CP violation and cosmology

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1 Introduction

CP violation may have played a crucial role in the formation of matter in the universe. It must have, if the inflationary cosmology is right, thus ruling out the (very unpalatable) possibility that the baryon asymmetry was an initial condition of the Big Bang. If inflation took place, as most of us believe based on the growing observational evidence, it made the universe devoid of matter and set the stage for reheating. The baryon asymmetry then must have been produced at some later point through CP-violating processes.

2 CP violation and electroweak baryogenesis

That CP, as well as C and B must be broken for baryogenesis to work, was first noted by Sakharov [1]. In 1967 the only reason for considering the baryon number violation was theorists' ambitions. Neither experiment, nor favored theoretical models supported this hypothesis. In addition to breaking the symmetries, one needs an out-of-equilibrium state of the universe to generate the asymmetry.

The advent of the Standard Model and 't Hooft's discovery of a baryon number violating instanton provided a requisite source of B violation. The Standard Model also incorporates C, P, and CP breaking. Although the baryon number violation is highly suppressed in the Standard Model at zero temperature, Kuzmin, Rubakov, and Shaposhnikov [2] realized that at high temperatures the baryon number violating processes could go unsuppressed. In addition, the universe might be out of thermal equilibrium at the time of the electroweak phase transition. Hence, Kuzmin, Rubakov, and Shaposhnikov [2] put forth a very plausible and appealing possibility that the baryon asymmetry might arise from the Standard Model physics, at the time of the electroweak phase transition [3].

Unfortunately, in the minimal Standard Model, this scenario does not work. First, the phase transition is too weak, unless the Higgs mass is $M_{_H} < 45$ GeV, which is ruled out by experiment. Second, the CP violation from the CKM matrix makes a vanishing contribution to baryon asymmetry because it is suppressed by a product of Yukawa couplings [5].

Baryogenesis in the supersymmetric extensions of the Standard Model is less problematic because the additional scalar states can provide both the new sources of CP violation [6, 7, 8, 9] and a way to make the phase transition more strongly first-order [11, 12, 13]. The phase transition is stronger if one of the stops is very light [12]. The new sources of CP violation may come, for example, from the chargino mass matrix:

$$\overline{\psi}_R M_\chi \psi_L = (\overline{\widetilde{w}^+},\ \overline{\widetilde{h}_2^+})_R \begin{pmatrix} m_2 & gH_2(x) \\ gH_1(x) & \mu \end{pmatrix} \begin{pmatrix} \widetilde{w}^+ \\ \widetilde{h}_1^+ \end{pmatrix}_L + \text{h.c.} \qquad (1)$$

As long as m_2 and μ are complex, spatially varying phases in the bubble wall provide a source of (spontaneous) CP violation [10, 7]. The remaining window for electroweak baryogenesis in the MSSM is very narrow [4]; several parameters must be adjusted to maximize the resulting baryon asymmetry (in particular, one must assume that the wall is very thin, take $\tan\beta < 3$, and choose the "optimal" bubble wall velocity $v_w \approx 0.02$), as shown in Fig. 1.

CP violation from the chargino sector (1) may enhance the B_s mixing as compared to the Standard Model value [14], especially if the stop is light (Fig. 2). In practice, however, this effect is observable only if the CKM matrix elements are known to a very high precision. In particular, one would need to reduce theoretical uncertainties in V_{ub} to 5-10% and in $\sin 2\beta$ to a few percent.

3 CP violation and leptogenesis

If a lepton asymmetry of the universe formed after inflation but before the electroweak phase transition, the sphalerons, which violate B and L but preserve $(B-L)$, would convert (roughly, a half of) the lepton asymmetry into a baryon asymmetry. This observation gave rise to an extremely appealing scenario of leptogenesis [15]. The relevant CP violation may reside in the neutrino mass matrix, which, in general, has a number of complex phases [16, 17].

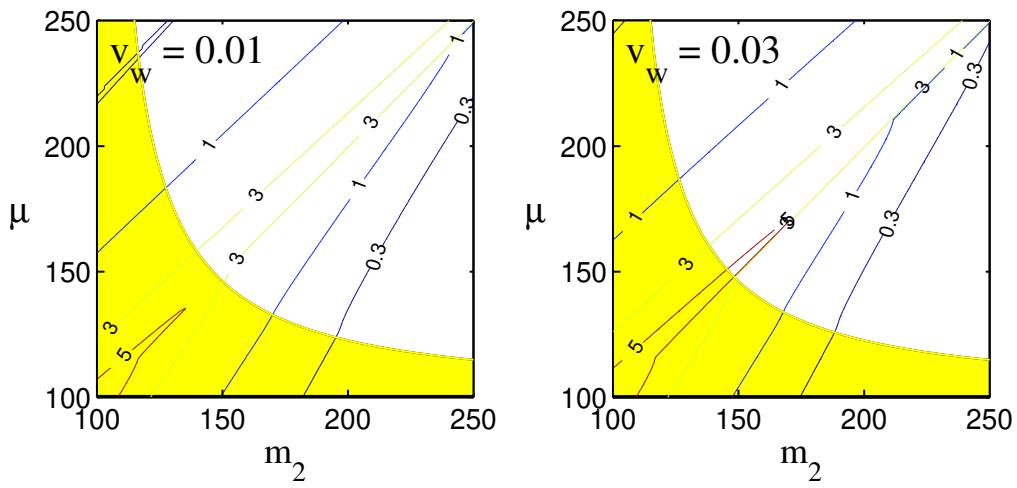


Figure 1: Contours of constant baryon asymmetry in units 10^{-10} with $\sin\delta_\mu = 1$ for (a) $v_w = 0.01$ and (b) $v_w = 0.03$. Mass units are GeV/c^2. Shaded regions are excluded by the LEP2 limit on the chargino mass, $m_{\chi^\pm} > 104$ GeV/c^2. To maximize the baryon asymmetry, one assumes that $\tan\beta \lesssim 3$ and that the bubble wall is very narrow, $\ell_w \simeq 6/T$. From J.M. Cline et al. [4].

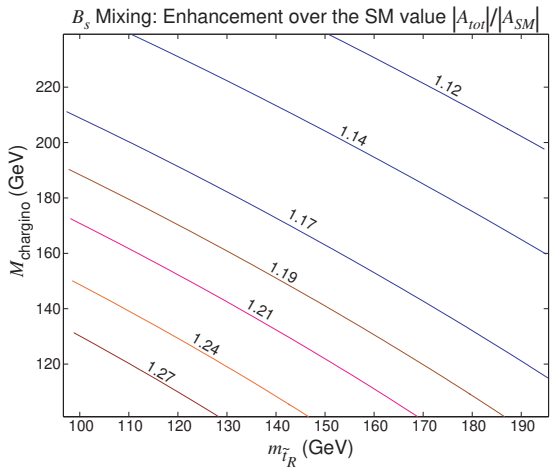


Figure 2: Enhancement of B_s in the MSSM, for parameters consistent with electroweak baryogenesis [14].

4 Transient CP violation, baryogenesis, and dark matter

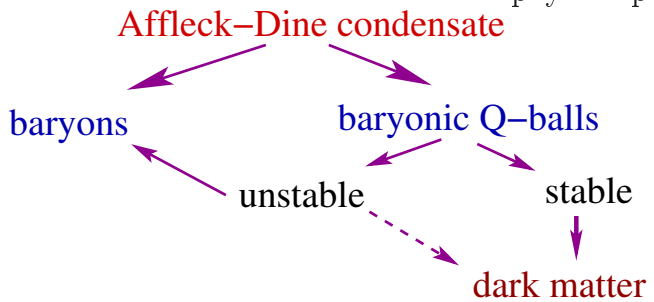
In addition to CP violation hard-wired into the lagrangian, some manifestations of CP non-conservation may occur for a short period of time in the early universe, during which time the baryon asymmetry might have formed. A well-know example is the Affleck-Dine scenario for baryogenesis [18, 19], in which CP violating seeds may be effectively amplified by the motion of the scalar condensate. Similarly, electroweak baryogenesis at preheating [20, 21, 22, 23] can take advantage of CP-violating motions of time-dependent condensates during preheating [23]. CP violation of this kind is poorly constrained by experiment because it becomes small after thermalization.

4.1 Affleck-Dine baryogenesis and dark-matter-genesis

In models with low-energy supersymmetry inflation can lead to formation of the Affleck-Dine condensate [18, 19] with a large VEV. A high-scale physics undoubtedly violates B and CP through higher-dimension operators. Hence, the motion of the scalar condensate after inflation is not B and CP symmetric. Thus, the universe acquires a baryon asymmetry. The Affleck-Dine scenario [18] is simple, appealing, and flexible in that the final baryon asymmetry can easily be made consistent with the data.

In addition, the Affleck-Dine baryogenesis can produce dark matter as well. In general, the Affleck-Dine condensate does not remain homogeneous and can break up [24] into SUSY Q-balls [25]. This affords a number of interesting possibilities for generating baryons and dark matter simultaneously [24, 26, 27].

Since baryons and dark matter arise form the same physical process,



the ratio of $\Omega_{\rm dark}$ to Ω_B may have a natural explanation in some models [28].

4.2 Electroweak baryogenesis at preheating

Several viable scenarios for electroweak baryogenesis at preheating were presented in Ref. [23]. For example, a modified spontaneous baryogenesis a la Cohen, Kaplan, and Nelson [7] becomes very efficient at preheating. Their original scenario used

the variation of the Higgs field inside a wall of a bubble formed in a first-order phase transition. A similar effect can occur at preheating uniformly in space, on the horizon scales [23]. One can obtain the desired baryon asymmetry in a Standard Model supplemented by an additional Higgs doublet and an inflaton sector [23]. The difference with the scenario proposed by Cohen, Kaplan and Nelson [7] is that in our case CP violation occurs homogeneously in space, not only inside a bubble wall. In addition, the final prediction for the baryon asymmetry in the CKN scenario was very far from the equilibrium value because the sphaleron rate was slow on the time scales associated with the growth of bubbles. In the case of preheating, the Higgs parameters change slowly in time while the baryon number non-conservation is rapid. This allows a slow adiabatic adjustment of the baryon number to that which minimizes the free energy.

Several additional sources of CP violation might affect the physics of preheating and facilitate baryogenesis [23].

5 Strong CP violation and the axion cosmology

The QCD vacuum is a superposition $|\theta\rangle = \sum_n \exp\{-in\theta\}|n\rangle$ of topologically distinct vacuum states $|n\rangle$. As a result, the QCD Lagrangian can be written as

$$\mathcal{L}_{QCD} = \mathcal{L}_{\rm pert} + \overline{\theta}\frac{g^2}{32\pi^2}F\tilde{F}, \tag{2}$$

where

$$\overline{\theta} = \theta + \arg\det M \tag{3}$$

Experimentally, the value of $\overline{\theta}$ must vanish to a high precision, $\overline{\theta} \ll 10^{-10}$. However, if all the quarks have non-zero masses, there is no (simple) reason why the phase in the Yukawa matrix should cancel the QCD vacuum phase, unless $\overline{\theta}$ relaxes to zero dynamically, by a VEV of a scalar field. This elegant solution to the strong CP problem was proposed by Peccei and Quinn [29]. The breaking of a global U(1) symmetry gives rise to a light scalar field, the axion [30].

Several models can accommodate an axion consistent with the existing experimental bounds [31]. A light, weakly interacting axion makes a good candidate for dark matter. The present experimental limits are shown in (Fig. 3).

6 Conclusions

There is every reason to believe that matter-antimatter asymmetry is a consequence of CP non-conservation in particle physics. On the other hand, CP violation from

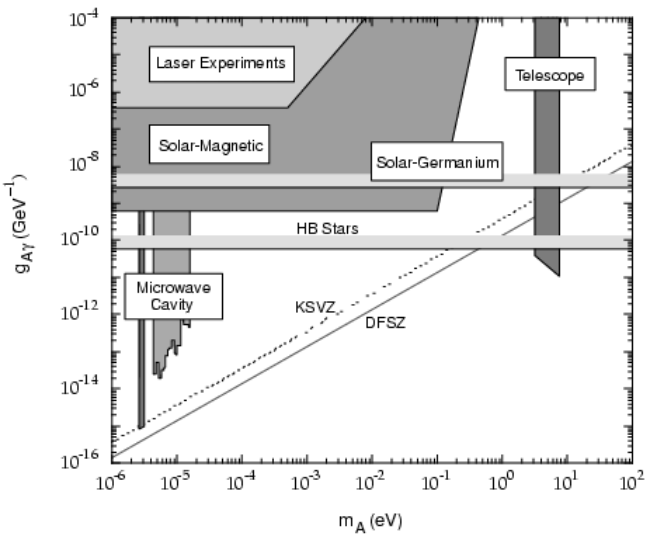


Figure 3: Exclusion regions for the axion mass vs. coupling, from Particle Data Book [32].

the quark mixing is not sufficient for baryogenesis. This implies the existence of new, yet undiscovered, sources of CP violation in nature.

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