Strict Limit on *CPT* Violation from Polarization of γ-Ray Bursts

Kenji Toma,[1] Shinji Mukohyama,[2] Daisuke Yonetoku,[3] Toshio Murakami,[3] Shuichi Gunji,[4] Tatehiro Mihara,[5] Yoshiyuki Morihara,[3] Tomonori Sakashita,[3] Takuya Takahashi,[3] Yudai Wakashima,[3] Hajime Yonemochi,[3] and Noriyuki Toukairin[4]

[1]*Department of Earth and Space Science, Osaka University, Toyonaka 560-0043, Japan*
[2]*Kavli Institute for the Physics and Mathematics of the Universe, Todai Institutes for Advanced Study, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan*
[3]*College of Science and Engineering, School of Mathematics and Physics, Kanazawa University, Kakuma, Kanazawa, Ishikawa 920-1192, Japan*
[4]*Department of Physics, Faculty of Science, Yamagata University, 1-4-12, Koshirakawa, Yamagata, Yamagata 990-8560, Japan*
[5]*Cosmic Radiation Laboratory, RIKEN, 2-1, Hirosawa, Wako City, Saitama 351-0198, Japan*
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We report the strictest observational verification of *CPT* invariance in the photon sector, as a result of γ-ray polarization measurement of distant gamma-ray bursts (GRBs), which are the brightest stellar-sized explosions in the Universe. We detected γ-ray polarization of three GRBs with high significance levels, and the source distances may be constrained by a well-known luminosity indicator for GRBs. For the Lorentz- and *CPT*-violating dispersion relation $E_{\pm}^2 = p^2 \pm 2\xi p^3/M_{Pl}$, where $\pm$ denotes different circular polarization states of the photon, the parameter ξ is constrained as $|\xi| < O(10^{-15})$. Barring precise cancellation between quantum gravity effects and dark energy effects, the stringent limit on the *CPT*-violating effect leads to the expectation that quantum gravity presumably respects the *CPT* invariance.

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Introduction.—Lorentz invariance is the fundamental symmetry of Einstein's theory of relativity. However, in quantum gravity such as superstring theory [1], loop quantum gravity [2], and Hořava-Lifshitz gravity [3], Lorentz invariance may be broken either spontaneously or explicitly. Dark energy, if it is a rolling scalar field, may also break Lorentz invariance spontaneously. In the absence of Lorentz invariance, the *CPT* theorem in quantum field theory does not hold, and thus *CPT* invariance, if needed, should be imposed as an additional assumption. Hence, tests of Lorentz invariance and those of *CPT* invariance can independently deepen our understanding of the nature of spacetime.

If *CPT* invariance is broken then group velocities of photons with right-handed and left-handed circular polarizations should differ slightly, leading to birefringence and a phase rotation of linear polarization. Therefore, a test of *CPT* invariance violation can be performed with the polarization observations, especially in high frequency γ rays.

The purpose of this Letter is to report the strictest observational verification of *CPT* invariance in the photon sector, as a result of γ-ray polarization measurement of prompt emission of distant gamma-ray bursts (GRBs), which are bright stellar-sized explosions in the universe. We detected γ-ray polarization of three GRBs with high significance levels, and we can estimate lower limits on the source distances for those bursts by a well-known luminosity indicator. For the Lorentz- and *CPT*-violating dispersion relation $E_{\pm}^2 = p^2 \pm 2\xi p^3/M_{\rm Pl}$, where $\pm$ denotes different circular polarization states of the photon, the parameter ξ is strictly constrained. The data of one of those bursts, GRB 110721A, give us the strictest limit, $|\xi| < O(10^{-15})$. This is the strictest limit on the *CPT* invariance violation posed by directly observing the photon sector, and it is about 8 orders better than the previous limit $|\xi| < 10^{-7}$ [4]. (As explained later in the present Letter, we refute a more recent limit claimed in Ref. [5].) Barring precise cancellation between quantum gravity effects and dark energy effects, the stringent limit on the *CPT*-violating effect leads to the expectation that quantum gravity presumably respects the *CPT* invariance.

Observation and analysis.—Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) is a small solar-power-sail demonstrator [6], and it was successfully launched on 21 May 2010. IKAROS has a large polyimide membrane of 20 m in diameter, and this translates the solar radiation pressure to the thrust of the spacecraft. Since the deployment of the sail on 9 June 2010, IKAROS started solar sailing towards Venus. The gamma-ray burst polarimeter (GAP) [7] onboard IKAROS is fully designed to measure linear polarization in prompt emission of GRBs in the energy range of 70–300 keV. Its detection principle is due to anisotropy of Compton scattered photons. If incident γ rays are linearly polarized, the azimuthal distribution function of scattered photons should basically shape as $\sin^2\phi$. The GAP consists of a central plastic scatterer of 17 cm in diameter and 6 cm in thickness and surrounding 12 CsI(Tl) scintillators. Coincidence events within a gate time of 5 μsec between the signal from any CsI and that from the plastic scintillator are selected for polarization analysis. The GAP's high axial symmetry in shape and high gain uniformity are keys for reliable measurement of polarization and avoiding fake modulation due to background γ rays.

The GAP detected GRB 110721A on 21 July 2011 at 04:47:38.9 (UT) at about 0.70 AU apart from Earth. The burst was also detected by the Gamma-Ray Burst Monitor [8] and Large Area Telescope [9] aboard the Fermi satellite. Energy fluence of this burst is $(3.52 \pm 0.03) \times 10^{-5}$ erg cm^{-2} in 10–1000 keV band, and the photon number flux is well fitted by a power law $N_\nu \propto \nu^\alpha$ with $\alpha = -0.94 \pm 0.02$ in the GAP energy range 70–300 keV [8]. We performed polarization analysis for the entire duration of GRB 110721A. We clearly detected a polarization signal with a polarization degree of $\Pi = 84^{+16}_{-28}\%$ and a polarization angle of $\phi_p = 160 \pm 11$ degrees, and a null polarization degree is ruled out with 3.3σ confidence level. The 2σ lower limit on the polarization degree is $\Pi > 35\%$ [10].

IKAROS-GAP also detected γ-ray polarizations of two other GRBs with high significance levels, with $\Pi = 27 \pm 11\%$ for GRB 100826A [11], and $\Pi = 70 \pm 22\%$ for GRB 110301A [10]. The detection significance is 2.9σ and 3.7σ, respectively. The 2σ lower limit on polarization degrees are $\Pi > 6\%$ and $\Pi > 31\%$, respectively. Therefore, we conclude that the prompt emission of GRBs is highly polarized.

Several of the emission mechanisms (e.g., synchrotron emission) proposed for GRB prompt emission may produce linear polarization as high as $\Pi \sim 60\%$ [10,12]. Observed polarization degree and angle do not depend on photon energy E significantly in such emission mechanisms. In order to support this picture, we separately analyzed the polarization signals for two energy bands, 70–100 keV and 100–300 keV, and actually confirmed that the polarizations of GRB 110721A in the two bands are consistent within the statistical errors ($\Pi = 71^{+29}_{-38}\%$ and $\phi_p = 155 \pm 15$ degrees for 70–100 keV and $\Pi = 100^{+0}_{-35}\%$ and $\phi_p = 161 \pm 14$ degrees for 100–300 keV).

As we explicitly show in the next section, the reliable observation of γ-ray linear polarization reported here enables us to obtain a strict limit on *CPT* violation. In order to do this, source distances of the three GRBs are required to be estimated, but unfortunately their redshifts are not measured. Instead, we use a well-known distance indicator for GRBs, the $E_{\rm peak}$ peak luminosity correlation, $L_p = 10^{52.43\pm0.33} \times (E_{\rm peak}/355\ {\rm keV})^{1.60\pm0.082}$ erg s^{-1}, where $E_{\rm peak}$ is the peak energy in the source frame νF_ν spectrum [13]. Once we measure the observer frame $E_{\rm peak}$ and peak flux we can calculate a possible redshift. This correlation equation includes systematic uncertainty caused by the data scatter. Possible redshifts are then estimated to be $0.45 < z < 3.12$, $0.71 < z < 6.84$, and $0.21 < z < 1.09$ with 2σ confidence level for GRB 110721A, GRB 100826A, and GRB 110301A, respectively. Hereafter, we use 2σ lower limit values for robust discussions for *CPT* violation.

Before going into the details of the limit on *CPT* violation, however, let us briefly mention that there are several other works claiming detections of linear polarization with low significance, but all of the previous reports are controversial. Reference [14] reported detection of strong polarization from GRB 021206 with the *RHESSI* solar satellite. However, independent authors analyzed the same data, and failed to detect any polarization signals [15]. In these cases, the data selection criteria for the polarization signal was remarkably different, and the latter two authors used more realistic and reasonable ones. They concluded that the *RHESSI* satellite has less capability to measure the γ-ray polarization from GRBs even if one of the brightest GRBs is observed. Reference [16] reported detections of polarization with $\sim 2\sigma$ confidence level from GRB 041219 by *INTEGRAL*-SPI, and [17] reported possible detections of time variable polarization with *INTEGRAL*-IBIS data. However, in Fig. 3 of Ref. [17], for example, all of the data are not due to the Poisson statistics and also completely acceptable to the nonpolarized model while they insist detection of linear polarization. This is because the systematic or instrumental uncertainties for the polarization measurement dominate the photon statistics in these systems. Moreover, the results of SPI and IBIS for the brightest pulse of GRB 041219 appear inconsistent with each other; i.e., the SPI teams detected strong polarization of $\Pi = 98 \pm 33\%$ and $\Pi = 63^{+31}_{-30}\%$ with 2σ statistical level [16], but the IBIS team reported a strict upper limit of $\Pi < 4\%$ [17]. (But it should be mentioned that their results for the other temporal intervals are consistent.) Therefore, the previous reports of the γ-ray polarimetry for GRBs are all controversial and, thus, the argument for the limit on *CPT* violation given by Ref. [5] is still open to questions.

Contrary to those controversial previous reports, the detection of γ-ray linear polarization by IKAROS-GAP is fairly reliable and thus can be used to set a limit on *CPT* violation.

Limit on CPT violation.—Using these highly polarized γ-ray photons from the cosmological distance, we constrain the dimension-5, Lorentz violating (LV) operator in the photon sector. Hereafter, $M_{\rm Pl} = (\hbar c/G)^{1/2} = 1.22 \times 10^{19}$ GeV is the Planck mass, and we shall adopt the unit with $\hbar = c = 1$.

In the effective field theory approach [18], LV effects suppressed by $E/M_{\rm Pl}$ arise from dimension-5 LV operators. In the photon sector they manifest as the Lorentz- and *CPT*-violating dispersion relation of the form

$$E_\pm^2 = p^2 \pm \frac{2\xi}{M_{\rm Pl}} p^3, \tag{1}$$

where $\pm$ denotes different circular polarization states and ξ is a dimensionless parameter.

If $\xi \neq 0$, then the dispersion relation (1) leads to slightly different group velocities for different polarization states. Hence, the polarization vector of a linearly polarized wave rotates during its propagation [19]. The rotation angle in the infinitesimal time interval dt is $d\theta = (E_+ - E_-)dt/2 \simeq \xi p^2 dt/M_{\rm Pl}$. Substituting $p = (1+z)k$,

$dt = -dz/[(1+z)H]$ and $H^2 = H_0^2[\Omega_m(1+z)^3 + \Omega_\Lambda]$, the rotation angle during the propagation from the redshift z to the present is expressed as

$$\Delta\theta(k,z) \simeq \xi \frac{k^2 F(z)}{M_{\rm Pl} H_0}, \qquad F(z) = \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}. \tag{2}$$

Here, k is the comoving momentum, $H_0 = 1.51 \times 10^{-42}$ GeV, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

If the rotation angle differs by more than $\pi/2$ over a range of momenta ($E_1 < k < E_2$) in which a certain proportion of the total number of photons in a signal are included, then the net polarization of the signal is significantly depleted and cannot be as high as the observed level. This is the case, unless the momentum dependence of the intrinsic polarization direction of the source is fine-tuned to cancel the momentum-dependent rotation of the polarization vector induced by quantum gravity. Such an accidental cancellation is rather unnatural, and thus we shall not consider this possibility. Hence, the detection of highly polarized γ-ray photons by the GAP implies that $|\Delta\theta(E_2,z) - \Delta\theta(E_1,z)| \le \pi/2$. In order to obtain an upper bound on $|\xi|$ from this inequality, we set $E_1 = E_{\rm min}$ and determine E_2 by $\int_{E_{\rm min}}^{E_2} E^\alpha dE / \int_{E_{\rm min}}^{E_{\rm max}} E^\alpha dE = \Pi$, where Π is the net polarization degree over the GAP energy range $E_{\rm min} \le k \le E_{\rm max}$ and we have adopted the power law $\propto k^\alpha$ with $\alpha < 0$ for the photon number spectrum. This prescription for $E_{1,2}$ corresponds to an ideal situation in which the detected signal has 100% of the polarization degree and uniform polarization direction over the range $E_{\rm min} \le k < E_2$, but has no polarization in the range $E_2 \le k \le E_{\rm max}$. With more realistic momentum-dependencies of the polarization degree and direction, E_2 would be higher and, hence, the bound on $|\xi|$ would be tighter. Without specifying the nature of the intrinsic polarization of the source, we adopt the one that gives the weakest bound on $|\xi|$ among those that do not exhibit the accidental cancellation mentioned above.

For GRB 110721A, the 2σ lower limits $\alpha > -0.98$ and $\Pi > 35\%$ in the whole energy band ($E_{\rm min} = 70$ keV, $E_{\rm max} = 300$ keV) lead to $E_2 \simeq 120$ keV. Setting $z > 0.45$ in $|\Delta\theta(E_2,z) - \Delta\theta(E_{\rm min},z)| \le \pi/2$, we obtain the constraint from GRB 110721A as $|\xi| < 7 \times 10^{-15}$.

More accurate constraints are obtained by requiring that $\sqrt{Q^2+U^2}/N > \Pi$, where $N = \int_{E_{\rm min}}^{E_{\rm max}} E^\alpha dE$, $Q = \int_{E_{\rm min}}^{E_{\rm max}} E^\alpha \Pi_i \cos[2\Delta\theta(E,z)]$, and $U = \int_{E_{\rm min}}^{E_{\rm max}} E^\alpha \Pi_i \times \sin[2\Delta\theta(E,z)]$ with the intrinsic polarization degree $\Pi_i = 1$. Using $\Pi > 0.35$ and $\alpha > -0.98$, we obtain the constraint from GRB 110721A as

$$|\xi| < 2 \times 10^{-15}, \tag{3}$$

which is tighter than the above rough estimate. Alternatively, we may assume that the intrinsic polarization degree is not as high as 100% but given by the maximum level in the synchrotron mechanism, i.e., $\Pi_i = -\alpha/(-\alpha + 2/3)$ with $\alpha = -0.98$. This leads to the more stringent limit $|\xi| < 8 \times 10^{-16}$. Generically speaking, if we assume a lower intrinsic polarization degree, then the bound on $|\xi|$ becomes tighter.

From the other GRBs, we obtain weaker constraints. GRB 100826A has 2σ limits as $\Pi > 6\%$, $\alpha > -1.41$ [11], and $z > 0.71$. Setting $\Pi_i = 1$ (or $\Pi_i = -\alpha/[-\alpha + 2/3]$), we obtain the constraint $|\xi| < 2 \times 10^{-14}$ (or $|\xi| < 1 \times 10^{-14}$). GRB 110301A has 2σ limits as $\Pi > 31\%$, $\alpha > -2.8$ [20], and $z > 0.21$. Setting $\Pi_i = 1$ [or $\Pi_i = -\alpha/(-\alpha + 2/3)$], we obtain the constraint $|\xi| < 2 \times 10^{-14}$ (or $|\xi| < 1 \times 10^{-14}$).

One may consider a more direct constraint from the difference of the polarization angles in the two energy bands for GRB 110721A, say $\Delta\theta(E = 170\ \text{keV}, z) - \Delta\theta(E = 80\ \text{keV}, z) < 64$ degree at 2σ confidence level. This provides $|\xi| < 2 \times 10^{-15}$. If polarization angles are measured more accurately as a function of energy for GRBs in the future, a more stringent limit would be obtained.

Comparison with other limits.—Our bound (3) is the strictest limit on the *CPT* invariance posed by directly observing the photon sector, and it is about 8 orders better than the previous limit $|\xi| < 10^{-7}$ [4]. (As already explained, we consider the limit claimed in Ref. [5] unreliable.) The constraint from nondetection of ultrahigh-energy photons ($E > 10^{19}$ GeV), $|\xi| < 10^{-14}$ [21], appears to be closer to our bound. However, the constraint from ultrahigh-energy photons relies on the assumption that the dimension-5 LV operator in the electron sector is sufficiently suppressed [22]. On the other hand, the previous bound in Ref. [4] and our bound do not depend on such an assumption.

The dimension-5 LV operator in the photon sector induces dimension-3 *CPT*-odd LV operators in the fermion sector by radiative corrections due to particle interactions. Assuming supersymmetry [23] above $M_{\rm susy}$(>TeV), the radiatively generated dimension-3 *CPT*-odd LV operators generically have coefficients of order $b \simeq M_{\rm susy}^2/M_{\rm Pl}$. Hence, existing experimental bounds on b can be reinterpreted as bounds on ξ. For example, the bound $|b| < 10^{-27}$ GeV from the Xe/He maser [24] implies $|\xi| < 10^{-14}$. Our bound (3) is slightly stronger than this. On the other hand, the bound $|b| < 10^{-33}$ GeV from the K/He magnetometer [25] corresponds to the stronger bound $|\xi| < 10^{-20}$. Note, however, that these bounds inferred from radiatively generated dimension-3 *CPT*-odd LV operators are indirect and rely on supersymmetry. Our bound (3), on the contrary, does not rely on supersymmetry and is direct.

In the effective field theory approach [18], there is only one operator that leads to a linear energy dependence of the speed of light in vacuum, and it is the dimension-5 *CPT*-odd LV operator considered in the present Letter. Constraints on the same operator from observation of energy dependence of GRB light curves [26] are not as significant as those from observation of polarization such as ours. For this reason, once the stringent bound from the latter type of observation is imposed on the unique dimension-5 LV operator, it is natural to interpret the former type of observation as limits on the dimension-6 LV operator. In this case, observation of GRB 090510 by the Fermi satellite [27] leads to the lower bound on the quantum gravity mass scale as $M_{\mathrm{QG},2} > 10^{11}$ GeV. This is consistent with the natural expectation that the quantum gravity mass scale is of the order of the Planck mass.

Conclusion.—In some quantum gravity theories such as superstring theory [1], loop quantum gravity [2], and Hořava-Lifshitz gravity [3], Lorentz invariance may be broken either spontaneously or explicitly. Dark energy, if it is a rolling scalar field, may also break Lorentz invariance spontaneously. Barring precise cancellation between quantum gravity effects and dark energy effects, the stringent limit (3) on the Lorentz- and *CPT*-violating parameter ξ then naturally leads us to the expectation that quantum gravity theory and/or state may break Lorentz invariance but presumably respect the *CPT* invariance. The celebrated *CPT* theorem in quantum field theory assumes Lorentz symmetry and locality. In the absence of Lorentz symmetry, the *CPT* invariance, if needed, should be imposed as a part of the definition of the theory. In LV but *CPT* invariant theories, the parameter ξ exactly vanishes, and thus, all existing limits on ξ are trivially satisfied.

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