Searching for *CPT* Violation with Cosmic Microwave Background Data from WMAP and BOOMERANG

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We search for signatures of Lorentz and *CPT* violations in the cosmic microwave background (CMB) temperature and polarization anisotropies by using the Wilkinson Microwave Anisotropy Probe (WMAP) and the 2003 flight of BOOMERANG (B03) data. We note that if the Lorentz and *CPT* symmetries are broken by a Chern-Simons term in the effective Lagrangian, which couples the dual electromagnetic field strength tensor to an external four-vector, the polarization vectors of propagating CMB photons will get rotated. Using the WMAP data alone, one could put an interesting constraint on the size of such a term. Combined with the B03 data, we found that a nonzero rotation angle of the photons is mildly favored: $\Delta\alpha = -6.0^{+4.0}_{-4.0}\,^{+3.9}_{-3.7}$ deg$(1, 2\sigma)$.

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After decades of pursuance and many advances in both the theoretical and the observational fronts of cosmological research, a "standard model" of structure formation has been established. It is now possible, with the unprecedented precision of the cosmological observations [1,2], to have robust tests and effective distinctions of the many theoretical models of new physics.

A possible signature of new physics is the *CPT* violation. In the standard model of particle physics *CPT* is an exact symmetry. The detection of *CPT* violation will reveal new physics beyond the standard model. There have been a number of high precision experimental tests on *CPT* conservation in the laboratory [3]. Now cosmology provides another way to test this important symmetry. Also, breaking of the *CPT* symmetry may have played an active role in cosmological evolution. For example, *CPT*-violating interactions in the baryons and leptons provide a baryogenesis mechanism where the baryon number asymmetry is produced in thermal equilibrium [4–9].

In this Letter we study the cosmological *CPT* violation in the photon sector. Phenomenologically, we introduce a Chern-Simons term in the effective Lagrangian of the form [10,11]

$$\mathcal{L}_{\rm int} \sim p_\mu A_\nu \tilde{F}^{\mu\nu}, \tag{1}$$

where p_μ is a four-vector and $\tilde{F}^{\mu\nu} = (1/2)\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$ is the dual of the electromagnetic tensor. The action of (1) is gauge invariant if p_μ is a constant and homogeneous vector or the gradient of a scalar. It violates Lorentz and *CPT* symmetries if the background value of p_μ is nonzero. In the scenario of quintessential baryo- or leptogenesis the four-vector p_μ is in the form of the derivative of the quintessence [12] scalar, $\partial_\mu\phi$. During the evolution of quintessence, the time component of $\partial_\mu\phi$ does not vanish, which causes *CPT* violation. In the scenario of gravitational baryo- or leptogenesis [7,8], p_μ is the gradient of a function of Ricci scalar R [13].

The interaction in (1) violates also the *P* and *CP* symmetries, as long as p_0 does not vanish (e.g., in the case p_μ is the gradient of a time dependent scalar field) [14]. This term can lead to a rotation of the polarization vector of electromagnetic waves when they are propagating over cosmological distances [10]. This effect is known as "cosmological birefringence." The change in the position angle of the polarization plane $\Delta\alpha$, which is obtained by observing polarized radiation from distant radio galaxies and quasars, provides a sensitive measure of the strength of the cosmological birefringence, and this has been used to constrain modified electrodynamics [10,11,15,16].

In the present Letter we use the current cosmic microwave background (CMB) polarization data to measure this type of Lorentz- and *CPT*-violating term *for the first time*. Our results show that the current CMB data provide an interesting indication for a nonzero p_μ.

The Stokes parameters Q and U of the CMB polarization can be decomposed into a gradientlike (G) and a curl-like (C) component [17]. If parity is not violated in the temperature/polarization distribution, the TC and GC cross correlation power spectra vanish due to the intrinsic properties of the tensor spherical harmonics. With the presence of cosmological birefringence, the polarization vector of each photon is rotated by an angle $\Delta\alpha$, and one would observe nonzero TC and GC correlations, even if they are zero at the last scattering surface. Denoting the rotated quantities with a prime, one gets [18]

$$C_l'^{\rm TC} = C_l^{\rm TG}\sin 2\Delta\alpha \tag{2}$$

and [19]

$$C_l'^{\rm GC} = \tfrac{1}{2}(C_l^{\rm GG} - C_l^{\rm CC})\sin 4\Delta\alpha. \tag{3}$$

On the other hand, the original TG, GG, and CC spectra are also modified:

$$C_l'^{\mathrm{TG}} = C_l^{\mathrm{TG}} \cos 2\Delta\alpha, \tag{4}$$

$$C_l'^{\mathrm{GG}} = C_l^{\mathrm{GG}} \cos^2 2\Delta\alpha + C_l^{\mathrm{CC}} \sin^2 2\Delta\alpha, \tag{5}$$

$$C_l'^{\mathrm{CC}} = C_l^{\mathrm{CC}} \cos^2 2\Delta\alpha + C_l^{\mathrm{GG}} \sin^2 2\Delta\alpha. \tag{6}$$

From the above discussion, we see that even with only the TG cross correlation power spectrum (and the TT autocorrelation power spectrum), the Lorentz- and CPT-violating term can still be measured. Of course, direct measurements of the TC and GC power spectra would allow more stringent constraints. Indeed, the GC spectrum will be the most sensitive probe of such a Lorentz- and CPT-violating term [19]; this is because the GC power spectrum is generated by the rotation of the GG power spectrum, which is a more sensitive probe of the primordial fluctuation than the TT and TG spectra [20].

To break possible degeneracy between this term and the variation of other parameters, we make a global fit to the CMB data with the publicly available Markov Chain Monte Carlo package COSMOMC [21,22], which has been modified to allow the rotation of the power spectra discussed above, with a new free parameter $\Delta\alpha$. We assume purely adiabatic initial conditions, and impose the flatness condition motivated by inflation. The following set of 8 cosmological parameters are sampled: the Hubble constant h, the physical baryon and cold dark matter densities, $\omega_b = \Omega_b h^2$ and $\omega_c = \Omega_c h^2$, the ratio of the sound horizon to the angular diameter distance at decoupling, Θ_s, the scalar spectral index, and the overall normalization of the spectrum, n_s and A_s, the tensor to scalar ratio of the primordial spectrum r, and, finally, the optical depth to reionization, τ_r. We have imposed the Gaussian Hubble Space Telescope prior [23], $h = 0.72 \pm 0.08$, and also a weak big-bang nucleosynthesis prior [24], $\Omega_b h^2 = 0.022 \pm 0.002$ (1σ). For the other parameters we have adopted flat priors, and in the computation of the CMB spectra, we have considered lensing contributions.

When the first version of this Letter was being prepared, the available temperature and polarization power spectra included the results from the first-year observation of Wilkinson Microwave Anisotropy Probe (WMAP) [1,25–27], and those from the January 2003 Antarctic flight of BOOMERANG (Hereafter B03) [28–30]. The WMAP 3 yr data (WMAP3) has since been released, with significant improvements on the estimate of the TE power at small ℓ [31]. We have repeated our analysis with the new WMAP three-year data.

In Fig. 1 we plot our one-dimensional constraints on $\Delta\alpha$ from the WMAP data alone and from the combined WMAP and B03 data. We have assumed that the cosmic rotation is not too large and imposed a flat prior $-\pi/2 \leq \Delta\alpha \leq \pi/2$. The CMB temperature power spectrum remains unchanged with the rotation while the TG power spectrum gets modified, as given by Eq. (4).

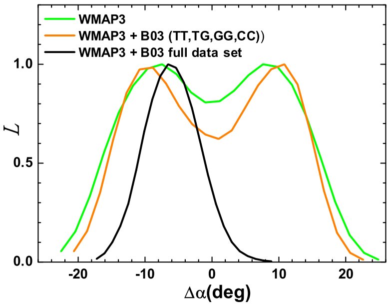

FIG. 1 (color online). One-dimensional constraints on the rotation angle $\Delta\alpha$ from WMAP data alone (green or light gray line), WMAP and the 2003 flight of BOOMERANG B03 TT, TG, GG and CC (orange or gray line), and from WMAP and the full B03 observations (TT, TG, GG, CC, TC, GC) (black line).

Using the data from WMAP alone, for both the first and three-year data set, we obtain a null detection within the error limits. For WMAP3 the $1, 2\sigma$ constraints are $\Delta\alpha = 0.0^{+11.6}_{-11.7}{}^{+5.9}_{-5.9}$ deg. The uncertainty is considerable, as the error bars of the WMAP TG data are relatively large, and TG data are not very sensitive probe. In the likelihood of Fig. 1 we have gained double peaks, which can be easily understood from Eq. (4) due to the symmetry around $\Delta\alpha = 0$.

With the inclusion of the B03 data, the measurement could be improved dramatically. In a first step we also consider the indirect measurements only by including the B03 TT, TG, GG, and CC data. We find the constraint on $\Delta\alpha$ becomes a bit more stringent compared with WMAP only; a nonzero $\Delta\alpha$ is slightly favored and the double peaks are still present. When the B03 TC and GC data are also included the degeneracy around $\Delta\alpha = 0$ is broken. We get the $1, 2\sigma$ constraints to be $\Delta\alpha = -6.0^{+4.0}_{-4.0} \times {}^{+3.9}_{-3.7}$ deg with WMAP3 and the B03 full data set.

The covariance matrices of the B03 TC and GC data are correlated. In order to find out what role the TC and GC data play in our fitting, respectively, we have made fits with, in one case, only the TC spectrum rotated as Eq. (2), and in the other case only the GC spectrum rotated. To make the comparison clear and avoid the problem of convergence we set the flat prior $-1.2 \leq \Delta\alpha \leq 0.8$. In Fig. 2, we plot the resulting one-dimensional constraints. In neither case is the likelihood symmetric at $\Delta\alpha = 0$. In the TC rotated only case, the symmetric points are around $\pm\pi/4$, as we can see from Eq. (2). Such a symmetry is lost for this narrower prior, but in our global fittings (Fig. 1) we have allowed a larger range of $\Delta\alpha$. We find from Fig. 2 that the TC data are very weak in breaking the degeneracy around $\Delta\alpha = 0$, while for GC the rotation is more eminent, where the likelihood in Fig. 2 is centered at around $\Delta\alpha = -\pi/8$. In this fit $\Delta\alpha = 0$ has an excess of $\Delta\chi^2 = 4$, which is disfavored compared with the best fit case.

The effect of the polarization rotation is degenerate with variation on the amplitude of the primordial spectrum and the tensor to scalar ratio. These parameters are also degen-

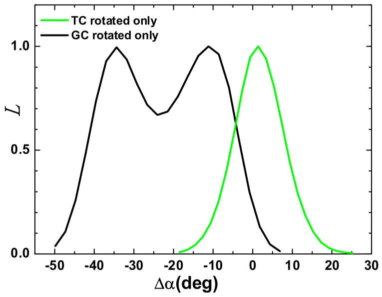

FIG. 2 (color online). One-dimensional constraints on the rotation angle $\Delta\alpha$ from WMAP and the B03 observations, assuming only CMB TC is rotated to be nonzero by $\Delta\alpha$ (green or gray line) and only GC rotated (black line).

erate with the optical depth of reionization. In Fig. 3 we plot the joint two-dimensional posterior probability contours of $\Delta\alpha$ with τ_r, n_S, A_S, and r. More precise measurements on these four parameters will help to break the degeneracy on the constraints of cosmic Lorentz and *CPT* violations discussed here. We have also made fits with a running spectrum index, but found that it does not affect the above results significantly. The inclusion of the matter power spectrum obtained from large scale structure measurements also does not change our constraints on $\Delta\alpha$ significantly.

Previously, the cosmological birefringence effect has been constrained by looking for correlations between the elongation axes and polarization vectors of distant radio galaxies and quasars. The most recent searches yield null results, with an error on $\Delta\alpha$ at the order of 1° level [11,15,16]. The typical redshifts of the sources in these searches are of order of unity. Conceivably, for the much greater redshift range between the last scattering surface and the present-day observer, the cumulative effect of cosmological birefringence could be stronger.

It was claimed that the individual B03 CC and CG data are consistent with zero [29]; however, we found that a negative rotation angle is preferred in our combined analysis. It is noteworthy that our result relies mainly on the fact that at $l \sim 350$, GG power of B03 is positive, CC power is (slightly) positive, and GC power is (slightly) negative. Using Eq. (3), the GC power spectrum helps to increase the statistical significance on nonzero $\Delta\alpha$. At present, the only publicly available (polarization) data are the three-year WMAP and the data from a 200-hour flight of the BOOMERANG balloon. In the coming few years, the quantity and quality of the CMB polarization data are likely to be improved rapidly, with the ongoing WMAP observations and many balloon experiments like the BOOMERANG. These would allow better measurements of $\Delta\alpha$.

While nonzero TG and CG power can also be induced by Faraday rotations [32] and higher dimensional Lorentz and *CPT* violating operators [33], these are often frequency dependent, while the effects described here are not [34]. This provides, at least in principle, a way to distinguish between these different effects. The Faraday rotation induced by magnetic field is given by

$$\frac{\Delta\alpha}{\mathrm{rad}} = 8.1 \times 10^5 \left(\frac{\lambda}{\mathrm{m}}\right)^2 \int_0^L \left(\frac{B_\parallel}{\mathrm{Gs}}\right)\left(\frac{n_e}{\mathrm{cm}^{-3}}\right)\frac{dL}{\mathrm{pc}}. \qquad (7)$$

If we assume that reionization occurs at $z < 20$, then for a global intergalactic magnetic field of 10^{-9} Gs, at the frequency of 145 GHz where BOOMERANG operates, the Faraday rotation is only of the order of 10^{-3} deg, which is much smaller than the range of α uncertainty distribution and hence insignificant. The apparent rotation might also be due to contamination from foreground emission. In some attempts to obtain CMB temperature and polarization spectra, including those of WMAP, foreground-removing procedure has been applied. For the BOOMERANG experiment, which operates at relatively high frequency, it is believed that the primary CMB polarization signal is dominant, and the contribution of the polarized galactic synchrotron foreground is small [29], but at present a small contamination cannot be ruled out completely. Future multiwavelength polarization observations would help distinguish this possibility.

We could not yet conclude that *CPT* is definitely violated if a nonzero $\Delta\alpha$ is detected. However, if such a detection is confirmed, it would certainly raise the possibility of a Lorentz-violating term like that given in Eq. (1), or others of the similar form. For example, a term of this form could be due to the interaction between dark energy and the electromagnetic sector, if we take p_μ as $\partial_\mu\phi$ with ϕ being quintessence field. Thus, the results we obtained can be used to put additional constraints on the behaviors of dynamical dark energy between the redshift range from $z \sim 1$ to $z \sim 1000$.

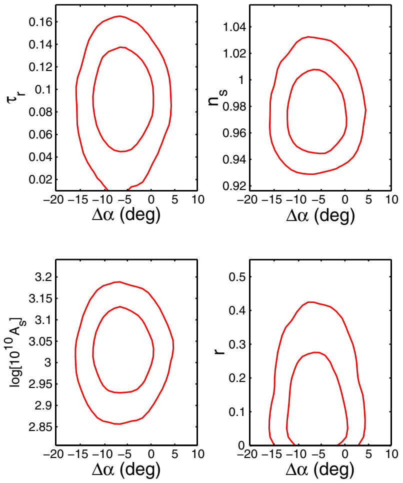

FIG. 3 (color online). Joint two-dimensional posterior probability contour plots in the $\Delta\alpha - \tau_r$ (top left panel), $\Delta\alpha - n_S$ (top right panel), $\Delta\alpha - \log[10^{10}A_S]$ (bottom left panel), and $\Delta\alpha - r$ (bottom right panel), showing the 68% and 95% contours from the WMAP + B03 constraints.

A Lorentz violation also implies the violation of the equivalence principle. In our case where only a small violation is present, the group velocity of light remains unchanged, and the weak equivalence principle is satisfied. On the other hand, the Einstein equivalence principle is violated, as there would be a split of photon helicities [35]. Furthermore, causality is violated for timelike p_μ. However, this violation is significant only in the regions where the wavelengths of photons are very large [36].

In summary, current cosmological observations have opened a new window for probing new physics. In this Letter we show that the current data from WMAP and BOOMERANG might indicate a rotated polarization angle, which can be resulted from the *CPT* and Lorentz violations. Such a result, if confirmed at greater significance by future observations, would reveal hitherto unknown dynamics of the nature.

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