PLANCK-SCALE LORENTZ INVARIANCE VIOLATIONS AND CMB POLARIZATION DATA

GIULIA GUBITOSI
Dipartimento di Fisica, Università di Roma "La Sapienza"
and Sez. Roma1 INFN, P.le A. Moro 2, 00185 Roma, Italy
giulia.gubitosi@roma1.infn.it

Some models of spacetime quantization leading to violations of Lorentz symmetries predict a minute effect of birefringence for the propagation of photons. For Cosmic Microwave Background (CMB) photons, which have some degree of linear polarization, this results in a rotation of their polarization direction. The effect is greatly amplified by their long time of propagation, and could have observably large implications for analyses of CMB polarization. Here we mainly report the results of previous works[1,2,3], in which it is shown that for the most studied model of quantum-spacetime-induced birefringence, available BOOMERanG 2003 and WMAP data can be used to establish a bound of Planck-scale significance. We give forecasts on the sensitivities achievable by future CMB polarization measures and we comment on how systematic effects of CMB experiments could influence these constraints. As a final point we discuss how Lorentz violations can also produce non-isotropic birefringence effects.

Motivations to study Planck-scale physics come from quantum-gravity research, that essentially tries to solve the problem of finding a common description for quantum and general-relativistic phenomena, to be used in the physical situations in which both of them are non-negligible. The lacking of a unifying theory, despite all the efforts made toward it, can be traced back to the difficulties encountered in accessing experimentally the ultra-high energy (and correspondingly the ultra-short length) scale at which these phenomena should be relevant. So it is clear the crucial importance of looking for physical situations in which one could find clues of what the quantum-gravity theory should look like.

One of the most common expectations emerging from quantum-gravity research is that spacetime should show some quantum properties (such as discreteness, coordinates noncommutativity or fuzziness) when probed at scales of the order of the Planck length $L_P \sim 10^{-35} m$. It is commonly agreed that this quantization may cause a deformation of spacetime symmetries, which acquire some "quantum" features themselves [4], leading to violations of Lorentz symmetries. Among the many ways in which these violations could show up, much studied are possible consequences on particles' energy-momentum dispersion relations [6], characterized by corrective terms governed by the Planck scale $E_P \sim 10^{28} eV$. In the high-energy regime, to the first order in $\frac{1}{E_P}$, the modified dispersion relation for photons takes the form

$$E \simeq p + \frac{\eta}{E_P} p^2, \tag{1}$$

where η is a dimensionless parameter governing the amplitude of the correction.

It has been also studied the case [6,7] in which two states with opposite helicity behave differently, obeying different dispersion relations

$$E_\pm \simeq p \pm \frac{\eta_*}{E_P} p^2. \tag{2}$$

Since in this case the two helicity states of the electromagnetic waves have different phase velocity, linearly polarized monochromatic radiation rotates its polarization vector during propagation [a]. This behaviour is known as *in-vacuo* birefringence, due to its similarity with the birefringence effects observed when light propagates in materials with chiral molecules.

Modifications of photon dispersion relation of the form $\frac{p^2}{E_P}$ can be formalized through an effective field theory for electrodynamics with mass-dimension five corrections to the standard Maxwell Lagrangian density. A well-studied model (both on the theoretical and the phenomenological sides) is the one proposed by Myers and Pospelov [5], in which the electromagnetic tensor $F_{\mu\nu}$ is coupled to a fixed four vector n_α and the nonrenormalizable operator in the Lagrangian has a coupling constant proportional to $\frac{1}{E_P}$, to ensure that the new physics effects originate at the Planck scale:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2E_P} n^\alpha F_{\alpha\delta} n^\sigma \partial_\sigma (n_\beta \varepsilon^{\beta\delta\gamma\lambda} F_{\gamma\lambda}) \tag{3}$$

Until now only a simplified version of the model has been studied, in which the four-vector n_α has the spatial components set to zero ($n_\alpha = \{n_0, 0, 0, 0\}$), so that space isotropy is preserved, and only invariance under boost transformations is violated [b]. Within this assumption, the Lagrangian density takes the form:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\xi}{2E_P} F_{0j} \varepsilon^{jkl} \partial_0 F_{kl} \tag{4}$$

where $\xi \equiv (n_0)^3$ is the parameter governing the amplitude of non-standard effects so that its ratio with E_P sets the scale at which new phenomena are originating. Constraining ξ roughly to order one means testing new effects originating genuinely at the Planck scale. From the above Lagrangian a birefringent behavior of photons can be deduced [5,1], of the kind of (2) with $\eta_* = \xi$, so, if the field is linearly polarized, after propagation for a time T its polarization vector will rotate of an angle [1]

$$\alpha(T) = 2 \frac{\xi}{E_P} p^2 T. \tag{5}$$

This formula has a peculiar energy dependence. If we want to test the rotation using CMB photons, for which the energy redshift due to the universe expansion can not be neglected, the above formula has to be corrected. For a photon traveling from epochs with redshift z toward us, where it is measured to have momentum p_0, the total rotation angle is given by

$$\alpha(z) = \frac{2\xi}{E_P} \frac{p_0^2}{H_0} \int_0^z \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz' \tag{6}$$

where H_0 is the value of the Hubble function today, Ω_m and Ω_Λ are respectively the matter and dark energy densities and we assumed a standard ΛCDM cosmological model.

The reason why it is actually possible to constrain this rotation effects using CMB photons is that their production process is very well understood, and it is known to produce partially linearly polarized radiation, and to be parity invariant[8]. Expanding the polarization pattern on the sky in spherical harmonics it is possible to separate the modes with different properties under

[a] If one considers non-monochromatic waves, when the propagation time is sufficiently long the polarization ends up disappearing [7].

[b] This choice clearly is not reference frame independent. We discuss later this issue.

parity transformations (the so-called “electric” and “magnetic” modes of polarization). Due to parity invariance of the original polarization pattern, we would expect to see only parity-even modes (the “electric” ones). Parity-odd modes are produced instead from the parity-even ones if a rotation of polarization occurs. We have analyzed WMAP5 and BOOMERanG2003 data. The results are reported in Table 1. Notice that since the two experiments detect photons with slightly different energies, we cannot give a joint estimate on α, which is energy-dependent, but we have to rely on the ξ parameter.

Experiment	$\alpha \pm \sigma(\alpha)$	$\xi \pm \sigma(\xi)$
WMAP (94 GHz)	-1.6 $\pm$ 2.1	-0.09 $\pm$ 0.12
BOOMERanG (145 GHz)	-5.2 $\pm$ 4.0	-0.123 $\pm$ 0.096
WMAP+BOOMERanG	-	-0.110 $\pm$ 0.075

Table 1: Mean values and 1σ error on α(in degrees) and ξ.

The constraints on ξ are

$$-0.260 < \xi < 0.040 \tag{7}$$

at 95% confidence level, which are even beyond the desired Planck scale sensitivity. We have also given an estimate of the sensitivities reachable with the recently-launched PLANCK satellite and some other future experiments (see Table 2 and also the more detailed table reported in our previous work [1], where we report also the sensitivities reachable with an ideal cosmic-variance limited experiment).

Experiment	Channel	$\sigma(\alpha)$	$\sigma(\xi)$
PLANCK	100+143+217	-	$8.5 \cdot 10^{-4}$
Spider	145	0.27	$6.1 \cdot 10^{-3}$
EPIC	70+100+150+200	-	$1.0 \cdot 10^{-5}$

Table 2: Expected 1σ error for PLANCK $70, 100, 143, 217$ GHz, Spider 145 GHz, EPIC $70, 100, 150, 220$ GHz and two ideal CVL experiment at 150 GHz and 217 GHz on α (in degrees) and ξ.

Thanks to the multi-frequency data provided by some of these experiments, exploiting the energy dependence peculiar of Planck scale effects will make it possible to give quite stringent limits on ξ up to 10^{-5} and disentangle this kind of rotation effect from other phenomena giving analogous signatures in CMB polarization data. An example are sistematic effects. To this regard, we have checked how much a misalignment of the polarimeters, which could mimic a polarization rotation effect, could have influenced our constraints [2]. For multi-frequency experiments it is possible to exploit the peculiar energy dependence to disentangle a genuine rotation due to Plank-scale birefringence from other effects. On the other hand, this issue is particularly worrisome in single-frequency experiments like BOOMERanG. So we considered a realistic miscalibration of BOOMERanG polarimeters of 0.9 ± 0.7 degrees, which leads to a different estimate on α: $\alpha = -4.3 \pm 4.1$ degrees. This weakens the (already faint) indication of rotation we found before. The estimate on ξ, including also WMAP data, becomes $\xi = 0.097 \pm 0.075$.

We have shown that present CMB polarization data provide sensitivity to the Planck scale birefringence parameter ξ of order 10^{-1}. Actually there are analyses exploiting astrophysical sources that are able to put much more stringent constraints (using Crab Nebula observations allows to put the limit [9] $|\xi| \leq 10^{-9}$). But it is necessary to be very careful in comparing these limits, since they are obtained in different reference frames and ξ is actually related to the time component of a four vector (the limit of 10^{-9} on ξ translates into a limit of 10^{-3} on n_0). In particular one could have $n_\alpha = (0, 1, 1, 1)$ in some reference frame, but then in another reference frame moving with velocity $\beta = 10^{-3}$ with respect to the first one one would have n_0 of order 10^{-3}. And this value for β is of the same order of magnitude of the relative velocity between CMB reference frame and our galactic cluster reference frame.

So it is clear the importance on putting bounds all the four components of n_α. And when studying the phenomenological consequences of the Lagrangian (3) another feature emerges that suggests caution when interpreting the bounds on the model (4) with only n_0 different from zero. In fact when also the spatial components of the vector are considered, the photon dispersion relation becomes direction-dependent [3]:

$$\omega_\pm = |\vec{p}| \pm \frac{|\vec{p}|^2}{E_P} \left(n_0 + \vec{n} \cdot \hat{p}\right)^3 . \tag{8}$$

If n_α is space-like, there are some propagation directions for the photons, in which they behave classically. So using point-like astrophysical sources to constrain Lorentz violations induced by the Lagrangian (3) can be misleading [c]. To this respect CMB data can be very competitive in constraining the general model, since CMB radiation covers almost all the sky and so is capable of giving a better statistics than point-like astrophysical sources.

References

1. G. Gubitosi, L. Pagano, G. Amelino-Camelia, A. Melchiorri and A. Cooray, arXiv:0904.3201 [astro-ph.CO].
2. L. Pagano *et al.*, arXiv:0905.1651 [astro-ph.CO].
3. G. Gubitosi, G. Genovese, G. Amelino-Camelia and A. Melchiorri, arXiv:1003.0878 [Unknown].
4. G. Amelino-Camelia and S. Majid, Int. J. Mod. Phys. A **15** (2000) 4301 [arXiv:hep-th/9907110].
5. R. C. Myers, M. Pospelov, Phys. Rev. Lett. 90 (2003) 211601
6. R. Gambini and J. Pullin, Phys. Rev. D **59** (1999) 124021 [arXiv:gr-qc/9809038].
7. R. J. Gleiser and C. N. Kozameh, Phys. Rev. D **64** (2001) 083007 [arXiv:gr-qc/0102093].
8. W. Hu, Phys. Rev. D **62** (2000) 043007 [arXiv:astro-ph/0001303].
9. L. Maccione and S. Liberati, JCAP **0808** (2008) 027 [arXiv:0805.2548 [astro-ph]].

[c] Besides the completely blind directions, in a quite large fraction of the sky the birefringent effect can be weakened of a significant amount [3]