Probing CPT Violation with CMB Polarization Measurements

Jun-Qing Xia¹, Hong Li²,³, and Xinmin Zhang²,³

¹Scuola Internazionale Superiore di Studi Avanzati, Via Beirut 2-4, I-34014 Trieste, Italy
²Institute of High Energy Physics, Chinese Academy of Science, P. O. Box 918-4, Beijing 100049, P. R. China
³Theoretical Physics Center for Science Facilities (TPCSF), Chinese Academy of Science, P. R. China

The electrodynamics modified by the Chern-Simons term \( L_{cs} \sim p_{\mu} A_{\nu} F^{\mu\nu} \) with a non-vanishing \( p_{\mu} \) violates the Charge-Parity-Time Reversal symmetry (CPT) and rotates the linear polarizations of the propagating Cosmic Microwave Background (CMB) photons. In this paper we measure the rotation angle \( \Delta\alpha \) by performing a global analysis on the current CMB polarization measurements from the seven-year Wilkinson Microwave Anisotropy Probe (WMAP7), BOOMERanG 2003 (B03), BICEP and QUaD using a Markov Chain Monte Carlo method. Neglecting the systematic errors of these experiments, we find that the results from WMAP7, B03 and BICEP are all consistent and their combination gives \( \Delta\alpha = -2.33 \pm 0.72 \) deg (68% C.L.), indicating a 3 \( \sigma \) detection of the CPT violation. The QUaD data alone gives \( \Delta\alpha = 0.59 \pm 0.42 \) deg (68% C.L.) which has an opposite sign for the central value and smaller error bar compared to that obtained from WMAP7, B03 and BICEP. When combining all the polarization data together, we find \( \Delta\alpha = -0.04 \pm 0.35 \) deg (68% C.L.) which significantly improves the previous constraint on \( \Delta\alpha \) and test the validity of the fundamental CPT symmetry at a higher level.

PACS numbers: 98.80.Es, 11.30.Cp, 11.30.Er

Introduction – The accumulating high precision observational data of the CMB temperature and polarization spectra are not only crucial to determine the cosmological parameters [1], but also make it possible to search for new physics beyond the standard model of particle physics. One striking example along this line is the test of the CPT symmetry. As a fundamental requirement of particle physics, the CPT symmetry has been proved to be exact and well tested by various laboratory experiments. However, the validity of this symmetry needs to be reevaluated in the context of cosmology. And in fact, there have been some theoretical studies indicating the possible break-down of the CPT symmetry at some level, and interestingly, the cosmological measurements of the CMB polarization facilitate the direct detection of the CPT violating signal [2, 3].

To begin with, consider an effective Lagrangian of electrodynamics including a Chern-Simons term \( L_{cs} \sim p_{\mu} A_{\nu} F^{\mu\nu} \), where \( p_{\mu} \) is an external vector, and \( F^{\mu\nu} = (1/2)\epsilon^{\mu\nu\sigma} F_{\rho\sigma} \) denotes the dual of the electromagnetic tensor. Note that this model violates the Lorentz and CPT symmetries if \( p_{\mu} \) is non-vanishing. Also, this effective Lagrangian is not generally gauge invariant, but its action is invariant if \( \partial_{\mu} p_{\nu} = \partial_{\nu} p_{\mu} \). This equality holds in some cases, for example, \( p_{\mu} \) is a constant in spacetime or the gradient of a scalar field in the quintessential baryo-/leptogenesis [5]; or the gradient of a function of the Ricci scalar in the gravitational baryo-/leptogenesis [6].

This CPT violating interaction yields a rotation, quantified by \( \Delta\alpha \), of the polarization vector of the electromagnetic waves traveling over a distance on the cosmological scale, and this mechanism is dubbed the Cosmological Birefringence (CB) [4]. The rotation angle \( \Delta\alpha \) is given in term of \( p_{\mu} \) by \( \Delta\alpha \sim \int p_{\mu} dx^{\mu} \) [2], and it has imprints on the CMB polarization data, namely, all the CMB two-point functions, except for the temperature-temperature auto correlation (TT), will be altered, and most importantly, the cosmological birefringence can induce non-zero TB and EB spectra, which is vanishing in the standard cosmological model. Denoting the rotated quantity with a prime, one has the following relations [5, 6] :

\[
\begin{align*}
C_{\ell}^{\prime TB} & = C_{\ell}^{TB} \sin(2\Delta\alpha), \\
C_{\ell}^{\prime EB} & = \frac{1}{2}(C_{\ell}^{EE} - C_{\ell}^{BB}) \sin(4\Delta\alpha), \\
C_{\ell}^{\prime TE} & = C_{\ell}^{TE} \cos(2\Delta\alpha), \\
C_{\ell}^{\prime EE} & = C_{\ell}^{EE} \cos^2(2\Delta\alpha) + C_{\ell}^{BB} \sin^2(2\Delta\alpha), \\
C_{\ell}^{\prime BB} & = C_{\ell}^{BB} \cos^2(2\Delta\alpha) + C_{\ell}^{EE} \sin^2(2\Delta\alpha).
\end{align*}
\]

Given the CMB polarization data and Eq. (1), one can constrain the rotation angle to test the CPT symmetry.

In this work, we report the latest result on the measurement of the rotation angle using the most up-to-date CMB polarization data including WMAP7, BOOMERanG 2003, BICEP and QUaD.

CMB Polarization Measurements – In our previous analysis [5], we measured the rotation angle using the polarization data from WMAP7 [10] and the BOOMERanG dated January 2003 Antarctic flight [11]. The WMAP5 polarization data are composed of TE/TB/EE/BB/EB power spectra on large scales (2 \( \leq \ell \leq 23 \)) and TE/EB power spectra on small scales (24 \( \leq \ell \leq 800 \)), while the B03 experiment measures the small-scale polarization power spectra in the range of 150 \( \leq \ell \leq 1000 \).

Recently, the Background Imaging of Cosmic Extragalactic Polarization (BICEP) [12] and QU Extragalactic Survey Telescope at DASI (QUaD) [13] collaborations...
released their high precision data of the CMB temperature and polarization including the TB and EB power spectra. These two experiments, locating at the South Pole, are the bolometric polarimeters designed to capture the CMB information at two different frequency bands of 100GHz and 150GHz, and on small scales – the released first two-year BICEP data are in the range of \(21 \leq \ell \leq 335\) \[12\]; whereas the QUaD team measures the polarization spectra at \(164 \leq \ell \leq 2026\), based on an analysis of the observation in the second and third season \[14\].

In Fig. 1, we show the binned TB and EB power spectra released by the BOOMERanG, BICEP and QUaD collaborations. Compared to the B03 data, one can see that the BICEP and QUaD data have apparently smaller errors, implying that adding these data to the previous data, we make a global analysis to constrain the rotation angle, which is essentially the aim of this work.

**Method** – Given the aforementioned CMB polarization data, we make a global analysis to constrain the rotation angle \(\Delta \alpha\) using a modified version of **CosmoMC**, a publicly available Markov Chain Monte Carlo engine \[16\]. Without loss of generality, we assume the purely adiabatic initial conditions and a flat universe, and explore the parameter space of \(P \equiv (\omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10} A_s], r, \Delta \alpha)\). Here, \(\omega_b \equiv \Omega_b h^2\) and \(\omega_c \equiv \Omega_c h^2\) are the physical baryon and cold dark matter densities relative to the critical density, respectively, \(\Theta_s\) denotes the ratio of the sound horizon to the angular diameter distance at decoupling, \(\tau\) measures the optical depth to re-ionization, \(A_s\) and \(n_s\) characterize the amplitude and the spectral index of the primordial scalar power spectrum, respectively, \(r\) is the tensor to scalar ratio of the primordial spectrum, and we choose \(k_{s0} = 0.05\) Mpc\(^{-1}\) as the pivot scale of the primordial spectrum. Furthermore, in our analysis we include the CMB lensing effect, which also produces B modes from E modes \[17\], when we calculate the theoretical CMB power spectra.

The rotation angle \(\Delta \alpha\) is accumulated along the journey of CMB photons, and the constraints on the rotation angle depends on the multipoles \(\ell\) \[18\]. In Ref.\[1\], the WMAP5 group found that the rotation angle is mainly constrained from the high-\(\ell\) polarization data, and the polarization data at low multipoles do not affect the result significantly. Therefore, in our analysis, we assume a constant rotation angle \(\Delta \alpha\) at all multipoles. Further, we also impose a conservative flat prior on \(\Delta \alpha\) as, \(-\pi/2 \leq \Delta \alpha \leq \pi/2\).

**Numerical Results** – We present our result derived from the WMAP7, B03 and BICEP polarization data in Table I and Fig. 2 in comparison with the published results. Since it is still not very clear how to combine the system-

---

**TABLE I:** Constraints on the rotation angle from various CMB data sets. The Mean values and 68% C.L. error bars are shown.

| Data          | \(\Delta \alpha\) (deg) | Reference |
|---------------|-------------------------|-----------|
| WMAP5+B03+BICEP | \(-2.62 \pm 0.87\)     | This work |
| WMAP7+B03+BICEP | \(-2.33 \pm 0.72\)     | This work |
| BICEP         | \(-2.60 \pm 1.02\)     | This work |
| WMAP7         | \(-1.1 \pm 1.3\)       | Ref.[19]  |
| WMAP5+B03     | \(-2.6 \pm 1.9\)       | Ref.[9]   |
| WMAP5         | \(-1.7 \pm 2.1\)       | Ref.[1]   |
| WMAP3+B03     | \(-6.2 \pm 3.8\)       | Ref.[20]  |
| WMAP3         | \(-2.5 \pm 3.0\)       | Ref.[21]  |
| WMAP3+B03     | \(-6.0 \pm 4.0\)       | Ref.[7]   |

**FIG. 1:** The binned TB and EB spectra measured by the small-scale CMB experiments of BOOMERanG (black squares), BICEP (red circles) and QUaD (blue triangles). The black solid curves show the theoretical prediction of a model with \(\Delta \alpha = -2.62\) deg.

**FIG. 2:** One-dimensional posterior distributions of the rotation angle derived from various data combinations. The dotted vertical line illustrates the unrotated case (\(\Delta \alpha = 0\)) to guide eyes.
atic errors from different polarization measurements, in our calculations we do not include the systematic errors of the CMB measurements [12, 11, 19].

As shown, the previously published constraints on the rotation angle, including the most stringent constraints $\Delta \alpha = -2.6 \pm 1.9 \, \text{deg (1}$ $\sigma \text{)}$ from WMAP5+B03 presented in Ref.[8], are all consistent with $\Delta \alpha = 0$ at 95% confidence level. However, in this work we find that the BICEP data alone give almost the same central value as that from WMAP5+B03, but tighten the constraints by roughly a factor of two, giving $\Delta \alpha = -2.60 \pm 1.02 \, \text{deg (68\% C.L.)}$. This means that BICEP alone favors a non-zero $\Delta \alpha$ at about 2.4$\sigma$ confidence level. Further, when WMAP7 and B03 data are added to the BICEP sample, the constraints get tightened again while the central value remains. In this case,

$$\Delta \alpha = -2.33 \pm 0.72 \, \text{deg (68\% C.L.)} \,. \quad (2)$$

This result gives a more than 3$\sigma$ detection of a non-vanishing rotation angle. Note that we do not include the systematic errors of CMB measurements in our analysis, since it is not very clear how to combine those systematic errors together in a global analysis.

Compared with WMAP7 and B03 data, BICEP data have smaller error bars, making it dominant in the joint analysis. Therefore, our result is largely due to the BICEP TB and EB polarization data. As an illustration, we plot a curve predicted by a $\Delta \alpha = -2.62 \, \text{deg model}$ with the data points in Fig[4]. Apparently, the bump structure in BICEP TB data ($\ell < 400$) is perfectly fitted by the curve, and another excellent fit can be found in the EB panel. In Fig[3] we show the constraints on the rotation angle $\Delta \alpha$ from BICEP polarization data. We can see that the tight constraint on $\Delta \alpha$ mainly comes from the TB and EB power spectra of BICEP data, and TB and EB data give consistent limits on the rotation angle.

Note, however, the sources of the CMB polarization, especially for the B-mode, are not unique. For example, the B-mode can be generated by the cosmological birefringence as mentioned above; it might be converted from E-mode by cosmic shear [17]; it could be the signature of the gravitational waves; or it can even be produced by the instrumental systematics [22]. Therefore, one should bear in mind that the rotation angle might be degenerate with other cosmological parameters or nuisance parameters when fitted to the polarization data. As an example, we illustrate this degeneracy on the CMB BB power spectra in Fig[4]. As shown, the three curves stand for three different mechanisms producing the BB power spectra. Interestingly, we find that the cosmological birefringence degenerate with tensor mode perturbations and with the gravitational lensing on large scales and on small scales, respectively. Therefore, in order to distinguish these effects and obtain the clean information of the primordial tensor B-mode, the rotation angle has to be constrained, and the measurements of TB and EB power spectra are really necessary.

The QUaD data, shown in Fig[1] seem to have good quality, thus it is interesting to re-do the analysis on the rotation angle using this data set. We use the different combinations of the two-point functions measured by QUaD and obtain the result shown in Fig[5]. We start with the TE and EE data, and the constraint on $\Delta \alpha$ is found to be $\Delta \alpha = 0.01 \pm 3.89 \, \text{deg (68\% C.L.)}$. This constraint is very weak and the one-dimensional distribution is almost symmetric around $\Delta \alpha = 0$, which is as expected – the rotated TE and EE spectra are re-

![FIG. 3: The one-dimensional posterior distributions of the rotation angle derived from the BICEP polarization data.](image)

![FIG. 4: The theoretical predictions of the BB power spectra from three different sources: primordial tensor B-mode with $r = 0.01$ (black solid line); lensing-induced (red dashed line) and rotation-induced (blue dash-dot line). The cosmological parameters used here are $\Omega_c h^2 = 0.022$, $\Omega_b h^2 = 0.12$, $\tau = 0.084$, $n_s = 1$, $A_s = 2.3 \times 10^{-9}$, and $\bar{h} = 0.70$.](image)
related to the even functions of $\Delta \alpha$ as shown in Eq. (11), therefore the distribution must be invariant under a sign flip of $\Delta \alpha$. Then we add BB data, the distribution becomes bimodal, and peaks at $|\Delta \alpha| \sim 5.27$ deg. The symmetry is also due to the foregoing arguments since BB still has no sign sensitivity on $\Delta \alpha$. But the shift of the peaks is non-trivial. After a careful investigation, we find that the shift is due to the low-$\ell$ BB data, specially $\ell \sim 370$, which might suffer from the unaccounted systematic errors [23]. Then, we add all the two-point angular power spectra of the QUaD data together, and we find, $\Delta \alpha = 0.59 \pm 0.42$ deg ($68\% \ C.L.$), which is consistent with the published result in Ref. [14], but it seems in tension with the results using other data samples, namely, QUaD is currently the only data sample favoring a positive $\Delta \alpha$ at 68% confidence level. Finally, we combine QUaD with WMAP7, B03 and BICEP data, and the constraint is further tightened to,

$$\Delta \alpha = -0.04 \pm 0.35 \text{ deg} \ (1\sigma) \ .$$ (3)

This means that the non-vanishing $\Delta \alpha$ preference disappears, which is because QUaD prefers a positive $\Delta \alpha$, while other samples favor a negative one.

Summary – In this work, we utilize the most recent observational data of the CMB polarization to constrain the rotation angle $\Delta \alpha$, an indicator of the cosmological CPT violation. Our results significantly improve the previous constraints on the rotation angle, and are already more stringent than those obtained from the polarization data of radio galaxies and quasars [24]. Furthermore we emphasize that the radio galaxies and quasars only measure the rotation of the photon polarization from redshift up to $z \sim 2$ till the present epoch, whereas for CMB polarization data the distance is much longer. Therefore, the constraint on the CPT violating parameter $p_\alpha$, which is the time component of $p_\mu$, will be much stronger. And in this paper we report a $3\sigma$ detection of a non-vanishing rotation angle based on a joint analysis of the BICEP, B03 and WMAP7 data, when neglecting the systematic errors.

Acknowledgments – 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. Our numerical analysis was performed on the MagicCube of Shanghai Supercomputer Center (SSC). We thank M. Brown, Y.-F. Cai, H. C. Chiang, M.-Z. Li and G.-B. Zhao for helpful discussions. This research has been supported in part by National Science Foundation of China under Grant Nos. 10803001, 10533010, 10821063 and 10675136, and the 973 program No. 2007CB815401, and by the Chinese Academy of Science under Grant No. KJCX3-SYW-N2.

[1] E. Komatsu et al., Astrophys. J. Suppl. 180, 330 (2009).
[2] B. Feng, H. Li, M. Li, and X. Zhang, Phys. Lett. B 620, 27 (2005); M. Li, J. Q. Xia, H. Li, and X. Zhang, Phys. Lett. B 651, 357 (2007).
[3] See e.g. V. A. Kostelecky and M. Mewes, Phys. Rev. Lett. 99, 011601 (2007).
[4] S. M. Carroll, G. B. Field, and R. Jackiw, Phys. Rev. D 41, 1231 (1990); S. M. Carroll and G. B. Field, Phys. Rev. D 43, 3789 (1991).
[5] M. Li, X. Wang, B. Feng, and X. Zhang, Phys. Rev. D 65, 103511 (2002); M. Li and X. Zhang, Phys. Lett. B 573, 20 (2003); A. De Felice, S. Nasri, and M. Trodden, Phys. Rev. D 67, 043509 (2003).
[6] H. Li, M. Li, and X. Zhang, Phys. Rev. D 70, 047302 (2004); H. Davoudiasl, R. Kitano, G. D. Kribs, H. Murayama, and P. J. Steinhardt, Phys. Rev. Lett. 93, 201301 (2004).
[7] B. Feng, M. Li, J. Q. Xia, X. Chen, and X. Zhang, Phys. Rev. Lett. 96, 221302 (2006).
[8] A. Lue, L. M. Wang, and M. Kamionkowski, Phys. Rev. Lett. 83, 1506 (1999).
[9] J. Q. Xia, H. Li, G. B. Zhao, and X. Zhang, Astrophys. J. 679, L61 (2008).
[10] D. Larson et al., arXiv:1001.4635 [astro-ph.CO].
[11] T. E. Montroy et al., Astrophys. J. 647, 813 (2006); W. C. Jones et al., Astrophys. J. 647, 823 (2006); F. Picentini et al., Astrophys. J. 647, 833 (2006).
[12] H. C. Chiang et al., arXiv:0906.1181.
[13] J. R. Hinderks et al., Astrophys. J. 692, 1221 (2009).
[14] M. L. Brown et al., arXiv:0906.1003.
[15] E. Komatsu et al., arXiv:1001.4538 [astro-ph.CO].
[16] A. Lewis and S. Bridle, Phys. Rev. D 66, 103511 (2002); URL: http://cosmologist.info/cosmomc/
[17] M. Zaldarriaga and U. Seljak, Phys. Rev. D 58, 023003 (1998).
[18] G. C. Liu, S. Lee, and K. W. Ng, Phys. Rev. Lett. 97, 161303 (2006).
[19] L. Pagano et al., arXiv:0905.1651 N. J. Miller, M. Shimony and B. G. Keating, Phys. Rev. D 79, 103002 (2009).
[20] J. Q. Xia, H. Li, X. Wang, and X. Zhang, Astron. Astro-

FIG. 5: The one-dimensional posterior distributions of the rotation angle derived from the QUaD polarization data.
phys. 483, 715 (2008).
[21] P. Cabella, P. Natoli and J. Silk, Phys. Rev. D 76, 123014 (2007).
[22] N. J. Miller, M. Shimon and B. G. Keating, Phys. Rev. D 79, 063008 (2008).
[23] Private Communications with M. Brown, (2009).
[24] S. M. Carroll, Phys. Rev. Lett. 81, 3067 (1998).