Electroweak baryogenesis via chiral gravitational waves

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We propose a new mechanism for electroweak baryogenesis based on gravitational waves generated by helical magnetic fields that are present during a first order electroweak phase transition. We generate a net lepton number through the gravitational chiral anomaly which appears due to the chiral gravitational waves produced by these magnetic fields. The observed value of baryon asymmetry can be obtained in our mechanism within parameter space of scenarios with an inverse cascade evolution for magnetic fields which can also be candidates for large-scale magnetic fields.

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1. Introduction

Cosmological evidence implies the excess of matter over anti-matter in the Universe. This asymmetry is characterized by $\eta_B \equiv n_B/s$, where n_B is the net baryon number density and s is the entropy density of the Universe. Based on the Big Bang nucleosynthesis and cosmological abundances of light nuclei, this ratio is determined to be $\eta_B = (0.84 \pm 0.07) \times 10^{-10}$, which is in agreement with CMB observations [1].

To explain the baryon asymmetry of the Universe each scenario of interest should contain three conditions proposed by Sakharov [2]: 1—baryon number violation, 2—C and CP violation, 3—departure from thermal equilibrium. Baryon production scenarios suggested during the Electroweak Phase Transition (EWPT), which is one of cosmological PTs manifestly containing the third condition, are known as EW baryogenesis. In the Standard Model (SM), the first Sakharov condition can be achieved by the triangle anomaly

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{3g^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}W_{\mu\nu}^a W_{\alpha\beta}^a - \frac{3g'^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta},$$
(1)

where J_B^μ, J_L^μ are baryon and lepton currents, respectively, $W_{\mu\nu}^a$ is the SU(2) field strength and $F_{\mu\nu}$ is the U(1) field strength. The second term can contribute to the baryon and lepton number violation in the case of helical gauge field [3]. Moreover, in the SM

there is a gravitational chiral anomaly which can lead to a lepton number violation [4]. This anomaly is given by

$$\partial_\mu J_L^\mu = \frac{N}{32\pi^2}\epsilon^{\mu\nu\alpha\beta}R_{\mu\nu\rho\sigma}R_{\alpha\beta}^{\rho\sigma} = \frac{N}{16\pi^2}R\tilde{R},$$
(2)

where $N = 3$ in the SM due to different number of left and right-handed degrees of freedom in the leptonic sector, whereas in beyond the SM it can be less than 3 [5]. Also, $R_{\mu\nu\rho\sigma}$ denotes the curvature tensor of the space-time. The value of quantity $R\tilde{R}$ does not change from its initial value which is supposedly zero unless chiral components of the metric evolve differently. This can be achieved if there is a CP violating source in the system. Due to this gravitational anomaly, chiral leptons and antileptons can be generated in the processes. Sphalerons act on left-handed leptons and convert them into antiquarks and also act on right-handed antileptons and convert them into quarks. These rival processes do not lead to a net matter asymmetry without a CP violating source. In the case of a strong first-order EWPT, sphaleron-mediated processes are suppressed in the broken phase and the produced matter asymmetry is preserved [6]. However, the usual scenarios for the EW baryogenesis within the SM cannot account for the observed baryon asymmetry since strongly first-order PT and sufficient CP violation cannot be provided. As a consequence, many beyond the SMs including supersymmetric SMs and SMs with an extended Higgs sector have been proposed to solve this puzzle [7]. In these models, due to electroweak symmetry breaking, a first-order PT at which two thermodynamic states are separated through bubble walls is fulfilled.

During the history of the Universe, cosmic first-order PTs are important yet from another aspect. That is, they are sources of the Gravitational Wave (GW) radiation which can not only be a pow-

erful probe for the early Universe, but also impact its evolution (see [8] for GW production at EWPT and [9] for QCD PT with a holographic approach). Three different mechanisms have been proposed for the production of these GWs: the collision of bubbles nucleated during a first-order PT [10], sound waves [11], and Magnetohydrodynamic (MHD) turbulence [12] produced by turbulent fluid and magnetic field in the plasma.

In this work, we propose a novel mechanism for baryon production during a first-order EWPT based on the gravitational anomaly. We show that this effect can be as important as other conventional mechanisms proposed for the electroweak baryogenesis. In fact, during a first-order EWPT the GWs produced due to the presence of helical (chiral) magnetic fields are also chiral so that left and right-handed fluctuations of the metric components have different dispersion relations. In addition, the helical component of the magnetic field provides a CP violating source in the model. We demonstrate that this mechanism leads to a non-zero gravitational anomaly and find that for magnetic field values compatible with large-scale magnetic fields observed today, baryon asymmetry relying on sphaleron processes can be explained. Although it is possible to choose a specific model, our mechanism works for any extension of the SM which provides a first-order EWPT and generates chiral GWs. Henceforth, we shall assume that such a strong first order EWPT is provided by an extension of the SM.

In Section 2, we express the gravitational anomaly in terms of FRW metric perturbations, and then study the magnetic field generated in a first-order EWPT and derive the energy momentum tensor for such magnetic fields contributing to generation of chiral gravitational waves. Subsequently, we solve the equation of motion for these GWs and calculate the gravitational anomaly term and the lepton number density. Then, the numerical results for baryon asymmetry is presented. Finally, we present our conclusions in Section 3.

2. The electroweak baryogenesis mechanism

2.1. Metric perturbations

A homogeneous and isotropic universe is described by FRW metric which has no contribution to $\langle R\tilde{R}\rangle$, where $\langle\rangle$ denotes the quantum expectation value. The generic perturbed form of this background may be parametrized as

$$ds^2 = a^2\Big\{-(1+2\phi)d\tau^2 + v_i d\tau dx^i + \big[(1+2\varphi)\delta_{ij} + h_{ij}\big]dx^i dx^j\Big\}, \tag{3}$$

where $a(\tau)$ is the scale factor and $d\tau = a^{-1}dt$ is the conformal time. Also, ϕ, φ, v_i, and h_{ij} are scalar, vector, and tensor perturbations of the metric, respectively. Among these perturbations only h_{ij} has non-vanishing contribution to $\langle R\tilde{R}\rangle$. Hence, we consider tensor modes as GW polarization and neglect other fluctuations. Furthermore, we restrict to the transverse and traceless gauge for h_{ij}. In this gauge, one can write $R\tilde{R}$ as follows [13]

$$R\tilde{R} = \frac{-2\epsilon^{ijk}}{a^4}\Big(\ddot{h}_{jl}\partial_i\dot{h}_{lk} - \partial_m\dot{h}_{jl}\partial^2_{im}h_{lk} + \partial_l\dot{h}_{jm}\partial^2_{mi}h_{kl}\Big) + \mathcal{O}(h^4), \tag{4}$$

where $\dot{h}_{ij} \equiv \partial_\tau h_{ij}$. We assume the GWs propagate in the z direction. The left and right-handed polarizations can be defined as $h_{R,L} \equiv (h_{11} \pm ih_{12})/2$. The term $R\tilde{R}$ is odd under the parity operation which exchanges the left and right components and can be generated only if these components have different dispersion relations. In the next part, we investigate the helical magnetic field as the source of these GW components.

2.2. Energy momentum tensor of helical magnetic field

During a first-order EWPT with high Reynolds number, bubble collisions processes give rise to turbulence and charge separation in the plasma. This process leads to the generation of magnetic fields which can be helical due to chiral anomaly during this era, as pointed out by many investigations [14]. In addition, in order to consider the coupling between the turbulent fluid and magnetic fields, MHD effects must be taken into account. On the other hand, these helical magnetic fields can create chiral GWs and as we will see in the following, these birefringent GWs bring about non-zero $R\tilde{R}$. The equation of motion for the GWs in the radiation-dominated epoch of the Universe is given by [15]:

$$\ddot{h}_{R,L}(k,\tau) + 2\mathcal{H}\dot{h}_{R,L}(k,\tau) + k^2 h_{R,L}(k,\tau) = \frac{a^2(\tau)}{M_p^2}\Pi^\pm(k), \tag{5}$$

where $\mathcal{H} = aH$, H is the Hubble expansion rate, $M_p = 2.44 \times 10^{18}$ GeV is the reduced Planck mass and $\Pi^\pm$ are the sources for $h_{R,L}$, respectively. Moreover, $a(\tau) \sim H_0\tau\sqrt{\Omega_{rad}}$ where $H_0 \simeq 10^{-43}$ GeV is the Hubble rate today and $\Omega_{rad} \simeq 10^{-4}$ is the radiation density parameter today. $\Pi^\pm$ are components of Π_{ij} in the helical basis such that $\Pi_{ij}(k) = e^+_{ij}\Pi^+(k) + e^-_{ij}\Pi^-(k)$ and $\Pi_{ij}(k) = (P_{im}P_{jn} - \frac{1}{2}P_{ij}P_{mn})T_{mn}(k)$ is the transverse and traceless part of anisotropic energy-momentum tensor which is given by [16]

$$T_{ij}(\mathbf{k}) = \frac{1}{2(2\pi)^4}\int d^3p\Big[B_i(\mathbf{p})B^*_j(\mathbf{p}-\mathbf{k}) - \frac{1}{2}B_m(\mathbf{p})B^*_m(\mathbf{p}-\mathbf{k})\delta_{ij}\Big], \tag{6}$$

where $P_{ij} = \delta_{ij} - \hat{k}_i\hat{k}_j$ is the transverse projector and B_i is the magnetic field. Considering the interaction of magnetic fields with plasma and back-reaction effects, at small scales the viscous plasma and turbulent decay force the energy spectrum of the magnetic field to be exponentially damped. This damping effect can be taken into account by introducing an UV cutoff, k_d, in the spectrum [16]. Assuming that the helical magnetic field in momentum space is a stochastic quantity, it can be described by a Gaussian profile with the UV cutoff, $k_d = 1/\lambda_d$, where λ_d is the dissipation length in the spectrum. For a stochastic magnetic field, all required quantities are characterized by its two-point correlation function. If primordial magnetic fields are produced by causal mechanisms, the magnetic field correlation length should be shorter than the horizon and its two-point correlation function vanishes on scales larger than the horizon. Therefore, the correlation function has compact support. Moreover, the magnetic field is divergence-free and we expect its correlation function to be square-integrable. Then, according to the Paley–Wiener–Schwartz theorem [17], its Fourier transform is an analytic function for any value of k. The most general ansatz containing such properties for the magnetic field two-point function in momentum space which respects stochastic homogeneity and isotropy can be considered as [16,18,19]

$$\langle B_i(\mathbf{k})B^*_j(\mathbf{k}')\rangle = \frac{(2\pi)^3}{2}\delta(\mathbf{k} - \mathbf{k}')[(\delta_{ij} - \hat{k}_i\hat{k}_j)S(k) + i\epsilon_{ijm}\hat{k}_m A(k)], \tag{7}$$

where $S(k)$ and $A(k)$ are the symmetric and helical components of the magnetic field two-point function, respectively, which are also analytic functions and have Taylor expansions. For wavenumbers smaller than k_d, which as we shall show is of the order of 10^{-3} GeV, we can model them by a simple power law as $S(k) = S_0 k^{n_S}$ and $A(k) = A_0 k^{n_A}$ [16,18,19]. The requirement of analyticity for the term containing $\hat{k}_i\hat{k}_j$ implies that $n_S \geq 2$. Since