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

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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 $0.55^\circ \pm 0.82^\circ$ (random) $\pm 0.5^\circ$ (systematic) using QUaD’s 100 and 150 GHz temperature-curl and gradient-curl 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.

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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]:

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

(1)

Here $F^{\mu\nu}$ denotes the field tensor, $\tilde{F}^{\mu\nu}$ is its dual, $p_\mu$ is an external vector, and $A_\mu$ the 4-vector potential. Nonzero time or space components of $p_\mu$ 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 $\Lambda$-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, cosmologically parity-violating interactions. The set offers the strongest constraining power to date on cosmological-scale parity-violating interactions. The QUaD Collaboration maintains two code independent, 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:

$$C_{\ell}^{XY} = \frac{1}{2\ell + 1} \sum_{m} a_{\ell m} a_{\ell m}^*,$$  \hspace{1cm} (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 $C_{\ell}^{TB}$ and $C_{\ell}^{EB}$ 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:

$$C_{\ell}^{EE,\text{obs}} = C_{\ell}^{EE} \cos(2\Delta \alpha), \hspace{1cm} (3)$$  
$$C_{\ell}^{TE,\text{obs}} = C_{\ell}^{TE} \sin(2\Delta \alpha), \hspace{1cm} (4)$$  
$$C_{\ell}^{EE,\text{obs}} = C_{\ell}^{EE} \cos^2(2\Delta \alpha), \hspace{1cm} (5)$$  
$$C_{\ell}^{BB,\text{obs}} = C_{\ell}^{EE} \sin^2(2\Delta \alpha), \hspace{1cm} (6)$$  
$$C_{\ell}^{EB,\text{obs}} = \frac{1}{2}(C_{\ell}^{EE}) \sin(4\Delta \alpha). \hspace{1cm} (7)$$

For the purposes of plotting and analysis, we can derive a theory-independent $\chi^2$ 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 $\ell(\ell + 1)C_{\ell}^{XY,\text{obs}}$ is constant within a band power and define the quantities below for each band power:

$$D_{TB,\ell} = C_{\ell}^{TB,\text{obs}} \cos(2\Delta \alpha) - C_{\ell}^{TE,\text{obs}} \sin(2\Delta \alpha), \hspace{1cm} (8)$$  
$$D_{EB,\ell} = C_{\ell}^{EB,\text{obs}} - \frac{1}{2}(C_{\ell}^{BB,\text{obs}} + C_{\ell}^{EE,\text{obs}}) \sin(4\Delta \alpha). \hspace{1cm} (9)$$

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 $2C_{\ell}^{TB,\text{obs}}/(C_{\ell}^{EE,\text{obs}} + C_{\ell}^{BB,\text{obs}})$ and $C_{\ell}^{TB,\text{obs}}/\sqrt{(C_{\ell}^{EE,\text{obs}})^2 + (C_{\ell}^{TB,\text{obs}})^2}$ 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.):

$$\chi^2(\Delta \alpha) = \sum_{\ell \ell'} D_{TB,\ell} M_{\ell \ell'}^{-1} D_{TB,\ell'}, \hspace{1cm} (10)$$  
$$\chi^2(\Delta \alpha) = \sum_{\ell \ell'} D_{EB,\ell} M_{\ell \ell'}^{-1} D_{EB,\ell'}. \hspace{1cm} (11)$$

We empirically measure the covariance matrix $M_{\ell \ell'}$ of the band powers in each spectrum $D_{EB,\ell}$ and $D_{TB,\ell}$ from a set of simulated band powers combining realizations of $\Lambda$-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
of QUaD’s simulation method against a variety of system-
atics 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
among that the systematic error is 0.5°. It is clear that the
observed data can easily be drawn from the set of simula-
tions in which no parity-violating interactions have been
included; we therefore conclude that there is no detection.

To obtain a visual representation of a “Δα spectrum,”
we can also estimate the best fit for Δα on a per-band-
power basis by minimizing:

\[
\chi^2_{\ell}(\Delta \alpha) = \sum_{\ell'} D_{TB,\ell'} M_{\ell'\ell}^{-1} D_{TB,\ell'},
\]

(12)

\[
\chi^2_{\ell}(\Delta \alpha) = \sum_{\ell'} D_{EB,\ell'} M_{\ell'\ell}^{-1} D_{EB,\ell'},
\]

(13)

The Δα 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
Δα = −1.2° ± 2.2°. Other authors have found weak evi-
dence for parity violation by combining the WMAP five-
year data and data from the BOOMERanG balloon exper-
iment, reporting Δα = −2.6° ± 1.9° [11]. Carroll et al.
[10] Carroll derived constraints on Δα 10 high-redshift
radio galaxies in 1990, yielding Δα = −0.6° ± 1.5°. The
best single redshift number, for 3C9 at z = 2.012, is Δα = 2° ± 3°.

QUaD’s results broken down by individual spectrum and
frequency, as well as combined within and between fre-
quencies, are shown in Table I. Reported errors are 68.2%
confidence limits as determined by the distribution of
signal and noise simulations. 150 GHz EB alone is signifi-
cantly more constraining than any current result. At no
frequency, nor in any spectrum, is there a significant de-
tection. We also present values for Δα where the system-
atic 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 com-
bination the EB spectra dominate the analysis and there is
virtually no bias. These results are consistent with a con-
straint on isotropic Lorentz-violating interactions of
\[k^{(3)}_{\perp 00} < 2 \times 10^{-43} \text{ GeV} \]

Systematic effects and checks.—The primary system-
atics 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 Δα = −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 mea-
sured offsets of the beams of each detector from the tele-
scope pointing direction on an astronomical source. These
two methods agree nearly exactly indicating that any sys-
tematic 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 as-
sign 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 Δα 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 pre-
sumed angle at reconstruction, drawn from a Gaussian
distribution with σ = 1°. We also assume that the polar-
ization grids are sensitive to the orthogonal polarization

![FIG. 2 (color online). 150 GHz Δα per–band power derived
from the EB spectrum. Note that in practice these points are
combined before the final transformation to Δα—the purpose
of this plot is to give a visual representation of the relative un-
certainties across the band powers.](161302-3)
TABLE I.\n
<table>
<thead>
<tr>
<th>Spectrum</th>
<th>(\Delta \alpha) (random and sys. errors)</th>
<th>Systematic bias</th>
<th>Bias-corrected (\Delta \alpha) (random and sys. errors)</th>
<th>Signal-only simulation scatter</th>
<th>% simulations exceeding 71.5%</th>
<th>49.6%</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 GHz EB</td>
<td>0.76(^\pm) 0.92(^\pm) 0.5(^\pm) 0.003(^\pm) 0.003(^\pm)</td>
<td>1.19(^\pm) 3.26(^\pm) 0.5(^\pm) 0.025(^\pm) 0.017(^\pm)</td>
<td>1.68(^\pm) 3.26(^\pm) 0.5(^\pm) 0.037(^\pm) 0.022(^\pm)</td>
<td>0.88(^\pm) 0.94(^\pm) 0.5(^\pm) 0.07(^\pm) 0.003(^\pm)</td>
<td>0.37(^\pm) 0.10(^\pm) 0.50(^\pm) 0.07(^\pm) 0.11(^\pm)</td>
<td>41.3%</td>
</tr>
<tr>
<td>100 GHz EB</td>
<td>-3.74(^\pm) 2.22(^\pm) 0.5(^\pm) 0.011(^\pm) 0.004(^\pm)</td>
<td>3.72(^\pm) 5.69(^\pm) 0.5(^\pm) 0.073(^\pm) 0.002(^\pm)</td>
<td>-3.75(^\pm) 2.22(^\pm) 0.5(^\pm) 0.010(^\pm) 0.005(^\pm)</td>
<td>0.83(^\pm) 0.94(^\pm) 0.5(^\pm) 0.07(^\pm) 0.003(^\pm)</td>
<td>0.10(^\pm) 0.07(^\pm) 0.11(^\pm) 0.07(^\pm) 0.005(^\pm)</td>
<td>52.2%</td>
</tr>
<tr>
<td>150 GHz combined</td>
<td>0.85(^\pm) 0.94(^\pm) 0.5(^\pm) 0.015(^\pm) 0.003(^\pm)</td>
<td>1.86(^\pm) 2.24(^\pm) 0.5(^\pm) 0.031(^\pm) 0.005(^\pm)</td>
<td>-1.89(^\pm) 2.24(^\pm) 0.5(^\pm) 0.011(^\pm) 0.005(^\pm)</td>
<td>0.55(^\pm) 0.82(^\pm) 0.5(^\pm) 0.08(^\pm) 0.004(^\pm)</td>
<td>0.08(^\pm) 0.07(^\pm) 0.08(^\pm) 0.08(^\pm) 0.004(^\pm)</td>
<td>49.6%</td>
</tr>
<tr>
<td>100/150 combined</td>
<td>0.56(^\pm) 0.82(^\pm) 0.5(^\pm) 0.011(^\pm) 0.004(^\pm)</td>
<td>0.08(^\pm) 0.07(^\pm) 0.08(^\pm) 0.08(^\pm) 0.004(^\pm)</td>
<td>0.08(^\pm) 0.07(^\pm) 0.08(^\pm) 0.08(^\pm) 0.004(^\pm)</td>
<td>0.08(^\pm) 0.07(^\pm) 0.08(^\pm) 0.08(^\pm) 0.004(^\pm)</td>
<td>0.08(^\pm) 0.07(^\pm) 0.08(^\pm) 0.08(^\pm) 0.004(^\pm)</td>
<td>49.6%</td>
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As detailed in Table I, our analysis of signal-only simulations reveals 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.

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