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Article

New Tests on Lorentz Invariance Violation Using Energy-Resolved Polarimetry of Gamma-Ray Bursts

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Abstract: One of the manifestations of Lorentz invariance violation (LIV) is vacuum birefringence, which leads to an energy-dependent rotation of the polarization plane of linearly polarized photons arising from an astrophysical source. Here we use the energy-resolved polarization measurements in the prompt γ -ray emission of five bright gamma-ray bursts (GRBs) to constrain this vacuum birefringent effect. Our results show that at the 95% confidence level, the birefringent parameter η characterizing the broken degree of Lorentz invariance can be constrained to be $|\eta| < \mathcal{O}(10^{-15} - 10^{-16})$, which represent an improvement of at least eight orders of magnitude over existing limits from multi-band optical polarization observations. Moreover, our constraints are competitive with previous best bounds from the single γ -ray polarimetry of other GRBs. We emphasize that, thanks to the adoption of the energy-resolved polarimetric data set, our results on η are statistically more robust. Future polarization measurements of GRBs at higher energies and larger distances would further improve LIV limits through the birefringent effect.

Keywords: gamma-ray bursts; astroparticle physics; gravitation; quantum gravity

1. Introduction

Lorentz invariance is a fundamental postulate of Einstein's theory of relativity as well as of the Standard Model of particle physics. However, a violation or deformation of Lorentz invariance at around the Planck energy scale $E_{\text{Pl}} = \sqrt{\hbar c^5/G} \simeq 1.22 \times 10^{19}$ GeV are predicted in many quantum gravity theories attempting to unify quantum theory and gravity [1–16]. Experimental searches for potential signatures of Lorentz invariance violation (LIV) have been conducted in various systems (see [17] for a continuously updated compilation).

For photons with energy $E \ll E_{\text{Pl}}$, one of the most discussed LIV-induced modifications to the dispersion relation can be parameterized as [18]

$$E_{\pm}^2 = p^2 c^2 \pm \frac{2\eta}{E_{\text{Pl}}} p^3 c^3, \quad (1)$$

where $\pm$ represents opposite helicities, i.e., right- and left-handed circular polarization states of the photon, and η is a dimensionless parameter describing the broken degree of Lorentz invariance. This modified dispersion relation with $\eta \neq 0$ implies that group velocities of photons with different circular polarizations should differ slightly. Consequently, the polarization vector of a linearly polarized light may experience an energy-dependent rotation, also known as vacuum birefringence. Observations of linear polarization can therefore be used to test Lorentz invariance (e.g., [19–41]). Although the effects of vacuum birefringence are supposed to be minuscule at attainable energies, they can increase with energy and accumulate over vast propagation distances, leading to a measurable rotation of the plane of linear polarization as a function of energy. The rotation angle during the propagation from the redshift z to the observer is given by [30,32]:

$$\Delta\phi_{\text{LIV}}(E) \simeq \eta \frac{E^2}{\hbar E_{\text{Pl}}} \int_0^z \frac{1+z'}{H(z')} dz', \quad (2)$$

where E is the observed photon energy. Also, $H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$ is the cosmic expansion rate, assuming a flat Λ CDM model with Hubble constant $H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, matter energy density $\Omega_m = 0.315$, and vacuum energy density $\Omega_\Lambda = 1 - \Omega_m$ [42].

To date, the most stringent limits on the birefringent parameter η have been obtained using the single multi-hundred keV polarimetry of gamma-ray bursts (GRBs), yielding $\eta < \mathcal{O}(10^{-15} - 10^{-16})$ [32–35,38]. These upper limits stem from the argument that vacuum birefringence would produce opposite oriented polarization vectors, thereby washing out most of the net polarization of the signal. Hence, the detection of highly polarized sources can place upper bounds on η . Even though such LIV tests have reached an extremely high accuracy [32–35,38], the outcomes of these upper limits on η are lack of significantly statistical robustness.

Instead of requiring the indirect argument that the net polarization would be severely depleted by the presence of LIV, some studies directly searched for an energy-dependent change of the linear polarization angle, resulting from vacuum birefringence, in the energy-resolved spectro-polarimetric data [28,40,41]. By fitting the energy-resolved polarization data of the optical afterglows of GRB 020813 and GRB 021004, Fan et al. [28] obtained a limit of $-2 \times 10^{-7} < \eta < 1.4 \times 10^{-7}$ at the 3σ confidence level (see also [40]). Zhou et al. [41] applied the same treatment to multi-band optical polarization measurements of five blazars, and showed that Lorentz invariance passes the strict test with a similar accuracy of $\mathcal{O}(10^{-7})$. It is obvious from Equation (2) that the greater sensitivity to small values of η can be expected from those astrophysical sources with higher-energy polarimetry and larger cosmological distances. Compared to γ -ray polarization constraints [32–35,38], observations of optical polarization set less stringent constraints on η as expected [28,40,41].

Recently, Gupta et al. [43] presented a systematic and uniform spectro-polarimetric analysis on five bright GRBs detected by *AstroSat* CZTI, providing the first energy-resolved polarization measurements in the prompt γ -ray emission of GRBs. In this work, we study Lorentz-violating effects by analyzing the energy-dependent behavior of polarization angle during the prompt phase of these five GRBs.

2. Energy-Resolved Polarization Measurements of Prompt GRB Emission

Gupta et al. [43] performed an energy-resolved polarization analysis on the prompt γ -ray emission of five bright GRBs using archival data from *AstroSat* CZTI. The linear polarization measurements obtained using the energy sliding binning algorithm are displayed in Figure 8 of Gupta et al. [43], from which we can extract the calculated values of the energy-resolved polarization angles and the corresponding energy segments of all the five bursts.

In order to obtain bounds on LIV with observations of γ -ray linear polarization, we also need to know the source distances. But except for GRB 160623A at $z = 0.367$ [44], the other four GRBs have no measured redshifts. The well-known luminosity relation with a standard deviation $\sigma_{\text{sc}} = 0.30$ [45,46], $\log_{10}[E_p(1+z)/\text{keV}] = (-22.98 \pm 1.81) + (0.49 \pm 0.03) \log_{10}[L_{\text{iso}}/\text{erg s}^{-1}]$, is therefore adopted to estimate the redshifts of the four GRBs. Here E_p is the spectral peak energy in the observer frame and L_{iso} is the isotropic peak luminosity. We use the observed flux and E_p of the four bursts (GRB 160325A: 10–40000 keV flux $5.28 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $E_p = 228.54 \text{ keV}$; GRB 160703A: 15–150 keV flux $2.29 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $E_p = 332.46 \text{ keV}$; GRB 160802A: 10–40000 keV flux $5.05 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $E_p = 279.43 \text{ keV}$; GRB 160821A: 10–40000 keV flux $3.12 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $E_p = 941.35 \text{ keV}$) to calculate L_{iso} for different redshifts. Detailed information regarding the time-integrated spectral parameters for these GRBs can be found in Table B1 of Gupta et al. [43]. By requiring that the bursts enter the 3σ region of the luminosity relation, we derive $z \geq 0.267$ for GRB 160325A, $z \geq 0.316$ for GRB 160703A, $z \geq 0.102$ for GRB 160802A, and $z \geq 0.153$ for GRB 160821A. Hereafter, we conservatively take the lower limits of redshifts for robust discussions on LIV.

3. New Precision Limits on LIV

Considering the energy-dependent rotation angle of the linear polarization plane induced by the vacuum birefringent effect ($\Delta\phi_{\text{LIV}}$; i.e., Equation 2), the observed linear polarization angle (ϕ_{obs}) for photons emitted at a certain energy range from a given astrophysical source should consist of two terms

$$\phi_{\text{obs}} = \phi_0 + \Delta\phi_{\text{LIV}}(E), \quad (3)$$

where ϕ_0 denotes the intrinsic polarization angle. In practice, it is hard to distinguish the LIV-induced rotation angle $\Delta\phi_{\text{LIV}}$ from an unknown intrinsic polarization angle ϕ_0 caused by the source's unknown emission mechanism. Following Fan et al. [28], we simply assume that all photons in different energy channels are emitted with the same (unknown) intrinsic polarization angle (see also [40,41]). As ϕ_0 is assumed to be an unknown constant, potential evidence for vacuum birefringence (or robust limits on the birefringent parameter η and ϕ_0) could be directly obtained by fitting the energy-dependent behavior of observed polarization angles with Equation (3). Here we explore the implications and limits that can be set from the energy-resolved polarization measurements of the prompt γ -ray emission of five GRBs [43].

The observed polarization angles as a function of energy for all five GRBs are shown in Figure 1. For each GRB, the two free parameters (η and ϕ_0) are optimized via a maximization of the likelihood function:

$$\mathcal{L} = \prod_i \frac{1}{\sqrt{2\pi} \sigma_{\text{tot},i}} \exp \left[-\frac{(\phi_{\text{obs},i} - \phi_0 - \Delta\phi_{\text{LIV}}(\eta, E_i))^2}{2\sigma_{\text{tot},i}^2} \right], \quad (4)$$

where the variance

$$\sigma_{\text{tot},i}^2 = \sigma_{\phi_{\text{obs},i}}^2 + \left(2 \frac{\Delta\phi_{\text{LIV}}}{E_i} \sigma_{E_i} \right)^2 \quad (5)$$

is given by the quadratic sum of the measurement error $\sigma_{\phi_{\text{obs},i}}$ in $\phi_{\text{obs},i}$ and the propagated error of σ_{E_i} . The Python Markov chain Monte Carlo module, EMCEE [47], is applied to explore the posterior probability distributions of the free parameters. The 1D marginalized probability distributions and 2D contours with 1–2 σ confidence levels for the two parameters, constrained by the energy-resolved polarization data of each GRB, are presented in Figure 2. These contours show that at the 95% confidence level, the inferred values are $\eta = (1.7^{+4.8}_{-3.2}) \times 10^{-16}$ and $\phi_0 = 0.15^{+0.93}_{-1.12}$ rad for GRB 160325A, $\eta = (2.0^{+3.8}_{-2.1}) \times 10^{-16}$ and $\phi_0 = -0.31^{+0.96}_{-1.36}$ rad for GRB 160623A, $\eta = (1.9^{+4.6}_{-5.1}) \times 10^{-16}$ and $\phi_0 = -0.29^{+1.33}_{-1.39}$ rad for GRB 160703A, $\eta = (-9.4^{+15.9}_{-15.4}) \times 10^{-16}$ and $\phi_0 = 1.25^{+1.31}_{-1.34}$ rad for GRB 160802A, and $\eta = (1.2^{+6.7}_{-5.2}) \times 10^{-16}$ and $\phi_0 = 0.49^{+0.82}_{-1.03}$ rad for GRB 160821A. The resulting constraints on η and ϕ_0 for each GRB data are summarized in Table 1. We can see that all the inferred values of η are consistent with 0 at the 2 σ confidence level, implying that there is no evidence of LIV. To illustrate the fits, the energy-dependence of polarization angle expected from the LIV model (see Equation 3; with each set of the best-fit parameters) are shown as solid curves in Figure 1. Also, the resulting goodness-of-fit values of reduced χ^2_{dof} are provided in Figure 1.

Compared with previous results obtained from multi-band optical polarization measurements ($|\eta| < 2 \times 10^{-7}$ [28,40,41]), our limits on η represent an improvement of at least eight orders of magnitude. While our limits are essentially as good as previous best bounds from γ -ray polarimetry of other GRBs ($\eta < \mathcal{O}(10^{-15} - 10^{-16})$ [32–35,38]), there is merit to the results. Thanks to the adoption of the energy-resolved polarization data, our constraints on η could be statistically more robust compared to previous results, which were based on a single polarization measurement in the 100s keV energy range and the argument that vacuum birefringence would significantly suppress the net polarization over a broad bandwidth.

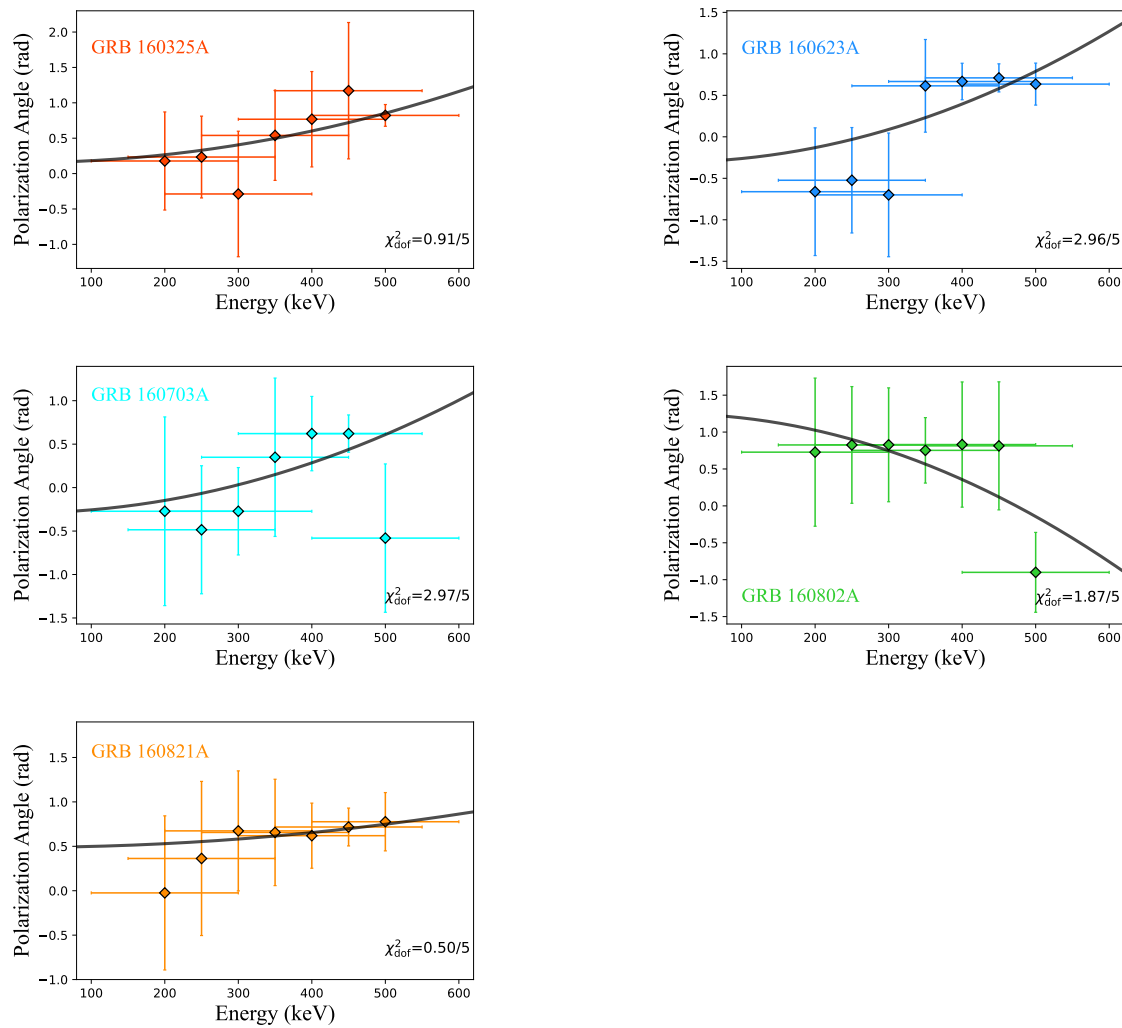


Figure 1. The evolution of polarization angle with energy. Data points are the energy-resolved polarization measurements of five GRBs, and the vertical and horizontal error bars, respectively, correspond to the measurement errors of the polarization angles and the ranges of each energy bin. Curves show the optimal predictions of the LIV model (see text and Equation 3). The goodness-of-fit χ^2_{dof} are also listed.

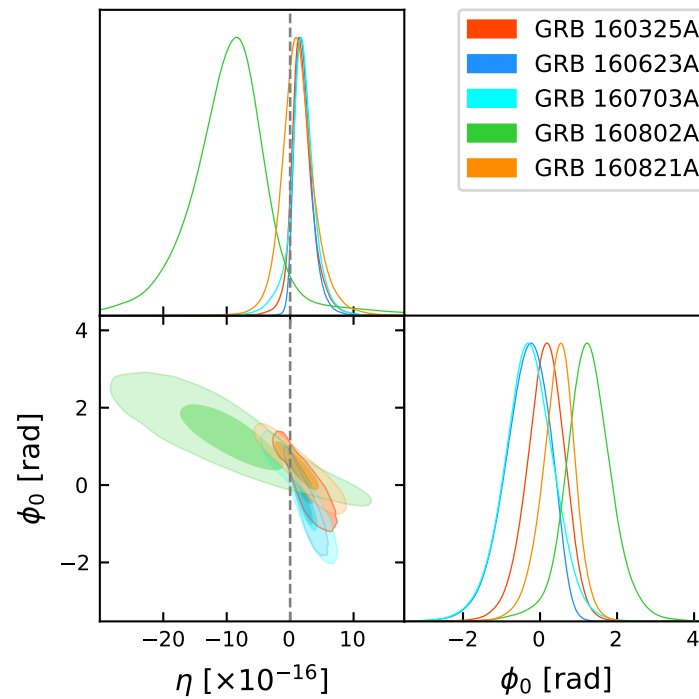


Figure 2. 1D and 2D marginalized probability distributions with 1–2 σ confidence contours for the birefringent parameter η and the intrinsic polarization angle ϕ_0 , constrained by the energy-resolved polarization data of the five different GRBs. The vertical dashed line corresponds to the case of no LIV (i.e., $\eta = 0$).

Table 1. Best-fit results (with 95% confidence-level uncertainties) on the birefringent parameter η and the intrinsic polarization angle ϕ_0 from energy-resolved polarization measurements of five GRBs.

Source	z	η ($\times 10^{-16}$)	ϕ_0 (rad)
GRB 160325A	0.267 ¹	$1.7^{+4.8}_{-3.2}$	$0.15^{+0.93}_{-1.12}$
GRB 160623A	0.367	$2.0^{+3.8}_{-2.1}$	$-0.31^{+0.96}_{-1.36}$
GRB 160703A	0.316 ¹	$1.9^{+4.6}_{-5.1}$	$-0.29^{+1.33}_{-1.39}$
GRB 160802A	0.102 ¹	$-9.4^{+15.9}_{-15.4}$	$1.25^{+1.31}_{-1.34}$
GRB 160821A	0.153 ¹	$1.2^{+6.7}_{-5.2}$	$0.49^{+0.82}_{-1.03}$

¹ The redshifts of the four GRBs are estimated by the luminosity realtion.

4. Summary

Violations of Lorentz invariance can lead to vacuum birefringence of light, which results in an energy-dependent rotation of the polarization plane of linearly polarized photons. Lorentz invariance can therefore be tested with astrophysical polarization measurements. Very recently, Gupta et al. [43] reported the energy-resolved polarization measurements in the prompt γ -ray emission of five bright GRBs detected by *AstroSat* CZTI. In this work, we investigated the implications and limits on LIV that can be set from these unique polarization observations.

Assuming an unknown constant for the intrinsic polarization angle, we searched for the energy-dependent change of the linear polarization angle, resulting from the birefringent effect, in the spectro-polarimetric data of these five GRBs. By fitting the polarization angle and energy measurements of

each GRB, we place a statistically robust limit on the birefringent parameter η quantifying the broken degree of Lorentz invariance. For instance, with the data of GRB 160623A, we have $-0.1 \times 10^{-16} < \eta < 5.8 \times 10^{-16}$ at the 2σ confidence level. Similar η constraints have been obtained from the other four GRBs. Our new results represent sensitivities improved by at least eight orders of magnitude over existing η bounds from multi-band optical polarization measurements. Moreover, our constraints are competitive with previous best bounds from γ -ray polarimetry of other GRBs. Unlike previous analyses that only rely on a single polarization measurement in the 100s keV rang, our constraints derived from energy-resolved polarimetric data set are statistically more robust. Future polarization measurements of astrophysical sources such as GRBs at higher γ -ray energies and larger distances would further enhance sensitivity to LIV tests through the vacuum birefringent effect.

It is well known that magnetized plasma can also produce the energy-dependent rotation of the linear polarization plane (the so-called Faraday rotation). The dependence of the rotation angle on Faraday rotation is $\Delta\phi_{\text{Far}} \propto E^{-2}$, quite different from its dependence on LIV effects as $\Delta\phi_{\text{LIV}} \propto E^2$ shown in Equation (2). The Faraday rotation angle $\Delta\phi_{\text{Far}}$ would be significant at the low-frequency radio band. But for high-energy photons, such as the γ -ray signals considered here, $\Delta\phi_{\text{Far}}$ is negligible.

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Data Availability Statement: The data underlying this article are available in Gupta et al. [43].

Conflicts of Interest: The authors declare no conflicts of interest.

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