Data tables for Lorentz and *CPT* violation

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This work tabulates measured and derived values of coefficients for Lorentz and *CPT* violation in the standard-model extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, and gravity sectors. Tables presenting definitions and properties are also compiled.

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CONTENTS

I. INTRODUCTION

Recent years have seen a renewed interest in experimental tests of Lorentz and *CPT* symmetry. Observable signals of Lorentz and *CPT* violation can be described in a model-independent way using effective field theory (Kostelecký and Potting, 1995).

The general realistic effective field theory for Lorentz violation is called the standard-model extension (SME) (Colladay and Kostelecký, 1997; 1998; Kostelecký, 2004). It includes the standard model coupled to general relativity along with all possible operators for Lorentz violation. Both global and local Lorentz violation are incorporated. Since *CPT* violation in realistic field theories is accompanied by Lorentz violation (Greenberg, 2002), the SME also describes general *CPT* violation. Reviews of the SME can be found in Kostelecký (1999), (2002), (2005), Bluhm (2006), Kostelecký (2008), (2011).

Each Lorentz-violating term in the Lagrange density of the SME is constructed as the coordinate-independent product of a coefficient for Lorentz violation with a Lorentz-violating operator. The Lorentz-violating physics associated with any operator is therefore controlled by the corresponding coefficient, and so any experimental signal for Lorentz violation can be expressed in terms of one or more of these coefficients.

The Lorentz-violating operators in the SME are systematically classified according to their mass dimension, and operators of arbitrarily large dimension can appear. At any fixed dimension, the operators are finite in number and can in principle be enumerated. A limiting case of particular interest is the minimal SME, which can be viewed as the restriction of the SME to include only Lorentz-violating operators of mass dimension 4 or less. The corresponding coefficients for Lorentz violation are dimensionless or have positive mass dimension.

The results summarized here concern primarily but not exclusively the coefficients for Lorentz violation in the minimal SME. We compile data tables for these SME coefficients, including both existing experimental measurements and some theory-derived limits. Each of these data tables provides information about the results of searches for Lorentz violation for a specific sector of the SME. For each measurement or constraint, we list the relevant coefficient or combination of coefficients, the result as presented in the literature, the context in which the search was performed, and the source citation. The tables include results available from the literature up to 31 July 2010, with updates provided by Kostelecký and Russell (2011).

The scope of the searches for Lorentz violation listed in the data tables can be characterized roughly in terms of depth, breadth, and refinement. Deep searches yield great sensitivity to a small number of SME coefficients. Broad searches cover substantial portions of the coefficient space, usually at a lesser sensitivity. Searches with high refinement disentangle combinations of coefficients. In the absence of a compelling signal for Lorentz violation, all types of searches are necessary to obtain complete coverage of the possibilities.

As a guide to the scope of the existing searches, we extract from the data tables three summary tables covering the sectors for matter (electrons, protons, neutrons, and their antiparticles), photons, and gravity. These summary tables list our best estimates for the maximal attained sensitivities to the relevant SME coefficients in the corresponding sectors. Each entry in the summary tables is obtained under the assumption that only one coefficient is nonzero. The summary tables therefore provide information about the overall search depth and breadth, at the cost of masking the search refinement.

In addition to the data tables and the summary tables, we also provide properties tables listing some features and definitions of the SME and the coefficients for Lorentz violation. The Lagrange densities for the minimal QED extension in Riemann spacetime, the minimal SME in Riemann-Cartan spacetime, and the nonminimal photon sector in Minkowski

TABLE I. List of tables.

Type	Table	Content
Summary	II	Maximal sensitivities for the matter sector
	III	Maximal sensitivities for the photon sector
	IV	Maximal sensitivities for the gravity sector
Data	V	Electron sector
	VI	Proton sector
	VII	Neutron sector
	VIII	Photon sector
	IX	Charged-lepton sector
	X	Neutrino sector
	XI	Meson sector
	XII	Electroweak sector
	XIII	Gluon sector
	XIV	Gravity sector
	XV	Nonminimal photon sector
Properties	XVI	Lagrange density for the minimal QED extension in Riemann spacetime
	XVII	*C*, *P*, *T*, properties for operators for Lorentz violation in QED
	XVIII	Definitions for the fermion sector of the minimal QED extension
	XIX	Definitions for the photon sector of the minimal QED extension
	XX	Lagrange density for the fermion sector of the minimal SME in Riemann-Cartan spacetime
	XXI	Lagrange density for the boson sector of the minimal SME in Riemann-Cartan spacetime
	XXII	Coefficients in the neutrino sector
	XXIII	Quadratic Lagrange density for the nonminimal photon sector in Minkowski spacetime
	XXIV	Spherical coefficients for the nonminimal photon sector in Minkowski spacetime

spacetime are provided in tabulated form. The mass dimensions of the operators for Lorentz violation and their properties under the various discrete spacetime transformations are displayed. Standard combinations of SME coefficients that appear in the literature are listed. Along with the data tables and the summary tables, the properties tables can be used to identify open directions for future searches. Among these are first measurements of unconstrained coefficients, improved sensitivities to constrained coefficients, and studies disentangling combinations of coefficients.

The order of the tables is as follows. Table I contains a list of all tables. The three summary tables are presented next, Tables II, III, and IV. These are followed by the data tables, Tables V, VI, VII, VIII, IX, X, XI, XII, XIII, XIV, and XV. The properties tables appear last, Tables XVI, XVII, XVIII, XIX, XX, XXI, XXII, XXIII, and XXIV.

A description of the summary tables is given in Sec. II. Information about the format and content of the data tables is presented in Sec. III, while Sec. IV provides an overview of the properties tables. The bibliography for the text and all the tables follows Sec. IV.

II. SUMMARY TABLES

Three summary tables are provided (Tables II, III, and IV), listing maximal experimental sensitivities attained for coefficients in the matter, photon, and gravity sectors of the minimal SME. To date, there is no compelling experimental evidence supporting Lorentz violation. A few measurements suggest nonzero coefficients at weak confidence levels. These latter results are excluded from the summary tables but are listed in the data tables.

In these three summary tables, each displayed sensitivity value represents our conservative estimate of a 2σ limit, given to the nearest order of magnitude, on the modulus of the corresponding coefficient. Our rounding convention is logarithmic: A factor greater than or equal to $10^{0.5}$ rounds to 10, while a factor less than $10^{0.5}$ rounds to 1. In a few cases, tighter results may exist when suitable theoretical assumptions are adopted; these results can be found in the data tables that follow.

Where observations involve a linear combination of the coefficients appearing in the summary tables, the displayed sensitivity for each coefficient assumes for definiteness that no other coefficient contributes. Some caution is therefore advisable in applying the results in these summary tables to situations involving two or more nonzero coefficient values. Care in applications is also required because under some circumstances certain coefficients can be intrinsically unobservable or can be absorbed into others by field or coordinate redefinitions as described in Sec. IV.A.

In presenting the physical sensitivities, we adopt natural units with $\hbar = c = \epsilon_0 = 1$ and express mass units in GeV. Our values are reported in the standard Sun-centered inertial reference frame (Bluhm *et al.*, 2002) widely used in the literature. This frame is illustrated in Fig. 1. The origin of the time coordinate T is at the 2000 vernal equinox. The Z axis is directed north and parallel to the rotational axis of the Earth at $T = 0$. The X axis points from the Sun toward the vernal equinox, while the Y axis completes a right-handed system. Some further details about this frame, including transformations to other frames, can be found in Sec. III A and Appendix C of Kostelecký and Mewes (2002).

Table II lists the maximal attained sensitivities involving electrons, protons, neutrons, and their antiparticles. For each distinct massive spin-half Dirac fermion in the minimal SME in Minkowski spacetime, there are 44 independent observable combinations of coefficients for Lorentz violation in the nonrelativistic limit. Of these, 20 also control *CPT* violation. The 44 combinations are conventionally chosen as the tilde

TABLE II. Maximal sensitivities for the matter sector.

Coefficient	Electron	Proton	Neutron
$\tilde{b}_X$	10^{-31} GeV	10^{-31} GeV	10^{-32} GeV
$\tilde{b}_Y$	10^{-31} GeV	10^{-31} GeV	10^{-32} GeV
$\tilde{b}_Z$	10^{-29} GeV	–	–
$\tilde{b}_T$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{b}^*_J$, $(J = X, Y, Z)$	10^{-22} GeV	–	–
$\tilde{c}_-$	10^{-18} GeV	10^{-24} GeV	10^{-27} GeV
$\tilde{c}_Q$	10^{-17} GeV	10^{-21} GeV	10^{-10} GeV
$\tilde{c}_X$	10^{-19} GeV	10^{-25} GeV	10^{-25} GeV
$\tilde{c}_Y$	10^{-19} GeV	10^{-25} GeV	10^{-25} GeV
$\tilde{c}_Z$	10^{-19} GeV	10^{-24} GeV	10^{-27} GeV
$\tilde{c}_{TX}$	10^{-18} GeV	10^{-20} GeV	–
$\tilde{c}_{TY}$	10^{-18} GeV	10^{-20} GeV	–
$\tilde{c}_{TZ}$	10^{-20} GeV	10^{-20} GeV	–
$\tilde{c}_{TT}$	10^{-18} GeV	10^{-11} GeV	10^{-11} GeV
$\tilde{d}_+$	10^{-27} GeV	–	10^{-27} GeV
$\tilde{d}_-$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{d}_Q$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{d}_{XY}$	10^{-26} GeV	–	10^{-27} GeV
$\tilde{d}_{YZ}$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{d}_{ZX}$	10^{-26} GeV	–	–
$\tilde{d}_X$	10^{-22} GeV	10^{-25} GeV	10^{-28} GeV
$\tilde{d}_Y$	10^{-22} GeV	10^{-25} GeV	10^{-28} GeV
$\tilde{d}_Z$	10^{-19} GeV	–	–
$\tilde{H}_{XT}$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{H}_{YT}$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{H}_{ZT}$	10^{-26} GeV	–	10^{-27} GeV
$\tilde{g}_T$	10^{-27} GeV	–	10^{-27} GeV
$\tilde{g}_c$	10^{-26} GeV	–	10^{-27} GeV
$\tilde{g}_Q$	–	–	–
$\tilde{g}_-$	–	–	–
$\tilde{g}_{TJ}$, $(J = X, Y, Z)$	–	–	–
$\tilde{g}_{XY}$	10^{-17} GeV	–	–
$\tilde{g}_{YX}$	10^{-17} GeV	–	–
$\tilde{g}_{ZX}$	10^{-18} GeV	–	–
$\tilde{g}_{XZ}$	10^{-17} GeV	–	–
$\tilde{g}_{YZ}$	10^{-17} GeV	–	–
$\tilde{g}_{ZY}$	10^{-18} GeV	–	–
$\tilde{g}_{DX}$	10^{-22} GeV	10^{-25} GeV	10^{-28} GeV
$\tilde{g}_{DY}$	10^{-22} GeV	10^{-25} GeV	10^{-28} GeV
$\tilde{g}_{DZ}$	10^{-22} GeV	–	–

coefficients shown. The definitions of these 44 tilde coefficients in terms of coefficients in the minimal SME are listed in Table XVIII. All the definitions appear elsewhere in the literature (Bluhm *et al.*, 2003) except the four combinations $\tilde{b}^*_J$ and $\tilde{c}_{TT}$. The three tilde coefficients $\tilde{b}^*_J$ are the antimatter equivalent of the tilde coefficients $\tilde{b}_J$. They appear in nonrelativistic studies of antimatter properties, such as the hyperfine transitions of antihydrogen (Bluhm *et al.*, 1999). The tilde coefficient $\tilde{c}_{TT}$ is a simple scaling of the coefficient c_{TT} in the minimal SME, introduced here to ensure completeness of the set of tilde coefficients. All tilde coefficients have dimensions of GeV in natural units. In Table II, a superscript indicating the particle species of relevance is understood on all coefficients. For example, the first line of the table presents limits on three different tilde coefficients, $\tilde{b}^e_X$, $\tilde{b}^p_X$, $\tilde{b}^n_X$. In the table, a dash indicates that no sensitivity to the coefficient has been identified to date. A few maximal sensitivities listed in the electron column are obtained by applying the inverse of the definitions in Table XVIII to the electron-sector data in Table V.

Table III displays the maximal attained sensitivities to coefficients for Lorentz violation in the photon sector of the minimal SME. There are 23 observable coefficient combinations for photons, of which four also control *CPT* violation. The 19 tilde coefficients listed in the table are conventional

TABLE III. Maximal sensitivities for the photon sector.

Coefficient	Sensitivity
$(\tilde{\kappa}_{e+})^{XY}$	10^{-32}
$(\tilde{\kappa}_{e+})^{XZ}$	10^{-32}
$(\tilde{\kappa}_{e+})^{YZ}$	10^{-32}
$(\tilde{\kappa}_{e+})^{XX} - (\tilde{\kappa}_{e+})^{YY}$	10^{-32}
$(\tilde{\kappa}_{e+})^{ZZ}$	10^{-32}
$(\tilde{\kappa}_{o-})^{XY}$	10^{-32}
$(\tilde{\kappa}_{o-})^{XZ}$	10^{-32}
$(\tilde{\kappa}_{o-})^{YZ}$	10^{-32}
$(\tilde{\kappa}_{o-})^{XX} - (\tilde{\kappa}_{o-})^{YY}$	10^{-32}
$(\tilde{\kappa}_{o-})^{ZZ}$	10^{-32}
$(\tilde{\kappa}_{e-})^{XY}$	10^{-17}
$(\tilde{\kappa}_{e-})^{XZ}$	10^{-17}
$(\tilde{\kappa}_{e-})^{YZ}$	10^{-17}
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	10^{-17}
$(\tilde{\kappa}_{e-})^{ZZ}$	10^{-16}
$(\tilde{\kappa}_{o+})^{XY}$	10^{-13}
$(\tilde{\kappa}_{o+})^{XZ}$	10^{-14}
$(\tilde{\kappa}_{o+})^{YZ}$	10^{-14}
$\tilde{\kappa}_{\rm tr}$	10^{-14}
$k^{(3)}_{(V)00}$	10^{-43} GeV
$k^{(3)}_{(V)10}$	10^{-42} GeV
${\rm Re}\,k^{(3)}_{(V)11}$	10^{-42} GeV
${\rm Im}\,k^{(3)}_{(V)11}$	10^{-42} GeV

TABLE IV. Maximal sensitivities for the gravity sector.

Coefficient	Electron	Proton	Neutron
$\alpha\bar{a}_T$	10^{-11} GeV	10^{-11} GeV	10^{-11} GeV
$\alpha\bar{a}_X$	10^{-6} GeV	10^{-6} GeV	10^{-5} GeV
$\alpha\bar{a}_Y$	10^{-5} GeV	10^{-5} GeV	10^{-4} GeV
$\alpha\bar{a}_Z$	10^{-5} GeV	10^{-5} GeV	10^{-4} GeV
$\alpha\bar{e}_T$	10^{-8}	10^{-11}	10^{-11}
$\alpha\bar{e}_X$	10^{-3}	10^{-6}	10^{-5}
$\alpha\bar{e}_Y$	10^{-2}	10^{-5}	10^{-4}
$\alpha\bar{e}_Z$	10^{-2}	10^{-5}	10^{-4}

Coefficient	Sensitivity
$\bar{s}^{XX} - \bar{s}^{YY}$	10^{-9}
$\bar{s}^{XX} + \bar{s}^{YY} - 2\bar{s}^{ZZ}$	10^{-7}
$\bar{s}^{XY}$	10^{-9}
$\bar{s}^{XZ}$	10^{-9}
$\bar{s}^{YZ}$	10^{-9}
$\bar{s}^{TX}$	10^{-6}
$\bar{s}^{TY}$	10^{-7}
$\bar{s}^{TZ}$	10^{-5}
$\bar{s}^{TT}$	–

TABLE V. Electron sector.

Combination	Result	System	Ref.
$\tilde{b}_X$	$(-0.9 \pm 1.4) \times 10^{-31}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$\tilde{b}_Y$	$(-0.9 \pm 1.4) \times 10^{-31}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$\tilde{b}_Z$	$(-0.3 \pm 4.4) \times 10^{-30}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$\frac{1}{2}(\tilde{b}_T + \tilde{d}_- - 2\tilde{g}_c - 3\tilde{g}_T + 4\tilde{d}_+ - \tilde{d}_Q)$	$(0.9 \pm 2.2) \times 10^{-27}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$\frac{1}{2}(2\tilde{g}_c - \tilde{g}_T - \tilde{b}_T + 4\tilde{d}_+ - \tilde{d}_- - \tilde{d}_Q)$ $+ \tan\eta(\tilde{d}_{YZ} - \tilde{H}_{XT})$	$(-0.8 \pm 2.0) \times 10^{-27}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$\tilde{b}_X$	$(2.8 \pm 6.1) \times 10^{-29}$ GeV	K/He magnetometer	Kornack *et al.* (2008)
$\tilde{b}_Y$	$(6.8 \pm 6.1) \times 10^{-29}$ GeV	K/He magnetometer	Kornack *et al.* (2008)
$\tilde{b}_X$	$(0.1 \pm 2.4) \times 10^{-31}$ GeV	Torsion pendulum	Heckel *et al.* (2006)
$\tilde{b}_Y$	$(-1.7 \pm 2.5) \times 10^{-31}$ GeV	Torsion pendulum	Heckel *et al.* (2006)
$\tilde{b}_Z$	$(-29 \pm 39) \times 10^{-31}$ GeV	Torsion pendulum	Heckel *et al.* (2006)
$\tilde{b}_\perp$	$<3.1 \times 10^{-29}$ GeV	Torsion pendulum	Hou, *et al.* (2003)
$\lvert\tilde{b}_Z\rvert$	$<7.1 \times 10^{-28}$ GeV	Torsion pendulum	Hou, *et al.* (2003)
r_e	$<3.2 \times 10^{-24}$	Hg/Cs comparison	Hunter *et al.* (1999)
$\lvert\vec{b}\rvert$	<50 rad/s	Penning trap	Dehmelt *et al.* (1999)
$r_{\omega_a^-,\text{diurnal}}$	$<1.6 \times 10^{-21}$	Penning trap	Mittleman *et al.* (1999)
$\lvert\tilde{b}_J\rvert,\ (J = X, Y)$	$<10^{-27}$ GeV	Hg/Cs comparison	Kostelecký and Lane (1999)*
c_{TT}	$(-4 \text{ to } 2) \times 10^{-15}$	Collider physics	Altschul (2010)b*
$c_{(TX)}$	$(-30 \text{ to } 1) \times 10^{-14}$	Collider physics	Altschul (2010)b*
$c_{(TY)}$	$(-80 \text{ to } 6) \times 10^{-15}$	Collider physics	Altschul (2010)b*
$c_{(TZ)}$	$(-11 \text{ to } 1.3) \times 10^{-13}$	Collider physics	Altschul (2010)b*
$0.83c_{(TX)} + 0.51c_{(TY)} + 0.22c_{(TZ)}$	$(4 \pm 8) \times 10^{-11}$	$1S$-$2S$ transition	Altschul (2010)a*
$c_{XX} - c_{YY}$	$(-2.9 \pm 6.3) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$\frac{1}{2}c_{(XY)}$	$(2.1 \pm 0.9) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$\frac{1}{2}c_{(XZ)}$	$(-1.5 \pm 0.9) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$\frac{1}{2}c_{(YZ)}$	$(-0.5 \pm 1.2) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$c_{XX} + c_{YY} - 2c_{ZZ}$	$(-106 \pm 147) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
λ^{ZZ}	$(13.3 \pm 9.8) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$\frac{1}{2}c_{(YZ)}$	$(2.1 \pm 4.6) \times 10^{-16}$	Optical, microwave resonators	Müller (2005)*
$\frac{1}{2}c_{(XZ)}$	$(-1.6 \pm 6.3) \times 10^{-16}$	Optical, microwave resonators	Müller (2005)*
$\frac{1}{2}c_{(XY)}$	$(7.6 \pm 3.5) \times 10^{-16}$	Optical, microwave resonators	Müller (2005)*
$c_{XX} - c_{YY}$	$(1.15 \pm 0.64) \times 10^{-15}$	Optical, microwave resonators	Müller (2005)*
$\lvert c_{XX} + c_{YY} - 2c_{ZZ} - 0.25(\tilde{\kappa}_{e-})^{ZZ}\rvert$	$<10^{-12}$	Optical, microwave resonators	Müller (2005)*
$\lvert\frac{1}{2}c_{(XY)}\rvert$	$<8 \times 10^{-15}$	Optical resonators	Müller *et al.* (2003)b*
$\lvert c_{XX} - c_{YY}\rvert$	$<1.6 \times 10^{-14}$	Optical resonators	Müller *et al.* (2003)b*
$\lvert c_{XX} + c_{YY} - 2c_{ZZ}\rvert$	$<10^{-5}$	Doppler shift	Lane (2005)*
$\lvert c_{TJ} + c_{JT}\rvert,\ (J = X, Y, Z)$	$<10^{-2}$	Doppler shift	Lane (2005)*
c_{XX}	$(-3 \text{ to } 5) \times 10^{-15}$	Astrophysics	Altschul (2006)b*
c_{YY}	$(-0.7 \text{ to } 2.5) \times 10^{-15}$	Astrophysics	Altschul (2006)b*
c_{ZZ}	$(-1.6 \text{ to } 2.5) \times 10^{-15}$	Astrophysics	Altschul (2006)b*
$c_{(YZ)}$	$(-2.5 \text{ to } 1.8) \times 10^{-15}$	Astrophysics	Altschul (2006)b*
c_{0X}	$(-7 \text{ to } 4) \times 10^{-15}$	Astrophysics	Altschul (2006)b*
c_{0Y}	$(-0.5 \text{ to } 1.5) \times 10^{-15}$	Astrophysics	Altschul (2006)b*
c_{0Z}	$(-4 \text{ to } 2) \times 10^{-17}$	Astrophysics	Altschul (2006)b*
$\lvert 0.05c_{XX} + 0.55c_{YY} + 0.41c_{ZZ}$ $+ 0.16c_{(XY)} - 0.14c_{(XZ)} - 0.47c_{(YZ)}$ $+ 0.22c_{(0X)} + 0.74c_{(0Y)} - 0.64c_{(0Z)} + c_{00}\rvert$	$<1.3 \times 10^{-15}$	Astrophysics	Altschul (2007)c*
$\lvert 0.58c_{XX} + 0.04c_{YY} + 0.38c_{ZZ}$ $- 0.14c_{(XY)} - 0.47c_{(XZ)} + 0.12c_{(YZ)}$ $+ 0.76c_{(0X)} - 0.19c_{(0Y)} - 0.62c_{(0Z)} + c_{00}\rvert$	$<2.5 \times 10^{-15}$	Astrophysics	Altschul (2007)c*

TABLE V. (*Continued*)

Combination	Result	System	Ref.
$c_{TT} \equiv -\delta$	$(-13 \text{ to } 2) \times 10^{-16}$	Astrophysics	Stecker and Glashow (2001)*
$\tilde{d}_{XY} - \tilde{H}_{ZT} + \tan\eta \tilde{H}_{YT}$	$(0.1 \pm 1.8) \times 10^{-27}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$\tilde{H}_{ZT}$	$(-4.1 \pm 2.4) \times 10^{-27}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$\tilde{H}_{YT} - \tilde{d}_{ZX}$	$(-4.9 \pm 8.9) \times 10^{-27}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$-\tilde{H}_{XT} + \tan\eta(\tilde{g}_T - 2\tilde{d}_+ + \tilde{d}_Q)$	$(1.1 \pm 9.2) \times 10^{-27}$ GeV	Torsion pendulum	Heckel *et al.* (2008)
$\lvert d_{XX}\rvert$	$<2 \times 10^{-14}$	Astrophysics	Altschul (2007)b*
$\lvert d_{YY}\rvert, \lvert d_{ZZ}\rvert$	$<3 \times 10^{-15}$	Astrophysics	Altschul (2007)b*
$\lvert d_{(XY)}\rvert$	$<2 \times 10^{-15}$	Astrophysics	Altschul (2007)b*
$\lvert d_{(XZ)}\rvert$	$<2 \times 10^{-14}$	Astrophysics	Altschul (2007)b*
$\lvert d_{(YZ)}\rvert$	$<7 \times 10^{-15}$	Astrophysics	Altschul (2007)b*
$\lvert d_{TX}\rvert$	$<5 \times 10^{-14}$	Astrophysics	Altschul (2007)b*
$\lvert d_{TY}\rvert$	$<5 \times 10^{-15}$	Astrophysics	Altschul (2007)b*
$\lvert d_{TZ}\rvert$	$<8 \times 10^{-17}$	Astrophysics	Altschul (2007)b*
$\lvert\tilde{d}_J\rvert, \lvert\tilde{g}_{D,J}\rvert, \ (J = X, Y)$	$<10^{-22}$ GeV	Hg/Cs comparison	Kostelecký and Lane (1999)*

TABLE VI. Proton sector.

Combination	Result	System	Ref.
$\tilde{b}_\perp$	$<6 \times 10^{-32}$ GeV	K/He magnetometer	Brown *et al.* (2010)
$\tilde{b}_X$	$(6.0 \pm 1.3) \times 10^{-31}$ GeV	K/He magnetometer	Kornack *et al.* (2008)
$\tilde{b}_Y$	$(1.5 \pm 1.2) \times 10^{-31}$ GeV	K/He magnetometer	Kornack *et al.* (2008)
$\sqrt{(\tilde{b}_X^e + \tilde{b}_X^p)^2 + (\tilde{b}_Y^e + \tilde{b}_Y^p)^2}$	$(3 \pm 2) \times 10^{-27}$ GeV	H maser	Humphrey *et al.* (2003)
$\lvert\tilde{b}_J\rvert \ (J = X, Y)$	$<2 \times 10^{-27}$ GeV	H maser	Phillips *et al.* (2001)
$\lvert\tilde{b}_J\rvert \ (J = X, Y)$	$<10^{-27}$ GeV	Hg/Cs comparison	Kostelecký and Lane (1999)*
$\tilde{c}_Q$	$(-0.3 \pm 2.2) \times 10^{-22}$ GeV	Cs fountain	Wolf *et al.* (2006)
$\tilde{c}_-$	$(-1.8 \pm 2.8) \times 10^{-25}$ GeV	Cs fountain	Wolf *et al.* (2006)
$\tilde{c}_X$	$(0.6 \pm 1.2) \times 10^{-25}$ GeV	Cs fountain	Wolf *et al.* (2006)
$\tilde{c}_Y$	$(-1.9 \pm 1.2) \times 10^{-25}$ GeV	Cs fountain	Wolf *et al.* (2006)
$\tilde{c}_Z$	$(-1.4 \pm 2.8) \times 10^{-25}$ GeV	Cs fountain	Wolf *et al.* (2006)
$\tilde{c}_{TX}$	$(-2.7 \pm 3.0) \times 10^{-21}$ GeV	Cs fountain	Wolf *et al.* (2006)
$\tilde{c}_{TY}$	$(-0.2 \pm 3.0) \times 10^{-21}$ GeV	Cs fountain	Wolf *et al.* (2006)
$\tilde{c}_{TZ}$	$(-0.4 \pm 2.0) \times 10^{-21}$ GeV	Cs fountain	Wolf *et al.* (2006)
$\lvert c_{XX} + c_{YY} - 2c_{ZZ}\rvert$	$<10^{-11}$	Doppler shift	Lane (2005)*
$\lvert c_{TJ} + c_{JT}\rvert, \ (J = X, Y, Z)$	$<10^{-8}$	Doppler shift	Lane (2005)*
$r^{H^-}_{\omega_c}$	$<4 \times 10^{-26}$	Penning trap	Gabrielse *et al.* (1999)
$\lvert\tilde{d}_J\rvert, \lvert\tilde{g}_{D,J}\rvert, \ (J = X, Y)$	$<10^{-25}$ GeV	Hg/Cs comparison	Kostelecký and Lane (1999)*

combinations of the 19 dimensionless coefficients in the minimal SME. The remaining entries in the table concern combinations of the four coefficients controlling *CPT* violation, which have dimensions of GeV in natural units. The definitions of all 23 combinations are taken from the literature (Kostelecký and Mewes, 2002, 2007) and are provided in Table XIX.

Table IV displays the maximal attained sensitivities to certain coefficients for Lorentz violation involving the gravity sector of the minimal SME. Two classes of coefficients can be distinguished in this context: ones appearing in the matter sector, and ones appearing in the pure-gravity sector. For the first class, Table IV contains results for the 24 coefficients $\bar{a}^e_\mu$, $\bar{a}^p_\mu$, $\bar{a}^n_\mu$ and $\bar{e}^e_\mu$, $\bar{e}^p_\mu$, $\bar{e}^n_\mu$ involving the electron, proton, and neutron sectors. These observables are associated with *CPT*-odd operators and have dimensions of GeV in natural units. The prefactor α is a model-dependent number (Kostelecký and Tasson, 2009). For the second class, the table displays nine combinations of the nine dimensionless coefficients for Lorentz violation $\bar{s}^{\mu\nu}$. Additional sets of coefficients involving the gravity sector exist, but no sensitivities to them have been identified to date.

III. DATA TABLES

We present 11 data tables compiled from the existing literature. Of these, 10 tables include results for various sectors of the minimal SME: the electron sector (Table V), the proton sector (Table VI), the neutron sector (Table VII), the photon sector (Table VIII), the charged-lepton sector (Table IX), the neutrino sector (Table X), the meson sector (Table XI), the electroweak sector (Table XII), the gluon sector (Table XIII), and the gravity sector (Table XIV). The remaining table (Table XV) lists existing bounds on nonminimal coefficients for Lorentz violation in the photon sector.

TABLE VII. Neutron sector.

Combination	Result	System	Ref.
$\tilde{b}_\perp$	$<3.72\times 10^{-32}$ GeV	He/Xe magnetometer	Tullney *et al.* (2010)
$\tilde{b}_X$	$(0.1\pm 1.6)\times 10^{-33}$ GeV	K/He magnetometer	Brown *et al.* (2010)
$\tilde{b}_Y$	$(2.5\pm 1.6)\times 10^{-33}$ GeV	K/He magnetometer	Brown *et al.* (2010)
$\lvert\tilde{b}_\perp\rvert$	$<3.7\times 10^{-33}$ GeV	K/He magnetometer	Brown *et al.* (2010)
$b_\perp$	$<2\times 10^{-29}$ GeV	Ultracold neutrons	Altarev *et al.* (2009)
$-4.2b_i^{(n)}+0.7b_i^{(p)}$	$2\pi(53\pm 45)$ nHz	Xe/He maser	Flambaum *et al.* (2009)*
$\lvert b_J-\frac{1}{2}\epsilon_{JKL}H_{KL}\rvert$, $(J=X,Y)$	$<10^{-28}$ GeV	Maser/magnetometer	Altschul (2009)a*
$\tilde{b}_X$	$(-3.7\pm 8.1)\times 10^{-32}$ GeV	K/He magnetometer	Kornack *et al.* (2008)
$\tilde{b}_Y$	$(-9.0\pm 7.5)\times 10^{-32}$ GeV	K/He magnetometer	Kornack *et al.* (2008)
$\tilde{b}_Y-0.0034\tilde{d}_Y+0.0034\tilde{g}_{DY}$	$(8.0\pm 9.5)\times 10^{-32}$ GeV	Xe/He maser	Canè *et al.* (2004)
$-\tilde{b}_X-0.0034\tilde{d}_X-0.0034\tilde{g}_{DX}$	$(2.2\pm 7.9)\times 10^{-32}$ GeV	Xe/He maser	Canè *et al.* (2004)
$-\cos\eta(\frac{1}{2}\tilde{b}_T+\frac{1}{2}\tilde{d}_--\tilde{g}_c-\frac{1}{2}\tilde{g}_T)$ $-\cos\eta(\tilde{g}_T-2\tilde{d}_++\frac{1}{2}\tilde{d}_Q)+\sin\eta(\tilde{d}_{YZ}-\tilde{H}_{XT})$	$(-1.1\pm 1.0)\times 10^{-27}$ GeV	Xe/He maser	Canè *et al.* (2004)
$-\tilde{H}_{ZT}$	$(0.2\pm 1.8)\times 10^{-27}$ GeV	Xe/He maser	Canè *et al.* (2004)
$(\frac{1}{2}\tilde{b}_T+\frac{1}{2}\tilde{d}_--\tilde{g}_c-\frac{1}{2}\tilde{g}_T)-(\tilde{g}_T-2\tilde{d}_++\frac{1}{2}\tilde{d}_Q)$	$(-1.8\pm 1.9)\times 10^{-27}$ GeV	Xe/He maser	Canè *et al.* (2004)
$\cos\eta(\tilde{H}_{ZT}-\tilde{d}_{XY})-\sin\eta\tilde{H}_{YT}$	$(-1.1\pm 0.8)\times 10^{-27}$ GeV	Xe/He maser	Canè *et al.* (2004)
$\sqrt{(\tilde{b}_X)^2+(\tilde{b}_Y)^2}$	$(6.4\pm 5.4)\times 10^{-32}$ GeV	Xe/He maser	Bear *et al.* (2000)
$r_{\underline{n}}$	$<1.5\times 10^{-30}$	Hg/Cs comparison	Hunter *et al.* (1999)
$\lvert\tilde{b}_J\rvert$, $(J=X,Y)$	$<10^{-30}$ GeV	Hg/Cs comparison	Kostelecký and Lane (1999)*
$\frac{1}{4}\lvert c_Q\rvert, \lvert c_{(TJ)}\rvert$, $(J=X,Y,Z)$	$<5\times 10^{-14}$	Astrophysics	Altschul (2008)b*
$\min(\lvert c_{11}-c_{22}\rvert, \lvert c_{11}-c_{33}\rvert, \lvert c_{22}-c_{33}\rvert)$	$<1.7\times 10^{-8}$	Pulsar timing	Altschul (2007)a*
$\lvert\tilde{c}_J\rvert$, $(J=X,Y)$	$<10^{-25}$ GeV	Be/H comparison	Kostelecký and Lane (1999)*
$\lvert\tilde{c}_-\rvert, \lvert\tilde{c}_Z\rvert$	$<10^{-27}$ GeV	Hg/Hg & Ne/He comparison	Kostelecký and Lane (1999)*
$\lvert md_{JT}-\frac{1}{2}\epsilon_{JKL}mg_{KLT}\rvert$, $(J=X,Y)$	$<10^{-28}$ GeV	Maser/magnetometer	Altschul (2009)a*
$\frac{1}{2}\lvert d_{(XZ)}\rvert, \lvert d_{(TZ)}\rvert$	$<5\times 10^{-14}$	Astrophysics	Altschul (2008)b*
$\lvert\tilde{d}_J\rvert, \lvert\tilde{g}_{D,J}\rvert$, $(J=X,Y)$	$<10^{-28}$ GeV	Hg/Cs comparison	Kostelecký and Lane (1999)*

Each of these 11 data tables contains four columns. The first column lists the coefficients for Lorentz violation or their relevant combinations. Results for coefficients of the same generic type are grouped together. Certain results involve combinations of coefficients across more than one sector; each of these has been listed only once in the table deemed most appropriate. Some minor changes in notation or format have been introduced as needed, but for the most part the results are quoted as they appear in the cited references. Definitions for standard combinations of coefficients are provided in the properties tables that follow. A few authors use unconventional notation; where immediate, the match to the standard notation is shown. Parentheses enclosing a pair of indices on a coefficient indicate symmetrization without a factor of 2.

The second column contains the measurements and bounds, presented in the same form as documented in the literature. For each generic type of coefficient, the results are listed in reverse chronological order. If no significant figures appear in the quoted limit on an absolute value, the order of magnitude of the limit is given as a power of 10. Where both statistical and systematic errors appear in a given result, they are quoted in that order.

The third column contains a succinct reminder of the physical context in which the bound is extracted, while the fourth column contains the source citations. The reader is referred to the latter for details of experimental and theoretical procedures, assumptions underlying the results, definitions of unconventional notations, and other relevant information. Results deduced on theoretical grounds are distinguished from those obtained via direct experimental measurement by an asterisk placed after the citation.

Tables V, VI, and VII contain data for the electron, proton, and neutron sectors, respectively. Each table is divided into sections focusing sequentially on combinations involving the coefficients b_ν, $c_{\mu\nu}$, $H_{\mu\nu}$, $d_{\mu\nu}$, and $g_{\mu\nu\lambda}$. A superscript indicating the particle species of relevance is understood on all coefficients in these three tables. Standard definitions for the coefficients and their combinations are provided in Tables XVI and XVIII. Some results depend on $\eta\simeq 23.5°$, which is the angle between the equatorial and ecliptic planes in the solar system. Note that existing bounds on observables involving a_ν^e, a_ν^p, a_ν^n and e_ν^e, e_ν^p, e_ν^n are obtained from gravitational experiments and are listed with the gravity-sector results in Table XIV.

Table VIII presents the photon-sector data. Most of the combinations of coefficients for Lorentz violation appearing in the first column are defined in Tables XVI and XIX. The combinations $k_{(V)jm}^{(3)}$, $k_{(E)jm}^{(4)}$, and $k_{(B)jm}^{(4)}$ arise from analyses (Kostelecký and Mewes, 2007, 2008, 2009) using spin-weighted spherical harmonics. The factor of $\beta_\oplus$ appearing in some places is the speed of the Earth in the standard Sun-centered reference frame, which is about 10^{-4} in natural units.

Tables IX, X, and XI list measurements and bounds on coefficients for Lorentz violation involving second- and third-generation fermions in the minimal SME. Results for muons and tau leptons are in Table XI, while those for neutrinos are

TABLE VIII. Photon sector.

Combination	Result	System	Ref.
$(\tilde{\kappa}_{e-})^{XY}$	$(0.8 \pm 0.6) \times 10^{-16}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$(\tilde{\kappa}_{e-})^{XY}$	$(-0.31 \pm 0.73) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2009)
$(\tilde{\kappa}_{e-})^{XY}$	$(0.0 \pm 1.0 \pm 0.3) \times 10^{-17}$	Rotating optical resonators	Eisele, *et al.* (2009)
$(\tilde{\kappa}_{e-})^{XY}$	$(-0.1 \pm 0.6) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2008)
$(\tilde{\kappa}_{e-})^{XY}$	$(-7.7 \pm 4.0) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$(\tilde{\kappa}_{e-})^{XY}$	$(2.9 \pm 2.3) \times 10^{-16}$	Rotating microwave resonators	Stanwix *et al.* (2006)
$(\tilde{\kappa}_{e-})^{XY}$	$(-3.1 \pm 2.5) \times 10^{-16}$	Rotating optical resonators	Herrmann *et al.* (2005)
$(\tilde{\kappa}_{e-})^{XY}$	$(-0.63 \pm 0.43) \times 10^{-15}$	Rotating microwave resonators	Stanwix *et al.* (2005)
$(\tilde{\kappa}_{e-})^{XY}$	$(-1.7 \pm 1.6) \times 10^{-15}$	Optical, microwave resonators	Müller (2005)*
$(\tilde{\kappa}_{e-})^{XY}$	$(-5.7 \pm 2.3) \times 10^{-15}$	Microwave resonator, maser	Wolf *et al.* (2004)
$(\tilde{\kappa}_{e-})^{XY}$	$(1.7 \pm 2.6) \times 10^{-15}$	Optical resonators	Müller *et al.* (2003)a
$(\tilde{\kappa}_{e-})^{XY}$	$(1.4 \pm 1.4) \times 10^{-13}$	Microwave resonators	Lipa *et al.* (2003)
$(\tilde{\kappa}_{e-})^{XZ}$	$(1.5 \pm 1.3) \times 10^{-16}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$(\tilde{\kappa}_{e-})^{XZ}$	$(0.54 \pm 0.70) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2009)
$(\tilde{\kappa}_{e-})^{XZ}$	$(0.4 \pm 1.5 \pm 0.1) \times 10^{-17}$	Rotating optical resonators	Eisele *et al.* (2009)
$(\tilde{\kappa}_{e-})^{XZ}$	$(-2.0 \pm 0.9) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2008)
$(\tilde{\kappa}_{e-})^{XZ}$	$(-10.3 \pm 3.9) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$(\tilde{\kappa}_{e-})^{XZ}$	$(-6.9 \pm 2.2) \times 10^{-16}$	Rotating microwave resonators	Stanwix *et al.* (2006)
$(\tilde{\kappa}_{e-})^{XZ}$	$(5.7 \pm 4.9) \times 10^{-16}$	Rotating optical resonators	Herrmann *et al.* (2005)
$(\tilde{\kappa}_{e-})^{XZ}$	$(0.19 \pm 0.37) \times 10^{-15}$	Rotating microwave resonators	Stanwix *et al.* (2005)
$(\tilde{\kappa}_{e-})^{XZ}$	$(-4.0 \pm 3.3) \times 10^{-15}$	Optical, microwave resonators	Müller (2005)*
$(\tilde{\kappa}_{e-})^{XZ}$	$(-3.2 \pm 1.3) \times 10^{-15}$	Microwave resonator, maser	Wolf *et al.* (2004)
$(\tilde{\kappa}_{e-})^{XZ}$	$(-6.3 \pm 12.4) \times 10^{-15}$	Optical resonators	Müller *et al.* (2003)a
$(\tilde{\kappa}_{e-})^{XZ}$	$(-3.5 \pm 4.3) \times 10^{-13}$	Microwave resonators	Lipa *et al.* (2003)
$(\tilde{\kappa}_{e-})^{YZ}$	$(1.7 \pm 1.3) \times 10^{-16}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$(\tilde{\kappa}_{e-})^{YZ}$	$(-0.97 \pm 0.74) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2009)
$(\tilde{\kappa}_{e-})^{YZ}$	$(-0.6 \pm 1.4 \pm 0.5) \times 10^{-17}$	Rotating optical resonators	Eisele *et al.* (2009)
$(\tilde{\kappa}_{e-})^{YZ}$	$(-0.3 \pm 1.4) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2008)
$(\tilde{\kappa}_{e-})^{YZ}$	$(0.9 \pm 4.2) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$(\tilde{\kappa}_{e-})^{YZ}$	$(2.1 \pm 2.1) \times 10^{-16}$	Rotating microwave resonators	Stanwix *et al.* (2006)
$(\tilde{\kappa}_{e-})^{YZ}$	$(-1.5 \pm 4.4) \times 10^{-16}$	Rotating optical resonators	Herrmann *et al.* (2005)
$(\tilde{\kappa}_{e-})^{YZ}$	$(-0.45 \pm 0.37) \times 10^{-15}$	Rotating microwave resonators	Stanwix *et al.* (2005)
$(\tilde{\kappa}_{e-})^{YZ}$	$(0.52 \pm 2.52) \times 10^{-15}$	Optical, microwave resonators	Müller (2005)*
$(\tilde{\kappa}_{e-})^{YZ}$	$(-0.5 \pm 1.3) \times 10^{-15}$	Microwave resonator, maser	Wolf *et al.* (2004)
$(\tilde{\kappa}_{e-})^{YZ}$	$(3.6 \pm 9.0) \times 10^{-15}$	Optical resonators	Müller *et al.* (2003)a
$(\tilde{\kappa}_{e-})^{YZ}$	$(1.7 \pm 3.6) \times 10^{-13}$	Microwave resonators	Lipa *et al.* (2003)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(0.2 \pm 1.0) \times 10^{-16}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(0.80 \pm 1.27) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2009)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(0.8 \pm 2.0 \pm 0.3) \times 10^{-17}$	Rotating optical resonators	Eisele, *et al.* (2009)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(-2.0 \pm 1.7) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2008)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(-12 \pm 16) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(-5.0 \pm 4.7) \times 10^{-16}$	Rotating microwave resonators	Stanwix *et al.* (2006)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(5.4 \pm 4.8) \times 10^{-16}$	Rotating optical resonators	Herrmann *et al.* (2005)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(-1.3 \pm 0.9) \times 10^{-15}$	Rotating microwave resonators	Stanwix *et al.* (2005)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(2.8 \pm 3.3) \times 10^{-15}$	Optical, microwave resonators	Müller (2005)*
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(-3.2 \pm 4.6) \times 10^{-15}$	Microwave resonator, maser	Wolf *et al.* (2004)
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(8.9 \pm 4.9) \times 10^{-15}$	Optical resonators	Müller *et al.* (2003)a
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(-1.0 \pm 2.1) \times 10^{-13}$	Microwave resonators	Lipa *et al.* (2003)
$(\tilde{\kappa}_{e-})^{ZZ}$	$(143 \pm 179) \times 10^{-16}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$(\tilde{\kappa}_{e-})^{ZZ}$	$(-0.04 \pm 1.73) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2009)
$(\tilde{\kappa}_{e-})^{ZZ}$	$(1.6 \pm 2.4 \pm 1.1) \times 10^{-17}$	Rotating optical resonators	Eisele *et al.* (2009)
$(\tilde{\kappa}_{e-})^{ZZ}$	$(-0.2 \pm 3.1) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2008)
$(\tilde{\kappa}_{e-})^{ZZ}$	$(223 \pm 290) \times 10^{-16}$	Optical, microwave resonators	Müller *et al.* (2007)*
$(\tilde{\kappa}_{e-})^{ZZ}$	$(143 \pm 179) \times 10^{-16}$	Rotating microwave resonators	Stanwix *et al.* (2006)
$(\tilde{\kappa}_{e-})^{ZZ}$	$(-1.9 \pm 5.2) \times 10^{-15}$	Rotating optical resonators	Herrmann *et al.* (2005)
$(\tilde{\kappa}_{e-})^{ZZ}$	$(21 \pm 57) \times 10^{-15}$	Rotating microwave resonators	Stanwix *et al.* (2005)
$(\tilde{\kappa}_{e-})^{ZZ}$	$(-2.9 \pm 2.2) \times 10^{-14}$	Optical resonators	Antonini *et al.* (2005)
$\lvert(\tilde{\kappa}_{e-})^{(kl)}\rvert$	$<4 \times 10^{-18}$	Astrophysics	Klinkhamer and Risse (2008)*

TABLE VIII. (*Continued*)

Combination	Result	System	Ref.
$(\tilde{\kappa}_{o+})^{XY}$	$(-1.5 \pm 1.2) \times 10^{-12}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$\sqrt{[2c_{TX} - (\tilde{\kappa}_{o+})^{YZ}]^2 + [2c_{TY} - (\tilde{\kappa}_{o+})^{ZX}]^2}$	$<1.6 \times 10^{-14}$	Compton scattering	Bocquet *et al.* (2010)
$\beta_\oplus(\tilde{\kappa}_{o+})^{XY}$	$(-0.14 \pm 0.78) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2009)
$(\tilde{\kappa}_{o+})^{XY}$	$(1.5 \pm 1.5 \pm 0.2) \times 10^{-13}$	Rotating optical resonators	Eisele *et al.* (2009)
$\beta_\oplus(\tilde{\kappa}_{o+})^{XY}$	$(-2.5 \pm 2.5) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2008)
$(\tilde{\kappa}_{o+})^{XY}$	$(1.7 \pm 2.0) \times 10^{-12}$	Optical, microwave resonators	Müller *et al.* (2007)*
$(\tilde{\kappa}_{o+})^{XY}$	$(-0.9 \pm 2.6) \times 10^{-12}$	Rotating microwave resonators	Stanwix *et al.* (2006)
$(\tilde{\kappa}_{o+})^{XY}$	$(-2.5 \pm 5.1) \times 10^{-12}$	Rotating optical resonators	Herrmann *et al.* (2005)
$(\tilde{\kappa}_{o+})^{XY}$	$(0.20 \pm 0.21) \times 10^{-11}$	Rotating microwave resonators	Stanwix *et al.* (2005)
$(\tilde{\kappa}_{o+})^{XY}$	$(-1.8 \pm 1.5) \times 10^{-11}$	Microwave resonator, maser	Wolf *et al.* (2004)
$(\tilde{\kappa}_{o+})^{XY}$	$(14 \pm 14) \times 10^{-11}$	Optical resonators	Müller *et al.* (2003)a
$(\tilde{\kappa}_{o+})^{XZ}$	$(1.7 \pm 0.7) \times 10^{-12}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$\beta_\oplus(\tilde{\kappa}_{o+})^{XZ}$	$(-0.45 \pm 0.62) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2009)
$(\tilde{\kappa}_{o+})^{XZ}$	$(-0.1 \pm 1.0 \pm 0.2) \times 10^{-13}$	Rotating optical resonators	Eisele *et al.* (2009)
$\beta_\oplus(\tilde{\kappa}_{o+})^{XZ}$	$(1.5 \pm 1.7) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2008)
$(\tilde{\kappa}_{o+})^{XZ}$	$(-3.1 \pm 2.3) \times 10^{-12}$	Optical, microwave resonators	Müller *et al.* (2007)*
$(\tilde{\kappa}_{o+})^{XZ}$	$(-4.4 \pm 2.5) \times 10^{-12}$	Rotating microwave resonators	Stanwix *et al.* (2006)
$(\tilde{\kappa}_{o+})^{XZ}$	$(-3.6 \pm 2.7) \times 10^{-12}$	Rotating optical resonators	Herrmann *et al.* (2005)
$(\tilde{\kappa}_{o+})^{XZ}$	$(-0.91 \pm 0.46) \times 10^{-11}$	Rotating microwave resonators	Stanwix *et al.* (2005)
$(\tilde{\kappa}_{o+})^{XZ}$	$(-1.4 \pm 2.3) \times 10^{-11}$	Microwave resonator, maser	Wolf *et al.* (2004)
$(\tilde{\kappa}_{o+})^{XZ}$	$(-1.2 \pm 2.6) \times 10^{-11}$	Optical resonators	Müller *et al.* (2003)a
$(\tilde{\kappa}_{o+})^{YZ}$	$(0.2 \pm 0.7) \times 10^{-12}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$\beta_\oplus(\tilde{\kappa}_{o+})^{YZ}$	$(-0.34 \pm 0.61) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2009)
$(\tilde{\kappa}_{o+})^{YZ}$	$(-0.1 \pm 1.0 \pm 0.4) \times 10^{-13}$	Rotating optical resonators	Eisele *et al.* (2009)
$\beta_\oplus(\tilde{\kappa}_{o+})^{YZ}$	$(-1.0 \pm 1.5) \times 10^{-17}$	Rotating optical resonators	Herrmann *et al.* (2008)
$(\tilde{\kappa}_{o+})^{YZ}$	$(-2.8 \pm 2.2) \times 10^{-12}$	Optical, microwave resonators	Müller *et al.* (2007)*
$(\tilde{\kappa}_{o+})^{YZ}$	$(-3.2 \pm 2.3) \times 10^{-12}$	Rotating microwave resonators	Stanwix *et al.* (2006)
$(\tilde{\kappa}_{o+})^{YZ}$	$(2.9 \pm 2.8) \times 10^{-12}$	Rotating optical resonators	Herrmann *et al.* (2005)
$(\tilde{\kappa}_{o+})^{YZ}$	$(0.44 \pm 0.46) \times 10^{-11}$	Rotating microwave resonators	Stanwix *et al.* (2005)
$(\tilde{\kappa}_{o+})^{YZ}$	$(2.7 \pm 2.2) \times 10^{-11}$	Microwave resonator, maser	Wolf *et al.* (2004)
$(\tilde{\kappa}_{o+})^{YZ}$	$(0.1 \pm 2.7) \times 10^{-11}$	Optical resonators	Müller *et al.* (2003)a
$(\tilde{\kappa}_{o+})^{YX} - 0.432(\tilde{\kappa}_{o+})^{ZX}$	$(4.0 \pm 8.4) \times 10^{-9}$	Microwave resonators	Lipa *et al.* (2003)
$(\tilde{\kappa}_{o+})^{XY} - 0.209(\tilde{\kappa}_{o+})^{YZ}$	$(4.0 \pm 4.9) \times 10^{-9}$	Microwave resonators	Lipa *et al.* (2003)
$(\tilde{\kappa}_{o+})^{XZ} - 0.484(\tilde{\kappa}_{o+})^{YZ}$	$(1.6 \pm 1.7) \times 10^{-9}$	Microwave resonators	Lipa *et al.* (2003)
$(\tilde{\kappa}_{o+})^{YZ} + 0.484(\tilde{\kappa}_{o+})^{XZ}$	$(0.6 \pm 1.9) \times 10^{-9}$	Microwave resonators	Lipa *et al.* (2003)
$\lvert(\tilde{\kappa}_{o+})^{(ij)}\rvert$	$<2 \times 10^{-18}$	Astrophysics	Klinkhamer and Risse (2008)*
$\tilde{\kappa}_{\rm tr}$	$(-1.5 \pm 0.74) \times 10^{-8}$	Rotating microwave resonators	Hohensee *et al.* (2010)
$\tilde{\kappa}_{\rm tr}$	$(-0.3 \pm 3) \times 10^{-7}$	Microwave interferometer	Tobar *et al.* (2009)
$\lvert\tilde{\kappa}_{\rm tr} - \frac{4}{3}c^e_{00}\rvert$	$<5 \times 10^{-15}$	Collider physics	Altschul (2009)b*
$\tilde{\kappa}_{\rm tr} - \frac{4}{3}c^e_{00}$	$(-5.8 \text{ to } 12) \times 10^{-12}$	Collider physics	Hohensee *et al.* (2009)a, (2009)b*
$\tilde{\kappa}_{\rm tr} - \frac{4}{3}c^p_{00}$	$<6 \times 10^{-20}$	Astrophysics	Klinkhamer and Schreck (2008)*
$-[\tilde{\kappa}_{\rm tr} - \frac{4}{3}c^e_{00}]$	$<9 \times 10^{-16}$	Astrophysics	Klinkhamer and Schreck (2008)*
$\tilde{\kappa}_{\rm tr}$	$<1.4 \times 10^{-19}$	Astrophysics	Klinkhamer and Risse (2008)*
$\lvert\tilde{\kappa}_{\rm tr}\rvert$	$<8.4 \times 10^{-8}$	Optical atomic clocks	Reinhardt *et al.* (2007)
$\lvert\tilde{\kappa}_{\rm tr}\rvert$	$<2.2 \times 10^{-7}$	Heavy-ion storage ring	Hohensee *et al.* (2007)*
$\lvert\tilde{\kappa}_{\rm tr}\rvert$	$<2 \times 10^{-14}$	Astrophysics	Carone *et al.* (2006)*
$\lvert\tilde{\kappa}_{\rm tr}\rvert$	$<3 \times 10^{-8}$	$g_e - 2$	Carone *et al.* (2006)*
$\lvert\tilde{\kappa}_{\rm tr}\rvert$	$<1.6 \times 10^{-5}$	Sagnac interferometer	Cotter and Varcoe (2006)
$\lvert\sum_{jm\,2}Y_{jm}(98.2°, 182.1°)(k^{(4)}_{(E)jm} + ik^{(4)}_{(B)jm})\rvert$	$\lesssim 10^{-37}$	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,2}Y_{jm}(87.3°, 37.3°)(k^{(4)}_{(E)jm} + ik^{(4)}_{(B)jm})\rvert$	$\lesssim 10^{-37}$	Astrophysical birefringence	Kostelecký and Mewes (2009)*

TABLE VIII. (*Continued*)

Combination	Result	System	Ref.
$k^{(4)}_{(E)20}$	$\pm(17^{+7}_{-9})\times 10^{-31}$	CMB polarization	Kostelecký and Mewes (2007)*
$k^{(4)}_{(B)20}$	$\pm(17^{+7}_{-9})\times 10^{-31}$	CMB polarization	Kostelecký and Mewes (2007)*
$\sqrt{\sum_m(\lvert k^{(4)}_{(E)2m}\rvert^2+\lvert k^{(4)}_{(B)2m}\rvert^2)}$	$<5\times 10^{-32}$	Astrophysical birefringence	Kostelecký and Mewes (2002)*, (2009)*
$\lvert k^a\rvert$ for some a	$<2\times 10^{-37}$	Astrophysical birefringence	Kostelecký and Mewes (2006)*
$\lvert k^a\rvert$ for $a=1,\ldots,10$	$<2\times 10^{-32}$	Astrophysical birefringence	Kostelecký and Mewes (2002)*
$\lvert k^{(3)}_{(V)10}\rvert$	$<16\times 10^{-21}$ GeV	Schumann resonances	Mewes (2008)*
$\lvert k^{(3)}_{(V)11}\rvert$	$<12\times 10^{-21}$ GeV	Schumann resonances	Mewes (2008)*
$\lvert \mathbf{k}^{(3)}_{\rm AF}\rvert \equiv (6\lvert k^{(3)}_{(V)11}\rvert^2+3\lvert k^{(3)}_{(V)10}\rvert^2)^{1/2}/\sqrt{4\pi}$	$(10^{+4}_{-8})\times 10^{-43}$ GeV	CMB polarization	Kostelecký and Mewes (2008)*
$\lvert \mathbf{k}^{(3)}_{\rm AF}\rvert$	$(15\pm 6)\times 10^{-43}$ GeV	CMB polarization	Kostelecký and Mewes (2007)*, (2009)*
$k^{(3)}_{(V)10}$	$\pm(3\pm 1)\times 10^{-42}$ GeV	CMB polarization	Kostelecký and Mewes (2007)*
$\mathrm{Re}k^{(3)}_{(V)11}$	$\pm(21^{+7}_{-9})\times 10^{-43}$ GeV	CMB polarization	Kostelecký and Mewes (2007)*
$\lvert \mathbf{k}^{(3)}_{\rm AF}\rvert$	$(0.57\pm 0.70)H_0$	Astrophysical birefringence	Carroll and Field (1997)*
$\lvert 2\mathbf{k}^{(3)}_{\rm AF}\rvert$	10^{-41}GeV	Astrophysical birefringence	Nodland and Ralston (1997)*
$\lvert\sum_{jm0}Y_{jm}k^{(3)}_{(V)jm}\rvert$	$<6\times 10^{-43}$ GeV	Astrophysical birefringence	Carroll *et al.* (1990)*, Kostelecký and Mewes (2009)*
$\lvert k^{(3)}_{(V)00}\rvert$	$<14\times 10^{-21}$ GeV	Schumann resonances	Mewes (2008)*
$k^{(3)}_{(V)00}$	$(1.1\pm 1.3\pm 1.5)\times 10^{-43}$ GeV	CMB polarization	Komatsu *et al.* (2010)
$k^{(3)}_{(V)00}$	$(0.04\pm 0.35)\times 10^{-43}$ GeV	CMB polarization	Xia *et al.* (2010)*
$k^{(3)}_{(V)00}$	$(-0.64\pm 0.50\pm 0.50)\times 10^{-43}$ GeV	CMB polarization	Brown *et al.* (2009)
$k^{(3)}_{(V)00}$	$(4.3\pm 4.1)\times 10^{-43}$ GeV	CMB polarization	Pagano *et al.* (2009)
$k^{(3)}_{(V)00}$	$(-1.4\pm 0.9\pm 0.5)\times 10^{-43}$ GeV	CMB polarization	Wu *et al.* (2009)
$k^{(3)}_{(V)00}$	$(2.3\pm 5.4)\times 10^{-43}$ GeV	CMB polarization	Kostelecký and Mewes (2008)*
$k^{(3)}_{(V)00}$	$<2.5\times 10^{-43}$ GeV	CMB polarization	Kahniashvili *et al.* (2008)*, Kostelecký and Mewes (2008)*
$k^{(3)}_{(V)00}$	$(1.2\pm 2.2)\times 10^{-43}$ GeV	CMB polarization	Komatsu *et al.* (2009), Kostelecký and Mewes (2008)*
$k^{(3)}_{(V)00}$	$(12\pm 7)\times 10^{-43}$ GeV	CMB polarization	Kostelecký and Mewes (2007)*
$k^{(3)}_{(V)00}$	$(2.6\pm 1.9)\times 10^{-43}$ GeV	CMB polarization	Xia *et al.* (2008)*, Kostelecký and Mewes (2008)*
$k^{(3)}_{(V)00}$	$(2.5\pm 3.0)\times 10^{-43}$ GeV	CMB polarization	Cabella *et al.* (2007)*, Kostelecký and Mewes (2008)*
$k^{(3)}_{(V)00}$	$(6.0\pm 4.0)\times 10^{-43}$ GeV	CMB polarization	Feng *et al.* (2006)*, Kostelecký and Mewes (2007)*
$k^{(3)}_{(V)00}$	$(1.1\pm 1.4)H_0$	Astrophysical birefringence	Carroll and Field (1997)*
$k^{(3)}_{(V)00}$	$<2\times 10^{-42}$ GeV	Astrophysical birefringence	Carroll *et al.* (1990)*, Kostelecký and Mewes (2009)*

TABLE IX. Charged-lepton sector.

Combination	Result	System	Ref.
b_Z^μ	$-(1.0 \pm 1.1) \times 10^{-23}$ GeV	BNL $g_\mu - 2$	Bennett *et al.* (2008)
$\sqrt{(\check{b}_X^{\mu^+})^2 + (\check{b}_Y^{\mu^+})^2}$	$<1.4 \times 10^{-24}$ GeV	BNL $g_\mu - 2$	Bennett *et al.* (2008)
$\sqrt{(\check{b}_X^{\mu^-})^2 + (\check{b}_Y^{\mu^-})^2}$	$<2.6 \times 10^{-24}$ GeV	BNL $g_\mu - 2$	Bennett *et al.* (2008)
$\sqrt{(\tilde{b}_X^{\mu})^2 + (\tilde{b}_Y^{\mu})^2}$	$<2 \times 10^{-23}$ GeV	Muonium spectroscopy	Hughes *et al.* (2001)
$b_Z^\mu - 1.19(m_\mu d_{Z0}^\mu + H_{XY}^\mu)$	$(-1.4 \pm 1.0) \times 10^{-22}$ GeV	BNL, CERN $g_\mu - 2$ data	Deile *et al.* (2002)
b_Z^μ	$(-2.3 \pm 1.4) \times 10^{-22}$ GeV	CERN $g_\mu - 2$ data	Bluhm *et al.* (2000)*, Deile *et al.* (2002)
$m_\mu d_{Z0}^\mu + H_{XY}^\mu$	$(1.8 \pm 6.0) \times 10^{-23}$ GeV	BNL $g_\mu - 2$	Bennett *et al.* (2008)
$\lvert c^\mu \rvert$	$<10^{-11}$	Astrophysics	Altschul (2007)c*
$\lvert c^\tau \rvert$	$<10^{-8}$	Astrophysics	Altschul (2007)c*

in Table X. For both these tables, many of the coefficients appearing in the first column are specified in the lepton sector of Table XX. The neutrino results in Table X are obtained in the context of various simplified models, as discussed in the references. Experimental sensitivities to coefficients for operators involving second- and third-generation quark fields are presently limited to mesons and are presented in Table XI. The coefficients appearing in this table are composite quantities defined in the corresponding references. They are effective coefficients for which complete analytical expressions are as yet unknown, formed from certain quark-sector coefficients appearing in Table XX and from other quantities arising from the quark binding in the mesons.

Tables XII and XIII concern coefficients in the gauge sectors of the minimal SME. Results for the electroweak sector are listed in Table XII, while those for the gluon sector are in Table XIII. The coefficients for the electroweak sector are defined in the gauge and Higgs sections of Table XXI. The gluon-sector coefficient is the analog of the corresponding photon-sector coefficient defined in Table XIX. To date, all results for the gauge sector are deduced from theoretical considerations.

Table XIV presents measurements and bounds concerning the gravity sector of the minimal SME. The specific combinations of coefficients in the pure-gravity sector that appear in the first column are defined in the references. They are expressed in terms of the coefficients for Lorentz violation listed in the gravity section of Table XXI.

The final data table, Table XV, contains a compilation of some measurements and bounds on coefficients for Lorentz violation in the nonminimal SME. Attention is restricted to the photon sector, in which results are available for a variety of nonrenormalizable operators of dimensions 5, 6, 7, 8, and 9. A convenient basis for classifying operators of dimension d is given by the spin-weighted spherical harmonics (Kostelecký and Mewes, 2009). The corresponding coefficients are listed in Table XXIV. Some constraints have been obtained for the vacuum coefficients for Lorentz violation, which are $c_{(I)jm}^{(d)}$, $k_{(E)jm}^{(d)}$, $k_{(B)jm}^{(d)}$ for even d and $k_{(V)jm}^{(d)}$ for odd d, where the subscripts jm label the angular-momentum quantum numbers. In the first column of Table XV, the usual spherical harmonics ${}_0Y_{jm}$ are evaluated at specified angles, which are the celestial coordinates of certain astrophysical sources. None of the vacuum-orthogonal coefficients for Lorentz violation have been measured to date.

IV. PROPERTIES TABLES

Nine properties tables are provided, listing various features and definitions related to Lorentz violation. Four tables concern the terms in the restriction of the minimal SME to quantum electrodynamics (QED) in Riemann spacetime. For this theory, which is called the minimal QED extension, the tables include information about the operator structure (Table XVI), the action of discrete symmetries (Table XVII), and some useful coefficient combinations (Tables XVIII and XIX). Two tables contain information about the matter sector (Table XX) and the gauge and gravity sectors (Table XXI) of the minimal SME in Riemann-Cartan spacetime. Another table (Table XXII) summarizes some features of the coefficients for Lorentz violation in the neutrino sector. The two remaining tables (Tables XXIII and XXIV) provide information about the operator structure and the spherical coefficients for Lorentz violation in the nonminimal photon sector.

For these properties tables, our primary conventions are those of Kostelecký (2004). Greek indices $\mu, \nu, \lambda, \ldots$ refer to curved-spacetime coordinates and Latin indices $a, b, c, \ldots$ to local Lorentz coordinates. The vierbein formalism (Utiyama, 1956; Kibble, 1961)), which relates the two sets of coordinates, is adopted to facilitate the description of spinors on the spacetime manifold. The determinant e of the vierbein $e_\mu{}^a$ is related to the determinant g of the metric $g_{\mu\nu}$ by $e = \sqrt{-g}$. The conventions for the Dirac matrices γ^a are given in Appendix A of Kostelecký (2004). The Newton gravitational constant G_N enters as the combination $\kappa \equiv 8\pi G_N$, and it has dimensions of inverse mass squared.

In the Minkowski-spacetime limit, the metric $g_{\mu\nu}$ is written $\eta_{\mu\nu}$ with diagonal entries $(-1, 1, 1, 1)$. For decompositions into time and space components, we adopt the Sun-centered frame of Fig. 1 and use indices $J, K, L, \ldots$ to denote the three spatial components X, Y, Z. The sign of the antisymmetric tensor $\epsilon_{\kappa\lambda\mu\nu}$ is fixed via the component $\epsilon_{TXYZ} = +1$, and the antisymmetric symbol in three spatial dimensions is defined with $\epsilon_{XYZ} = +1$. Note that some of the literature on the SME in Minkowski spacetime adopts a metric $\eta_{\mu\nu}$ of opposite sign, following the common present

TABLE X. Neutrino sector.

Combination	Result	System	Ref.
$(a_L)^T_{e\mu}$	$(-3.1 \pm 0.9) \times 10^{-20}$ GeV	MiniBooNE	Katori (2010)
$(a_L)^X_{e\mu}$	$(0.6 \pm 1.9) \times 10^{-20}$ GeV	MiniBooNE	Katori (2010)
$(a_L)^Y_{e\mu}$	$(-0.9 \pm 1.8) \times 10^{-20}$ GeV	MiniBooNE	Katori (2010)
$(a_L)^Z_{e\mu}$	$(-4.2 \pm 1.2) \times 10^{-20}$ GeV	MiniBooNE	Katori (2010)
$(c_L)^{TT}_{e\mu}$	$(7.2 \pm 2.1) \times 10^{-20}$	MiniBooNE	Katori (2010)
$(c_L)^{TX}_{e\mu}$	$(-0.9 \pm 2.8) \times 10^{-20}$	MiniBooNE	Katori (2010)
$(c_L)^{TY}_{e\mu}$	$(1.3 \pm 2.6) \times 10^{-20}$	MiniBooNE	Katori (2010)
$(c_L)^{TZ}_{e\mu}$	$(5.9 \pm 1.7) \times 10^{-20}$	MiniBooNE	Katori (2010)
$(c_L)^{XZ}_{e\mu}$	$(-1.1 \pm 3.7) \times 10^{-20}$	MiniBooNE	Katori (2010)
$(c_L)^{YZ}_{e\mu}$	$(1.7 \pm 3.4) \times 10^{-20}$	MiniBooNE	Katori (2010)
$(c_L)^{ZZ}_{e\mu}$	$(2.6 \pm 0.8) \times 10^{-19}$	MiniBooNE	Katori (2010)
$\lvert(a_L)^X_{\mu\tau}\rvert$	$<5.9 \times 10^{-23}$ GeV	MINOS FD	Adamson *et al.* (2010)
$\lvert(a_L)^Y_{\mu\tau}\rvert$	$<6.1 \times 10^{-23}$ GeV	MINOS FD	Adamson *et al.* (2010)
$\lvert a^X_L\rvert, \lvert a^Y_L\rvert$	$<3.0 \times 10^{-20}$ GeV	MINOS ND	Adamson *et al.* (2008)
$\lvert(c_L)^{TX}_{\mu\tau}\rvert, \lvert(c_L)^{TY}_{\mu\tau}\rvert$	$<0.5 \times 10^{-23}$	MINOS FD	Adamson *et al.* (2010)
$\lvert(c_L)^{XX}_{\mu\tau}\rvert$	$<2.5 \times 10^{-23}$	MINOS FD	Adamson *et al.* (2010)
$\lvert(c_L)^{YY}_{\mu\tau}\rvert$	$<2.4 \times 10^{-23}$	MINOS FD	Adamson *et al.* (2010)
$\lvert(c_L)^{XY}_{\mu\tau}\rvert$	$<1.2 \times 10^{-23}$	MINOS FD	Adamson *et al.* (2010)
$\lvert(c_L)^{YZ}_{\mu\tau}\rvert, \lvert(c_L)^{XZ}_{\mu\tau}\rvert$	$<0.7 \times 10^{-23}$	MINOS FD	Adamson *et al.* (2010)
$\lvert c^{TX}_L\rvert, \lvert c^{TY}_L\rvert$	$<9 \times 10^{-23}$	MINOS ND	Adamson *et al.* (2008)
$\lvert c^{XX}_L\rvert$	$<5.6 \times 10^{-21}$	MINOS ND	Adamson *et al.* (2008)
$\lvert c^{YY}_L\rvert$	$<5.5 \times 10^{-21}$	MINOS ND	Adamson *et al.* (2008)
$\lvert c^{XY}_L\rvert$	$<2.7 \times 10^{-21}$	MINOS ND	Adamson *et al.* (2008)
$\lvert c^{YZ}_L\rvert$	$<1.2 \times 10^{-21}$	MINOS ND	Adamson *et al.* (2008)
$\lvert c^{XZ}_L\rvert$	$<1.3 \times 10^{-21}$	MINOS ND	Adamson *et al.* (2008)
$(a_L)^T_{\bar{e}\bar{\mu}}$	$(0.2 \pm 1.0) \times 10^{-19}$ GeV	LSND	Katori (2010)
$(a_L)^X_{\bar{e}\bar{\mu}}$	$(4.2 \pm 1.5) \times 10^{-19}$ GeV	LSND	Katori (2010)
$(a_L)^Y_{\bar{e}\bar{\mu}}$	$(-1.7 \pm 1.8) \times 10^{-19}$ GeV	LSND	Katori (2010)
$(a_L)^Z_{\bar{e}\bar{\mu}}$	$(1.0 \pm 5.4) \times 10^{-19}$ GeV	LSND	Katori (2010)
$(c_L)^{TT}_{\bar{e}\bar{\mu}}$	$(0.3 \pm 1.8) \times 10^{-18}$	LSND	Katori (2010)
$(c_L)^{TX}_{\bar{e}\bar{\mu}}$	$(-5.2 \pm 1.9) \times 10^{-18}$	LSND	Katori (2010)
$(c_L)^{TY}_{\bar{e}\bar{\mu}}$	$(2.1 \pm 2.2) \times 10^{-18}$	LSND	Katori (2010)
$(c_L)^{TZ}_{\bar{e}\bar{\mu}}$	$(1.3 \pm 6.7) \times 10^{-18}$	LSND	Katori (2010)
$(c_L)^{XZ}_{\bar{e}\bar{\mu}}$	$(-2.7 \pm 1.0) \times 10^{-17}$	LSND	Katori (2010)
$(c_L)^{YZ}_{\bar{e}\bar{\mu}}$	$(1.1 \pm 1.2) \times 10^{-17}$	LSND	Katori (2010)
$(c_L)^{ZZ}_{\bar{e}\bar{\mu}}$	$(-1.1 \pm 5.9) \times 10^{-18}$	LSND	Katori (2010)
$\lvert(\mathcal{C})_{\bar{e}\bar{\mu}}\rvert^2$	$(10.7 \pm 2.6 \pm 1.3) \times (10^{-19}\ \text{GeV})^2$	LSND	Auerbach *et al.* (2005)
$\lvert(\mathcal{C})_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{A}_s)_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{A}_c)_{\bar{e}\bar{\mu}}\rvert^2$	$(9.9 \pm 2.3 \pm 1.4) \times (10^{-19}\ \text{GeV})^2$	LSND	Auerbach *et al.* (2005)
$\lvert(\mathcal{C})_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{A}_s)_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{A}_c)_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{B}_s)_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{B}_c)_{\bar{e}\bar{\mu}}\rvert^2$	$(10.5 \pm 2.4 \pm 1.4) \times (10^{-19}\ \text{GeV})^2$	LSND	Auerbach *et al.* (2005)
$(c_L^{\nu_e})_{00}$	$<2 \times 10^{-11}$	Cosmic rays	Altschul (2009)c*
$a \cos\rho$	Excluded	Multiple	Barger *et al.* (2007)*
$a \sin\rho\hat{n}$	Excluded	Multiple	Barger *et al.* (2007)*
c	Excluded	Multiple	Barger *et al.* (2007)*
b	$<1.6 \times 10^{-23}$ GeV	Atmospheric	Messier (2005)
c	$<1.4 \times 10^{-26}$	Atmospheric	Messier (2005)
$\check{a}/\mathring{c}$	<5 GeV	Atmospheric	Messier (2005)

TABLE XI. Meson sector.

Combination	Result	System	Ref.
Δa_X^K	$(-6.3 \pm 6.0) \times 10^{-18}$ GeV	K oscillations	Di Domenico (2010)
Δa_Y^K	$(2.8 \pm 5.9) \times 10^{-18}$ GeV	K oscillations	Di Domenico (2010)
Δa_Z^K	$(2.4 \pm 9.7) \times 10^{-18}$ GeV	K oscillations	Di Domenico (2010)
Δa_0^K	$(0.4 \pm 1.8) \times 10^{-17}$ GeV	K oscillations	Di Domenico (2010), Di Domenico (2008)
Δa_Z^K	$(-1 \pm 4) \times 10^{-17}$ GeV	K oscillations	Di Domenico (2008)
$\lvert\Delta a_1^K\rvert$	$<9.2 \times 10^{-22}$ GeV	K oscillations	Nguyen (2002)
$\lvert\Delta a_2^K\rvert$	$<9.2 \times 10^{-22}$ GeV	K oscillations	Nguyen (2002)
$\lvert(\Delta a^K)_T - 0.60(\Delta a^K)_Z\rvert$	$<5 \times 10^{-21}$ GeV	K oscillations	Kostelecký (1998)*, Kostelecký and Van Kooten (2010)*
$N^D(\Delta a_0^D - 0.6\Delta a_Z^D)$	$(-2.8$ to $4.8) \times 10^{-16}$ GeV	D oscillations	Link *et al.* (2003)
$N^D\Delta a_X^D$	$(-7$ to $3.8) \times 10^{-16}$ GeV	D oscillations	Link *et al.* (2003)
$N^D\Delta a_Y^D$	$(-7$ to $3.8) \times 10^{-16}$ GeV	D oscillations	Link *et al.* (2003)
$N^B(\Delta a_0^B - 0.30\Delta a_Z^B)$	$(-3.0 \pm 2.4) \times 10^{-15}$ GeV	B_d oscillations	Aubert *et al.* (2008)
$N^B\Delta a_X$	$(-22 \pm 7) \times 10^{-15}$ GeV	B_d oscillations	Aubert *et al.* (2008)
$N^B\Delta a_Y$	$(-27$ to $-4) \times 10^{-15}$GeV	B_d oscillations	Aubert *et al.* (2008)
$N^B(\Delta a_0^B - 0.3\Delta a_Z^B)$	$-(5.2 \pm 4.0) \times 10^{-15}$ GeV	B_d oscillations	Aubert *et al.* (2006)
$N^B\sqrt{(\Delta a_X^B)^2 + (\Delta a_Y^B)^2}$	$(37 \pm 16) \times 10^{-15}$ GeV	B_d oscillations	Kostelecký and Van Kooten (2010)*
$(\Delta a^{B_s})_T$	$(3.7 \pm 3.8) \times 10^{-12}$ GeV	B_s oscillations	Kostelecký and Van Kooten (2010)*
δ^π	$(-1.5$ to $200) \times 10^{-11}$	Astrophysics	Altschul (2008)a*
$\lvert c^\pi\rvert$	$<10^{-10}$	Astrophysics	Altschul (2007)c*
$\lvert c^K\rvert$	$<10^{-9}$	Astrophysics	Altschul (2007)c*
$\lvert c^D\rvert$	$<10^{-8}$	Astrophysics	Altschul (2007)c*
$\lvert c^{B_d}\rvert, \lvert c^{B_s}\rvert$	$<10^{-7}$	Astrophysics	Altschul (2007)c*

TABLE XII. Electroweak sector.

Combination	Result	System	Ref.
$\lvert(k_{\phi\phi}^A)_{\mu\nu}\rvert$	$<3 \times 10^{-16}$	Cosmological birefringence	Anderson *et al.* (2004)*
$\lvert(k_{\phi B})_{\mu\nu}\rvert$	$<0.9 \times 10^{-16}$	Cosmological birefringence	Anderson *et al.* (2004)*
$\lvert(k_{\phi W})_{\mu\nu}\rvert$	$<1.7 \times 10^{-16}$	Cosmological birefringence	Anderson *et al.* (2004)*
$\lvert(k_{\phi\phi}^S)_{XX}\rvert, \lvert(k_{\phi\phi}^S)_{YY}\rvert, \lvert(k_{\phi\phi}^S)_{ZZ}\rvert$	$<10^{-27}$	Clock comparisons	Anderson *et al.* (2004)*
$\lvert(k_{\phi\phi}^S)_{XY}\rvert$	$<10^{-27}$	Clock comparisons	Anderson *et al.* (2004)*
$\lvert(k_{\phi\phi}^S)_{XZ}\rvert, \lvert(k_{\phi\phi}^S)_{YZ}\rvert$	$<10^{-25}$	Clock comparisons	Anderson *et al.* (2004)*
$\lvert(k_{\phi\phi}^S)_{TT}\rvert$	$<4 \times 10^{-13}$	H^- ion, $\bar{p}$ comparison	Anderson *et al.* (2004)*
$\lvert(k_\phi)_X\rvert, \lvert(k_\phi)_Y\rvert$	$<10^{-31}$	Xe-He maser	Anderson *et al.* (2004)*
$\lvert(k_\phi)_Z\rvert, \lvert(k_\phi)_T\rvert$	$<2.8 \times 10^{-27}$	Xe-He maser	Anderson *et al.* (2004)*
$\lvert k_W\rvert$	$<10^{-5}$	Astrophysics	Altschul (2007)c*

usage in quantum physics instead of the one in relativity. Under this alternative convention, terms in the Lagrange density with an odd number of index contractions have opposite signs to those appearing in this work. The numerical results for the SME coefficients in the tables are unaffected by the convention.

A. Minimal QED extension

Table XVI concerns the minimal QED extension, for which the basic nongravitational fields are a Dirac fermion ψ and the photon A_μ. The electromagnetic field-strength tensor is $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. The pure-gravity sector involves the Riemann tensor $R_{\kappa\lambda\mu\nu}$, the Ricci tensor $R_{\mu\nu}$, the curvature scalar R, and the cosmological constant Λ. The spacetime covariant derivative D_μ corrects local Lorentz indices using the spin connection, corrects spacetime indices using the Cartan connection, and contains the usual gauge field A_μ for the photon. The notation $\overleftrightarrow{D}_\mu$ is an abbreviation for the difference of two terms, the first with derivative acting to the right and the second acting to the left. Note that Table XVI is restricted to the zero-torsion limit of the minimal SME. The general case (Kostelecký,

TABLE XIII. Gluon sector.

Combination	Result	System	Ref.
$\lvert\tilde{\kappa}_{\rm tr}^{\rm QCD}\rvert$	$<2 \times 10^{-13}$	Astrophysics	Carone *et al.* (2006)*

TABLE XIV. Gravity sector.

Combination	Result	System	Ref.
$\lvert\alpha(\overline{a}^{e+p}_{\rm eff})_T\rvert$	$<10^{-7}$ GeV	Free-fall weak equivalence principle (WEP)	Kostelecký and Tasson (2010)*
$\lvert\alpha(\overline{a}^{e+p}_{\rm eff})_T\rvert$	$<10^{-10}$ GeV	Force-comparison WEP	Kostelecký and Tasson (2010)*
$\lvert\alpha(\overline{a}^{n}_{\rm eff})_T\rvert$	$<10^{-7}$ GeV	Free-fall WEP	Kostelecký and Tasson (2010)*
$\lvert\alpha(\overline{a}^{n}_{\rm eff})_T\rvert$	$<10^{-10}$ GeV	Force-comparison WEP	Kostelecký and Tasson (2010)*
$\lvert\alpha(\overline{a}^{e+p-n}_{\rm eff})_T - \frac{1}{3}m^p(\overline{c}^{e+p-n})_{TT}\rvert$	$<10^{-8}$ GeV	Combined WEP	Kostelecký and Tasson (2010)*
$\lvert\alpha(\overline{a}^{e+p-n}_{\rm eff})_T - \frac{1}{3}m^p(\overline{c}^{e+p-n})_{TT} + (\frac{1}{2}\cos^2\chi - \frac{1}{6})m^n(\overline{c}^n)_Q\rvert$	$<10^{-8}$ GeV	Free-fall WEP	Kostelecký and Tasson (2010)*
$\lvert\alpha(\overline{a}^{e+p-n}_{\rm eff})_T - \frac{1}{3}m^p(\overline{c}^{e+p-n})_{TT} - \frac{1}{6}m^n(\overline{c}^n)_Q\rvert$	$<10^{-11}$ GeV	Force-comparison WEP	Kostelecký and Tasson (2010)*
$\lvert(\overline{a}^{e}_{\rm eff})_☿ + (\overline{a}^{p}_{\rm eff})_☿ + 0.1(\overline{a}^{n}_{\rm eff})_☿\rvert$	$<10^{-6}$ GeV	Solar System	Kostelecký and Tasson (2010)*
$\lvert(\overline{a}^{e}_{\rm eff})_\oplus + (\overline{a}^{p}_{\rm eff})_\oplus + 0.1(\overline{a}^{n}_{\rm eff})_\oplus\rvert$	$<10^{-6}$ GeV	Solar System	Kostelecký and Tasson (2010)*
$\lvert\alpha\overline{a}^e_T + \alpha\overline{a}^p_T - 0.8\alpha\overline{a}^n_T\rvert$	$<1\times10^{-11}$ GeV	Torsion pendulum	Kostelecký and Tasson (2009)*
$\lvert(\overline{c}^n)_Q\rvert$	$<10^{-8}$	Combined WEP	Kostelecký and Tasson (2010)*
$\lvert(\overline{c}^n)_☿\rvert$	$<10^{-8}$	Solar System	Kostelecký and Tasson (2010)*
$\lvert(\overline{c}^n)_\oplus\rvert$	$<10^{-7}$	Solar System	Kostelecký and Tasson (2010)*
$\sigma^{XX} - \sigma^{YY}$	$(4.4 \pm 11)\times10^{-9}$	Atom interferometry	Chung *et al.* (2009)
σ^{XY}	$(0.2 \pm 3.9)\times10^{-9}$	Atom interferometry	Chung *et al.* (2009)
σ^{XZ}	$(-2.6 \pm 4.4)\times10^{-9}$	Atom interferometry	Chung *et al.* (2009)
σ^{YZ}	$(-0.3 \pm 4.5)\times10^{-9}$	Atom interferometry	Chung *et al.* (2009)
σ^{TX}	$(-3.1 \pm 5.1)\times10^{-5}$	Atom interferometry	Chung *et al.* (2009)
σ^{TY}	$(0.1 \pm 5.4)\times10^{-5}$	Atom interferometry	Chung *et al.* (2009)
σ^{TZ}	$(1.4 \pm 6.6)\times10^{-5}$	Atom interferometry	Chung *et al.* (2009)
$\sigma^{XX} - \sigma^{YY}$	$(-5.6 \pm 2.1)\times10^{-9}$	Atom interferometry	Müller *et al.* (2008)
σ^{XY}	$(-0.09 \pm 79)\times10^{-9}$	Atom interferometry	Müller *et al.* (2008)
σ^{XZ}	$(-13 \pm 37)\times10^{-9}$	Atom interferometry	Müller *et al.* (2008)
σ^{YZ}	$(-61 \pm 38)\times10^{-9}$	Atom interferometry	Müller *et al.* (2008)
σ^{TX}	$(5.4 \pm 4.5)\times10^{-5}$	Atom interferometry	Müller *et al.* (2008)
σ^{TY}	$(-2.0 \pm 4.4)\times10^{-5}$	Atom interferometry	Müller *et al.* (2008)
σ^{TZ}	$(1.1 \pm 26)\times10^{-5}$	Atom interferometry	Müller *et al.* (2008)
$\overline{s}^{XX} - \overline{s}^{YY}$	$(-1.2 \pm 1.6)\times10^{-9}$	LLR & atom interferometry	Battat *et al.* (2007)*, Chung *et al.* (2009)*
$\overline{s}^{XX} + \overline{s}^{YY} - 2\overline{s}^{ZZ}$	$(1.8 \pm 38)\times10^{-9}$	LLR & atom interferometry	Battat *et al.* (2007)*, Chung *et al.* (2009)*
$\overline{s}^{XY}$	$(-0.6 \pm 1.5)\times10^{-9}$	LLR & atom interferometry	Battat *et al.* (2007)*, Chung *et al.* (2009)*
$\overline{s}^{XZ}$	$(-2.7 \pm 1.4)\times10^{-9}$	LLR & atom interferometry	Battat *et al.* (2007)*, Chung *et al.* (2009)*
$\overline{s}^{YZ}$	$(0.6 \pm 1.4)\times10^{-9}$	LLR & atom interferometry	Battat *et al.* (2007)*, Chung *et al.* (2009)*
$\overline{s}^{TX}$	$(0.5 \pm 6.2)\times10^{-7}$	LLR & atom interferometry	Battat *et al.* (2007)*, Chung *et al.* (2009)*
$\overline{s}^{TY}$	$(0.1 \pm 1.3)\times10^{-6}$	LLR & atom interferometry	Battat *et al.* (2007)*, Chung *et al.* (2009)*
$\overline{s}^{TZ}$	$(-0.4 \pm 3.8)\times10^{-6}$	LLR & atom interferometry	Battat *et al.* (2007)*, Chung *et al.* (2009)*
$\overline{s}^{11} - \overline{s}^{22}$	$(1.3 \pm 0.9)\times10^{-10}$	Lunar laser ranging (LLR)	Battat *et al.* (2007)*
$\overline{s}^{12}$	$(6.9 \pm 4.5)\times10^{-11}$	LLR	Battat *et al.* (2007)*
$\overline{s}^{01}$	$(-0.8 \pm 1.1)\times10^{-6}$	LLR	Battat *et al.* (2007)*
$\overline{s}^{02}$	$(-5.2 \pm 4.8)\times10^{-7}$	LLR	Battat *et al.* (2007)*
$\overline{s}_{\Omega_\oplus c}$	$(0.2 \pm 3.9)\times10^{-7}$	LLR	Battat *et al.* (2007)*
$\overline{s}_{\Omega_\oplus s}$	$(-1.3 \pm 4.1)\times10^{-7}$	LLR	Battat *et al.* (2007)*
$\lvert\overline{s}\rvert_☿$	$\le10^{-9}$	Perihelion precession	Bailey and Kostelecký (2006)*
$\lvert\overline{s}_\oplus\rvert$	$\le10^{-8}$	Perihelion precession	Bailey and Kostelecký (2006)*
$\lvert\overline{s}_{\rm SSP}\rvert$	$\le10^{-13}$	Solar-spin precession	Bailey and Kostelecký (2006)*

TABLE XV. Nonminimal photon sector.

Combination	Result	System	Ref.
$\lvert\sum_{jm\,0}Y_{jm}(98.2°, 182.1°)k^{(5)}_{(V)jm}\rvert$	$<7\times 10^{-33}$ GeV^{-1}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\lvert k^{(5)}_{(V)00}\rvert$	$<2\times 10^{-32}$ GeV^{-1}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,0}Y_{jm}(87.3°, 37.3°)k^{(5)}_{(V)jm}\rvert$	$<4\times 10^{-33}$ GeV^{-1}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\lvert k^{(5)}_{(V)00}\rvert$	$<1\times 10^{-32}$ GeV^{-1}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$k^{(5)}_{(V)00}$	$(3.2\pm 2.1)\times 10^{-20}$ GeV^{-1}	CMB polarization	Gubitosi *et al.* (2009)*
$k^{(5)}_{(V)00}$	$(3\pm 2)\times 10^{-20}$ GeV^{-1}	CMB polarization	Kostelecký and Mewes (2007)*
$k^{(5)}_{(V)10}$	$(8^{+2}_{-3})\times 10^{-20}$ GeV^{-1}	CMB polarization	Kostelecký and Mewes (2007)*
	$-(8^{+3}_{-4})\times 10^{-20}$ GeV^{-1}	CMB polarization	Kostelecký and Mewes (2007)*
$k^{(5)}_{(V)20}$	$-(10\pm 3)\times 10^{-20}$ GeV^{-1}	CMB polarization	Kostelecký and Mewes (2007)*
$k^{(5)}_{(V)30}$	$(8^{+3}_{-4})\times 10^{-20}$ GeV^{-1}	CMB polarization	Kostelecký and Mewes (2007)*
	$-(8\pm 3)\times 10^{-20}$ GeV^{-1}	CMB polarization	Kostelecký and Mewes (2007)*
$\sum_{jm\,0}Y_{jm}(116°, 334°)c^{(6)}_{(I)jm}$	$<3.9\times 10^{-22}$ GeV^{-2}	Astrophysical dispersion	Vasileiou (2010)
$c^{(6)}_{(I)00}$	$<1.4\times 10^{-21}$ GeV^{-2}	Astrophysical dispersion	Vasileiou (2010)
$\sum_{jm\,0}Y_{jm}(147°, 120°)c^{(6)}_{(I)jm}$	$<3.2\times 10^{-20}$ GeV^{-2}	Astrophysical dispersion	Abdo *et al.* (2009), Kostelecký and Mewes (2009)*
$c^{(6)}_{(I)00}$	$<1.1\times 10^{-19}$ GeV^{-2}	Astrophysical dispersion	Abdo *et al.* (2009), Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,0}Y_{jm}(120°, 330°)c^{(6)}_{(I)jm}\rvert$	$<7.4\times 10^{-22}$ GeV^{-2}	Astrophysical dispersion	Aharonian *et al.* (2008), Kostelecký and Mewes (2009)*
$\lvert c^{(6)}_{(I)00}\rvert$	$<2.6\times 10^{-21}$ GeV^{-2}	Astrophysical dispersion	Aharonian *et al.* (2008), Kostelecký and Mewes (2009)*
$\sum_{jm\,0}Y_{jm}(50.2°, 253°)c^{(6)}_{(I)jm}$	$3^{+1}_{-2}\times 10^{-22}$ GeV^{-2}	Astrophysical dispersion	Albert *et al.* (2008), Kostelecký and Mewes (2009)*
$c^{(6)}_{(I)00}$	$10^{+4}_{-7}\times 10^{-22}$ GeV^{-2}	Astrophysical dispersion	Albert *et al.* (2008), Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,0}Y_{jm}(99.7°, 240°)c^{(6)}_{(I)jm}\rvert$	$<1\times 10^{-16}$ GeV^{-2}	Astrophysical dispersion	Boggs *et al.* (2004), Kostelecký and Mewes (2009)*
$\lvert c^{(6)}_{(I)00}\rvert$	$<4\times 10^{-16}$ GeV^{-2}	Astrophysical dispersion	Boggs *et al.* (2004), Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,2}Y_{jm}(98.2°, 182.1°)(k^{(6)}_{(E)jm}+ik^{(6)}_{(B)jm})\rvert$	$\lesssim 10^{-29}$ GeV^{-2}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,2}Y_{jm}(87.3°, 37.3°)(k^{(6)}_{(E)jm}+ik^{(6)}_{(B)jm})\rvert$	$\lesssim 10^{-29}$ GeV^{-2}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$k^{(6)}_{(E)20}$	$\pm(11^{+4}_{-5})\times 10^{-10}$ GeV^{-2}	CMB polarization	Kostelecký and Mewes (2007)*
$k^{(6)}_{(E)30}$	$\pm(11^{+5}_{-6})\times 10^{-10}$ GeV^{-2}	CMB polarization	Kostelecký and Mewes (2007)*
$k^{(6)}_{(E)40}$	$\pm(11^{+5}_{-6})\times 10^{-10}$ GeV^{-2}	CMB polarization	Kostelecký and Mewes (2007)*
$\lvert\sum_{jm\,0}Y_{jm}(98.2°, 182.1°)k^{(7)}_{(V)jm}\rvert$	$<2\times 10^{-24}$ GeV^{-3}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\lvert k^{(7)}_{(V)00}\rvert$	$<7\times 10^{-24}$ GeV^{-3}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,0}Y_{jm}(87.3°, 37.3°)k^{(7)}_{(V)jm}\rvert$	$<5\times 10^{-25}$ GeV^{-3}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\lvert k^{(7)}_{(V)00}\rvert$	$<2\times 10^{-24}$ GeV^{-3}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\sum_{jm\,0}Y_{jm}(116°, 334°)c^{(8)}_{(I)jm}$	$<2.1\times 10^{-25}$ GeV^{-4}	Astrophysical dispersion	Vasileiou (2010)
$c^{(8)}_{(I)00}$	$<7.6\times 10^{-25}$ GeV^{-4}	Astrophysical dispersion	Vasileiou (2010)
$\sum_{jm\,0}Y_{jm}(147°, 120°)c^{(8)}_{(I)jm}$	$<2.6\times 10^{-23}$ GeV^{-4}	Astrophysical dispersion	Abdo *et al.* (2009), Kostelecký and Mewes (2009)*
$c^{(8)}_{(I)00}$	$<9.2\times 10^{-23}$ GeV^{-4}	Astrophysical dispersion	Abdo *et al.* (2009), Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,0}Y_{jm}(99.7°, 240°)c^{(8)}_{(I)jm}\rvert$	$<3\times 10^{-13}$ GeV^{-4}	Astrophysical dispersion	Boggs *et al.* (2004), Kostelecký and Mewes (2009)*
$\lvert c^{(8)}_{(I)00}\rvert$	$<9\times 10^{-13}$ GeV^{-4}	Astrophysical dispersion	Boggs *et al.* (2004), Kostelecký and Mewes (2009)*
$\lvert\sum_{jm\,2}Y_{jm}(98.2°, 182.1°)(k^{(8)}_{(E)jm}+ik^{(8)}_{(B)jm})\rvert$	$\lesssim 10^{-20}$ GeV^{-4}	Astrophysical birefringence	Kostelecký and Mewes (2009)*

TABLE XV. (*Continued*)

Combination	Result	System	Ref.
$\vert\sum_{jm\ 2}Y_{jm}(87.3°, 37.3°)(k^{(8)}_{(E)jm} + ik^{(8)}_{(B)jm})\vert$	$\lesssim 10^{-20}$ GeV^{-4}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\vert\sum_{jm\ 0}Y_{jm}(98.2°, 182.1°)k^{(9)}_{(V)jm}\vert$	$<6\times10^{-16}$ GeV^{-5}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\vert k^{(9)}_{(V)00}\vert$	$<2\times10^{-15}$ GeV^{-5}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\vert\sum_{jm\ 0}Y_{jm}(87.3°, 37.3°)k^{(9)}_{(V)jm}\vert$	$<1\times10^{-16}$ GeV^{-5}	Astrophysical birefringence	Kostelecký and Mewes (2009)*
$\vert k^{(9)}_{(V)00}\vert$	$<4\times10^{-16}$ GeV^{-5}	Astrophysical birefringence	Kostelecký and Mewes (2009)*

TABLE XVI. Lagrange density for the minimal QED extension in Riemann spacetime.

Sector	Coeff.	No.	Operator	Dim.	Factor	*CPT*	L.V.
Fermion	m		$\bar{\psi}\psi$	3	$-e$	+	
	m_5		$\bar{\psi}\gamma_5\psi$	3	$-ie$	+	
			$\bar{\psi}\gamma^a\overleftrightarrow{D}_\mu\psi$	4	$\frac{1}{2}iee^\mu{}_a$	+	
	a_μ	4	$\bar{\psi}\gamma^a\psi$	3	$-ee^\mu{}_a$	−	√
	b_μ	4	$\bar{\psi}\gamma_5\gamma^a\psi$	3	$-ee^\mu{}_a$	−	√
	$H_{\mu\nu}$	6	$\bar{\psi}\sigma^{ab}\psi$	3	$-ee^\mu{}_a e^\nu{}_b$	+	√
	$c_{\lambda\nu}$	16	$\bar{\psi}\gamma^b\overleftrightarrow{D}_\mu\psi$	4	$-\frac{1}{2}iee^\mu{}_a e^{\nu a}e^\lambda{}_b$	+	√
	$d_{\lambda\nu}$	16	$\bar{\psi}\gamma_5\gamma^b\overleftrightarrow{D}_\mu\psi$	4	$-\frac{1}{2}iee^\mu{}_a e^{\nu a}e^\lambda{}_b$	+	√
	e_λ	4	$\bar{\psi}\overleftrightarrow{D}_\mu\psi$	4	$-\frac{1}{2}iee^\mu{}_a e^{\lambda a}$	−	√
	f_λ	4	$\bar{\psi}\gamma_5\overleftrightarrow{D}_\mu\psi$	4	$-\frac{1}{2}iee^\mu{}_a e^{\lambda a}$	−	√
	$g_{\lambda\kappa\nu}$	24	$\bar{\psi}\sigma^{bc}\overleftrightarrow{D}_\mu\psi$	4	$-\frac{1}{4}iee^\mu{}_a e^{\nu a}e^\lambda{}_b e^\kappa{}_c$	−	√
Photon			$F_{\mu\nu}F^{\mu\nu}$	4	$-\frac{1}{4}e$	+	
	$(k_{AF})^\kappa$	4	$A^\lambda F^{\mu\nu}$	3	$\frac{1}{2}e\epsilon_{\kappa\lambda\mu\nu}$	−	√
	$(k_F)_{\kappa\lambda\mu\nu}$	19	$F^{\kappa\lambda}F^{\mu\nu}$	4	$-\frac{1}{4}e$	+	√
Gravity			R	2	$e/2\kappa$	+	
	Λ		1	0	$-e/\kappa$	+	
	u	1	R	2	$-e/2\kappa$	+	
	$s^{\mu\nu}$	9	$R_{\mu\nu}$	2	$e/2\kappa$	+	√
	$t^{\kappa\lambda\mu\nu}$	10	$R_{\kappa\lambda\mu\nu}$	2	$e/2\kappa$	+	√

TABLE XVII. *C*, *P*, *T* properties of operators for Lorentz violation in QED.

Coefficient	*C*	*P*	*T*	*CP*	*CT*	*PT*	*CPT*
c_{TT}, c_{JK}, $(k_F)_{TJTK}$, $(k_F)_{JKLM}$	+	+	+	+	+	+	+
b_J, g_{JTL}, g_{JKT}, $(k_{AF})_J$	+	+	−	+	−	−	−
b_T, g_{JTT}, g_{JKL}, $(k_{AF})_T$	+	−	+	−	+	−	−
c_{TJ}, c_{JT}, $(k_F)_{TJKL}$	+	−	−	−	−	+	+
a_T, e_T, f_J	−	+	+	−	−	+	−
H_{JK}, d_{TJ}, d_{JT}	−	+	−	−	+	−	+
H_{TJ}, d_{TT}, d_{JK}	−	−	+	+	−	−	+
a_J, e_J, f_T	−	−	−	+	+	+	−

2004) involves additional operators constructed with the torsion tensor $T^\alpha{}_{\mu\nu}$. The Minkowski-spacetime limit of QED with nonzero torsion contains terms that mimic Lorentz violation, so searches for Lorentz violation can be used to bound components of the torsion tensor (Kostelecký *et al.*, 2008).

In Table XVI, each line specifies one term in the Lagrange density for the QED extension in Riemann spacetime. Both conventional QED terms and ones with Lorentz violation are included. The first column indicates the sector to which the term belongs. The second column lists the coefficient controlling the corresponding operator. Note the standard use of an uppercase letter for the coefficient $H_{\mu\nu}$, which distinguishes it from the metric fluctuation $h_{\mu\nu}$. The third column shows the number of components for the coefficient. The next three columns list the operator, its mass dimension, and the vierbein factor contracting the coefficient and the operator. The final two columns list the properties of the term under *CPT* and Lorentz transformations. A *CPT*-even operator is indicated by a plus sign and a *CPT*-odd one by a minus sign, while terms violating Lorentz invariance are identified by a check mark.

TABLE XVIII. Definitions for the fermion sector of the minimal QED extension.

Symbol	Combination	Components
$\tilde{b}_J$	$b_J - \frac{1}{2}\varepsilon_{JKL}H_{KL} - m(d_{JT} - \frac{1}{2}\varepsilon_{JKL}g_{KLT})$	3
$\tilde{b}^*_J$	$b_J + \frac{1}{2}\varepsilon_{JKL}H_{KL} + m(d_{JT} + \frac{1}{2}\varepsilon_{JKL}g_{KLT})$,	3
$\tilde{b}_T$	$b_T + mg_{XYZ}$	1
$\tilde{g}_T$	$b_T - m(g_{XYZ} - g_{YZX} - g_{ZXY})$	1
$\tilde{H}_{XT}$	$H_{XT} + m(d_{ZY} - g_{XTT} - g_{XYY})$	1
$\tilde{H}_{YT}$	$H_{YT} + m(d_{XZ} - g_{YTT} - g_{YZZ})$	1
$\tilde{H}_{ZT}$	$H_{ZT} + m(d_{YX} - g_{ZTT} - g_{ZXX})$	1
$\tilde{d}_\pm$	$m(d_{XX} \pm d_{YY})$	2
$\tilde{d}_Q$	$m(d_{XX} + d_{YY} - 2d_{ZZ} - g_{YZX} - g_{ZXY} + 2g_{XYZ})$	1
$\tilde{d}_J$	$m(d_{TJ} + \frac{1}{2}d_{JT}) - \frac{1}{4}\varepsilon_{JKL}H_{KL}$	3
$\tilde{d}_{YZ}$	$m(d_{YZ} + d_{ZY} - g_{XYY} + g_{XZZ})$	1
$\tilde{d}_{ZX}$	$m(d_{ZX} + d_{XZ} - g_{YZZ} + g_{YXX})$	1
$\tilde{d}_{XY}$	$m(d_{XY} + d_{YX} - g_{ZXX} + g_{ZYY})$	1
$\tilde{g}_c$	$m(g_{XYZ} - g_{ZXY})$	1
$\tilde{g}_-$	$m(g_{XTX} - g_{YTY})$	1
$\tilde{g}_Q$	$m(g_{XTX} + g_{YTY} - 2g_{ZTZ})$	1
$\tilde{g}_{TJ}$	$m\lvert\varepsilon_{JKL}\rvert g_{KTL}$	3
$\tilde{g}_{DJ}$	$-b_J + m\varepsilon_{JKL}(g_{KTL} + \frac{1}{2}g_{KLT})$	3
$\tilde{g}_{JK}$	$m(g_{JTT} + g_{JKK})$, (no K sum, $J \neq K$)	6
$\tilde{c}_Q$	$m(c_{XX} + c_{YY} - 2c_{ZZ})$	1
$\tilde{c}_-$	$m(c_{XX} - c_{YY})$	1
$\tilde{c}_J$	$m\lvert\varepsilon_{JKL}\rvert c_{KL}$	3
$\tilde{c}_{TJ}$	$m(c_{TJ} + c_{JT})$	3
$\tilde{c}_{TT}$	mc_{TT}	1
		Total: 44

TABLE XIX. Definitions for the photon sector of the minimal QED extension.

Symbol	Combination	Components
$(\tilde{\kappa}_{e+})^{JK}$	$-(k_F)^{TJTK} + \frac{1}{4}\epsilon^{JPQ}\epsilon^{KRS}(k_F)^{PQRS}$	5
$(\tilde{\kappa}_{o-})^{JK}$	$\frac{1}{2}\epsilon^{KPQ}(k_F)^{TJPQ} + \frac{1}{2}\epsilon^{JPQ}(k_F)^{TKPQ}$	5
$(\tilde{\kappa}_{e-})^{JK}$	$-(k_F)^{TJTK} - \frac{1}{4}\epsilon^{JPQ}\epsilon^{KRS}(k_F)^{PQRS} + \frac{2}{3}(k_F)^{TLTL}\delta^{JK}$	5
$(\tilde{\kappa}_{o+})^{JK}$	$\frac{1}{2}\epsilon^{KPQ}(k_F)^{TJPQ} - \frac{1}{2}\epsilon^{JPQ}(k_F)^{TKPQ}$	3
$\tilde{\kappa}_{\text{tr}}$	$-\frac{2}{3}[(k_F)^{TXTX} + (k_F)^{TYTY} + (k_F)^{TZTZ}]$	1
		Total: 19
k^1	$(k_F)^{TYXZ}$	1
k^2	$(k_F)^{TXYZ}$	1
k^3	$(k_F)^{TYTY} - (k_F)^{XZXZ}$	1
k^4	$(k_F)^{TZTZ} - (k_F)^{XYXY}$	1
k^5	$(k_F)^{TXTY} + (k_F)^{XZYZ}$	1
k^6	$(k_F)^{TXTZ} - (k_F)^{XYYZ}$	1
k^7	$(k_F)^{TYTZ} + (k_F)^{XYXZ}$	1
k^8	$(k_F)^{TXXY} + (k_F)^{TZYZ}$	1
k^9	$(k_F)^{TXXZ} - (k_F)^{TYYZ}$	1
k^{10}	$(k_F)^{TYXY} - (k_F)^{TZXZ}$	1
$k^{(3)}_{(V)00}$	$-\sqrt{4\pi}(k_{AF})^T$	1
$k^{(3)}_{(V)10}$	$-\sqrt{4\pi/3}(k_{AF})^Z$	1
$\mathrm{Re}k^{(3)}_{(V)11}$	$\sqrt{2\pi/3}(k_{AF})^X$	1
$\mathrm{Im}k^{(3)}_{(V)11}$	$-\sqrt{2\pi/3}(k_{AF})^Y$	1
		Total: 4

As an example, consider the fourth row of Table XVI. This concerns the term in the fermion sector with coefficient a_μ for Lorentz violation. The coefficient has four independent components, which control the four Lorentz-violating operators $\bar{\psi}\gamma^a\psi$. The gravitational couplings of this operator are contained in the vierbein product $ee^\mu{}_a$. The corresponding term in the Lagrange density for the minimal QED extension in Riemann spacetime is $\mathcal{L}_a = -ea_\mu e^\mu{}_a\bar{\psi}\gamma^a\psi$. It has mass dimension 3 and is *CPT* odd. The Minkowski-spacetime limit of this term can be obtained by the vierbein replacement $e_\mu{}^a \to \delta_\mu{}^a$. The number of index contractions in $\mathcal{L}_a$ is two, one each for the μ and a indices, so the overall sign of $\mathcal{L}_a$ is unaffected by the choice of convention for the Minkowski metric.

The properties listed in Table XVI are those of the operators in the Lagrange density rather than those associated with observables. The issue of observability of a given coefficient can be subtle because experiments always involve comparisons of at least two quantities. The point is that in certain tests a given coefficient may produce the same effect on two or more quantities and so may be unobservable, or it may produce effects indistinguishable from those of other coefficients. This situation can often be theoretically understood via a field redefinition that eliminates the coefficient from the relevant part of the Lagrange density without affecting the dynamics of the experiment in question. For example, a constant coefficient a_μ in the minimal QED extension in Minkowski spacetime is unobservable in any experiment involving a single fermion flavor because it can be absorbed as a phase shift in the fermion field (Colladay and Kostelecký, 1997, 1998). The situation changes in Riemann spacetime, where three of the four components of a_μ become observables affecting the gravitational properties of the fermion (Kostelecký, 2004). Another example is provided by the coefficient f_μ in the minimal QED extension in Minkowski spacetime, which can be converted into a coefficient of the $c_{\mu\nu}$ type via a change of spinor basis (Altschul, 2006a). Additional subtleties arise because any experiment must always choose definitions of clock ticking rates, clock synchronizations, rod lengths, and rod isotropies. This involves 10 free coordinate choices and implies the unobservability of 10 combinations of coefficients for Lorentz violation (Kostelecký and Tasson, 2010).

Table XVII lists the properties under discrete-symmetry transformations of the Lorentz-violating operators in the minimal QED extension (Kostelecký *et al.*, 2002). The seven transformations considered are charge conjugation C, parity inversion P, time reversal T, and their combinations CP, CT, PT, and CPT. The first column specifies the operator by indicating its corresponding coefficient. Each of the other columns concerns one of the seven transformations. An even operator is indicated by a plus sign and an odd one by a minus sign. The table contains eight rows, one for each of the eight possible combinations of signs under C, P, and T.

Table XVIII lists the definitions of the 44 combinations of coefficients for Lorentz violation that frequently appear in experimental analyses involving the fermion sector of the minimal QED extension in Minkowski spacetime in the nonrelativistic limit. These combinations are conventionally denoted by tilde coefficients, listed in the first column of the table. Note that six of these combinations, $\tilde{c}_X$, $\tilde{c}_Y$, $\tilde{c}_Z$, $\tilde{g}_{TX}$, $\tilde{g}_{TY}$, and $\tilde{g}_{TZ}$, are denoted as $\tilde{c}_{Q,Y}$, $\tilde{c}_{Q,X}$, $\tilde{c}_{XY}$, $\tilde{g}_{Q,Y}$, $\tilde{g}_{Q,X}$, and

TABLE XX. Lagrange density for the fermion sector of the minimal SME in Riemann-Cartan spacetime.

Sector	Coeff.	Operator	Dim.	Factor	*CPT*	L.V.
Lepton		$\bar{L}_A \gamma^a \overleftrightarrow{D}_\mu L_A$	4	$\frac{1}{2} iee^\mu{}_a$	+	
		$\bar{R}_A \gamma^a \overleftrightarrow{D}_\mu R_A$	4	$\frac{1}{2} iee^\mu{}_a$	+	
	$(a_L)_{\mu AB}$	$\bar{L}_A \gamma^a L_B$	3	$-ee^\mu{}_a$	−	√
	$(a_R)_{\mu AB}$	$\bar{R}_A \gamma^a R_B$	3	$-ee^\mu{}_a$	−	√
	$(c_L)_{\mu\nu AB}$	$\bar{L}_A \gamma^a \overleftrightarrow{D}^\nu L_B$	4	$-\frac{1}{2} iee^\mu{}_a$	+	√
	$(c_R)_{\mu\nu AB}$	$\bar{R}_A \gamma^a \overleftrightarrow{D}^\nu R_B$	4	$-\frac{1}{2} iee^\mu{}_a$	+	√
Quark		$\bar{Q}_A \gamma^a \overleftrightarrow{D}_\mu Q_A$	4	$\frac{1}{2} iee^\mu{}_a$	+	
		$\bar{U}_A \gamma^a \overleftrightarrow{D}_\mu U_A$	4	$\frac{1}{2} iee^\mu{}_a$	+	
		$\bar{D}_A \gamma^a \overleftrightarrow{D}_\mu D_A$	4	$\frac{1}{2} iee^\mu{}_a$	+	
	$(a_Q)_{\mu AB}$	$\bar{Q}_A \gamma^a Q_B$	3	$-ee^\mu{}_a$	−	√
	$(a_U)_{\mu AB}$	$\bar{U}_A \gamma^a U_B$	3	$-ee^\mu{}_a$	−	√
	$(a_D)_{\mu AB}$	$\bar{D}_A \gamma^a D_B$	3	$-ee^\mu{}_a$	−	√
	$(c_Q)_{\mu\nu AB}$	$\bar{Q}_A \gamma^a \overleftrightarrow{D}^\nu Q_B$	4	$-\frac{1}{2} iee^\mu{}_a$	+	√
	$(c_U)_{\mu\nu AB}$	$\bar{U}_A \gamma^a \overleftrightarrow{D}^\nu U_B$	4	$-\frac{1}{2} iee^\mu{}_a$	+	√
	$(c_D)_{\mu\nu AB}$	$\bar{D}_A \gamma^a \overleftrightarrow{D}^\nu D_B$	4	$-\frac{1}{2} iee^\mu{}_a$	+	√
Yukawa	$(G_L)_{AB}$	$\bar{L}_A \phi R_B$ + H.c.	4	$-e$	+	
	$(G_U)_{AB}$	$\bar{Q}_A \phi^c U_B$ + H.c.	4	$-e$	+	
	$(G_D)_{AB}$	$\bar{Q}_A \phi D_B$ + H.c.	4	$-e$	+	
	$(H_L)_{\mu\nu AB}$	$\bar{L}_A \phi \sigma^{ab} R_B$ + H.c.	4	$-\frac{1}{2} ee^\mu{}_a e^\nu{}_b$	+	√
	$(H_U)_{\mu\nu AB}$	$\bar{Q}_A \phi^c \sigma^{ab} U_B$ + H.c.	4	$-\frac{1}{2} ee^\mu{}_a e^\nu{}_b$	+	√
	$(H_D)_{\mu\nu AB}$	$\bar{Q}_A \phi \sigma^{ab} D_B$ + H.c.	4	$-\frac{1}{2} ee^\mu{}_a e^\nu{}_b$	+	√

TABLE XXI. Lagrange density for the boson sector of the minimal SME in Riemann-Cartan spacetime.

Sector	Coeff.	Operator	Dim.	Factor	*CPT*	L.V.
Higgs	μ^2	$\phi^\dagger \phi$	2	e	+	
	λ	$(\phi^\dagger \phi)^2$	4	$-\frac{1}{3!} e$	+	
		$(D_\mu \phi)^\dagger (D^\mu \phi)$	4	$-e$	+	
	$(k_\phi)^\mu$	$\phi^\dagger D_\mu \phi$ + H.c.	3	ie	−	√
	$(k_{\phi\phi})^{\mu\nu}$	$(D_\mu \phi)^\dagger (D_\nu \phi)$ + H.c.	4	$\frac{1}{2} e$	+	√
	$(k_{\phi W})^{\mu\nu}$	$\phi^\dagger W_{\mu\nu} \phi$	4	$-\frac{1}{2} e$	+	√
	$(k_{\phi B})^{\mu\nu}$	$\phi^\dagger \phi B_{\mu\nu}$	4	$-\frac{1}{2} e$	+	√
Gauge		$\mathrm{Tr}(G_{\mu\nu} G^{\mu\nu})$	4	$-\frac{1}{2} e$	+	
		$\mathrm{Tr}(W_{\mu\nu} W^{\mu\nu})$	4	$-\frac{1}{2} e$	+	
		$B_{\mu\nu} B^{\mu\nu}$	4	$-\frac{1}{4} e$	+	
	$(k_0)_\kappa$	B^κ	1	e	−	√
	$(k_1)_\kappa$	$B_\lambda B_{\mu\nu}$	3	$e\epsilon^{\kappa\lambda\mu\nu}$	−	√
	$(k_2)_\kappa$	$\mathrm{Tr}(W_\lambda W_{\mu\nu} + \frac{2}{3} igW_\lambda W_\mu W_\nu)$	3	$e\epsilon^{\kappa\lambda\mu\nu}$	−	√
	$(k_3)_\kappa$	$\mathrm{Tr}(G_\lambda G_{\mu\nu} + \frac{2}{3} ig_3 G_\lambda G_\mu G_\nu)$	3	$e\epsilon^{\kappa\lambda\mu\nu}$	−	√
	$(k_G)_{\kappa\lambda\mu\nu}$	$\mathrm{Tr}(G^{\kappa\lambda} G^{\mu\nu})$	4	$-\frac{1}{2} e$	+	√
	$(k_W)_{\kappa\lambda\mu\nu}$	$\mathrm{Tr}(W^{\kappa\lambda} W^{\mu\nu})$	4	$-\frac{1}{2} e$	+	√
	$(k_B)_{\kappa\lambda\mu\nu}$	$B^{\kappa\lambda} B^{\mu\nu}$	4	$-\frac{1}{4} e$	+	√
Gravity		R	2	$e/2\kappa$	+	
	Λ	1	0	$-e/\kappa$	+	
	u	R	2	$-e/2\kappa$	+	
	$(k_T)^{\lambda\mu\nu}$	$T_{\lambda\mu\nu}$	1	$e/2\kappa$	+	√
	$s^{\mu\nu}$	$R_{\mu\nu}$	2	$e/2\kappa$	+	√
	$t^{\kappa\lambda\mu\nu}$	$R_{\kappa\lambda\mu\nu}$	2	$e/2\kappa$	+	√
	$(k_{TT})^{\alpha\beta\gamma\lambda\mu\nu}$	$T_{\alpha\beta\gamma} T_{\lambda\mu\nu}$	2	$e/2\kappa$	+	√
	$(k_{DT})^{\kappa\lambda\mu\nu}$	$D_\kappa T_{\lambda\mu\nu}$	2	$e/2\kappa$	+	√

TABLE XXII. Coefficients in the neutrino sector.

Coeff.	Dim.	Oscillation	*CPT*	L.V.
$\widetilde{m}_{AB}$	3	$\nu \leftrightarrow \nu$, $\bar{\nu} \leftrightarrow \bar{\nu}$	$+$	
$[(a_L)^\mu]_{AB}$	3	$\nu \leftrightarrow \nu$, $\bar{\nu} \leftrightarrow \bar{\nu}$	$-$	$\surd$
$[H^{\mu\nu}]_{AB}$	3	$\nu \leftrightarrow \bar{\nu}$	$+$	$\surd$
$[(c_L)^{\mu\nu}]_{AB}$	4	$\nu \leftrightarrow \nu$, $\bar{\nu} \leftrightarrow \bar{\nu}$	$+$	$\surd$
$[g^{\mu\nu\sigma}]_{AB}$	4	$\nu \leftrightarrow \bar{\nu}$	$-$	$\surd$

$\tilde{g}_{XY}$, respectively, in some early publications. The definitions in the table are given for a generic fermion of mass m. Most applications in the literature involve electrons, protons, neutrons, and their antiparticles, for which the corresponding mass is understood. The final column lists the number of independent components of each coefficient. For matter involving electrons, protons, neutrons, and their antiparticles, there are therefore 132 independent observable coefficients for Lorentz violation in the minimal QED sector of the SME in Minkowski spacetime.

Table XIX presents definitions for certain combinations of the 23 coefficients for Lorentz violation in the photon sector of the minimal QED extension in Minkowski spacetime. This table has three sections. The first section consists of five rows listing 19 widely used combinations of the 19 coefficients for *CPT*-even Lorentz violation. The second section provides 10 alternative combinations involving the 10 *CPT*-even Lorentz-violating operators relevant to leading-order birefringence (Kostelecký and Mewes, 2002). The third section lists four combinations of the four coefficients for *CPT*-odd Lorentz violation. These combinations appear when a basis of spin-weighted spherical harmonics is adopted.

B. Minimal SME

Table XX concerns the fermion-sector terms in the Lagrange density of the minimal SME in Riemann-Cartan spacetime. The column headings are similar to those in Table XVI. In the lepton sector, the left- and right-handed

TABLE XXIII. Quadratic Lagrange density for the nonminimal photon sector in Minkowski spacetime.

Coeff.	No.	Operator	Dim.	Factor	*CPT*	L.V.
		$F_{\mu\nu}F^{\mu\nu}$	4	$-\frac{1}{4}$	$+$	
$(k_{AF}^{(3)})_\kappa \equiv (k_{AF})_\kappa$	4	$A_\lambda F_{\mu\nu}$	3	$\frac{1}{2}\epsilon^{\kappa\lambda\mu\nu}$	$-$	$\surd$
$(k_{AF}^{(5)})_\kappa{}^{\alpha_1\alpha_2}$	36	$A_\lambda \partial_{\alpha_1}\partial_{\alpha_2} F_{\mu\nu}$	5	$\frac{1}{2}\epsilon^{\kappa\lambda\mu\nu}$	$-$	$\surd$
$(k_{AF}^{(7)})_\kappa{}^{\alpha_1\alpha_2\alpha_3\alpha_4}$	120	$A_\lambda \partial_{\alpha_1}\partial_{\alpha_2}\partial_{\alpha_3}\partial_{\alpha_4} F_{\mu\nu}$	7	$\frac{1}{2}\epsilon^{\kappa\lambda\mu\nu}$	$-$	$\surd$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		
$(k_{AF}^{(d)})_\kappa{}^{\alpha_1\cdots\alpha_{(d-3)}}$	$\frac{1}{2}(d+1)(d-1)(d-2)$	$A_\lambda \partial_{\alpha_1}\cdots\partial_{\alpha_{(d-3)}} F_{\mu\nu}$	odd d	$\frac{1}{2}\epsilon^{\kappa\lambda\mu\nu}$	$-$	$\surd$
$(k_F^{(4)})^{\kappa\lambda\mu\nu} \equiv (k_F)^{\kappa\lambda\mu\nu}$	$19+1$	$F_{\kappa\lambda}F_{\mu\nu}$	4	$-\frac{1}{4}$	$+$	$\surd$
$(k_F^{(6)})^{\kappa\lambda\mu\nu\alpha_1\alpha_2}$	126	$F_{\kappa\lambda}\partial_{\alpha_1}\partial_{\alpha_2}F_{\mu\nu}$	6	$-\frac{1}{4}$	$+$	$\surd$
$(k_F^{(8)})^{\kappa\lambda\mu\nu\alpha_1\alpha_2\alpha_3\alpha_4}$	360	$F_{\kappa\lambda}\partial_{\alpha_1}\partial_{\alpha_2}\partial_{\alpha_3}\partial_{\alpha_4}F_{\mu\nu}$	8	$-\frac{1}{4}$	$+$	$\surd$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		
$(k_F^{(d)})^{\kappa\lambda\mu\nu\alpha_1\cdots\alpha_{(d-4)}}$	$(d+1)d(d-3)$	$F_{\kappa\lambda}\partial_{\alpha_1}\cdots\partial_{\alpha_{(d-4)}}F_{\mu\nu}$	even d	$-\frac{1}{4}$	$+$	$\surd$

TABLE XXIV. Spherical coefficients for the nonminimal photon sector in Minkowski spacetime.

Type	Coeff.	Dim.	n	j	No.
Vacuum	$c_{(I)jm}^{(d)}$	Even, ≥ 4	–	$0, 1, \ldots, d-2$	$(d-1)^2$
	$k_{(E)jm}^{(d)}$	Even, ≥ 4	–	$2, 3, \ldots, d-2$	$(d-1)^2 - 4$
	$k_{(B)jm}^{(d)}$	Even, ≥ 4	–	$2, 3, \ldots, d-2$	$(d-1)^2 - 4$
	$k_{(V)jm}^{(d)}$	Odd, ≥ 3	–	$0, 1, \ldots, d-2$	$(d-1)^2$
Vacuum orthogonal	$(\overset{\neg}{c}{}_F^{(d)})_{njm}^{(0E)}$	Even, ≥ 4	$0, 1, \ldots, d-4$	$n, n-2, n-4, \ldots, \geq 0$	$\frac{(d-1)(d-2)(d-3)}{6}$
	$(\overset{\neg}{k}{}_F^{(d)})_{njm}^{(0E)}$	Even, ≥ 6	$1, 2, \ldots, d-4$	$n, n-2, n-4, \ldots, \geq 0$	$\frac{(d-1)(d-2)(d-3)}{6} - 1$
	$(\overset{\neg}{k}{}_F^{(d)})_{njm}^{(1E)}$	Even, ≥ 6	$1, 2, \ldots, d-4$	$n+1, n-1, n-3, \ldots, \geq 1$	$\frac{(d-4)(d^2+d+3)}{6}$
	$(\overset{\neg}{k}{}_F^{(d)})_{njm}^{(2E)}$	Even, ≥ 6	$2, 3, \ldots, d-4$	$n, n-2, n-4, \ldots, \geq 2$	$\frac{(d-4)(d^2-2d-9)}{6}$
	$(\overset{\neg}{k}{}_F^{(d)})_{njm}^{(1B)}$	Even, ≥ 6	$1, 2, \ldots, d-4$	$n, n-2, n-4, \ldots, \geq 1$	$\frac{d(d-2)(d-4)}{6}$
	$(\overset{\neg}{k}{}_F^{(d)})_{njm}^{(2B)}$	Even, ≥ 6	$1, 2, \ldots, d-4$	$n+1, n-1, n-3, \ldots, \geq 2$	$\frac{(d+3)(d-2)(d-4)}{6}$
	$(\overset{\neg}{k}{}_{AF}^{(d)})_{njm}^{(0B)}$	Odd, ≥ 5	$0, 1, \ldots, d-4$	$n, n-2, n-4, \ldots, \geq 0$	$\frac{(d-1)(d-2)(d-3)}{6}$
	$(\overset{\neg}{k}{}_{AF}^{(d)})_{njm}^{(1B)}$	Odd, ≥ 5	$0, 1, \ldots, d-4$	$n+1, n-1, n-3, \ldots, \geq 1$	$\frac{(d+1)(d-1)(d-3)}{6}$
	$(\overset{\neg}{k}{}_{AF}^{(d)})_{njm}^{(1E)}$	Odd, ≥ 5	$1, 2, \ldots, d-3$	$n, n-2, n-4, \ldots, \geq 1$	$\frac{(d+1)(d-1)(d-3)}{6}$

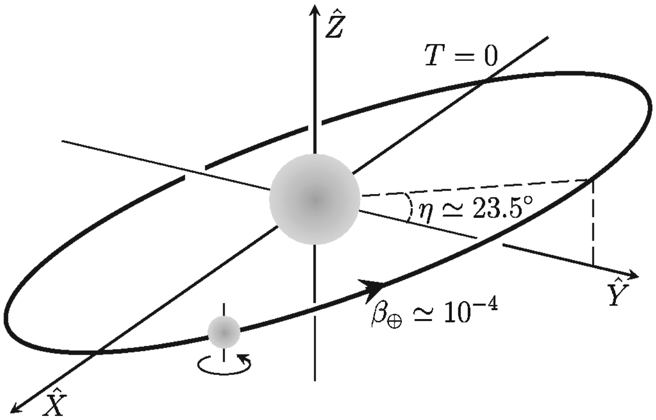

FIG. 1. Standard Sun-centered inertial reference frame (Bluhm *et al.*, 2003).

leptons are denoted by L_A and R_A, where A is the generation index. The SU(2) doublet L_A includes the three neutrino fields ν_e, ν_μ, and ν_τ and the left-handed components of the three charged leptons e, μ, and τ. The SU(2) singlet R_A contains the right-handed components of e, μ, and τ. The derivative D_μ is both spacetime and SU(3) $\times$ SU(2) $\times$ U(1) covariant. The quark fields are denoted U_A, D_A, and Q_A, where A is the generation index. The right-handed components of the u, c, and t quarks are the SU(2) singlets U_A, while the right-handed components of d, s, and b are the SU(2) singlets D_A. The six left-handed quark fields are contained in the SU(2) doublet Q_A. The Yukawa sector involves terms coupling the Higgs doublet ϕ to the leptons and to the quarks. The conventional Yukawa-coupling matrices are denoted $(G_L)_{AB}$, $(G_U)_{AB}$, and $(G_D)_{AB}$. The Hermitian conjugate of an operator is abbreviated H.c. in the table.

Table XXI presents information about the Higgs, gauge, and pure-gravity sectors for the Lagrange density of the minimal SME in Riemann-Cartan spacetime. The structure of the table is the same as that of Table XX. As before, D_μ is both a spacetime and an SU(3) $\times$ SU(2) $\times$ U(1) covariant derivative. The complex Higgs field is denoted ϕ, the SU(3) color gauge fields and the SU(2) gauge fields are the Hermitian adjoint matrices G_μ and W_μ, respectively, while the U(1) hypercharge gauge field is the singlet B_μ. Each gauge field has an associated field strength, denoted $G_{\mu\nu}$ for the strong interactions, $W_{\mu\nu}$ for the weak interactions, and $B_{\mu\nu}$ for the hypercharge. The pure-gravity sector of Table XXI differs from that in Table XVI only in the addition of terms involving the torsion field $T^\alpha{}_{\mu\nu}$.

The minimal SME in Riemann-Cartan spacetime described in Tables XX and XXI can be reduced to the minimal QED in Riemann spacetime described in Table XVI as follows. For the gauge sector, including the covariant derivatives, remove all the gauge fields except the charge U(1) field in the photon limit $B_\mu \to A_\mu$, and remove all the Higgs terms. For the gravity sector, remove all the torsion terms. For the fermion sector, restrict the lepton generation index to a single value, remove all quark and neutrino terms, and replace the Yukawa-coupling terms with the relevant fermion mass terms.

Table XXII concerns the neutrino sector of the SME, including both neutrino masses and Lorentz-violating terms. For the latter, we restrict our attention to terms of mass dimension 4 or less that involve three generations of active neutrinos and antineutrinos, allowing for possible violations of SU(3) $\times$ SU(2) $\times$ U(1) gauge symmetry and lepton number (Kostelecký and Mewes, 2004). In the table, the first row involves the usual neutrino mass matrix $\widetilde{m}_{AB}$, where the indices A, B take values e, μ, and τ, while the other rows concern coefficients for Lorentz violation. The first column lists the coefficients, and the second column gives the dimension of the corresponding operators in the Lagrange density. The third column indicates generically the type of neutrino oscillations controlled by the coefficients. The final two columns list the properties of the operators under *CPT* and Lorentz transformations.

C. Nonminimal photon sector

Table XXIII provides information on the nonminimal photon sector of the full SME in Minkowski spacetime. The relevant part of the Lagrange density includes operators of arbitrary dimension d that are both gauge invariant and quadratic in the photon field A_μ (Kostelecký and Mewes, 2009). The structure of the table is similar to that adopted for Tables XVI, XX, and XXI, with each row associated with a term in the Lagrange density. The first column lists the coefficient for Lorentz violation, while the second column counts its independent components. The next three columns provide the corresponding operator appearing in the Lagrange density, its mass dimension, and the factor contracting the coefficient and the operator. The last two columns list the properties of the operator under *CPT* and Lorentz transformations, using the same conventions as Table XVI.

Three sections appear in Table XXIII, separated by horizontal lines. The first section concerns the conventional Lorentz-preserving Maxwell term in the Lagrange density for the photon sector. The second and third sections concern coefficients associated with operators of odd and even dimensions d, respectively. Each of these sections has three rows for the lowest three values of d, along with a final row applicable to the case of general d. The notation for the coefficients incorporates a superscript specifying the dimension d of the corresponding operator. Note that the mass dimension of the coefficients is $4 - d$. In each section, the first row describes terms in the minimal SME, and the match is provided between the general notation for nonminimal coefficients and the standard notation used for the minimal SME in Table XVI. In the case of mass dimension 4, there are 19 independent Lorentz-violating operators. However, for this case the number in the second column is listed as 19 + 1 to allow for an additional Lorentz-preserving trace term, which maintains consistency with the expression for general d in the last row.

Table XXIV summarizes properties of spherical coefficients for Lorentz violation in the nonminimal photon sector of the full SME in Minkowski spacetime (Kostelecký and Mewes, 2009). The spherical coefficients are combinations of the coefficients listed in Table XXIII that are of particular relevance for observation and experiment. They can be separated into two types. One set consists of vacuum coefficients that control leading-order effects on photon propagation in the vacuum, including birefringence and dispersion. The complementary set contains the vacuum-orthogonal coefficients, which leave photon propagation in the vacuum unaffected at leading order. The two parts of Table XXIV reflect this separation, with the part above the horizontal line involving the vacuum coefficients and the part below involving the vacuum-orthogonal ones.

In Table XXIV, the first column of the table identifies the type of spherical coefficients, while the second column lists the specific coefficient. The coefficient notation reflects properties of the corresponding operator. Coefficients associated with operators leaving unchanged the leading-order photon propagation in the vacuum are distinguished by a negation diacritic ¬. A symbol k denotes coefficients for birefringent operators, while c denotes nonbirefringent ones. The superscript d refers to the operator mass dimension, while the subscripts n, j, and m determine the frequency or wavelength dependence, the total angular momentum, and the z component of the angular momentum, respectively. The superscripts E and B refer to the parity of the operator, while the numerals 0, 1, or 2 preceding E or B refer to the spin weight. Note that the photon-sector coefficients in the minimal SME correspond to the vacuum coefficients with $d = 3, 4$. The third, fourth, and fifth columns of Table XXIV provide the allowed ranges of the dimension d and of the indices n and j. The index m can take values ranging from $-j$ to j in unit increments. The final column gives the number of independent coefficient components for each operator of dimension d.

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