Baryon Asymmetry:
Evidence of CP Violation and
Phase Transition in the Early Universe ?

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Abstract

A talk was given on the baryon asymmetry of our universe within the electroweak energy scale which was the theme for the 23rd INS Symposium. It was intended for non-experts by a non-expert speaker. A model is analyzed explicitly in which the lepton number produced from the bubble walls is converted afterwards to the baryon asymmetry. Phase transition dynamics is simulated, including the temporal development and the fusion effect of the nucleated bubbles.

1invited talk given at 23rd INS Symposium on Nucleon and Particle Physics with Mesons Beams in the 1Gev/c region
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A Introduction

Baryon Asymmetry is the problem to explain why baryons (constituents of the matter) dominate asymmetrically over anti-baryons (those of the anti-matter) in our present universe, $n_B \gg n_{\bar{B}}$, and to give the number $n_B/n_\gamma \sim 10^{-8} \sim 10^{-10}$. \cite{1} $n_B$ , $n_{\bar{B}}$ , and $n_\gamma$ are respectively the number densities of baryon, anti-baryon, and photon in our present universe.\[ Let us roughly, very roughly estimate the number;\]

- Baryon number $\sim 10^{-8} \text{Nucleons}/cc$ coming from:
  - the average distance between galaxies : $6Mpc$
  - the number of stras of the sun type including a galaxy : $3 \times 10^{11}$
  - the mass of the sun : $2 \times 10^{33}g$

- Photon number $\sim 400\text{photons}/cc$ coming from:
  - cosmic Back Ground radiation $2.7K$

Here the difficult problems on the dark matter and the helium synthesis are of course ignored. First recognize that a naive discussion on this problem gives a difficulty. Naive means that at high temperature we have thermal distribution of $n_B = n_{\bar{B}} = 3/4 \cdot n_\gamma$. According to the cooling down of the universe, baryons and anti-baryons annihilate each other, resulting non-baryonic mesons. But, at about the temperature $T \sim 20MeV$ the annihilation stops, where the reaction rate becomes much less than the expansion rate of the universe, namely, the reaction cannot catch up with the expansion. The ratio is then freezed, giving $n_B/n_\gamma = n_{\bar{B}}/n_\gamma \sim 10^{-17}$ which is, however, too small. Therefore, something should be added in order to explain the observed data on the baryon asymmetry. These are the A.D.Sakharov’s conditions \cite{1}: These are (1) existence of the baryon number $B$ violating interactions, (2) existence of the $CP$ and $C$ violations, and (3) existence of the thermal non-equilibrium. (1) raises the number from $10^{-17}$ to $10^{-10}$, (2) makes the difference between $B$ and $\bar{B}$, and (3) supressed the inverse reaction of the $B$ number producing one. $C$ is always violated in the weak interaction so that CP violation is more important. Now the baryon asymmetry is the evidence of these three conditions.

In 1978, M.Yoshimura, S.Weinberg, and other people \cite{2} invented the GUT’s scenario baryon asymmetry, where $B$ is supplied by the heavy $(10^{16}GeV)$ Higgs’ decay $X \rightarrow \bar{q} + \bar{q}$ and $q + l$ , CP violation is given by the complex phase in the Yukawa couplings, and the thermal non-equilibrium is realized by the heavy particles’ decay, the inverse reaction of which is naturally supressed at the lower temperature.
B Electroweak Baryogenesis

The GUT’s baryogenesis is the physics of 10^{16}GeV. We wishes to go down to the lower energy scale, say 100GeV of the electroweak energy scale, in order to be included in this 23rd INS Symposium. This is called Electroweak Baryogenesis after the work by Kuzmin, Rubakov, and Shaposhnikov [3] (’85).

One of the motivations is of course the energy scale of 100GeV is the experimentally familiar place. The other motivation comes from the SPHALERON given by Manton [4] (’83) and Klinkhammer and Manton [5] (’84). I did a similar work [6] (’83), using Nambu’s solution of the monopolium. Important ingredient is the chiral anomaly. Anomaly means the violation of the charge conservation in the presence of the topologically non-trivial gauge field configurations. Without the configurations, B and L conserve exactly. However, in the presence of a topologically entangled non-trivial gauge configuration classified by the integer number \( N_{Chern-Simons} \) (\( N_{C-S} \)), conservation of B and L is violated. Instead we have \( \{ B \ or \ L \} - N_g \cdot N_{C-S} = \) conserves. \( N_g \) is the number of the generations. If you are the nuclear physists, let’s think of the Skyrmion, where the nontrivial (entangled) configuration of the meson fields gives the proton having the baryon number. Here the Skyrmion-like objects are the vacua having zero energy, which are classified by the integer numbers of \( N_{C-S} \). Now the Sphaleron is the saddle point solution of the Weinberg-Salam model, located in between the two different vacua, having the energy of about 10TeV with \( N_{C-S} = 1/2 \). Therfore the Sphaleron controls the transition between the two different vacua.

We have the following chemical reaction between three kinds of "atoms";

\[
[B] + [L] + [\text{vacuum, } N_{C-S}] \leftrightarrow [B + N_g] + [L + N_g] + [\text{vac, } N_g - 1]
\]

Sphaleron Transition

B and L are violated, but keeping \( B - L \). We can consider the following two cases:

Case 1. Sphaleron transition rate \( \gg \) expansion rate. Then, the thermal equilibrium is realized, where the equilibrium value is determined by the conserved \( B - L \) as \( < B > = O(1) \cdot < B - L > \). If \( < B - L > \neq 0 \), then \( < B > \neq 0 \), but if \( < B - L > = 0 \), then \( < B > = 0 \). The former mechanism is originally adopted by Fukugita and Yanagida7 [8] (’86), and is used in the unbroken phase of the model in the next section. The latter is the sphaleron’s washing away mechanism.

Case 2. Sphaleron transition rate \( \gg \) expansion rate \( \star \).

In this case, thermal non-equilibrium is realized and we have a possibility of having \( < B > \neq 0 \). But the condition \( \star \) gives a severe constraint of \( m_{H_0} < 45GeV \), compared
with the LEP data of $m_{H_0} > 58\text{GeV}$. We can, however, increase the upper bound by introducing additional bosons. Introduction of the additional singlet Higgs scalar increases the bound up to $150\text{GeV}$ due to Anderson and Hall [9] (`92). We will use this mechanism, which is just the thing wanted, in the broken phase of our model. [The additional Higgs doublet may raise the upper bound to $190\text{GeV}$.]

C The Model

Now, let us examine the model presented by A.G.Cohen, D.B.Kaplan, and A.E.Nelson [10], based on our work [11] performed in collaboration with my student Azusa Yamaguchi. The model is the standard model modified by the see-saw mechanism [12] with the additional singlet scalar $\phi$ and the right-handed neutrinos $N_R$. The vacuum expectation value $< \phi > \neq 0$ violates the L-conservation spontaneously. This $L \neq 0$ introduces the $(B-L) \neq 0$ which is converted to $B \neq 0$ by the fast sphaleron transition of the Case 1 in the unbroken phase where the recovered L-conservation protects the washing away of the produced L (or $B - L$).

The Lagrangian reads

$$\mathcal{L} = -\mathcal{L}(\text{standard model}) + \nu_L, N_R \text{kinetic terms} + \Psi(x)^\dagger M(x)\Psi(x)$$

where

$$\Psi(x) = [\nu_1, \nu_2, \ldots, \nu_G, N_1, N_2, \ldots, N_G]^T$$

In Eq.(2) the mass matrix $M(x)$ is given by

$$M(x) = \left(\begin{array}{cc} 0, & \lambda_D \varphi(x) \\ \lambda_D^T \varphi(x), & \lambda_M \varphi(x)^* \end{array}\right)$$

where the position dependency of the mass matrix $M(x)$ comes from the bubble nucleation in the electroweak phase transition which is of the 1st order (?) at least in the perturbative analysis. The phenomenon is similar to the formation of liquid droplets in the vapor vessel when the temperature is lowered to a certain critical value $T$. Inside the bubble the mass matrix takes the larger value which plays the role of the potential barrier for the incoming neutrinos $\nu_i$ and the anti-neutrinos $\bar{\nu}_i$.

The reflection coefficients $R$ and $\bar{R}$ for the above two processes

$\nu_i \rightarrow \nu_j |\Delta L = -2|$

and $\bar{n}_i \rightarrow \nu_j |\Delta L = 2|$
can be expressed respectively by

\[ R_{ji} = -U^T_{jm} D_m(E) U_{mi} \] (5)

and

\[ \bar{R}_{ji} = U^\dagger_{jm} D_m(E) U^*_{mi} \] (6)

where \( U_{M_{\text{broken phase}}} U^T = \text{diagonal} \), and the analytic expression for \( D_m(E) \) is obtained. The \( L \)-production rate \( D_{ji} \) is now obtained by

\[ \Delta_{ji} = |R_{ji}|^2 - |\bar{R}_{ji}|^2 = -2 \sum_{k \neq l} \text{Im}(D_k D_l^*) \times J^{kl}_{ji}, \] (7)

with

\[ J^{kl}_{ji} \equiv \text{Im}(U_{kj} U_{ki} U_{lj} U^*_{li}) \] (8)

which is the product of the two complex phases, one from the scattering phase shift and the other from the \( CP \) phase, \( J \), expressed similarly as in the Jarlskog’s parameter in the Kobayashi-Maskawa model. In our case \( J \) can be non-vanishing when \( N_g \geq 2 \).

Here another difficulty comes out. Since the universe is so democratic to all the particles, they are in the common thermal distribution in the broken phase, where they are equally massless. In this situation, summation of \( D_{ji} \) over the initial \( i \) or the final \( j \) leads to the no \( L \) number production. This is the CPT theorem or the GIM-like cancellation mechanism. To avoid this difficulty we introduce the thermal mass \( M(T) \) proportional to \( T \), following Farrar and Shaposhnikov [13] ('94).

Thermal averaging of the \( L \)-flux produced from the moving wall is approximately given by

\[ f_L(T^3) \sim (A \ln \gamma + B - C \gamma) \cdot J, \] (9)

where \( A, B, \) and \( C \) are \( O(10^{-3}) \) for an example having 2-generation n’s with the masses \( M_1(T) = T \) and \( M_2(T) = 0.5T \) for \( T = 100 \) or 200 GeV.

Here we should notice that the \( f_L \) depends on the wall velocity \( v_\omega \) (its \( \gamma \) factor is \( \gamma_\omega \)).

\section{The Phase Transition Dynamics}

If the wall velocity \( v_\omega \) is constant, then the total \( L \) number produced reads

\[ N_L = f_L(v_\omega) v_\omega^{-1} \cdot v_\omega A(t) dt, \] (10)
and the L number density is

\[ n_L = f_L(v_\omega)v_\omega^{-1}. \]  \hspace{1cm} (11)

However, \( v_\omega \) is the time-dependent:

\[ v_\omega(t) = \frac{dR(T)}{dt} = 2\Gamma \left( \frac{1}{R_c} - \frac{1}{R(t)} \right) \]  \hspace{1cm} (12)

where \( R_c \) is the critical radius with which the bubble is nucleated. The \( \Gamma^{-1} \) is the friction coefficient \( O(T) \).

Furthermore, the fusion effect of bubbles occurs during the development of the 1st order phase transition. Like the cooling down of the vapor (unbroken vacuum of the electroweak theory), liquid droplets of water (bubbles of the broken vacuum) are nucleated, they fuse with themselves, and finally the whole vessel (the whole universe) is filled up with the water (broken phase): We need to know the temporal development of the total area of the bubble walls from which the L number is produced. It is incredible to know that for such a difficult problem the theory exists, which is called the Kolmogorov-Avrami theory [14], within the restriction of the critical radius \( R_c = 0 \), the wall velocity \( v_\omega = \text{const.} \), and the nucleation rate \( I = \text{const.} \). This restriction should be modified realistically. About the critical radius (the minimum radius of the produced bubble, being obtained from the balancing between the surface energy \( \sim +R^2 \) and the volume energy \( \sim -\epsilon R^3 \)), the latent heat \( \epsilon \) (the difference of the energy inside the broken phase from the one outside the unbroken phase), and the nucleation rate \( I \) (the probability for the small bubble to overcome the surface tension) can be understood from the following: 1-loop effective potential at \( T \)

\[ V = \frac{\lambda T}{4} \phi^4 - E T \phi^3 + D(T^2 - T_0^2) \phi^2 \]  \hspace{1cm} (13)

with

\[ D = \frac{1}{4e^2}(2m_W^2 + m_Z^2 + 2m_t^2) \]  \hspace{1cm} (14)

\[ E = \frac{1}{\sqrt{2\pi v^3}}(2m_W^3 + 3m_Z^3) \]  \hspace{1cm} (15)

\[ T_0 \sim \frac{1}{2\sqrt{D}m_H} \]  \hspace{1cm} (16)

and

\[ \lambda_T \sim \lambda \sim \frac{1}{2}(m_H/v)^2. \]  \hspace{1cm} (17)
Here we encounter another difficulty. What is the phase transition temperature \( T \)? It may be a little lower than the critical temperature \( T_c \) where the latent heat begins to be non-vanishing; \( T = T_c - \Delta \). The value is roughly the mass of the Higgs scalar \( m_H \) (100 or 200 GeV?). In our problem the time scale of the phase transition is \( 10^{-26} \) s since the every parameter involved is the weak scale of \( O(100 GeV) \), whereas the time scale of the expansion rate at the time is \( 10^{-12} \) s.

Therefore

\[
\text{[the time scale of the phase transition]} \gg \text{[the time scale of the expansion rate]}
\]

This means the slowly cooling down (the annealing but not the quenching) of the universe, during which the phase transition undergoes. In order to answer the value \( \Delta \) we should couple the phase transition dynamics with the gravity which is responsible for the cooling down of the universe. [In this respect we are reminded of the Maxwell’s equal area low in the gas-liquid phase transition.]

E  The Simulation

We performed the simulation\(^{10}\) using the KEK and the INS computers, including the time-dependency of the wall velocity as well as the fusion effect of the bubbles. At a proper choice of \( \Delta \) for 100 GeV and 200 GeV, we have the following figures:

Now the total \( L \) number density \( n_L \) can be simulated by

\[
n_L = \sum_i \int f_L(v_i^w)A(t)^i dt/V,
\]

where the summation is carried out over the various segments \( i \) of the bubble walls behaving differently. The result is

\[
n_L/T^3 = \begin{cases} 
\text{ours} & -0.299 \times 10^{-2} \cdot J \\
0.303 \times 10^{-2} \cdot J & \text{Kolmogorov – Avrami} (K – A) \\
0.108 \times 10^{-2} \cdot J & (T_c = 100 GeV) \\
0.209 \times 10^{-2} \cdot J & (T_c = 200 GeV),
\end{cases}
\]

so that we have

\[
n_L(\text{ours})/n_L(K – A) = 2.77/1.45
\]

or the difference of the factor \( 2 \sim 3 \) occurs depending the details of the phase transition dynamics. Here the models adopted are the 2 n’s models given above.
F  Baryogenesis from Leptogenesis

Chemical equilibrium is used to generate the $B$ from the produced $L$ from the bubblewall. This is realized in the unbroken phase (outside of the bubbles) where the sphaleron transition is very rapid (Case 1 of the Sec. 2), but the $L$ number conservation is recovered in this spontaneously broken $L$-conservation model. After $B$ comes into the broken phase (inside of the bubbles which fill up the whole universe in the end of the phase transition), $B$ survives against the washing out mechanism by the sphaleron, since in this region the additional singlet scalar supresses the sphaleron’s effect (Case 2 of the Sec. 2). To reproduce the observed value of the baryon asymmetry, $CP$ violation factor $J$ should be $O(10^{-5} \sim 10^{-7})$.

G  Conclusion

1. In the problem of the electroweak baryogenesis the severe restriction of $m_{H_0} < 45 GeV$ may be avoided with the model of the explicit production of $B - L$, where the spontaneous $L$ violation by the singlet scalar is essential.

2. Simulation of the 1st order phase transition is possible by including the temporal dependency of the bubble-wall’s velocity as well as the fusion effect of the bubbles. By these effects, the total $B$ number produced increases by the factor $2 \sim 3$ from the simple model of Kolmogorov and Avrami.

3. A lot of difficulties, however, exist on the following points:
   - avoidance of the CPT by the introdution of the finite $T$ masses? ;
   - phase transition temperature ? ,
     phase transition dynamics including gravity? ;
   - friction? ,
     effective potential or effective action?,
     sphaleron transition? .

4. How about the reliability of the model and the predicted number? So far so good, but we are still in the middle of producing various models and examining them carefully. It is, however, true that the $CP$ violation really exists as well as the thermal non-equilibrium does.
5. The problem of the electroweak baryogenesis includes a variety of various regions of physics, so that I think it is the interesting problem to pursue.

This is the end of my talk. Thank you.

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Figure 1: nucleation rate; $V$ is $T^4[GeV^4]$
Figure 2: The area of the wall for simulation and Kolmgorov-Avrami (solid line: simulation, dots line: Kolmgorov-Avrami)
