Physics Letters B 664 (2008) 154–156

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# Hypermagnetic baryogenesis

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ARTICLE INFO

*Article history:*
Received 20 February 2008
Accepted 13 May 2008
Available online 16 May 2008
Editor: T. Yanagida

*PACS:*
98.80.Cq
98.80.Es
11.30.Fs
98.62.En

ABSTRACT

We study a new scenario for baryogenesis due to the spontaneous breaking of the *CPT* invariance through the interaction between a baryon current and a hypermagnetic helicity. The hypermagnetic helicity (Chern–Simons number) of $U(1)_Y$ provides a *CPT* violation background for the generation of baryons via sphaleron processes, which protects these baryons from the sphaleron wash-out effect in thermal equilibrium. It is shown that if the present amplitude of the resultant magnetic fields are sufficiently large, for a wide range mass scale (from TeV to the Planck scale), the observational magnitude of the baryon asymmetry of the Universe can be realized.

The origin of the matter–antimatter asymmetry of the Universe is still an unsolved problem. The magnitude of the baryon asymmetry of the Universe (BAU) is characterized by the ratio of the baryonic number density $n_B$ to the entropy density $s$, which is observationally estimated as

$$\frac{n_B}{s} = 0.92^{+0.06}_{-0.04} \times 10^{-10}, \tag{1}$$

by using the first year Wilkinson Microwave Anisotropy Probe (WMAP) data on the anisotropy of the cosmic microwave background (CMB) radiation [1]. There exist various scenarios to explain the observational value in Eq. (1) from the baryon symmetric universe [2–4]. Under the assumption of the *CPT* invariance, Sakharov stated that three conditions are necessary to generate the BAU: (i) baryon number violation, (ii) $C$ and $CP$ violation, (iii) a departure from thermal equilibrium [5]. However, if the *CPT* invariance is violated in the early universe, the condition (iii) is no longer necessary [2,6]. An effective mechanism of this idea with a derivative scalar field coupled to the baryon current was first proposed by Cohen and Kaplan [7], which is called "spontaneous baryogenesis". If the time derivative of the scalar field has a nonzero expectation value, this interaction violates the *CPT* invariance spontaneously and hence an effective chemical potential difference between baryons and antibaryons is produced.

On the other hand, it has been pointed out [8–11] that hypercharge electromagnetic fields can play a significant role in the electroweak (EW) scenario [3,12,13] for baryogenesis. In particular, Giovannini and Shaposhnikov (GS) [9] have shown that the Chern–Simons number stored in the hypercharge electromagnetic fields, corresponding to the hypermagnetic helicity, is converted into fermions at the electroweak phase transition (EWPT) due to the anomaly if it is strongly first order [9], while the hypermagnetic fields are replaced by the ordinary magnetic fields, which survive after the EWPT up to the present time and hence can be cosmic magnetic fields observed in galaxies and clusters of galaxies.

The most natural origin of large-scale hypermagnetic fields before the EWPT is hypercharge electromagnetic quantum fluctuations in the inflationary stage [14,15]. If the conformal invariance of the Maxwell theory is broken by some mechanism in the inflationary stage [14,16], hypercharge electromagnetic quantum fluctuations exist even in the conformal flat Friedmann–Robertson–Walker (FRW) spacetime. Furthermore, if the hypercharge electromagnetic fields couple to an axion-like pseudoscalar field with a time-dependent expectation value, the hypermagnetic helicity can be generated [17–20]. (Incidentally, in Refs. [17,21] baryogenesis due to the above coupling has been discussed. Moreover, in Ref. [22] helical magnetic fields from sphaleron decay and baryogenesis have recently been considered.) In this case, the scale of the hypermagnetic fields with the helicity can be larger than or equal to the Hubble horizon. As a result, the homogeneous baryogenesis over the whole present universe can be realized [20].

In this Letter, we propose a new scenario for baryogenesis through the *CPT*-even dimension-six Chern–Simons-like interaction given by Geng, Ho and Ng (GHN) in Ref. [23]. We will concentrate on the interaction between a baryonic current and a hypermagnetic helicity. This type of the helicity can be produced much before the EWPT as hypercharge electromagnetic quantum fluctuations in the inflationary stage through some breaking mechanism

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0370-2693/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.physletb.2008.05.027

of the conformal invariance of the hypercharge electromagnetic field. It is clear that, in the Standard Model (SM) we cannot use the GS mechanism [9] to induce baryogenesis as the EWPT is not first order [24] and the resultant baryons will be destroyed by the sphaleron processes [25] (see also [26]). In our new scenario, however, because the *CPT* invariance is broken spontaneously [27] by the hypermagnetic helicity with its non-zero classical expectation value, the resultant baryons will not be destroyed by the sphaleron processes even in the SM [28].

In our study, we will adopt the Heaviside–Lorentz units and $k_{\rm B} = c = \hbar = 1$ and assume the spatially flat FRW spacetime with the metric

$$ds^2 = -dt^2 + a^2(t)\,d\vec{x}^2, \tag{2}$$

where $a(t)$ is the scale factor.

We start with the *CPT*-even dimension-six Chern–Simons-like effective interaction [23]:

$$\mathcal{L}_{\rm CS} = -\frac{\beta}{M^2} j_\mu \big(Y_\nu \tilde{Y}^{\mu\nu} + \partial_\nu S^{\mu\nu}\big), \tag{3}$$

where $Y_\nu$ is the $U(1)_Y$ gauge field, $\tilde{Y}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} Y_{\rho\sigma}$ is the dual of the $U(1)_Y$ hypercharge field strength tensor, $Y_{\mu\nu} = \partial_\mu Y_\nu - \partial_\nu Y_\mu$, $j_\nu$ is a fermion current, $\beta$ is a dimensionless coupling parameter, $S$ is the Stückelberg for maintaining the general gauge invariance [29], and $M = \Lambda/4\pi$ with $\Lambda$ being the scale of the effective interaction. Here, $\epsilon^{\mu\nu\rho\sigma}$ is the totally anti-symmetric Levi-Civita tensor with the normalization of $\epsilon^{0123} = +1$. Note that in Eq. (3) we have extended the electromagnetic field and neutrino current in the interaction given by GHN [23] to the hypercharge field and any fermion current, respectively.

In Ref. [23], it is concluded that the fermion current $j_\nu$ to a comoving observer has the form:

$$j_\mu = \bar{\psi}\gamma_\mu\psi = (n_\psi - n_{\bar{\psi}}, \vec{0}), \tag{4}$$

where $n_\psi$ and $n_{\bar{\psi}}$ are the number densities of the fermion $\psi$ and antifermion $\bar{\psi}$, respectively. It is interesting to note that, as pointed out in Ref. [23], the modified interaction would originate from superstring theory, in which the role of the Stückelberg field is played by the anti-symmetric Kolb–Ramond field $B_{\mu\nu}$. In the homogeneous and isotropic universe, it is reasonable to assume that this $B_{\mu\nu}$ field is only a function of the cosmic time $t$ [30]. Then the second term in Eq. (3) becomes $j_\mu \epsilon^{\mu\nu\rho\sigma}\partial_\nu B_{\rho\sigma}$, which vanishes in the spatially flat FRW spacetime. Hence, the Lagrangian in Eq. (3) reduces to

$$\mathcal{L}_{\rm CS} = -\frac{\beta}{M^2} j_0 \vec{Y}\cdot(\nabla\times\vec{Y}), \tag{5}$$

where $j_0 = n_\psi - n_{\bar{\psi}}$. We now consider that $j_\mu$ is the baryon current and there exists a non-vanishing hypermagnetic helicity before the EWPT. The interaction between the baryon current and the hypermagnetic helicity in Eq. (5) splits the spectrum of the baryons and antibaryons by giving them effective chemical potentials,

$$\mu_B = -\mu_{\bar{B}} \equiv \mu = \frac{\beta}{M^2}\big\langle \vec{Y}\cdot(\nabla\times\vec{Y})\big\rangle, \tag{6}$$

which lead to the net baryonic number density in the thermal equilibrium as [31]

$$n_B \equiv n_b - n_{\bar{b}} = \frac{g_b T^3}{6}\left(\frac{\mu}{T}\right) + O\left(\frac{\mu}{T}\right)^3, \tag{7}$$

where $n_b$ and $n_{\bar{b}}$ are the baryonic and antibaryonic number densities, respectively, $g_b$ counts the internal degrees of freedom of the baryons, and $T$ is the background temperature of the Universe.

The density of the hypermagnetic helicity is defined by

$$h_B \equiv \vec{Y}\cdot(\nabla\times\vec{Y}) = \vec{Y}\cdot\vec{H}_Y, \tag{8}$$

where $\vec{H}_Y$ is the hypermagnetic field. The energy density of the hypermagnetic fields, $\rho_{H_Y} \equiv |\vec{H}_Y|^2/2$, and the density of the hypermagnetic helicity have to satisfy the realizability condition [19, 32]:

$$h_B \leqslant 2L\rho_{H_Y}, \tag{9}$$

where $L$ is the coherence scale of the hypermagnetic fields. In the case of the hypermagnetic fields with its maximum helicity, the effective chemical potential is given by

$$\begin{aligned}\mu &= \frac{\beta}{M^2}\langle h_B\rangle \\ &= \frac{\beta}{M^2}(2L\rho_{H_Y}) = \frac{\beta}{M^2}L|\vec{H}_Y|^2. \end{aligned} \tag{10}$$

After the freeze-out temperature $T_{\rm f}$, it follows from Eq. (7) that the density of the residual baryonic number is given by

$$n_B(T_{\rm f}) = \frac{g_b T_{\rm f}^3}{6}\left[\frac{\mu(T_{\rm f})}{T_{\rm f}}\right], \tag{11}$$

where we have neglected the term of $O(\mu/T)^3$. After reheating following inflation, a number of charged particles are produced, so that the conductivity of the Universe is much larger than the Hubble parameter at that time. The hypermagnetic fields evolve as $|\vec{H}_Y| \propto a^{-2} \propto g_s^{2/3} T^2$ due to the magnetic flux conservation, while the entropy density and the coherence scale of the hypermagnetic fields behave as $s \propto g_s T^3$ and $L \propto a \propto g_s^{-1/3} T^{-1}$, respectively, where $g_s$ represents the total number of effective massless degrees of freedom referring to the entropy density of the Universe [31]. Note that reheating occurs much before the EWPT. We emphasize that in our scenario, since the sphaleron effect is served as the source of the baryon number violation, the freeze-out temperature $T_{\rm f}$ corresponds to the background temperature at the EWPT to be $T_{\rm EW} \sim 150$ GeV.

Consequently, after putting in the corrected baryon numbers and three generations of quarks, it follows from Eqs. (10) and (11) that the baryon-to-entropy ratio at the freeze-out temperature $T_{\rm f}$ is expressed as

$$\frac{n_B}{s}(T_{\rm f}) = \beta g_b\left(\frac{T_{\rm f}}{M}\right)^2 \frac{L_0 {B_0}^2}{s_0} \tag{12}$$

$$\approx 1.2\times 10^{40}\beta\left(\frac{T_{\rm f}}{M}\right)^2\left(\frac{B_0}{[{\rm G}]}\right)^2, \tag{13}$$

where the subscript suffix '0' represents the quantities at the present time, and $B_0 \equiv |\vec{B}_0|$ is the present field strength of the magnetic fields. Note that in Eq. (12), we have rescaled the coherence scale of the magnetic fields, the amplitude of the magnetic fields, and the entropy density from the values at $T_{\rm f}$ to the values at the present time, respectively. Moreover, in Eq. (13), we have used that $g_b = 2$ and the coherent length of the magnetic fields at the present time $L_0$ is equal to the current horizon scale $H_0^{-1}$ because we are considering the homogeneous baryogenesis over the whole present universe.

As an illustration, by taking $\beta \sim 1$, the freeze-out temperature $T_{\rm f} = T_{\rm EW} \sim 150$ GeV, and the present field strength of the magnetic fields on the horizon scale $B_0 \sim 10^{-9}$ G, which is the upper limit on the present field strength of the primordial magnetic fields on the horizon scale obtained by carrying out a statistical analysis for the angular anisotropy of the CMB radiation [33], we find from Eq. (13) that the resultant value of the baryon-to-entropy ratio, $n_B/s \sim 10^{-10}$, can be realized if the mass scale is $\Lambda = 4\pi M \sim M_{\rm Planck}$. Moreover, for $\beta \sim 1$, $T_{\rm f} = T_{\rm EW} \sim 150$ GeV, and $B_0 \sim 10^{-24}$ G, it follows from Eq. (13) that $n_B/s \sim 10^{-10}$ can be obtained with $\Lambda \sim 1$ TeV.

In summary, we have proposed a new scenario for baryogenesis due to the spontaneous breaking of the *CPT* invariance through the interaction in Eq. (3). The hypermagnetic helicity can be generated much before the EWPT as hypercharge electromagnetic quantum fluctuations in the inflationary stage through some breaking mechanism of the conformal invariance of the hypercharge electromagnetic field. In this scenario, the resultant baryons will not be destroyed by the sphaleron processes even if the EWPT is not first order due to the spontaneous breaking of the *CPT* invariance. We have found that if there are magnetic fields with the field strength $B_0$ being $10^{-24}$–$10^{-9}$ G on the horizon scale at the present time, while the corresponding mass scale $\Lambda$ in terms of a baryon current interacting to a hypermagnetic helicity is TeV–$M_{\mathrm{Planck}}$, the resultant value of the baryon-to-entropy ratio, $n_B/s \sim 10^{-10}$, can be achieved, which is consistent with the magnitude of the BAU suggested by observations obtained from the WMAP. Finally, we remark that if the effective Chern–Simons-like interaction in Eq. (3) is originated from superstring theory with $\Lambda \sim M_{\mathrm{Planck}}$, $B_0$ should be $\geqslant 10^{-10}$ G, which can be tested [34, 35] in future experiments such as PLANCK [36], SPIDERS (post-PLANCK) [37] and Inflation Probe (CMBPol mission) in the Beyond Einstein program of NASA [38].

## Acknowledgements

K.B. thanks all the members of the particle physics group at National Tsing Hua University for their very kind hospitality. This work is supported in part by the open research center project at Kinki University (K.B.) and the National Science Council of ROC under Grant #: NSC-95-2112-M-007-059-MY3 (C.Q.G. and S.H.H.).

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