A Violação da simetria de Lorentz e suas consequências: no Brasil e J.A. Helayël-Neto

Homenagem de 60 anos a José A. Helayël-Neto

(08/11/2013 – CBPF – RIO DE JANEIRO)

Manoel M. Ferreira Jr

(UFMA- Universidade Federal do Maranhão - Brasil)

José A. Helayel-Neto

- Mestre, professor
- Professor, formador
- Pesquisador independente, pensador
- Guia inspirador, aglutinador
- Liderança natural
- Amigo
- Acolhedor, humanista agressivo
- Humanista generoso
- Trabalha educação em todos os níveis (ensino médio, graduação, pós-graduação)

Minha trajetória no CBPF

- **Início: 1998**
- **Descaminho: 1999**
- **Acolhimento no DCP e Mudança de rumo**
- **Trabalho sob orientação do Helayël e Del Cima em interações de férmions no plano**
- **Concurso do CBPF (tormentas...)**
- **Manifesto, e-mails, discussões**
- **2001: Defesa da tese**
- **2002: pós-doc informal**
- **2003: retorno à UFMA**

Um pouco sobre modelos dotados de violação de Lorentz:

Why to study Lorentz symmetry violation??

- **This is an exact symmetry of nature?**
- **To what extent this symmetry holds? It is possible to answer this question?**
- **How?**

- Allowing the insercion of Lorentz-violating terms in the different sectors of the Standard Model.
- Investigating how these terms modify the usual systems.
- Comparing the new LV effects with the usual experiments → **upper bounds on the LV terms.**

Why to study Lorentz symmetry violation??

- **As an element for effective theories for describing new physics.**

Examples:

- It may be useful in Condensed Matter systems;
- Topological defects and solutions.

There is a theoretical framework for studying Lorentz symmetry??

□ **YES, There is!**

□ **THE STANDARD MODEL EXTENSION**

• **Conceived by D. Colladay & A. Kostelecky as an extension of the Minimal Standard Model.** [PRD 55,6760 (1997); PRD 58, 116002 (1998).]

PRD 55, 6760 (1997).

CPT violation and the standard model

Don Colladay and V. Alan Kostelecký
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(Received 22 January 1997)

Spontaneous *CPT* breaking arising in string theory has been suggested as a possible observable experimental signature in neutral-meson systems. We provide a theoretical framework for the treatment of low-energy effects of spontaneous *CPT* violation and the attendant partial Lorentz breaking. The analysis is within the context of conventional relativistic quantum mechanics and quantum field theory in four dimensions. We use the framework to develop a *CPT*-violating extension to the minimal standard model that could serve as a basis for establishing quantitative *CPT* bounds.
[S0556-2821(97)05211-9]

PRD 58, 116002 (1998).

Lorentz-violating extension of the standard model

D. Colladay and V. Alan Kostelecký

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In the context of conventional quantum field theory, we present a general Lorentz-violating extension of the minimal $SU(3) \times SU(2) \times U(1)$ standard model including CPT-even and CPT-odd terms. It can be viewed as the low-energy limit of a physically relevant fundamental theory with Lorentz-covariant dynamics in which spontaneous Lorentz violation occurs. The extension has gauge invariance, energy-momentum conservation, and covariance under observer rotations and boosts, while covariance under particle rotations and boosts is broken. The quantized theory is Hermitian and power-counting renormalizable, and other desirable features such as microcausality, positivity of the energy, and the usual anomaly cancellation are expected. Spontaneous symmetry breaking to the electromagnetic $U(1)$ is maintained, although the Higgs expectation is shifted by a small amount relative to its usual value and the Z^0 field acquires a small expectation. A general Lorentz-breaking extension of quantum electrodynamics is extracted from the theory, and some experimental tests are considered. In particular, we study modifications to photon behavior. One possible effect is vacuum birefringence, which could be bounded from cosmological observations by experiments using existing techniques. Radiative corrections to the photon propagator are examined. They are compatible with spontaneous Lorentz and CPT violation in the fermion sector at levels suggested by Planck-scale physics and accessible to other terrestrial laboratory experiments. [S0556-2821(99)01601-X]

Standard Model Extension –SME

- The underlying theory undergoes spontaneous breaking of Lorentz symmetry.

- Conceived as a speculation for probing a fundamental model for describing the Planck scale physics endowed with SSB of Lorentz covariance (high energy scale – 10^{19} GeV). Issue relevant for Planck scale physics.

- The low-energy effective model incorporates Lorentz-violating terms in all sectors of interaction.

- The renormalizability, gauge invariance and energy-momentum conservation of the effective model are preserved.

Key ideas of the SME

- **It embraces small LV terms as corrections to the usually known Lagrangians**

- **It keeps coordinate independence (observer Lorentz invariance)**

- **It introduces preferred directions – tensor anisotropy terms, which violate rotation symmetry.**

- **Lorentz covariance is broken in the frame of particles but is preserved in the observer frame.**

Key ideas of the SME

Threshold analyses and Lorentz violation

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(Received 20 April 2003; published 7 October 2003)

In the context of threshold investigations of Lorentz violation, we discuss the fundamental principle of coordinate independence, the role of an effective dynamical framework, and the conditions of positivity and causality. Our analysis excludes a variety of previously considered Lorentz-breaking parameters and opens an avenue for viable dispersion-relation investigations of Lorentz violation.
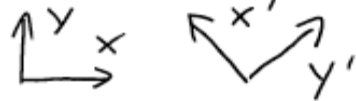
- **Coordinate independence** $\rightarrow$ **Lorentz violating terms as "tensors" coupling to the physical fields.**
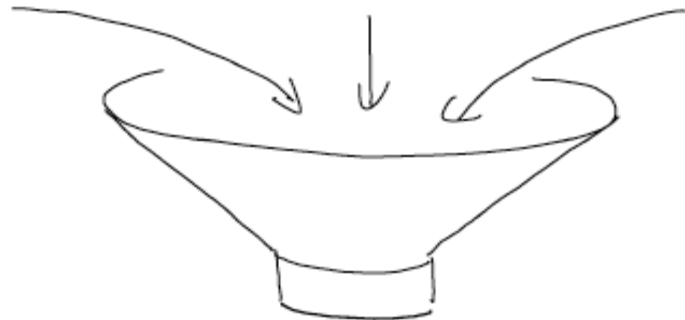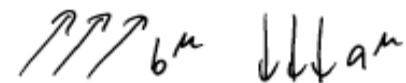
Key ideas of the SME

coordinate independence

all of established physics: $\mathcal{L}_{SM} + \mathcal{L}_{GR}$

preferred directions b^μ a^μ

$$\mathcal{L}_{SME} = \mathcal{L}_{SM} + \mathcal{L}_{GR} + \delta\mathcal{L} \qquad \text{Standard-Model Extension (SME)}$$

all of known phys.
$\Rightarrow$ applicable to all feasible expts.

all possible LV terms (c.f. $\vec{b} \times \vec{a}$ before)
$a^\mu \bar\Psi \gamma_\mu \Psi$, $b^\mu \bar\Psi \gamma^5 \gamma_\mu \Psi$, ...
$\Rightarrow \infty$ many

Standard Model Extension

- LV terms are inserted in:

- SM Fermion sector
- SM Photon sector
- SM Higgs sector

Usual SM:

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{lepton}} + \mathcal{L}_{\mathrm{quark}} + \mathcal{L}_{\mathrm{Yukawa}} + \mathcal{L}_{\mathrm{Higgs}} + \mathcal{L}_{\mathrm{gauge}}.$$

Standard Model Extension:

$$S_{\mathrm{SME}} = S_{\mathrm{SM}} + S_{\mathrm{LV}} + S_{\mathrm{gravity}}$$

$$\mathcal{L}_{\mathrm{LV}} = \mathcal{L}_{\mathrm{lepton}}^{CPT+} + \mathcal{L}_{\mathrm{lepton}}^{CPT-} + \mathcal{L}_{\mathrm{quark}}^{CPT+} + \mathcal{L}_{\mathrm{quark}}^{CPT-} + \mathcal{L}_{\mathrm{Yukawa}}^{CPT+} + \mathcal{L}_{\mathrm{Higgs}}^{CPT+}$$
$$+ \mathcal{L}_{\mathrm{Higgs}}^{CPT-} + \mathcal{L}_{\mathrm{gauge}}^{CPT+} + \mathcal{L}_{\mathrm{gauge}}^{CPT-}. \tag{42}$$

Standard Model Extension: gauge sector

Gauge sector:

$$\mathcal{L}_{gauge} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} \left(K_{AF}\right)^{\mu} \epsilon_{\mu\nu\alpha\beta} A^{\nu} F^{\alpha\beta} - \frac{1}{4} \left(K_{F}\right)_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta},$$

$\varepsilon_{\mu\nu\alpha\beta} \left(K_{AF}\right)^{\mu} A^{\nu} F^{\alpha\beta} \rightarrow$ **CPT-odd CFJ term**

$\left(K_{F}\right)_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta} \longrightarrow$ **CPT-even term**

$\left.\begin{array}{c} \left(K_{AF}\right)^{\mu} \\ \left(K_{F}\right)_{\mu\nu\alpha\beta} \end{array}\right\} \rightarrow$ **Fixed background tensors**

Standard Model Extension: fermion sector

□ Fermion sector:

$$\mathcal{L} = \frac{1}{2} i \overline{\psi} \Gamma^\nu \overleftrightarrow{\partial}_\nu \psi - \overline{\psi} M \psi$$

Where:

$$\Gamma^\nu \equiv \gamma^\nu + c^{\mu\nu} \gamma_\mu + d^{\mu\nu} \gamma_5 \gamma_\mu + e^\nu + i f^\nu \gamma_5 + \frac{1}{2} g^{\lambda\mu\nu} \sigma_{\lambda\mu}$$

$$M \equiv m + a_\mu \gamma^\mu + b_\mu \gamma_5 \gamma^\mu + \frac{1}{2} H^{\mu\nu} \sigma_{\mu\nu}$$

The modified Dirac equation is:

$$(i\Gamma^\mu \partial_\mu - M)\psi(x) = 0$$

$$\left. \begin{array}{l} c^{\mu\nu}, d^{\mu\nu}, e^\nu, f^\nu, g^{\lambda\mu\nu} \\[2mm] a^\mu, b^\mu, H^{\mu\nu} \end{array} \right\} \rightarrow \textbf{Fixed background tensors}$$

Standard Model Extension

SM Higgs sector:

$$\mathcal{L}_{\text{Higgs}} = -e(D_\mu \phi)^\dagger D^\mu \phi + \mu^2 e \phi^\dagger \phi - \frac{\lambda}{3!} e (\phi^\dagger \phi)^2,$$

Non Abelian Higgs sector:

$$\mathcal{L}_{\text{Higgs}}^{CPT-} = i(k_\phi)^\mu e \phi^\dagger D_\mu \phi + \text{H.c.}$$

$$\mathcal{L}_{\text{Higgs}}^{CPT+} = \frac{1}{2}(k_{\phi\phi})^{\mu\nu} e (D_\mu \phi)^\dagger D_\nu \phi + \text{H.c.}$$

$$- \frac{1}{2}(k_{\phi W})^{\mu\nu} e \phi^\dagger W_{\mu\nu} \phi - \frac{1}{2}(k_{\phi B})^{\mu\nu} e \phi^\dagger \phi B_{\mu\nu}.$$

Vortex configurations!

Abelian Higgs sector: $(k_{\phi\phi})^{\mu\nu}(\mathcal{D}_\mu \phi)^*(\mathcal{D}_\nu \phi)$ $(k_{\phi F})^{\mu\nu} F_{\mu\nu} |\phi|^2$

$(k_{\phi\phi})_{\mu\nu},\ (k_{\phi F})_{\mu\nu}$ $\rightarrow$ **Fixed background tensors**

Violação da simetria de Lorentz no Brasil: trabalhos iniciais (2003)

hep-th/9912251: **Induced Lorentz and PCT symmetry breaking in an external electromagnetic field,** M.B. Hott, J.L. Tomazelli.

Helayël-Neto, J.A. ; SCARPELLI, A. P. B. ; BELICH JR., H.; Boldo, J.L. . Aspects of Causality and Unitarity and Comments on Vortex-Like Configurations in an Abelian Model with Lorentz-Breaking Term. Phys. Rev. D, v. 67, p. 85021, 2003.

Aspects of causality and unitarity and comments on vortexlike configurations in an Abelian model with a Lorentz-breaking term

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The gauge-invariant Chern-Simons-type Lorentz- and *CPT*-breaking term is here reassessed and a spin-projector method is adopted to account for the breaking (vector) parameter. Issues such as causality, unitarity, spontaneous gauge-symmetry breaking, and vortex formation are investigated, and consistency conditions on the external vector are identified.

Violação da simetria de Lorentz no Brasil: trabalhos iniciais (2003)

Helayël-Neto, J.A. ; BELICH JR., H. ; FERREIRA JR., M. M. ; ORLANDO, M. . Dimensional Reduction of a Lorentz- and CPT-Violating Chern-Simons Model. Phys. Rev. D67 (2003) 125011, 2003.

Dimensional reduction of a Lorentz- and *CPT*-violating Maxwell-Chern-Simons model

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(Received 27 January 2003; published 18 June 2003)

Taking as a starting point a Lorentz and *CPT* noninvariant Chern-Simons-like model defined in $1+3$ dimensions, we proceed to realize its dimensional reduction to $D=1+2$. One then obtains a new planar model, composed by the Maxwell-Chern-Simons (MCS) sector, a Klein-Gordon massless scalar field, and a coupling term that mixes the gauge field to the external vector v^{μ}. In spite of breaking Lorentz invariance in the particle frame, this model may preserve *CPT* symmetry for a single particular choice of v^{μ}. Analyzing the dispersion relations, one verifies that the reduced model exhibits stability, but the causality can be jeopardized by some modes. The unitarity of the gauge sector is assured without any restriction, while the scalar sector is unitary only in the spacelike case.

Violação da simetria de Lorentz no Brasil: trabalhos iniciais (2003)

Helayël-Neto, J.A. ; BELICH JR., H. ; FERREIRA JR., M. M. ; ORLANDO, M. . Classical Solutions in a Lorentz-Violating Maxwell-Chern-Simons Electrodynamics. Phys. Rev. D68 (2003) 025005, 2003.

Classical solutions in a Lorentz-violating Maxwell-Chern-Simons electrodynamics

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We take as a starting point the planar model arising from the dimensional reduction of Maxwell electrodynamics with the (Lorentz-violating) Carroll-Field-Jackiw term. We then write and study the extended Maxwell equations and the corresponding wave equations for the potentials. The solution to these equations shows some interesting deviations from the usual MCS electrodynamics, with background-dependent correction terms. In the case of a timelike background, the correction terms dominate over the MCS sector in the region far from the origin, and establish the behavior of a massless electrodynamics (in the electric sector). In the spacelike case, the solutions indicate the clear manifestation of spatial anisotropy, which is consistent with the existence of a privileged direction in space.

Trabalhos iniciais (2003-2004)

Helayël-Neto, J.A. ; GODINHO, C. ; SCARPELLI, A. P. B. ; CANTCHEFF, M. N. B. . Dual Embedding of the Lorentz-Violating Electrodynamics and The Batalin-Vilkovisky Quantisation. Phys. Rev. D, v. 68, p. 06502, 2003.

Helayël-Neto, J.A. ; BELICH JR., H. ; Boldo, J.L.; Colatto, L.P.; NOGUEIRA, A. L. M. A. . Supersymmetric Extension of the Lorentz- and CPT-Violating Maxwell-Chern-Simons Model. Phys. Rev. D, v. 68, p. 06503, 2003.

Helayël-Neto, J.A. ; SCARPELLI, A. P. B. ; BELICH JR., H. ; BOLDO, J. L. ; Colatto, L.P. ; NOGUEIRA, A. L. M. A. . Remarks on the Causality, Unitarity and Supersymmetric Extension of the Lorentz- and CPT-Violating Maxwell-Chern-Simons Model. Nucl. Phys. B127 (2004) 105 (Proc. Suppl.), 2004.

Belich, H; Ferreira, M. M. ; Helayel-Neto, J. A. . Dimensional reduction of the Abelian Higgs Carroll-Field-Jackiw model. European Physical Journal C, Alemanha, v. 38, p. 511-519, 2005.

Trabalhos intermediários (2005-2006)

Belich, H; Costa-Soares, T. ; Ferreira, M. M. ; Helayël-Neto, J. A. . Classical solutions in a Lorentz violating scenario of Maxwell-Chern-Simons-Proca electrodynamics. European Physical Journal C, v. 42, p. 127-137, 2005.

Belich, H; Costa-Soares, T. ; FerreiraJr., M. M. ; Helayël-Neto, J. A. . Non-minimal coupling to a Lorentz-violating background and topological implications. European Physical Journal C, v. 41, p. 421-426, 2005.

Non-minimal coupling to a Lorentz-violating background and topological implications

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Trabalhos intermediários (2005-2006)

Belich, H; COSTASOARES, T ; FERREIRAJR, M ; HELAYEL NETO, J; Orlando, M.; **A comment on the topological phase for anti-particles in a Lorentz-violating environment. Physics Letters. Section B 639, p. 675-678, 2006.**

Helayël-Neto, J.A. ; SCARPELLI, A. P. B. . **A LORENTZ-VIOLATING SO(3)-MODEL: DISCUSSING THE UNITARITY, CAUSALITY AND THE 'T HOOFT - POLYAKOV MONOPOLES. Physical Review D 73, p. 105020, 2006.**

Lorentz-violating SO(3) model: Discussing unitarity, causality, and 't Hooft-Polyakov monopoles

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(Received 10 January 2006; published 31 May 2006)

In this paper, we extend the analysis of the Lorentz-violating Quantum Electrodynamics to the non-Abelian case: an SO(3) Yang-Mills Lagrangian with the addition of the non-Abelian Chern-Simons-type term. We consider the spontaneous symmetry breaking of the model and inspect its spectrum in order to check if unitarity and causality are respected. An analysis of the topological structure is also carried out and we show that a 't Hooft-Polyakov solution for monopoles is still present.

Trabalhos posteriores (2006-2009)

BELICH JR., H. ; Costa-Soares, T; FERREIRA JR., M. M. ; Helayël-Neto, J.A. ; MOUCHERECK, F. M. . LORENTZ-VIOLATING CORRECTIONS ON THE HYDROGEN SPECTRUM INDUCED BY A NON-MINIMAL COUPLING. Physical Review D, v. 74, p. 065009, 2006.

BELICH JR., H. ; Costa-Soares, T ; FERREIRA JR., M. M. ; Helayël-Neto, J.A. ; ORLANDO, M. . GAUGE THEORIES WITH LORENTZ-SYMMETRY VIOLATION AND ELECTRICALLY CHARGED VORTICES IN THE PLANAR REGIME. International Journal of Modern Physics A, v. A21, p. 2415, 2006.

BARRAZ JUNIOR, N. M. ; Fonseca, J.M. ; MOURA MELO, W. A. ; Helayël-Neto, J.A. . On Dirac-like Monopoles in a Lorentz and CPT-Violating Electrodynamics. Physical Review D 76, p. 027701, 2007.

BELICH JR., H. ; Colatto, L.P. ; Costa-Soares, T; Helayël-Neto, J.A. ; ORLANDO, M. . Magnetic Moment Generation from non-Minimal Couplings in a Scenario with Lorentz-Symmetry Violation. European Physical Journal C, v. 62, p. 425-432, 2009.

Trabalhos recentes (2010 -2012)

J.L. Boldo a, J.A. Helayël-Neto , L.M. de Moraesa, C.A.G. Sasaki , V.J. Vásquez Otoya , Graviton excitations and Lorentz–Violating gravity with cosmological constant, Phys. Lett. B 689, 112 (2010)

Physics Letters B 689 (2010) 112–115

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PHYSICS LETTERS B

Graviton excitations and Lorentz–Violating gravity with cosmological constant

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Trabalhos recentes (2010 -2012)

B. Pereira-Dias et al., Phys. Rev. D 83, 084011 (2011)

Probing the effects of Lorentz-symmetry violating Chern-Simons and Ricci-Cotton terms in higher derivative gravity

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The combined effects of the Lorentz-symmetry violating Chern-Simons and Ricci-Cotton actions are investigated for the Einstein-Hilbert gravity in the second-order formalism modified by higher derivative terms, and their consequences on the spectrum of excitations are analyzed. We follow the lines of previous works and build up an orthonormal basis of projector-like operators for the degrees of freedom, rather than for the spin modes of the fields. With this new basis, the attainment of the propagators is remarkably

Chern-Simons gravity with (curvature)^2 and (torsion)^2 terms and a basis of degree-of-freedom projection operators

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The effects of (curvature)^2- and (torsion)^2-terms in the Einstein-Hilbert-Chern-Simons Lagrangian are investigated. The purposes are two-fold: (i) to show the efficacy of an orthogonal basis of degree-of-freedom projection operators recently proposed and to ascertain its adequacy for obtaining propagators of general parity-breaking gravity models in three dimensions; (ii) to analyze the role of the topological Chern-Simons term for the unitarity and the particle spectrum of the model squared-curvature terms in

Trabalhos recentes (2010 -2012)

H. Belich et al., **Phys. Rev. D 86, 125037 (2012)**

Investigation of the K_F-type Lorentz-symmetry breaking gauge models with vortexlike configurations

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For the *CPT*-even case of the minimal Standard Model extension, the spin-projector method is adopted to account for the breaking (tensor) $K_{\mu\nu\kappa\lambda}$ term. We adopt a particular decomposition of this term in four vectors, and carry out a detailed analysis of causality and unitarity. From this study, we are able to impose conditions on the decomposition of the $K_{\mu\nu\kappa\lambda}$ and vortex formation is also investigated in different situations.

Trabalhos disseminados pelo pais

☐ **Grupo da UFMG** (Scarpelli, Nemes, Sampaio, Hiller): aspectos de esquemas de regularização da teorias de campos com LV, incluindo geração radiativa de termos LV.

• **SCARPELLI, A. P. Baêta ; Sampaio, Marcos ; NEMES, M. C. ; HILLER, B.** . Gauge invariance and the CPT and Lorentz violating induced Chern-Simons-like term in extended QED. European Physical Journal C , v. 56, p. 571-578, 2008.

• **Scarpelli, A P Baêta .** QED with chiral nonminimal coupling: aspects of the Lorentz-violating quantum corrections. Journal of Physics. G, Nuclear and Particle Physics , v. 39, p. 125001, 2012.

• Gazzola, G ; Fargnoli, H G ; **Scarpelli, A P Baêta ; Sampaio, Marcos ; Nemes, M C .** QED with minimal and nonminimal couplings: on the quantum generation of Lorentz-violating terms in the pure photon sector. Journal of Physics. G, Nuclear and Particle Physics , v. 39, p. 035002, 2012.

Trabalhos em LV pelo pais

- **Grupo da USP e UFPB** (Petrov, Nascimento, Ferrari, Gomes): esquemas de regularização da teorias de campos com LV e geração radiativa de termos LV.

• FERRARI, A. F. ; GOMES, M. ; NASCIMENTO, J. R. S. ; **PETROV, A. ; Passos, E ; SILVA, A. J. . Lorentz violation** in the linearized gravity. Physics Letters. B (Print) , v. 652, p. 174-180, 2007.

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Trabalhos em LV pelo pais

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Trabalhos recentes...

Effects of a *CPT*-even and Lorentz-violating nonminimal coupling on electron-positron scattering

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(Received 5 October 2012; published 20 December 2012)

We propose a new *CPT*-even and Lorentz-violating nonminimal coupling between fermions and Abelian gauge fields involving the *CPT*-even tensor $(K_F)_{\mu\nu\alpha\beta}$ of the standard model extension. We thus

Uncharged compactlike and fractional Lorentz-violating BPS vortices in the *CPT*-even sector of the standard model extension

C. Miller,[1] R. Casana,[1] M. M. Ferreira, Jr.,[1] and E. da Hora[2]

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(Received 5 March 2012; revised manuscript received 9 August 2012; published 10 September 2012)

We have investigated and verified the existence of stable uncharged Bogomol'nyi-Prasad-Sommerfeld (BPS) vortices in the framework of an Abelian Maxwell-Higgs model supplemented with *CPT*-even and Lorentz-violating (LV) terms belonging to the gauge and Higgs sectors of the standard model extension.

Trabalhos recentes...

Magnetic flux inversion in charged BPS vortices in a Lorentz-violating Maxwell–Higgs framework

R. Casana [a,*], M.M. Ferreira Jr. [a], E. da Hora [a,c], C. Miller [a,b]

New *CPT*-even and Lorentz-violating nonminimal coupling in the Dirac equation

R. Casana,[1] M. M. Ferreira, Jr.,[1] E. Passos,[2] F. E. P. dos Santos,[1] and E. O. Silva[1]

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In this work, we propose a *CPT*-even and Lorentz-violating dimension-five nonminimal coupling between fermionic and gauge fields, involving the *CPT*-even and Lorentz-violating gauge tensor of the

Trabalhos recentes...

Radiative generation of the CPT-even gauge term of the SME from a dimension-five nonminimal coupling term

R. Casana[a], M.M. Ferreira Jr.[a,*], R.V. Maluf[b], F.E.P. dos Santos[a]

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- Esta foi uma Breve descrição de linha de pesquisa que começou no DCP, com Helayel-Neto, e se espalhou pelo país....

Grupo de Física Teórica de Partículas e Campos do Maranhão

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- **Prof. Edilberto O. Silva (UFMA)**
- **Prof. Adalto R. Gomes (IFMA)**
- **Prof. Carlos Eduardo da Hora (UFMA)**
- **Prof. Manoel M. Ferreira Jr (UFMA)**

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            Frederico Elias Passos dos Santos **(Doutorado)**
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            Fabiano de Carvalho Simas **(Doutorado)**

Finalizando... Sem finalizar...

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Grupo de Física Teórica de Partículas e Campos do Maranhão

- **Prof. Rofolfo Casana (UFMA)**
- **Prof. Edilberto O. Silva (UFMA)**
- **Prof. Adalto R. Gomes (IFMA)**
- **Prof. Carlos Eduardo da Hora (UFMA)**
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