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Effective photon mass by Super and Lorentz symmetry breaking

Luca Bonetti [a,b,c], Luís R. dos Santos Filho [d], José A. Helayël-Neto [d], Alessandro D.A.M. Spallicci [a,b,c,*]

[a] Université d'Orléans, Observatoire des Sciences de l'Univers en région Centre (OSUC), UMS 3116, 1A rue de la Férollerie, 45071 Orléans, France
[b] Université d'Orléans, Collegium Sciences et Techniques (COST), Pôle de Physique, Rue de Chartres, 45100 Orléans, France
[c] Centre Nationale de la Recherche Scientifique (CNRS), Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E), UMR 7328, Campus CNRS, 3A Av. de la Recherche Scientifique, 45071 Orléans, France
[d] Centro Brasileiro de Pesquisas Físicas (CBPF), Rua Xavier Sigaud 150, 22290-180 Urca, Rio de Janeiro, RJ, Brasil

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ABSTRACT

In the context of Standard Model Extensions (SMEs), we analyse four general classes of Super Symmetry (SuSy) and Lorentz Symmetry (LoSy) breaking, leading to observable imprints at our energy scales. The photon dispersion relations show a non-Maxwellian behaviour for the CPT (Charge-Parity-Time reversal symmetry) odd and even sectors. The group velocities exhibit also a directional dependence with respect to the breaking background vector (odd CPT) or tensor (even CPT). In the former sector, the group velocity may decay following an inverse squared frequency behaviour. Thus, we extract a massive Carroll–Field–Jackiw photon term in the Lagrangian and show that the effective mass is proportional to the breaking vector and moderately dependent on the direction of observation. The breaking vector absolute value is estimated by ground measurements and leads to a photon mass upper limit of 10^{-19} eV or 2×10^{-55} kg, and thereby to a potentially measurable delay at low radio frequencies.

We largely base our understanding of particle physics on the Standard Model (SM). Despite having proven to be a very reliable reference, there are still unsolved problems, such as the Higgs Boson mass overestimate, the absence of a candidate particle for the dark universe, as well as the neutrino oscillations and their mass.

Standard Model Extensions (SMEs) tackle these problems. Among them, Super Symmetry (SuSy) [1,2] figures new physics at TeV scales [3]. Since, in SuSy, Bosonic and Fermionic particles each have a counterpart, their mass contributions cancel each other and allow the correct experimental low mass value for the Higgs Boson.

Lorentz Symmetry (LoSy) is assumed in the SM. It emerges [4–7] that in the context of Bosonic strings, the condensation of tensor fields is dynamically possible and determines LoSy violation. There are opportunities to test the low energy manifestations of LoSy violation, through SMEs [8,9]. The effective Lagrangian is given by the usual SM Lagrangian corrected by SM operators of any dimensionality contracted with suitable Lorentz breaking tensorial (or simply vectorial) background coefficients. In this letter, we show that photons exhibit a non-Maxwellian behaviour, and possibly manifest dispersion at low frequencies pursued by the newly operating ground radio observatories and future space missions.

LoSy violation has been analysed phenomenologically. Studies include electrons, photons, muons, mesons, baryons, neutrinos and Higgs sectors. Limits on the parameters associated with the breaking of relativistic covariance are set by numerous analyses [10–12], including with electromagnetic cavities and optical systems [13–19]. Also Fermionic strings have been proposed in the presence of LoSy violation. Indeed, the magnetic properties of spinless and/or neutral particles with a non-minimal coupling to a LoSy violation background have been placed in relation to Fermionic matter or gauge Bosons [20–25].

LoSy violation occurs at larger energy scales than those obtainable in particle accelerators [26–32]. At those energies, SuSy is still an exact symmetry, even if we assume that it might break at scales close to the primordial ones. However, LoSy violation naturally induces SuSy breaking because the background vector (or tensor) – that implies the LoSy violation – is in fact part of a SuSy multiplet [33], Fig. 1.

The sequence is assured by the supersymmetrisation, in the CPT (Charge-Parity-Time reversal symmetry) odd sector, of the Carroll–Field–Jackiw (CFJ) model [34] that emulates a Chern–Simons [35]

* Corresponding author at: Université d'Orléans, Observatoire des Sciences de l'Univers en région Centre (OSUC), UMS 3116, 1A rue de la Férollerie, 45071 Orléans, France.
E-mail address: spallicci@cnrs-orleans.fr (A.D.A.M. Spallicci).

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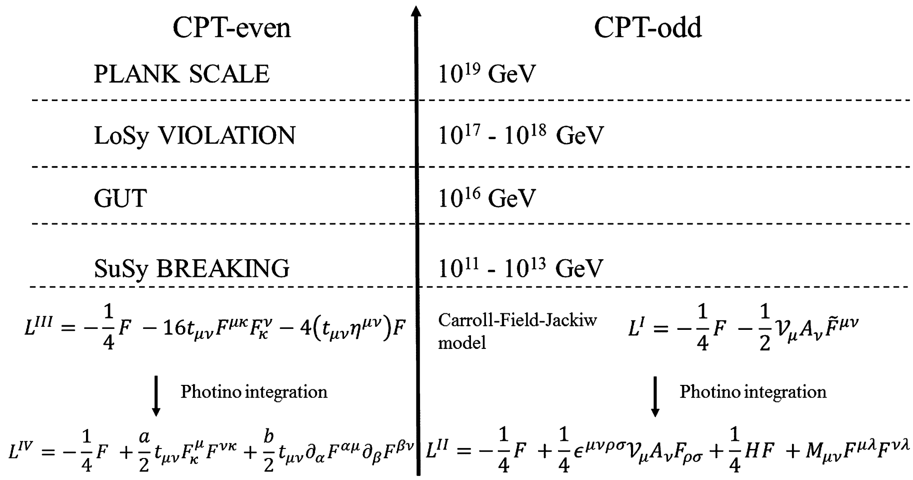

Fig. 1. Breaking energy values and the Lagrangians. A different hierarchy of LoSy, SuSy breaking and Grand Unification Theories (GUT) does not interfere with the dispersion laws of the photonic sector at low energies.

term and includes a background field that breaks LoSy, under the point of view of the so-called (active) particle transformations. The latter consists of transforming the potential A^{μ} and the field $F^{\mu\nu}$, while keeping the background vector $\mathcal{V}^{\mu}$ unchanged. For the photon sector, when unaffected by the photino contribution, the CFJ Lagrangian reads (Class I)

$$L^{I} = -\frac{1}{4}F - \frac{1}{2}\mathcal{V}_{\mu}A_{\nu}\tilde{F}^{\mu\nu}\,, \tag{1}$$

$$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}\,, \tag{2}$$

where $F = F^{\mu\nu}F_{\mu\nu}$. The term in Eq. (2) couples the photon to an external constant four vector and it violates parity even if gauge symmetry is respected [34]. If the CFJ model is supersymmetrised [36], the vector $\mathcal{V}^{\mu}$ is space-like constant and is given by the gradient of the SuSy breaking scalar background field, present in the matter supermultiplet. The dispersion relation yields, denoting $k^{\mu} = (\omega, \vec{k})$, $k^2 = (\omega^2 - |\vec{k}|^2)$, and $(\mathcal{V}^{\mu}k_{\mu})^2 = (\mathcal{V}^0\omega - \vec{\mathcal{V}}\cdot\vec{k})^2$,

$$k^4 + \mathcal{V}^2k^2 - (\mathcal{V}^{\mu}k_{\mu})^2 = 0\,. \tag{3}$$

If SuSy holds and the photino degrees of freedom are integrated out, we are led to the effective photonic action, *i.e.* the effect of the photino on the photon propagation. The Lagrangian (1) is recast as (Class II) [33]

$$L^{II} = -\frac{1}{4}F + \frac{1}{4}\epsilon^{\mu\nu\rho\sigma}\mathcal{V}_{\mu}A_{\nu}F_{\rho\sigma} + \frac{1}{4}HF + M_{\mu\nu}F^{\mu\lambda}F^{\nu\lambda}\,, \tag{4}$$

where H, the tensor $M_{\mu\nu} = \tilde{M}_{\mu\nu} + 1/4\eta_{\mu\nu}M$, and $\tilde{M}_{\mu\nu}$ depend on the background Fermionic condensate, originated by SuSy; $M_{\mu\nu}$ is traceless, M is the trace of $M_{\mu\nu}$ and $\eta_{\mu\nu}$ the metric. Thus, the Lagrangian, Eq. (4), in terms of the irreducible terms displays as

$$L^{II} = -\frac{1}{4}(1 - H - M)F + \frac{1}{4}\epsilon^{\mu\nu\rho\sigma}\mathcal{V}_{\mu}A_{\nu}F_{\rho\sigma} + \tilde{M}_{\mu\nu}F^{\mu\lambda}F^{\nu}_{\lambda}\,. \tag{5}$$

The corresponding dispersion relation reads

$$k^4 + \frac{\mathcal{V}^2}{(1-H-M)^2}k^2 - \frac{1}{(1-H-M)^2}\mathcal{V}^{\mu}k_{\mu} = 0\,. \tag{6}$$

The dispersion law given by Eq. (6) is just a rescaling of Eq. (3) as we integrated out the photino sector. The background parameters are very small, being suppressed exponentially at the Planck scale; they render the denominator in Eq. (6) close to unity, implying similar numerical outcomes for the two dispersions of Classes I and II.

The even sector [33] assumes that the Bosonic background, responsible of LoSy violation, is a background tensor $t_{\mu\nu}$. For the photon sector, if unaffected by the photino contribution, the Lagrangian reads (Class III)

$$L^{III} = -\frac{1}{4}F - 16t_{\mu\nu}F^{\mu\kappa}F^{\nu}_{\kappa} - 4\left(t_{\mu\nu}\eta^{\mu\nu}\right)F\,. \tag{7}$$

The dispersion relation for Class III [37] is

$$\omega^2 - (1+\rho+\sigma)^2\,|\vec{k}|^2 = 0\,, \tag{8}$$

where $\rho = 1/2\tilde{K}^{\alpha}_{\alpha}$, $\sigma = 1/2\tilde{K}^{\alpha\beta}\tilde{K}_{\alpha\beta} - \rho^2$, and $\tilde{K}^{\alpha\beta} = t^{\alpha\beta}t^{\mu\nu}p_{\mu}p_{\nu}/|\vec{k}|^2$ are associated to Fermionic condensates.

Integrating out the photino [33], we turn to the Lagrangian of Class IV

$$L^{IV} = -\frac{1}{4}F + \frac{a}{2}t_{\mu\nu}F^{\mu}_{\kappa}F^{\nu\kappa} + \frac{b}{2}t_{\mu\nu}\partial_{\alpha}F^{\alpha\mu}\partial_{\beta}F^{\beta\nu}\,, \tag{9}$$

where a is a dimensionless coefficient and b a parameter of dimension of mass^{-2} (herein, $c = 1$, unless otherwise stated). For the dispersion relation, we write the Euler–Lagrange equations, pass to Fourier space and set to zero the determinant of the matrix that multiplies the Fourier transformed potential. However, given the complexity of the matrix in this case and the smallness of the tensor $t_{\mu\nu}$, we develop the determinant in a series truncated at first order and get [37]

$$btk^4 - k^2 + \left(3a + bk^2\right)t^{\alpha\beta}k_{\alpha}k_{\beta} = 0\,, \tag{10}$$

where $t = t^{\mu}_{\mu}$.

For determining the group velocity, we first consider $\mathcal{V}_0 = 0$ for Class I [38,39] and obtain

$$\omega^4 - \left(2|\vec{k}|^2 + |\vec{\mathcal{V}}|^2\right)\omega^2 + |\vec{k}|^4 + |\vec{k}|^2|\vec{\mathcal{V}}^2 - \left(\vec{\mathcal{V}}\cdot\vec{k}\right)^2 = 0\,. \tag{11}$$

In [39], the authors do not exploit the consequences of the dispersion relations and do not consider a SuSy scenario. Dealing with Eq. (11), we have neglected the negative roots; it turns out that the two positive roots determine identical group velocities dw/dk up to second order in $\vec{\mathcal{V}}$. For θ, the angle between the background vector $\vec{\mathcal{V}}$ and $\vec{k}$, we get

$$v_g^I|^{\theta\neq\pi/2}_{\mathcal{V}_0=0} = 1 - \frac{|\vec{\mathcal{V}}|^2}{8\omega^2}(2+\cos^2\theta)\,, \tag{12}$$