Dynamical CP violation in the Early Universe

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Introduction

★ The observed baryon asymmetry (BA) requires CP violation as one of the three Sakharov conditions

★ The standard model of electroweak physics generates a CP asymmetry in the quark sector via the CKM phase

★ The conventional CKM phase generated CP asymmetry is far too small to explain the observed baryon asymmetry in the Universe $\sim 10^{-19}$ (Shaposhnikov’s talk)

★ A CP asymmetric phase generated in the scalar fields in the early Universe could lead to large enough asymmetry to explain the BA

★ The CP phase can be generated when the scalars are excited and inflation provides a large coherent effect

★ The CP asymmetry is dynamical and is determined by the scalar field dynamics
In the simplest scenario consider two scalar fields, $\phi_{\pm}$.

The Lagrangian which describes the interaction can is given as

$$L = -m^2_i \phi_i^\dagger \phi_i + g\phi_-^\dagger \phi_- \phi_+ + h.c.$$}

We take the coupling $g$ to be real $\rightarrow$ the interaction is CP conserving.

The fields $\phi_{\pm}$ can excite complex phase difference, say $\alpha$.

It is very natural for $\alpha \neq 0$ when the fields are in a hot early Universe.

The induced phase difference can give rise to large CP asymmetry (DOLGOV).
Asymmetric initial conditions

★ In the hot early Universe, the excited fields can create a quanta of field via fluctuations

★ In general the field fluctuations
\[ \phi'_- = \phi_- - c_- ; \quad \phi'_+ = \phi_+ - c_+ e^{i\alpha} \] (Kalopers talk)

★ Generically, the initial conditions are asymmetric since \( \alpha \neq 0 \) and \( c_+ \neq c_- \)

★ A new cubic interaction is induced
\[ V_3 = g(c_+ e^{i\alpha} \phi_- \dagger \phi_- \phi_- + c_- \phi_- \dagger \phi_- \phi_- \phi_+ + 2c_- \phi_- \dagger \phi_- \phi_- \phi_+) \]

★ \( V_3 \) can contribute to a two-body CP violating decay

★ The CP asymmetry in the scalar sector can lead to an asymmetry in the number density of the \( \phi_i \) particles

★ The dynamical nature is determined by the dynamics of the field values \( c_\pm \)
The CP violating two-body decay is via the process

\[ \phi^+ \rightarrow 2\phi^- \]

The tree level graph \( \sim g c_+ e^{i\alpha} \) while the loop level graph \( \sim (2g c_-)^2 e^{-i\alpha} \)

The net CP phase difference due to tree and loop interference is \( \sin 2\alpha \)

The decay \( \phi^+ \rightarrow 2\phi^- \) leads to an asymmetry in the number density \( \delta N = N(\phi^-) \neq N(\phi^+) \sim \sin 2\alpha \)

We require \( m_+ \geq 2m_- \) for (i) kinematics and (ii) absorptive contributions
Some additional remarks

★ The background field values $[c_-, c_+]$ in general are non-zero and hence support a CP asymmetry
★ The asymmetry is expected to occur after inflation to avoid any dilution
★ The requirement $\sin 2\alpha \neq 0$ is extended coherently over a large Hubble patch due to inflation and hence is not washed out due any conceivable averaging of the CP phase
★ The time dependence of the asymmetry is determined by the time evolution of the backround values $c_\pm$
★ In the slow-roll approximation

$$\dot{c}_\pm \approx -\frac{1}{3H} \frac{dV}{d\phi_\pm} \bigg|_{\phi_\pm = c_\pm}$$
Transfer of the asymmetry to fermions

- The scalar asymmetry $\delta N$ can be transferred to fermions
- A fermion asymmetry can be achieved via the Yukawa interaction
  $$Y = \bar{\psi}_L \phi_\sigma \psi_R + \text{h.c.}$$
- The interaction leads to the decays:
  $$\phi_\sigma \rightarrow \bar{\psi}_R \psi_L \text{ and } \phi_\sigma^\dagger \rightarrow \bar{\psi}_L \psi_R$$
- The decay leads to an asymmetry in the left-handed fermion number density
- The asymmetry: $\delta N_f = N(\bar{\psi}_L) - N(\psi_L) \sim \delta N \cdot \Gamma$
- The asymmetry is possible only if fermions are Dirac!
The left-handed fermion asymmetry can be transferred to a Dirac leptogenesis (Lindner et al.,)

The decay of $\phi_-$ to fermions leads to a lepton asymmetry

$$Y_l \sim \sin 2\alpha \Gamma = y_l \sin 2\alpha \frac{y_l^2 c}{8\pi}$$

The chances that the fermion asymmetry does not equilibrate are only if $y_l \ll 1$

The condition is easily satisfied if we choose $\phi_-$ to decay into Dirac neutrinos

The Dirac neutrino asymmetry is then converted to a baryon number asymmetry via sphaleron processes giving rise to:

$$Y_B \propto Y_l$$ where the proportionality is determined by the particle spectrum in a given model
Conclusions

- Early Universe can induce a large enough CP violation via initial conditions which are generic.
- Inflation redshifts this asymmetric initial conditions starting from a tiny region to a large Hubble patch.
- To generate a lepton asymmetry, it is preferable to have Dirac neutrinos since their small Yukawa couplings will ensure no wash-out of the generated asymmetry.
- The baryon asymmetry is generated via Dirac leptogenesis \( \leftrightarrow \) asymmetric scalar density.
- Other alternatives are viable for generating a baryon asymmetry using asymmetric initial conditions.
- The dynamical nature of the asymmetry depends on the background evolution of the fields and hence on the values \( c_\pm \).