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# Lorentz-violating dimension-five operator contribution to the black body radiation

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ABSTRACT

We investigate the thermodynamics of a photon gas in an effective field theory model that describes Lorentz violations through dimension-five operators and Horava–Lifshitz theory. We explore the electrodynamics of the model which includes higher order derivatives in the Lagrangian that can modify the dispersion relation for the propagation of the photons. We shall focus on the deformed black body radiation spectrum and modified Stefan–Boltzmann law to address the allowed bounds on the Lorentz-violating parameter.



## 1. Introduction

The Lorentz symmetry has been tested in many experiments at high energy. The possibility of being an exact or approximate symmetry has been addressed in many studies in the literature. Most of these studies are in essence inspired by Lorentz-violating Standard Model Extension proposed by Colladay and Kostelecký [1]. However, we shall first focus on thermal dynamics from the theories with higher derivative Lorentz-violating operators of quantum electrodynamics extended with dimension-five operators proposed by Myers and Pospelov [2] and then extend the analyses to the Horava–Lifshitz theory [3]. One of the main idea concerning such an issue is to assume that the Lorentz symmetry can be broken at very high energy. Recently, higher derivative or higher dimensional operators have been used in quantum gravity [3] and field theory [2,4–7] to explore new physics in the Lorentz symmetry violation context.

In more recent studies the issue of higher derivative theories has been considered in the context of Horava–Lifshitz (HL) gravity [3] which aims to solve the severe problems of quantum gravity. In such setup the theory breaks the Lorentz symmetry in the ultraviolet (UV) regime and recovers the symmetry at low energy — infrared (IR) regime. In this theory, there exists an explicit asymmetry between time and space coordinates such that the Lorentz symmetry is broken. The asymmetry flows between UV and IR scales according to a critical exponent that is also known as Lifshitz critical exponent [8]. This dynamical asymmetry makes the HL gravity a nonrelativistic theory that develops an anisotropic scaling symmetry of space and time. The higher spatial derivative terms added to the action enforces the theory power counting renormalizable.

In this work we shall both consider the gauge sector of Myers–Pospelov and Horava–Lifshitz theory in order to study the modifications in the thermodynamic properties of a photon gas in such a scenario where we have Lorentz-violating operators. It is natural to expect that fingerprints of Lorentz-violation will appear in observations involving cosmic microwave background (CMB) and ultra high energy sources such as cosmic rays or gamma ray bursts (GRB). As is well-known the CMB radiation develops a black body spectrum very accurate for low frequencies. However one expects that for more accurate measurements deviations from black body radiation at high frequencies may become the place to find the signs of Lorentz-symmetry violation. It is remarkable that fingerprints from such operators can be seen in the deformed black body

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**Table 1**
Astrophysical bounds for the Lorentz-breaking parameter.

| Adjustment | Result ($GeV^{-1}$) | Result (degree Kelvin − $K^{-1}$) | System |
|---|---|---|---|
| $\bar{\xi} \equiv k^{(5)}_{(V)00}$ | $\sim 10^{-32}$ | $\sim 10^{-45}$ | Astrophysical birefringence |
| $\bar{\xi} \equiv k^{(5)}_{(V)00}$ | $\sim 10^{-20}$ | $\sim 10^{-33}$ | CMB polarization |
| $\bar{\xi} \equiv \bar{\xi}_{\gamma}$ | $\sim 10^{-13}$ | $\sim 10^{-26}$ | GW-GRB waves |

radiation when $z$ is around (above or below) unit at CMB temperatures. Furthermore, whereas stronger modification for lower dimensional operators is favorable at CMB scale, stronger contribution from higher dimensional operators takes places at larger scales.

There are some previous investigations on the modification of the black body radiation due to Lorentz-violating theories — see e.g. [9] and particularly [10] for a noncommutative field theory. In the latter case, such theories present a deformed black body spectrum whose deviations from the usual one appear in the ultraviolet regime. This effect has been considered to find new bounds on the noncommutative parameters of the theory through, for instance, the GZK cut-off. In addition this modification at UV is in direct connection with the aforementioned theories whose Lorentz-symmetry violation arises due to influence of higher derivative terms. In Ref. [11] was found indeed that at the temperature around $T = 10^{14}$ GeV $\simeq 10^{27}$ K, which approximately corresponds to the temperature at the beginning of the inflation, the noncommutative parameters are in agreement with the bounds obtained through the GZK cut-off which is of the order of $10^{19}$ eV (the highest cosmic ray energy is assumed to be no greater than $10^{19}$ eV) More investigations on the deformed thermodynamics in noncommutative theories can be found in Ref. [12] where new bounds to the noncommutative parameters can also be found by using the critical temperature of a deformed Bose–Einstein condensate. In the following we delineate our investigations by following these ideas to address similar issues to the deformed black body in the present Lorentz-violating theory due to dimension-five operators.

The outline of this paper is as follows. In Sec. 2.1, we introduce the Myers–Pospelov model of electrodynamics with a Lorentz-violating background. The dispersion relation is obtained in a preferred frame defined by a time-like direction. In Sec. 2.3, we address the issues of the modified Stefan–Boltzmann law. In Sec. 3 we extend the previous analysis to Horava–Lifshitz theory and in Sec. 4 we make our final considerations.

## 2. The dimension-five operator and thermodynamic properties

### 2.1. Modified dispersion relation

As mentioned above, the Lorentz-violating dimension-five operator predicts a modified dispersion relation [2], which can be characterized by the following covariant form [13]:

$$k^4 - 4\bar{\xi}^2 (n\cdot k)^4 \Big[(k\cdot n)^2 - k^2 n^2\Big] = 0\,. \quad (1)$$

Such a dispersion relation reduces to its simplest form when the parameter $n_\mu$ is chosen to be purely time-like, i.e., $n_\mu \equiv (1, \vec{0})$:

$$\mathbf{k}^2 = E^2\big(1 - 2\lambda\bar{\xi}E\big)^{-1}\,, \quad (2)$$

where in this last form we work with the notation: $k^2 = k_\mu k^\mu = (E^2, -\mathbf{k}^2)$, $\mathbf{k}^2 = k_i k_i$ and $i = 1, 2, 3$. We should stress that the parameter $\lambda$ characterizes two polarization states, which are explicitly given by $\lambda = \pm 1$. Moreover, the standard dispersion relation can be recovered by setting $\bar{\xi} \to 0$. Notice also that the phase and group velocities derived from Eq. (2) are related through Rayleigh's formula [14]. By considering a subluminal case $\lambda = -1$ we consequently have that $v_p > v_g$, characterizing a normal dispersion medium. Moreover, in the superluminal case we take $\lambda = 1$ resulting in $v_g > v_p$, or in other words, we have an anomalous medium which is related to anisotropic effects. Therefore, we can conclude that a model truly isotropic must be attributed only to subluminal case. So, in our thermodynamic analyses, we consider only the normal dispersion medium corresponding to $\lambda = -1$.

The above configuration corresponds to a subset of Lorentz invariance violating (LIV) operators which preserves the rotational invariance. Such an isotropic inertial frame must be specified, once boosts to other frames can destroy the rotational invariance. One natural choice for the preferred frame is the frame of the Cosmic Microwave Background (CMB), however other frames are also available, as it was discussed in [15].

In this work, we consider astrophysical limits to $\bar{\xi}$ and use them to analyze the black body radiation due the modified dispersion relation given by Eq. (2). The bounds for these astrophysical limits were derived from collected data [16] (see the first and the second lines in the Table 1), and from simultaneous gravitational and electromagnetic waves [14] (see the third line in the Table 1).

### 2.2. The partition function

In order to study the thermodynamical features of Myers–Pospelov model, we need to build its partition function. As it is known, the first ingredient to derive the partition function is the establishment of the number of states. In general, the number of available states for a given system can be written as

$$\Omega = \frac{\gamma}{(2\pi)^3} \iint d\vec{r} d\vec{k}\,, \quad (3)$$

with $\gamma$ being the spin multiplicity ($\gamma = 2$ for photons). The last equation can be rewritten in spherical coordinates as

$$\Omega = \frac{V}{\pi^2} \int_0^\infty \mathbf{k}^2 d\mathbf{k}\,, \quad (4)$$

where $V$ is the volume of the reservoir. Then we can substitute $\mathbf{k}^2$ by the dispersion relation (2), leading us to

$$d\mathbf{k} = \left(\frac{1}{\sqrt{1+2E\bar{\xi}}} - \frac{E\bar{\xi}}{(1+2E\bar{\xi})^{3/2}}\right) dE. \quad (5)$$

Therefore, the number of states can be represented in the following form

$$\Omega = \frac{V}{\pi^2} \int_0^\infty E^2 \left(1 + E\bar{\xi}\right) \left(1 + 2E\bar{\xi}\right)^{-5/2} dE\,. \quad (6)$$

Let us now proceed to calculate the thermodynamic properties of such a photon gas. In order to achieve this objective, let us remember that the connection between macroscopic world and the thermodynamic behavior is done by the partition function $\mathcal{Z}$, i.e.,



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