Parity Violation Constraints Using Cosmic Microwave Background Polarization Spectra from 2006 and 2007 Observations by the QUaD Polarimeter

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(Received 4 November 2008; revised manuscript received 13 March 2009; published 21 April 2009)

We constrain parity-violating interactions to the surface of last scattering using spectra from the QUaD experiment's second and third seasons of observations by searching for a possible systematic rotation of the polarization directions of cosmic microwave background photons. We measure the rotation angle due to such a possible "cosmological birefringence" to be $0.55° \pm 0.82°$ (random) $\pm 0.5°$ (systematic) using QUaD's 100 and 150 GHz temperature-curl and gradient-curl spectra over the spectra over the multipole range $200 < \ell < 2000$, consistent with null, and constrain Lorentz-violating interactions to $< 2 \times 10^{-43}$ GeV (68% confidence limit). This is the best constraint to date on electrodynamic parity violation on cosmological scales.

DOI: 10.1103/PhysRevLett.102.161302 PACS numbers: 98.70.Vc, 11.30.Er, 95.85.Bh, 98.80.Es

Background.—Cosmic microwave background (CMB) polarization measurements at multipoles of $\ell > 20$ are unaffected by reionization and are an effective means to probe for cosmological-scale electrodynamic parity violation to the surface of last scattering. Using the CMB is particularly attractive because of the long path length to the surface of last scattering, the well-understood physics of the primordial Universe that generated the CMB photons, and two cross spectra, the temperature-curl (TB) and gradient-curl (EB) cross correlations, that should be null in a parity-conserving universe [1–5]. As the effect should be frequency independent, measurements of the CMB at multiple frequencies can distinguish it from other EB correlation inducing effects like Faraday rotation from magnetic fields in the intergalactic medium [6–8].

The known parity violation in the weak force is sufficient motivation for investigating electrodynamic parity violation, but it has been shown that parity-violating interactions are a potential solution to the problem of baryon number asymmetry because they can be a signature of *CPT* (charge-parity-time) violation in an expanding Universe [9].

The effect arises by adding a Cherns-Simons term to the normal electrodynamic Lagrangian, violating Lorentz, P and *CPT* symmetries [10,11]:

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + p_\mu A_\nu \tilde{F}^{\mu\nu} \tag{1}$$

Here $F^{\mu\nu}$ denotes the field tensor, $\tilde{F}^{\mu\nu}$ is its dual, p_μ is an external vector, and A_ν the 4-vector potential. Nonzero time or space components of p_μ induce a rotation of the polarization direction of each photon as it propagates from the surface of last scattering. This is equivalent to a local rotation of the Stokes parameters, Q and U, in the polarization maps made by CMB experiments, inducing gradient (E) to curl (B) mode mixing and therefore EB correlation. Lorentz violation can also be tested with these models [10,12]. In addition, models of quintessence can be probed by examining the EB and TB spectra for nonzero power [13].

QUaD was a 100 and 150 GHz bolometric polarimeter that made deep observations of the CMB from the South Pole during the austral winters of 2005 through 2007. A recent analysis of the second and third seasons of data from QUaD shows a series of acoustic peaks in the EE autospectra over the multipole range $200 < \ell < 2000$ consistent with the Λ-CDM model of the Universe [14]. This data set offers the strongest constraining power to date on cosmological-scale parity-violating interactions. The QUaD Collaboration maintains two code independent, but nearly algorithmically identical data analysis pipelines for the purposes of consistency checking. The results presented here use the 100 and 150 GHz spectra from the "alternative pipeline" described in section 6.8 of Pryke *et al.* [14] for reasons of computational convenience, derived using a modified version of the MASTER CMB analysis method [15].

Analysis.—Assuming that the CMB is a Gaussian random field, the entirety of its statistical properties can be described by the auto- and cross-correlation power spectra:

$$C_\ell^{XY} = \frac{1}{2\ell + 1}\sum_m a_{\ell m}^{X*} a_{\ell m}^{Y}, \tag{2}$$

where the $a_{\ell m}$ are the coefficients of the spherical harmonic decomposition of the temperature or polarization maps. X and Y here denote T, E, or B for the respective maps of temperature, gradient-polarization, and curl-polarization modes.

Normally the $C_\ell^{\rm TB}$ and $C_\ell^{\rm EB}$ are expected to be null because the spherical harmonic eigenfunctions $Y_{\ell m}^T$ and $Y_{\ell m}^E$ have parity $(-1)^\ell$ and $Y_{\ell m}^B$ has parity $(-1)^{\ell+1}$. Assuming that there is a parity-violating effect in the electrodynamics equations that prefers one polarization to another over cosmological scales, let us denote the average preferred rotation of the polarization direction of a photon from the surface of last scattering as it heads towards us as $\Delta\alpha$. This corresponds to a rotation of the polarization directions in the maps [1,9] inducing E to B mixing, and therefore EB cross correlation. Likewise, since there is already TE cross correlation, TB cross correlation is also induced. Following Komatsu *et al.* [16], we assume that cosmological BB modes are zero to simplify the equations and maximize the likelihood of a detection:

$$C_\ell^{\rm TE,obs} = C_\ell^{\rm TE}\cos(2\Delta\alpha), \tag{3}$$

$$C_\ell^{\rm TB,obs} = C_\ell^{\rm TE}\sin(2\Delta\alpha), \tag{4}$$

$$C_\ell^{\rm EE,obs} = C_\ell^{\rm EE}\cos^2(2\Delta\alpha), \tag{5}$$

$$C_\ell^{\rm BB,obs} = C_\ell^{\rm EE}\sin^2(2\Delta\alpha), \tag{6}$$

$$C_\ell^{\rm EB,obs} = \tfrac{1}{2}(C_\ell^{\rm EE})\sin(4\Delta\alpha). \tag{7}$$

For the purposes of plotting and analysis, we can derive a theory-independent χ^2 statistic to combine the first two and the last three equations separately to obtain an estimate of $\Delta\alpha$, utilizing constraining power from across our 23 reported band powers. First, we assume $\ell(\ell+1)C_\ell^{XX,\rm obs}$ is constant within a band power and define the quantities below for each band power:

$$D_{{\rm TB},\ell} = C_\ell^{\rm TB,obs}\cos(2\Delta\alpha) - C_\ell^{\rm TE,obs}\sin(2\Delta\alpha), \tag{8}$$

$$D_{{\rm EB},\ell} = C_\ell^{\rm EB,obs} - \frac{1}{2}(C_\ell^{\rm BB,obs} + C_\ell^{\rm EE,obs})\sin(4\Delta\alpha). \tag{9}$$

We can then minimize $\chi^2(\Delta\alpha)$ for the TB and EB combinations separately to estimate $\Delta\alpha$. (It is also possible to estimate $\Delta\alpha$ by measuring the quantities $2C_\ell^{\rm EB,obs}/(C_\ell^{\rm EE,obs} + C_\ell^{\rm BB,obs})$ and $C_\ell^{\rm TB,obs}/\sqrt{(C_\ell^{\rm TE,obs})^2 + (C_\ell^{\rm TB,obs})^2}$ on a per–band-power basis, combining them using the covariances as measured from simulations, and then applying inverse trigonometric functions. However, this is biased in the presence of noise.):

$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{{\rm TB},\ell} M_{\ell\ell'}^{-1} D_{{\rm TB},\ell'}, \tag{10}$$

$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{{\rm EB},\ell} M_{\ell\ell'}^{-1} D_{{\rm EB},\ell'}. \tag{11}$$

We empirically measure the covariance matrix $M_{\ell\ell'}$ of the band powers in each spectrum $D_{{\rm EB},\ell}$ and $D_{{\rm TB},\ell}$ from a set of simulated band powers combining realizations of Λ-CDM cosmology temperature and polarization fields for the signal component and accurate realizations of QUaD's instrumental noise. Our method utilizes a set of 496 signal and noise Monte Carlo simulations from the analysis pipeline of QUaD. Pryke *et al.* [14] demonstrates the robustness

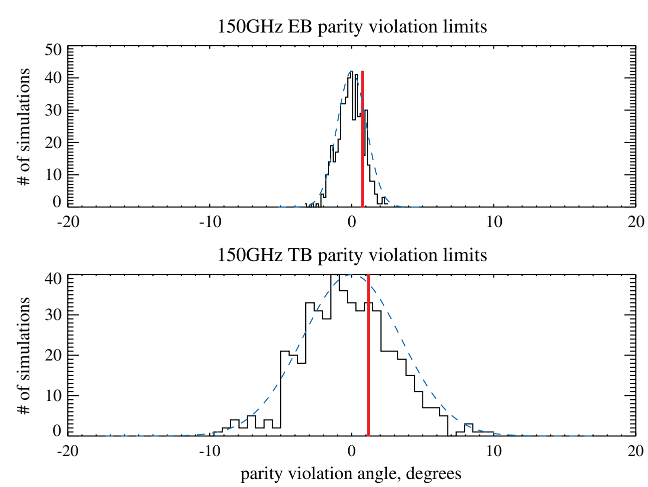

FIG. 1 (color). $\Delta\alpha$ measured from QUaD 150 GHz TB and EB spectra; histogram of simulations and red line for data. The histogram does not account for systematic error. The dotted line indicates total uncertainty assuming a Gaussian 0.5° systematic error.

of QUaD's simulation method against a variety of systematics tests.

Figure 1 shows the results of this combination for the data (red line) and simulations (histogram) for 150 GHz in both EB and TB. Overplotted is the total uncertainty assuming that the simulations reflect a normal distribution and that the systematic error is 0.5°. It is clear that the observed data can easily be drawn from the set of simulations in which no parity-violating interactions have been included; we therefore conclude that there is no detection.

To obtain a visual representation of a "$\Delta\alpha$ spectrum," We can also estimate the best fit for $\Delta\alpha$ on a per–band-power basis by minimizing:

$$\chi^2_\ell(\Delta\alpha) = \sum_{\ell'} D_{\mathrm{TB},\ell} M^{-1}_{\ell\ell'} D_{\mathrm{TB},\ell'}, \tag{12}$$

$$\chi^2_\ell(\Delta\alpha) = \sum_{\ell'} D_{\mathrm{EB},\ell} M^{-1}_{\ell\ell'} D_{\mathrm{EB},\ell'}. \tag{13}$$

The $\Delta\alpha$ spectrum using the EB, BB, and EE spectra for 150 GHz is shown in Fig. 2.

Current limits and QUaD results.—Komatsu *et al.* [16] report their limits from the WMAP five-year high-ℓ data as $\Delta\alpha = -1.2° \pm 2.2°$. Other authors have found weak evidence for parity violation by combining the WMAP five-year data and data from the BOOMERanG balloon experiment, reporting $\Delta\alpha = -2.6° \pm 1.9°$ [11]. Carroll *et al.* [10] Carroll derived constraints on $\Delta\alpha$ 10 high-redshift radio galaxies in 1990, yielding $\Delta\alpha = -0.6° \pm 1.5°$. The best single redshift number, for 3C9 at $z = 2.012$, is $\Delta\alpha = 2° \pm 3°$.

QUaD's results broken down by individual spectrum and frequency, as well as combined within and between frequencies, are shown in Table I. Reported errors are 68.2%

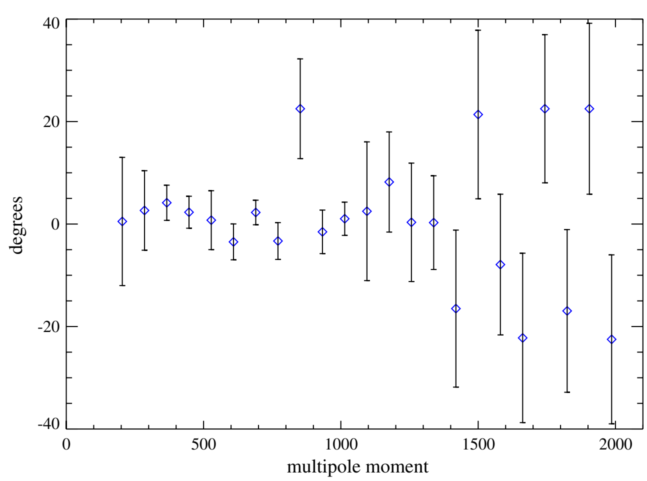

FIG. 2 (color online). 150 GHz $\Delta\alpha$ per–band power derived from the EB spectrum. Note that in practice these points are combined before the final transformation to $\Delta\alpha$—the purpose of this plot is to give a visual representation of the relative uncertainties across the band powers.

confidence limits as determined by the distribution of signal and noise simulations. 150 GHz EB alone is significantly more constraining than any current result. At no frequency, nor in any spectrum, is there a significant detection. We also present values for $\Delta\alpha$ where the systematic bias induced by a combination of time stream filtering and the slightly different, nonaligned, and elliptical nature of the beams of two orthogonally aligned polarization sensitive detectors within a single feedhorn leading to temperature to polarization leakage has been quantified by signal-only simulations. This effect is discussed in further detail in Hinderks *et al.* [17]. Note that in all frequencies and spectra this bias is an order of magnitude smaller than our random and systematic errors. After combination the EB spectra dominate the analysis and there is virtually no bias. These results are consistent with a constraint on isotropic Lorentz-violating interactions of $k^{(3)}_{(V)00} < 2 \times 10^{-43}$ GeV [12].

Systematic effects and checks.—The primary systematics concern is that there might be a systematic rotation of the true detector sensitivity angles, producing a false signal totally degenerate with that of parity violation; for example, a $-3°$ systematic misalignment and a $\Delta\alpha = -3°$ true parity violation signal would produce identical results. We have measured the overall rotation angle of our instrument using two methods. The first measures the polarization sensitivity angle of each bolometer using a near field polarization source. The second constrains the absolute angle of the focal plane by examining the measured offsets of the beams of each detector from the telescope pointing direction on an astronomical source. These two methods agree nearly exactly indicating that any systematic rotation of the bolometers within the focal plane structure is negligible. Given that there is no physical or mechanical reason to suspect such a rotation, and the uncertainties of the measurements, we conservatively assign a systematic uncertainty on the absolute rotation angle of the instrument of 0.5° and quote this value in the abstract and in Table I.

We have reanalyzed the entire data set after inserting an artificial 2° local polarization rotation only in the data maps, resulting in a 2° shift after deriving $\Delta\alpha$ identically to the procedure above, validating the analysis pipeline.

A secondary concern is random scatter in the assumed detector angles. This is a different effect than a systematic rotation of all of the detectors. The Monte Carlo simulation pipeline includes the injection of a degree of uncertainty about the true orientation of each polarization sensitive bolometer into every simulation commensurate with the uncertainty of the measurements described in Hinderks *et al.* [17]. Thus, when constructing a "fake focal plane" for signal-only simulations of a given CMB realization, we assign every bolometer a random deviation from its presumed angle at reconstruction, drawn from a Gaussian distribution with $\sigma = 1°$. We also assume that the polarization grids are sensitive to the orthogonal polarization

TABLE I. Column 1: $\Delta\alpha$ measurements from QUaD, including random and systematic errors. Column 2: bias and standard errors on mean sampled from 496 signal-only simulations. Column 3: column 2 subtracted from column 1. Column 4: scatter of signal-only simulations, indicating sample variance. Column 5: fraction of signal + noise simulations where $\|\Delta\alpha\|$ exceeds that of data.

Spectrum	$\Delta\alpha$ (random and sys. errors)	Systematic bias	Bias-corrected $\Delta\alpha$ (random and sys. errors)	Signal-only simulation scatter	% simulations exceeding
150 GHz EB	$0.76° \pm 0.92° \pm 0.5°$	$0.003° \pm 0.003°$	$0.76° \pm 0.92° \pm 0.5°$	0.08°	41.3%
150 GHz TB	$1.19° \pm 3.26° \pm 0.5°$	$0.025° \pm 0.017°$	$1.16° \pm 3.26° \pm 0.5°$	0.37°	71.5%
100 GHz EB	$-3.74° \pm 2.22° \pm 0.5°$	$0.011° \pm 0.004°$	$-3.75° \pm 2.22° \pm 0.5°$	0.10°	8.87%
100 GHz TB	$3.72° \pm 5.69° \pm 0.5°$	$0.073° \pm 0.022°$	$3.65° \pm 5.69° \pm 0.5°$	0.50°	52.2%
150 GHz combined	$0.85° \pm 0.94° \pm 0.5°$	$0.015° \pm 0.003°$	$0.83° \pm 0.94° \pm 0.5°$	0.07°	35.8%
100 GHz combined	$-1.86° \pm 2.24° \pm 0.5°$	$0.031° \pm 0.005°$	$-1.89° \pm 2.24° \pm 0.5°$	0.11°	38.7%
100/150 combined	$0.56° \pm 0.82° \pm 0.5°$	$0.011° \pm 0.004°$	$0.55° \pm 0.82° \pm 0.5°$	0.08°	49.6%

direction at a level of $7 \pm 3\%$ and include this effect in the simulation pipeline. Signal-only simulations with and without these effects included show that their contribution to the final uncertainty is small.

As detailed in Table I, our analysis of signal-only simulations reveal a small bias in the recovered $\Delta\alpha$ values. In order to isolate the source of this bias, we have performed additional sets of signal-only simulations, including in isolation the effects of filtering, misaligned beams, uncertainties in detector alignment, and cross-polar leakage. The results from these tests confirm that a combination of time stream filtering and beam misalignment is the source of the bias. Note that, although small compared to our noise-driven errors, our results do include a correction for the bias.

Conclusions.—We have presented the strongest constraints on parity violation to date. Assuming that there are no cosmological-scale parity-violating interactions, we have also demonstrated that it is possible to understand the cumulative effects of detector misalignment uncertainties in polarization sensitive bolometer-based instruments to under 1° through a combination of analysis of primary CMB polarization data and lab measurements. This is of potential interest with respect to analysis of data from the high frequency instrument of the upcoming Planck Satellite.

We thank the substantial contributions of an anonymous referee for improving our method. QUaD is funded by the National Science Foundation in the U.S., through Grants No. ANT-0637420, No. ANT-0739729, No. ANT-0638615, No. ANT-0638352, No. ANT-0739413, No. AST-0096778, No. ANT-0338138, No. ANT-0338335, and No. ANT-0338238, by the U.K. Science and Technology Facilities Council (STFC) and its predecessor the Particle Physics and Astronomy Research Council (PPARC), and by the Science Foundation Ireland. E. Y. W. acknowledges the support of the NDSEG program. J. R. H. acknowledges the support of the NSF Graduate Research program, the Stanford Graduate program, and NASA. P. G. C. is funded by the *Fundação para a Ciência e a Tecnologia*. C. P. and J. E. C. acknowledge partial support from the Kavli Institute for Cosmological Physics from Grant No. NSF PHY-0114422. M. Z. acknowledges the support of NASA.

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