Standard Model Baryogenesis revived with Horizontal Symmetries

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Plan of the talk

- Electroweak baryogenesis – close but no cigar
- Large cosmological variation of couplings
- Connecting to the flavor structure of the standard model
- The New SM baryogenesis scenario
- Conclusion and future work

Summary of main results

- Common Wisdon: additional sources of CP violation are needed beyond the standard model

  Will show: enough CP in the standard model. Bottle-necks can be alleviated in other ways.

- The mechanism is natural in a cosmological scaling.

  There is one high energy scale M. Otherwise all dimensionless parameters which we do not observe in the SM are of order 1.

- Generalizes to SUSY models. Relaxes baryogenesis constraints on the MSSM.

Sakharov's Criteria

- Baryon number violation
- CP and C violation
- Departure from thermal equilibrium

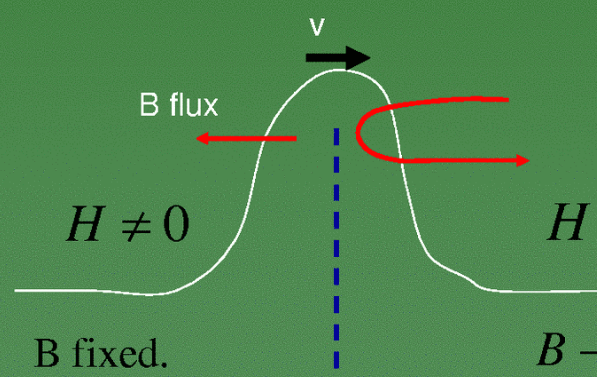
All of these occur in the standard model.

But these effects are not strong enough in the Standard model to make enough baryons.

SM Baryogenesis

Off equilibrium: Electroweak phase transition $H = 0 \rightarrow H \neq 0$

C, CP, B are violated in the SM (explicitly + Sphelaron processes)



Sphelaron processes suppressed | Sphelaron processes unsuppressed

Basic SM suppression factor 1

The two problems of the Standard model are quantitative, not qualitative.

- Any process which relies on CP violation from the KM matrix is proportional to

(*) $$\prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2) J_{cp} \qquad J_{cp} \approx 10^{-5}$$

For the EWPT, the relevant scale is $T_c \approx 100 GeV$

The dimensionless ration $(*)/T_c^{12} \sim 10^{-19}$

Basic SM suppression factor 1

Main lesson:

$$\frac{\prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2)}{T_c^{12}} J_{cp}$$

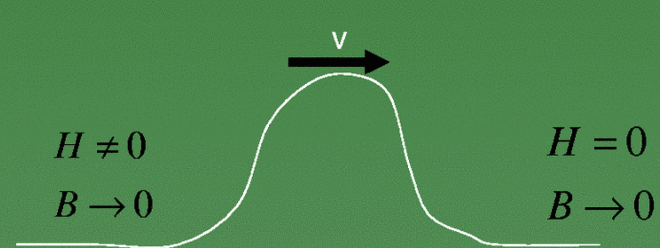
Suppression in the SM is (mostly) due to the hierarchy of masses in the flavor sector.

The modification suggested is related to the flavor structure of the theory.

Basic SM suppression factor 2

- The phase transition is not strongly first order enough for the current lower bounds on the Higgs mass.

Technical meaning: sphelaron processes are not suppressed after the phase transition. Baryon asymmetry is washed out.



The bound for strong 1st order phase transition is m_H<approx. 50Gev

Basic SM suppression factor 2

Currently $m_H \geq 114GeV$ We need $m_H \leq 50GeV$

Main lesson: had the standard model's parameters been different by (multiplicative) order 1, we might have been ok.

Variation of couplings

For concreteness, consider a scalar field coupled to the Standard model by high dimensional operators suppressed by some high scale M. For example

$$V(\Phi,\Phi^{\perp};H,H^{\perp}) = \quad ...+\mu^2\cdot F_\mu\left[|\Phi|^2/M^2\right]|H|^2+\lambda\cdot F_\lambda\left[|\Phi|^2/M^2\right]|H|^4$$

Very natural from theoretical point of view:

- String theory moduli.
- Φ couples to SM through some particles of mass M.
- Scalars in SUSY extension of the SM.

For example, $\mu^2 F_\mu(|\Phi|^2/M^2)|H|^2 \approx M_p^2 e^{-\frac{\#}{g^2}+\hat{F}(|\Phi|^2/M^2)}$
can come from 1-loop corrections

Usually has little consequence for the SM (or similar theory) at late times. Late times = $T=M_w$

Rough argument: the potential for **Φ** will be of the form

$$V = M_w^4 F(|\Phi|^2 / M^2)$$

If the scalar field is in the minima's basin of attraction, then it will remain fixed until

$$T^4 / M_p^2 = H \approx M(\Phi) = M_w^4 / M^2$$

So T(sliding)>>M_w. By the time T=M_w, **Φ** is very close to its true minima. (M<<M_p to avoid the moduli problem)

Large variation of couplings

This argument misses the fact that the potential can vary in time. Large variations can occur when the field closes traces its time dependant minuma, but the latter has large variations in time.

For example in our case

$$V(\Phi,\Phi^{\perp};T) =$$
$$M_w^4 \cdot F(|\Phi|^2 / M^2) + \mu^2 \cdot F_\mu\left[|\Phi|^2 / M^2\right] |H(T)|^2 + \lambda \cdot F_\lambda\left[|\Phi|^2 / M^2\right] |H(T)|^4$$

H(T) jumps at T_c from 0 to v.

Large variation of couplings

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$$M_w^4\cdot F(|\Phi|^2/M^2)+\mu^2\cdot F_\mu\left[|\Phi|^2/M^2\right]|H(T)|^2+\lambda\cdot F_\lambda\left[|\Phi|^2/M^2\right]|H(T)|^4$$

H(T) jumps at T_c from 0 to v.

$$T>T_c \qquad V(|\Phi|^2)=M_w^4\cdot F(|\Phi|^2/M^2)$$
$$\Rightarrow$$
$$T<T_c \qquad V(|\Phi|^2)=M_w^4\cdot F_2(|\Phi|^2/M^2)$$

At the EWPT, the minima of the effective potential jump. The VEV of Φ will jump as well. Φ/M will jump by order 1.

➔ The couplings in the SM, for example $\mu^2\cdot F_\mu\left[|\Phi|^2/M^2\right]$, $\lambda\cdot F_\lambda\left[|\Phi|^2/M^2\right]$ will change by a multiplicative factor, in this case of order 1.

The SM satisfies all of Sakharov's criteria. The devil was in the couplings.

But there is no reason for the couplings to be the same during baryogenesis and today. Could they have been different enough during the phase transition to allow efficient baryogenesis ?

The main idea is to make the factor

$$\prod_{\substack{i>j\\u,c,t}}(m_i^2-m_j^2)\prod_{\substack{i>j\\d,s,b}}(m_i^2-m_j^2)J_{cp} \qquad J_{cp}\approx 10^{-5}$$

large during EWPT. What is the cleanest way to arrange this ?

Flavor structure ⟷ Horizontal Symmetry

↓

Baryogenesis

The Froggatt-Nielsen mechanism:

1. assume an abelian symmetry (Z_N).
2. Different generations carry different charges under the symmetry.
3. The symmetry is broken by a VEV of the field Φ (of charge -1), and communicated to the SM by integrating out particles of mass M.

Denote ε=Φ/M. The Yukawa terms in the SM Lagrangian look like

$$L = \ldots + \hat{Y}^u_{ij}\varepsilon^{q(H)+q(Q_i)+q(\bar{u}_j)} H Q_i \bar{u}_j + \hat{Y}^d_{ij}\varepsilon^{q(H^\perp)+q(Q_i)+q(\bar{d}_j)} H^\perp Q_i \bar{d}_j + ..$$

The coefficients are numbers of orders 1. The observed Yukawas are these numbers times appropriate powers of ε, as determined by the charge assignment. For example:

$Q_1(+3)$	$Q_2(+2)$	$Q_3(0)$	⟶	$Y_u \approx \varepsilon^7$	$Y_c \approx \varepsilon^3$	$Y_t \approx 1$
$\bar{u}_1(+4)$	$\bar{u}_1(+1)$	$\bar{u}_1(0)$	⟶	$Y_d \approx \varepsilon^6$	$Y_s \approx \varepsilon^4$	$Y_b \approx \varepsilon^2$
$\bar{d}_1(+3)$	$\bar{d}_2(+2)$	$\bar{d}_3(+2)$		$s_{13} \approx \varepsilon^3$	$s_{23} \approx \varepsilon^2$	$s_{12} \approx \varepsilon$

Fits ε~0.2

CP violation suppression = $\varepsilon^{28} m_t^{12} / T_c^{12} \approx \varepsilon^{28}$

Now we can make baryons:

- The couplings of the Φ field of the Froggatt-Nielsen mechanism are precisely what we discussed in the section about large variation of couplings
- It may therefore have very different VEV's before and after the EWPT.
- After the phase transition we impose $\varepsilon \sim \Phi/M \sim 0.2$
- Before the phase transition, dimensional analysis $\varepsilon \sim \Phi/M \sim 1$
- At the EWPT wall, $\varepsilon \sim \Phi/M \sim 1$. What used to be a SM suppression factor of about 10^{-19} is now 1.

Estimates of Baryon number

We number of baryons we observe today $\left.\frac{n_B}{s}\right|_{observed} \approx 10^{-10} - 10^{-11}$

The "standard" Standard model $\left.\frac{n_B}{s}\right|_{SM} \approx 10^{-26} - 10^{-27}$

Standard model + time var. hor. symm. $\left.\frac{n_B}{s}\right|_{SM+time\ \mathrm{var}} \approx 10^{19} \cdot \left.\frac{n_B}{s}\right|_{SM} \approx 10^{-7} - 10^{-8}$

Loose ends

1. Exists a range of M for which there is no moduli decay problem $M<10^7$GeV

2. All uncharged parameters in the SM change by multiplicative order 1 number, all charged parameters can change by much more ➔ can make the SM phase transition 1st order enough.

Caveats

1. The details of the dynamics at the domain wall are very intricate. Full analysis not carried out yet. But

- We relied on dimensional analysis.
- One can ask what is the maximal value of ε in which we are still in the regime of the "thin wall" approximation. Not clear yet – seems to give a suppression factor of order 10^{-3}. Still the same range as observation.

2. Rely on terms like ε^{28}. Changes in ε change the estimates by a lot ➔ 10^{19} can change by a few orders of magnitude.

Summary

- Combining horizontal symmetry + dynamics of the Froggatt-Nielsen field in the early universe → lead to a new baryogenesis scenario.
- Flavor structure + time variations are combined in a natural way.
- Expect large variation of couplings to be able to provide other interesting solutions to cosmological problems.
- Can we really use constraints from the very early universe on the SM, or any extension of the SM ?