Aspects of CP violation in electroweak baryogenesis

Kaori Fuyuto
Saga University

In collaboration with Junji Hisano and Eibun Senaha


10 May, 2016
At Pheno 2016
Outline:

1. Introduction of Electroweak Baryogenesis

2. Relationship between the BAU and EDMs

3. Situation where BAU-unrelated CP phase exists

4. Conclusion
Introduction
Baryon Asymmetry of the Universe (BAU)

Observational facts indicates that our Universe is baryon-asymmetric.

\[ Y_B \equiv \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11} \]

P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076

One attractive scenario is

**Electroweak Baryogenesis (EWBG).**

Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)

Collider experiments and Electric Dipole Moments (EDM) can verify this scenario.

* Since LHC is running, it is urgent issue to clarify its possibility.
Baryon Asymmetry of the Universe (BAU)

Observational facts indicates that our Universe is baryon-asymmetric.

\[ Y_B \equiv \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11} \]

P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076

It turns out that the SM EWBG was ruled out.

- CP violation is too small to generate the BAU.
  

- EWPT becomes crossover for \( m_h > 73 \text{ GeV} \).

  Csikor et al, PRL 82, 21 (1999); Aoki et al, PRD 60, 013001 (1999)
  Laine et al, NPB 73, 180 (1999)
New physics


For the successful EWBG, physics beyond the SM is needed.

New Physics for EWBG

First order EWPT

CP violation
For the successful EWBG, physics beyond the SM is needed.

**New Physics for EWBG**

- **CP violation**: $\phi_{\text{BAU}}$
- **Two new fermions**
  - Dirac: $\left( \begin{array} \psi^+ \\ \psi_i \end{array} \right)$
  - Majorana: $\psi_j$
- SU(2) doublet
- Scalar for EWPT
- Fermion for CP violation
New physics

Particle contents

New Physics for EWBG

First order EWPT
Real singlet
\( S \)

CP violation : \( \phi_{\text{BAU}} \)

Two new fermions
Dirac : \( \begin{pmatrix} \psi^+ \\ \psi_i \end{pmatrix} \)
Majorana : \( \psi_j \)

SU(2) doublet

Two Higgs doublet : \( \Phi_1, \Phi_2 \)

UV complete model : NMSSM, U(1)' MSSM etc.
- Relationship between the BAU and EDM
- Possibility of EWBG
BAU and EDMs
CP violating process

Interactions between bubble wall and new fermions:

\[ \mathcal{L} = \frac{1}{\sqrt{2}} \bar{\psi}_i (c_L v_2 P_L + c_R v_1 P_R) \psi_j + \text{h.c.} \]

- \( c_{L,R} \): Complex number
- (BAU-related physical CP phase: Im[\( c_L c_R^* \)])
- \( v_{1,2} \): Space-dependent Higgs VEV

![Diagram of CP violating process](image)
CP violating process and EDM

BAU-related CP phase can induce two Barr-Zee diagrams.

\[ \mathcal{L} = \frac{1}{\sqrt{2}} \bar{\psi}_i (c_L v_2 P_L + c_R v_1 P_R) \psi_j + \frac{1}{\sqrt{2}} \bar{\psi}^+ (c_L^+ \phi_2^+ P_L + c_R^+ \phi_1^+ P_R) \psi_j \]

\( c_L^+ (R) \) is related to \( c_L (R) \) in SU(2), \( c_L^+ (R) = -c_L (R) \).
BAU and electron EDM

Input parameter:  \(|c_L| = |c_R| = 0.42, \quad \phi_{BAU} \equiv \phi_L - \phi_R = 225^\circ\)

Electron EDM constraint (Pink region):  \(|d_e^{\text{exp}}| < 8.7 \times 10^{-29} \text{ e } \cdot \text{ cm}\)

Black solid:  \(Y_B/Y_B^{\text{obs}} = 1\)

Black dashed:  \(Y_B/Y_B^{\text{obs}} = 0.1\)

- Degenerate masses lead to the successful BAU.
- If \(d_e = 1.0 \times 10^{-29} \text{ e } \cdot \text{ cm}\) is achieved, this scenario can be verified.
New physics


Concrete model

New Physics for EWBG

First order EWPT

Real singlet $S$

CP phase: $\phi_{BAU}$ $\phi_{\lambda H}$

BAU-related

both $\phi_{BAU}$

EDM-related $\phi_{\lambda H}$

The other CP phase comes from the interaction between singlet and charged fermions.

$$\mathcal{L} \ni h_S \bar{\psi}^+ (g^S + i\gamma_5 g^P) \psi^+$$

$$g^S = |\lambda| \cos \phi_{\lambda H}$$

$$g^P = -|\lambda| \sin \phi_{\lambda H}$$
BAU-unrelated CP phase

The total number of Barr-Zee diagrams are four.

\[ d_f^{WW} + d_f^{H \pm W \pm} + d_f^{H \gamma} + d_f^{HZ} \]

EDM: \[ d_f^{\text{sum}} = d_f^{WW} + d_f^{H \pm W \pm} + d_f^{H \gamma} + d_f^{HZ} \]

Cancellation between CP phases exists, which leads to \[ d_e^{\text{sum}} = 0 \].
BAU-unrelated CP phase

The total number of Barr-Zee diagrams are four.

Even if \( d^\text{sum}_e = 0 \), this scenario can be verified by

- Signal strength of the Higgs decay to two gammas, \( \mu_{\gamma\gamma} \)
- Other EDMs such as neutron and proton
Numerical results

Verifiability by EDMs and signal strength

Electron EDM: \[ d_{e}^{\text{sum}} = d_{e}^{WW} + d_{e}^{H^{\pm}W^{\pm}} + d_{e}^{H\gamma} + d_{e}^{HZ} \]

Input parameters:
- \( m_{\psi_i} = 300 \text{ GeV} \)
- \( m_{\psi_j} = 277 \text{ GeV} \)
* BAU can be explained.

Pink region:
Excluded by electron EDM

Grey line: \( \mu_{\gamma\gamma} \)
\( H_1 \to 2\gamma \) Signal strength
Verifiability by EDMs and signal strength

Electron EDM: \( d_e^{\text{sum}} = d_e^{WW} + d_e^{H\pm W\pm} + d_e^{H\gamma} + d_e^{HZ} \)

Light pink region:
Excluded if electron EDM reaches
\[ d_e = 1.0 \times 10^{-29} \text{ e \cdot cm} \]

White region: Still allowed
Neutron and Proton EDMs

The cancellation region can be covered by neutron and proton EDMs.
Conclusion

- EWBG can be verified by the collider experiments.
  Current situation is ripe for verification of EWBG.

- New Physics is needed for successful EWBG.
  We consider

- The degenerate masses of fermions lead to the successful BAU.
- The EDMs and Higgs physics can verify it in near future.
BACKUP
Particle contents

Particle contents are NMSSM-like.

<table>
<thead>
<tr>
<th>Scalars</th>
<th>$\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$</th>
<th>$Z_2$</th>
<th>$\Phi_1$</th>
<th>$\Phi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_1$</td>
<td>$(1, 2, 1/2)$</td>
<td></td>
<td>$(\phi_1^+)$</td>
<td>$(\phi_0^0)$</td>
</tr>
<tr>
<td>$\Phi_2$</td>
<td>$(1, 2, 1/2)$</td>
<td>$+$</td>
<td>$(\phi_2^+)$</td>
<td>$(\phi_0^0)$</td>
</tr>
<tr>
<td>$S$</td>
<td>$(1, 1, 0)$</td>
<td>$-$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fermions</th>
<th>$\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$</th>
<th>$Z_2$</th>
<th>$\tilde{\Phi}_1$</th>
<th>$\tilde{\Phi}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\Phi}_1$</td>
<td>$(1, 2, -1/2)$</td>
<td></td>
<td>$(\tilde{\phi}_1^0)$</td>
<td>$(\tilde{\phi}_1^+)$</td>
</tr>
<tr>
<td>$\tilde{\Phi}_2$</td>
<td>$(1, 2, 1/2)$</td>
<td>$+$</td>
<td>$(\tilde{\phi}_2^0)$</td>
<td>$(\tilde{\phi}_2^0)$</td>
</tr>
<tr>
<td>$\tilde{S}^0$</td>
<td>$(1, 1, 0)$</td>
<td>$-$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Parameters are set in such a way as to take the limit of the real-singlet model.
Neutron EDM と Proton EDM

Neutron EDM

\[ |d_n| = 4.0 \times 10^{-28} \text{ e \cdot cm} \]

Proton EDM

\[ |d_p| = 3.0 \times 10^{-28} \text{ e \cdot cm} \]
Electron EDM

\[ \lambda = 0.2 \quad \phi \lambda H = -90^\circ \]