Cosmological CPT Violation, Baryo/Leptogenesis and CMB Polarization

Mingzhe Li\textsuperscript{1}, Jun-Qing Xia\textsuperscript{2}, Hong Li\textsuperscript{3} and Xinmin Zhang\textsuperscript{2}

\textsuperscript{1}Institut für Theoretische Physik, Philosophenweg 16, 69120 Heidelberg, Germany
\textsuperscript{2}Institute of High Energy Physics, Chinese Academy of Science, P.O. Box 918-4, Beijing 100049, P. R. China and
\textsuperscript{3}Department of Astronomy, School of Physics, Peking University, Beijing, 100871, P. R. China

(Dated: March 26, 2022.)

In this paper we study the cosmological \textit{CPT} violation and its implications in baryo/leptogenesis and CMB polarization. We propose specifically a variant of the models of gravitational leptogenesis. By performing a global analysis with the Markov Chain Monte Carlo (MCMC) method, we find the current CMB polarization observations from the three-year WMAP (WMAP3) and the 2003 flight of BOOMERANG (BO03) data provide a weak evidence for our model. However to verify and especially exclude this type of mechanism for baryo/leptogenesis with cosmological \textit{CPT} violation, the future measurements on CMB polarization from PLANCK and CMBpol are necessary.

PACS number(s): 98.80.Es, 98.80.Cq

I. INTRODUCTION

The \textit{CPT} symmetry which has been proved to be exact within the framework of standard model of particle physics and Einstein gravity could be violated dynamically during the evolution of the universe. To show it, consider a scalar boson $\phi$ which couples to a fermion current $J^\mu$, with the lagrangian given by

$$\mathcal{L}_{\text{int}} = \frac{c}{M} \partial_\nu \phi J^{\mu \nu}, \quad (1)$$

where $c$ is a dimensionless constant and $M$ the cut-off scale of the theory which could be the grand unification (GUT) or Planck scale. The interaction in (1) is \textit{CPT} conserved, however during the evolution of the homogenous scalar field $\phi$ as the universe expands, $\phi$ does not vanish which violates \textit{CPT} symmetry. This type of \textit{CPT}-violation occurs naturally in theory of dynamical dark energy and has two interesting implications in particle physics and cosmology:

1) In models of quintessential baryo/leptogenesis,\textsuperscript{1, 2, 3} the scalar field $\phi$ in (1) is the dark energy scalar (quintessence, k-essence etc.). The dynamics of the field $\phi$ leads to the current accelerating expansion of the universe, meanwhile its interaction with the baryon current $J_B^\mu$ (or $B - L$ current $J_{(B-L)}^\mu$) helps to produce the baryon number asymmetry in thermal equilibrium. One of the features of these models is a unified description of the present accelerating expansion and the generation of the matter and antimatter asymmetry of our universe. Furthermore differing from the original proposal for spontaneous baryogenesis by Cohen and Kaplan\textsuperscript{4} since the quintessence scalar has been existing up to present epoch the corresponding \textit{CPT}-violation could be tested in laboratory experiments and cosmology. Along this line, the gravitational baryo/leptogenesis\textsuperscript{5, 6} has been proposed in which a function of \textit{CP T} violation and study the possibility of testing the baryo/leptogenesis with CMB polarization. We in this paper specifically propose a class of models which give rise to enough amount of baryon number asymmetry required and predict sizable rotations of CMB photons observable in the CMB polarization measurements. The paper is organized
as follows. In section II we present the model for leptogenesis. In section III we study the CPT violating effects of our model on the electromagnetic theory. We use the geometrical optics approximation to get the equation describing the rotations of polarizations of photons. In section IV the model is confronted with the data from CMB experiments. Section V is our conclusion.

II. OUR MODEL OF LEPTOGENESIS

We search for variants of the models of the quintessential or gravitational baryo/leptogenesis and study their implications in CMB polarization. To begin our discussions we start with gravitational baryo/leptogenesis. For this model the dark energy is given by the cosmological constant. Compared with the quintessential baryo/leptogenesis where the potential needs to be specified this will simplify our study, however the results obtained can be easily generalized into the cases for the quintessential baryo/leptogenesis.

The model under investigation is a variant of the model proposed in Ref. [6] with the lagrangian

\[ \mathcal{L}_{\text{int}} = -c \partial_\mu \ln R J_\mu^i, \]

where \( J_\mu^i \) is the fermion current. To study the possible connection between the CPT violations in gravitational baryo/leptogenesis and CMB polarization\(^1\) \( J_\mu^i \) is required to satisfy i) not orthogonal to the baryon or \( B - L \) current; and ii) anomalous with respect to the electromagnetic interaction. The first condition above guarantees the generation of baryon number asymmetry and the second one makes it possible to be connected with the CMB polarization. There are various possibilities for \( J_\mu^i \) required. One of the examples is \( J_1^\mu \) being the Peccei-Quinn current\(^2\). Here for the specific discussion we take \( J_1^\mu = J_1^{(B-L)i} \); the left-handed part of \( B - L \) current. Formally this current can be decomposed into the combination of a \( B - L \) current and an axial \( B - L \) current, namely \( J_1^{(B-L)i} = (1/2)J_1^{(B-L)} - (1/2)J_1^{3i} \). We will show below that the contribution of \( J_1^{(B-L)} \) to the generation of the baryon number asymmetry will dominate over \( J_1^{3i} \), however \( J_1^{3i} \) plays an essential role in connection to the effects in CMB polarization.

Following the calculations in Ref. [6], we obtain the final baryon number asymmetry

\[ \frac{n_B}{s} \sim \frac{2.52}{2} \eta_2 g_{ss}^{1/2} \frac{T_D}{m_{\text{pl}}} \simeq 0.24 \frac{T_D}{m_{\text{pl}}}, \]

where \( g_2 = 2 \) is the number of degrees of freedom of baryons, \( g_{ss} \) characterizes the total degrees of freedom of all the relativistic particles in the universe, and its value is about 106.75 at the epoch when the temperature is around \( O(100) \text{GeV} \) or higher. \( T_D \) is the decoupling temperature determined by the \( B - L \) violating interaction, which in Ref. [6] is given by

\[ \mathcal{L}_E = \frac{2}{F} l_L l_L \Phi \Phi + \text{H.c.}, \]

where \( F \) is a scale of new physics beyond the Standard Model of particle physics which generates the \( B - L \) violations, \( \Phi \) is the Higgs doublet and \( l_L \) the left-handed lepton doublet. When the Higgs field gets a vacuum expectation value \( \langle \Phi \rangle \sim \nu \), the left-handed neutrino receives a Majorana mass \( m_\nu \sim \frac{\nu^2}{F} \).

In the early universe the lepton number violating rate induced by the interaction in (4) is\(^2\) \( \Gamma_E \) is

\[ \Gamma_E \sim 0.04 \frac{T_D^3}{F^2}. \]

Since \( \Gamma_E \) is proportional to \( T_D^3 \), for a given \( F \), namely the neutrino mass, \( B - L \) violation will be more efficient at high temperature than at low temperature. Requiring this rate be larger than the Universe expansion rate \( H \simeq 1.66 g_2^{1/2} T^2 / m_{\text{pl}} \) until the temperature \( T_D \), we obtain a \( T_D \)-dependent lower limit on the neutrino mass:

\[ \sum_i m_i^2 = (0.2 \text{ eV} \frac{10^{12} \text{ GeV}}{T_D})^{1/2}. \]

---

1 The possible connection between the CPT violations in quintessential baryogenesis and the cosmological birefringence has been considered in Ref. [3].

2 \( J_1^{(B-L)} \) is violated by the Yukawa couplings, which give rise to a lower decoupling temperature \( T_D \sim 100 \text{ GeV} \).
The experimental bounds on the neutrino masses come from the neutrino oscillation experiments and the cosmological tests. The atmospheric and solar neutrino oscillation experiments give [24, 25]:

\[
\begin{align*}
\Delta m_{\text{atm}}^2 &= (2.6 \pm 0.4) \times 10^{-3} \text{eV}^2, \\
\Delta m_{\text{sol}}^2 &\simeq (8.0^{+0.6}_{-0.4}) \times 10^{-5} \text{eV}^2.
\end{align*}
\]

The cosmological tests provide the limits on the sum of the three neutrino masses, \( \Sigma \equiv \sum_i m_i \). The analysis of WMAP [13] and SDSS [26] show the constraints: \( \Sigma < 0.68 \) eV and \( \Sigma < 0.94 \) eV respectively.

For the case of normal hierarchy neutrino masses, \( m_3 \gg m_2, m_1 \), one has

\[
\begin{align*}
&\ m_3^2 - m_2^2 = \Delta m_{\text{atm}}^2, \\
&\ m_2^2 - m_1^2 = \Delta m_{\text{sol}}^2,
\end{align*}
\]

and

\[
\sum_i m_i^2 \simeq m_3^2 \gtrsim \Delta m_{\text{atm}}^2.
\]

We can see from Eq. (9) that this requires the decoupling temperature \( T_D \lesssim 1.6 \times 10^{13} \) GeV. For neutrino masses with inverted hierarchy, \( m_2 \sim m_1 \gg m_3 \), we get

\[
\begin{align*}
&\ m_2^2 - m_3^2 = \Delta m_{\text{atm}}^2, \\
&\ m_2^2 - m_1^2 = \Delta m_{\text{sol}}^2,
\end{align*}
\]

and

\[
\sum_i m_i^2 \simeq 2m_2^2 \gtrsim 2\Delta m_{\text{atm}}^2,
\]

which constrains the decoupling temperature as \( T_D \lesssim 8 \times 10^{12} \) GeV. If three neutrino masses are approximately degenerated, i.e., \( m_1 \sim m_2 \sim m_3 \sim \tilde{m} \), one has \( \sum_i m_i^2 \simeq \Sigma^2/3 \). In this case, the WMAP3 and SDSS data require \( T_D \) to be larger than \( 2.6 \times 10^{11} \) GeV and \( 1.4 \times 10^{11} \) GeV respectively. So, for a rather conservative estimate, we consider \( T_D \) in the range of \( 1.4 \times 10^{11} \text{GeV} \lesssim T_D \lesssim 1.6 \times 10^{13} \text{GeV} \). Combined with Eq. (3) and the observational limit for the baryon/photon ratio [27], \( n_B/n_\gamma = 7.04 n_B/s = (6.15 \pm 0.25) \times 10^{-10} \), we find that a successful leptogenesis requires the coupling constant \( c \) should be larger than \( 2.55 \times 10^{-4} \) (at 2\( \sigma \)).

### III. MODIFIED ELECTROMAGNETIC THEORY AND COSMOLOGICAL BIREFRINGENCE

The current \( J_{(B-L)_L}^\mu \) is anomalous under the electromagnetic interaction. Using the notation of [28] we obtain

\[
\partial_\mu J_{(B-L)_L}^\mu \sim -\frac{e^2}{12\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} = -\frac{\alpha_{em}}{3\pi} F_{\mu\nu} \tilde{F}^{\mu\nu},
\]

where \( \alpha_{em} = e^2/4\pi = 1/137 \) is the electromagnetic fine structure constant. So, by an integration in part one can see that the interaction in [28] induces a Chern-Simons term,

\[
\mathcal{L}_{\text{int}} \sim -\frac{c\alpha_{em}}{3\pi} \ln R F_{\mu\nu} \tilde{F}^{\mu\nu} \sim \frac{2c\alpha_{em}}{3\pi} \partial_\mu \ln RA_\nu \tilde{F}^{\mu\nu}.
\]

Hence the vacuum Maxwell equations are modified as

\[
\nabla_\mu F^{\mu\nu} = \delta \partial_\mu \ln R \tilde{F}^{\mu\nu},
\]

or in terms of the vector field \( A_\mu \),

\[
\nabla_\mu (\nabla^\mu A^\nu - \nabla^\nu A^\mu) = \frac{\delta}{2} \partial_\mu \ln R e^{\mu\nu\rho\sigma} (\nabla_\rho A_\sigma - \nabla_\sigma A_\rho),
\]

in above we have defined

\[
\delta \equiv \frac{4\alpha_{em}}{3\pi} c.
\]
The equation (16) contains gauge freedom. Usually we impose a gauge condition to get rid of it. In this paper, we impose Lorentz gauge
\[ \nabla_\mu A^\mu = 0. \] (18)

Under this gauge, Eq. (16) becomes
\[ \nabla_\mu \nabla_\nu A^\nu + R^\nu_\mu A^\mu = \frac{\delta}{2} \partial_\mu \ln \text{Re}^{\mu\nu\rho\sigma} (\nabla_\rho A_\sigma - \nabla_\sigma A_\rho), \] (19)

where the Ricci tensor \( R^\nu_\mu \) appeared due to the commutation of covariant derivatives acting on a vector field.

In the cases where the scale of variation of electromagnetic field is much smaller than that we are interested in as we do in this paper, the geometrical optics approximation is applicable. In such an approximation, the solutions to the Maxwell equations are expected to be in the form \[ A^\mu = \text{Re}[(a^\mu + \epsilon b^\mu + \epsilon^2 c^\mu + \ldots) e^{iS/\epsilon}], \] (20)

with \( \epsilon \) a small coefficient. It means that the phase \( S/\epsilon \) varies much faster than the amplitude does. With the help of it, one can easily see that the gauge condition (18) implies
\[ k^\mu a^\mu = 0, \] (21)

where the wave vector \( k_\mu \equiv \nabla_\mu S \) is orthogonal to the surfaces of constant phase and represents the direction which photons travel along. We can write the vector \( a^\mu \) as the product of a scalar amplitude \( A \) and a normalized polarization vector \( \epsilon^\mu \),
\[ a^\mu = A \epsilon^\mu, \] (22)

with
\[ \epsilon_\mu \epsilon^\mu = 1. \] (23)

We can see that under the Lorentz gauge, the wave vector \( k_\mu \) is orthogonal to the polarization vector \( \epsilon^\mu \). Substituting the equation (20) into the modified Maxwell equation (16) and neglecting the Ricci tensor term yield
\[ \nabla_\mu \nabla^\mu (a^\nu + \epsilon b^\nu + \ldots) + \frac{2i}{\epsilon} k^\mu \nabla_\mu (a^\nu + \epsilon b^\nu + \ldots) + \frac{i}{\epsilon} (\nabla_\mu k^\mu)(a^\nu + \epsilon b^\nu + \ldots) - \frac{1}{\epsilon^2} k^\mu k^\nu (a^\nu + \epsilon b^\nu + \ldots) = \frac{\delta}{2} \partial_\mu \ln \text{Re}^{\mu\nu\rho\sigma} \left\{ \left[ \nabla_\rho (a_\sigma + \epsilon b_\sigma + \ldots) - \nabla_\sigma (a_\rho + \epsilon b_\rho + \ldots) \right] + \frac{i}{\epsilon} [k_\rho (a_\sigma + \epsilon b_\sigma + \ldots) - k_\sigma (a_\rho + \epsilon b_\rho + \ldots)] \right\}. \] (24)

Collecting respectively the terms proportional to \( 1/\epsilon^2 \) and \( 1/\epsilon \) in both sides of above equation, we have
\[ k_\mu k^\mu = 0, \] (25)

and
\[ k^\mu \nabla_\mu a^\nu + \frac{1}{2} \nabla_\mu k^\mu a^\nu = \frac{\delta}{4} \partial_\mu \ln \text{Re}^{\mu\nu\rho\sigma} (k_\rho a_\sigma - k_\sigma a_\rho). \] (26)

The equation (26) indicates that photons propagate along the null geodesics, which are unaffected by the Chern-Simons term. This can be seen from its differentiation,
\[ 0 = \nabla_\nu (k_\mu k^\mu) = 2 \nabla^\mu S \nabla_\mu S = 2 \nabla^\mu S \nabla_\mu S = 2 k^\mu \nabla_\mu k_\nu. \] (27)

We can define the affine parameter \( \lambda \) which measures the distance along the light-ray,
\[ k^\mu = \frac{dx^\mu}{d\lambda}. \] (28)

So, from Eq. (27) we get the geodesic equation
\[ \frac{d x^\mu}{d \lambda} \nabla_\mu k_\nu = 0. \] (29)
The effect of Chern-Simons term appears in the equation (26). Multiplying Eq. (26) with $a_i$, and using the product (22) and the normalization (23) give,

$$\nabla_\mu k^\mu = -2k_\mu \nabla^\mu \ln A.$$  \hfill (30)

In terms of it, Eq. (26) gives the following equations describing how the polarization vector changes,

$$k^\mu \nabla_\mu \varepsilon^\nu = \frac{\delta}{4} \partial_\eta \ln R \epsilon^{\mu \nu \rho \sigma} (k_\rho \varepsilon_\sigma - k_\sigma \varepsilon_\rho).$$  \hfill (31)

We see that the Chern-Simons term makes $k^\mu \nabla_\mu \varepsilon^\nu$ not vanished. This means that the polarization vector $\varepsilon^\nu$ is not parallelly transported along the light-ray. It rotates as the photon propagates in spacetime.

We consider here the spacetime described by spatially flat Friedmann-Robertson-Walker (FRW) metric

$$ds^2 = a^2 (d\eta^2 - \delta_{ij} dx^i dx^j),$$  \hfill (32)

and the curvature scalar $R$ is homogeneous, i.e., only varies with time. The null condition (25) is

$$(k^0)^2 - k^i k^i = 0.$$  \hfill (33)

We assume that photons propagate along the positive direction of $x$ axis, i.e., $k^\mu = (k^0, k^1, 0, 0)$ and $k^1/k^0 > 0$. Above equation implies $k^1 = k^0$. Gauge invariance guarantees that the polarization vector of the photon has only two independent components which are orthogonal to the propagating direction. So, we are only interested in how the components of the polarization vector, $\varepsilon^2$ and $\varepsilon^3$, change. They satisfy the following equations,

$$k^\mu \nabla_\mu \varepsilon^i = \frac{\delta}{2} \frac{\dot{R}}{R} \epsilon^{0ijk} k_j \varepsilon_k = \frac{\delta}{2} \frac{\dot{R}}{R} \epsilon^{0ijk} \frac{\varepsilon_j k_k}{a^2} \varepsilon_k = -\frac{\delta}{2} \frac{\dot{R}}{R} \epsilon^{ijk} k^j \varepsilon^k = -\frac{\delta}{2} \frac{\dot{R}}{R} \epsilon^{ijk}, \text{ with } i = 2, 3,$$  \hfill (34)

where the dot means derivative with respect to the conformal time $\eta$. We have used $\epsilon^{\mu \nu \rho \sigma} = \epsilon^{\mu \nu \rho \sigma} / \sqrt{-\det[g]}$ and the components of the total antisymmetric tensor density $\epsilon^{\mu \nu \rho \sigma}$ are set to be $\epsilon^{0123} = 1$ and so on. $\epsilon^{ijk}$ is three dimensional total antisymmetric tensor density with $\epsilon^{123} = 1$. So we can match that $\epsilon^{0ijk} = \epsilon^{ijk}$. With the help of $k^\mu = d\alpha^\mu / d\lambda$ and the Christoffel symbols,

$$\Gamma^i_{0j} = \Gamma^i_{j0} = \mathcal{H} \delta^i_j, \quad \Gamma^i_{00} = \Gamma^i_{j0} = 0,$$  \hfill (35)

we get,

$$\frac{d\varepsilon^2}{d\lambda} + \mathcal{H} k^0 \varepsilon^2 = -\frac{\delta}{2} \frac{\dot{R}}{R} k^1 \varepsilon^3,$$  \hfill (36)

$$\frac{d\varepsilon^3}{d\lambda} + \mathcal{H} k^0 \varepsilon^3 = \frac{\delta}{2} \frac{\dot{R}}{R} k^1 \varepsilon^2,$$  \hfill (37)

where we have defined $\mathcal{H} \equiv \dot{a} / a$. Furthermore, using $k^1 = k^0 = d\eta / d\lambda$ yields,

$$\frac{d}{d \ln R} (a \varepsilon^2) = -\frac{\delta}{2} a \varepsilon^3,$$  \hfill (38)

$$\frac{d}{d \ln R} (a \varepsilon^3) = \frac{\delta}{2} a \varepsilon^2.$$  \hfill (39)

It is easy to find that the polarization angle is

$$\alpha \equiv \arctan \left( \frac{\varepsilon^3}{\varepsilon^2} \right) = \frac{\delta}{2} \ln R + \text{constant}.$$  \hfill (40)

Hence, for a source at a redshift $z$, the polarization angle is rotated by

$$\Delta \alpha = \frac{\delta}{2} \ln \left( \frac{R(0)}{R(z)} \right).$$  \hfill (41)

As we know, a vector rotated by an angle $\Delta \alpha$ in a fixed coordinates frame is equivalent to a fixed vector observed in a coordinates frame which is rotated by $-\Delta \alpha$. So, with the notion of coordinates frame rotation, the rotation angle is

$$\Delta \chi = -\Delta \alpha = \frac{\delta}{2} \ln \left( \frac{R(z)}{R(0)} \right).$$  \hfill (42)
FIG. 1: (color online). The effects of the rotation angle $\Delta \chi$ in Eq. (42) on the power spectra of TT, TG, GG, CC, TC and GC. The black solid line is for the case of $\delta = 0$, the red dashed line is for $\delta = 0.01$ and the blue dotted line is for $\delta = 0.001$.

IV. CMB POLARIZATION

Now we consider the constraints on the parameter $\delta$ in Eq. (42) from the current CMB data. The cosmic microwave background can be characterized by the temperature and polarization completely in each direction on the sky. Usually we describe the photon that come to us in terms of the Stokes parameters $I$, $Q$, $U$ and $V$[30]. $I$ and $V$ describe physical observables and are independent of the choice of the coordinate system. However, $Q$ and $U$ which characterize the orthogonal modes of the linear polarization depend on the axes where the linear polarization is defined. $Q$ and $U$ can be decomposed into a gradient-like (G) and a curl-like (C) components [31]. If the $\delta$ term is absent the TC and GC cross correlations power spectra vanish. However, with the presence of cosmological birefringence, the polarization vector of each photon is rotated by an angle $\Delta \chi$, which can give rise to non-zero TC and GC correlations, even though they are zero at the last scattering surface. With a prime we give the rotated quantities [11]

$$C^{TC'}_l = C^{TG}_l \sin 2\Delta \chi$$

and [32]

$$C^{GG'}_l = \frac{1}{2} (C^{GG}_l - C^{CC}_l) \sin 4\Delta \chi .$$

(44)

Also, the original TG, GG and CC spectra are modified as following:

$$C^{TG'}_l = C^{TG}_l \cos 2\Delta \chi ,$$

$$C^{GG'}_l = C^{GG}_l \cos^2 2\Delta \chi + C^{CC}_l \sin^2 2\Delta \chi ,$$

$$C^{CC'}_l = C^{CC}_l \cos^2 2\Delta \chi + C^{GG}_l \sin^2 2\Delta \chi .$$

(47)
The CMB temperature power spectrum remains unchanged.

With the notation given above we in fig. 1 illustrate the effects of the rotation angle $\Delta \chi$ in Eq. (42) for three cases $\delta = 0$, $\delta = 0.01$, and $\delta = 0.001$. The basic cosmological parameters we choose for these plots are given below and consistent with the current result of WMAP3[13]:

$$\left( \Omega_b h^2, \Omega_m h^2, \tau, H_0, n_s, A_s \right) = \left( 0.0223, 0.1265, 0.088, 73.5, 0.951, 2.37 \times 10^{-9} \right).$$  (48)

One can see from fig. 1 that the C-mode is very sensitive to $\delta$. So we expect the TC and GC data constrain $\delta$ efficiently.

To determine the parameter $\delta$, we make a global fitting to the CMB data with the publicly available Markov Chain Monte Carlo package cosmomc[33, 34]. During the calculations, we modified the programs by adding a new free parameter $\delta$ in Eq. (42) to allow the rotation of the power spectra given above. We sample the following 8 dimensional set of cosmological parameters:

$$p = (\omega_b, \omega_c, \Theta_S, \tau, \delta, n_s, r, \log[10^{10} A_s])$$  (49)

where $\omega_b = \Omega_b h^2$ and $\omega_c = \Omega_c h^2$ are the physical baryon and cold dark matter densities relative to critical density, $\Theta_S$ (multiplied by 100) is the ratio of the sound horizon and angular diameter distance, $\tau$ is the optical depth, $A_s$ is defined as the amplitude of initial power spectrum and $n_s$ measures the spectral index. Basing on the Bayesian analysis, we vary the above 8 parameters fitting to the observational data (such as WMAP3 and B03 data) with the MCMC method. Throughout, we assume a flat universe and take the weak priors as: $0.01 < \tau < 0.8, 0.5 < n_s < 1.5$, a cosmic age tophat prior as $10,000 < t_0 < 20,000$ Gyr. Furthermore, we make use of the HST measurement of the Hubble parameter $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$[35] by multiplying the likelihood by a Gaussian likelihood function centered around $h = 0.72$ and with a standard deviation $\sigma = 0.08$. We impose a weak Gaussian prior on the baryon density $\Omega_b h^2 = 0.022 \pm 0.002 (1\sigma)$ from Big Bang nucleosynthesis[36].

In our calculations we have taken the total likelihood to be the products of the separate likelihoods of WMAP3 and B03. Alternatively defining $\chi^2 = -2 \log L$, we get

$$\chi^2_{\text{total}} = \chi^2_{\text{WMAP3}} + \chi^2_{\text{B03}}.$$  (50)

In the computation of WMAP3 data we have included the cross correlations power spectra of TT, GG, TG and CC, while for the B03 data we added two more datasets: the spectra GC and TC, which give rise to the direct CPT-violation signal.

In the Fig 2 we plot the one dimensional constraint on the parameter $\delta$ from the current CMB polarization experiments. The numerical results give that the $1, 2\sigma$ limits: $\delta = -0.011^{+0.0074}_{-0.0079}$. This shows a weak preference for a non-zero $\delta$. But at $2\sigma$ $\delta$ is consistent with zero, which put a limit $|\delta| < 10^{-2}$.

![FIG. 2: (color online). One dimensional constraints on the parameter $\delta$ from WMAP3 and B03.](image-url)
V. CONCLUSIONS

In this paper we have studied the cosmological CPT-violation and its implications in cosmology. We proposed a specific model where baryo/leptogenesis is connected to the CMB polarization. Our model can generate the baryon number asymmetry required and predict a sizable effect on CMB polarization observable at the current measurements. Using the current CMB data, we have performed a global fitting to determine the rotation angle in ΛCDM cosmology. We found the current data mildly favor a non-vanishing δ which provides a weak evidence for the cosmological CPT-violation. However to verify and especially exclude this class of models of baryo/leptogenesis, more precision measurements on the CMB polarization from PLANCK and CMBpol are required[32].

Acknowledgement: We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA). Support for LAMBDA is provided by the NASA Office of Space Science. We have performed our numerical analysis on the Shanghai Supercomputer Center(SSC). We thank Pei-Hong Gu, Xiao-Jun Bi, Yi-Fu Cai, Bo Feng and Gong-Bo Zhao for helpful discussions. The author M.L. is grateful to the support from Alexander von Humboldt Foundation. This work is supported in part by National Natural Science Foundation of China under Grant Nos. 90303004, 10533010 and 19925523.

[1] M. Li, X. Wang, B. Feng, and X. Zhang, Phys. Rev. D 65, 103511 (2002).
[2] M. Li and X. Zhang, Phys. Lett. B 573, 20 (2003).
[3] A. De Felice, S. Nasri and M. Trodden, Phys. Rev. D 67, 043509 (2003).
[4] A. Cohen and D. Kaplan, Phys. Lett. B 199, 251 (1987).
[5] H. Davoudiasl, R. Kitano, C. Kribs, H. Murayama, and P. J. Steinhardt, Phys. Rev. Lett. 93, 201301 (2004).
[6] H. Li, M. Li, and X. Zhang, Phys. Rev. D 70, 047302 (2004).
[7] S. M. Carroll, G. B. Field, and R. Jackiw, Phys. Rev. D 41, 1231 (1990).
[8] S. M. Carroll and G. B. Field, Phys. Rev. D 43, 3789 (1991).
[9] S. M. Carroll and G. B. Field, Phys. Rev. Lett. 79, 2394 (1997).
[10] S. M. Carroll, Phys. Rev. Lett. 81, 3067 (1998).
[11] A. Lue, L. M. Wang, and M. Kamionkowski, Phys. Rev. Lett. 83, 1506 (1999).
[12] B. Feng, M. Li, J.-Q. Xia, X.-L. Chen and X. Zhang, Phys. Rev. Lett. 96, 221302 (2006).
[13] D. N. Spergel et al., arXiv: astro-ph/0603449.
[14] L. Page et al., arXiv: astro-ph/0603450.
[15] G. Hinshaw et al., arXiv: astro-ph/0603451.
[16] N. Jarosik et al., arXiv: astro-ph/0603452.
[17] Available from http://lambda.gsfc.nasa.gov/product/map/current/.
[18] W. C. Jones et al., Astrophys. J. 647, 823 (2006); F. Piacentini et al., Astrophys. J. 647, 833 (2006).
[19] T. E. Montroy et al., Astrophys. J. 647, 813 (2006).
[20] Available from http://cmb.phys.cwru.edu/boomerang/.
[21] G. C. Liu, S. Lee and K. W. Ng, Phys. Rev. Lett. 97, 161303 (2006).
[22] T. Chiba, F. Takahashi and M. Yamaguchi, Phys. Rev. Lett. 92, 011301 (2004).
[23] U. Sarkar, hep-ph/9809209; W. Buchmuller, hep-ph/0101102.
[24] G. L. Fogli et al., hep-ph/0310012; M. H. Ahn et al., Phys. Rev. Lett. 90, 041801 (2003).
[25] B. Aharmim et al. [SNO Collaboration], Phys. Rev. C 72, 055502 (2005).
[26] M. Tegmark et al., Phys. Rev. D 74, 123507 (2006).
[27] W. M. Yao et al. [Particle Data Group], J. Phys. G 33, 1 (2006).
[28] M.E. Peskin and D.V. Schroeder, An Introduction to Quantum Field Theory (Westview Press, 1995).
[29] C. W. Misner, K. S. Thorne and J. A. Wheeler, Gravitation (Freeman Press, San Francisco, 1973).
[30] See, e.g., J. D. Jackson, Classical Electrodynamics, 2nd ed. (New York: Wiley & Sons, 1975).
[31] See e.g. M. Kamionkowski, A. Kosowsky and A. Stebbins, Phys. Rev. D 55, 7368 (1997).
[32] B. Feng, H. Li, M. Li and X. Zhang, Phys. Lett. B 620, 27 (2005).
[33] A. Lewis and S. Bridle, Phys. Rev. D 66, 103511 (2002).
[34] Available from http://cosmologist.info.
[35] W. L. Freedman et al., Astrophys. J. 553, 47 (2001).
[36] S. Burles, K. M. Nollett and M. S. Turner, Astrophys. J. 552, L1 (2001).