estimate of the BAU, there are limitations to the predictivity of our relation. We cannot at this level discriminate between a discrete set of models that give the same baryon asymmetry but different values for ε'/ε. Clearly more experimental results are needed to sharpen the relation between the BAU and other CP violating observables.

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