

STATUS OF MATTER-GRAVITY COUPLINGS IN THE SME

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Constraints on Lorentz violation in matter-gravity couplings are summarized along with existing proposals to obtain sensitivities that exceed current limits by up to 11 orders of magnitude.

1. Introduction

The phenomenology of matter-gravity couplings and Lorentz violation in the Standard-Model Extension (SME)¹ was developed in Refs. 2,3. The first portion of Ref. 3 built upon existing analysis of the pure-gravity sector of the SME⁴ to develop the necessary theoretical tools for the experimental analysis. These theoretical developments are summarized in Ref. 5. The second portion of Ref. 3 generates explicit predictions for the detection of matter-sector coefficients for Lorentz violation in a large number of gravitational tests. Note that ‘explicit prediction’ here means that the experimental observable has been calculated and decomposed by signal frequency such that it is ready to fit with experimental data. Of special interest in this context are sensitivities to the 12 coefficient components of $\alpha(\bar{a}_{\text{eff}}^w)_\mu$, where w runs over species, proton, neutron, and electron, which are unobservable in the absence of gravity.² Experimental implications of the remaining spin-independent coefficient, $\bar{c}_{\mu\nu}$ were also considered. Consideration of spin-dependence in matter-gravity couplings is now underway.^{6,7}

Predictions were made for the following tests: laboratory tests such as gravimeter experiments and tests of the Weak Equivalence Principle (WEP) with ordinary neutral matter; versions of these experiments with electrically charged matter, higher-generation matter, and antimatter; WEP tests in space; solar-system tests such as lunar laser ranging and precession of the perihelion of various bodies; and light-travel tests such as time-delay, Doppler shift, redshift, and null-redshift tests. These predictions were then

used to place several constraints on the relevant coefficients. Following the publication of Refs. 2,3, analysis of additional tests has been performed obtaining additional constraints. Section 2 of this proceedings contribution summarizes these existing limits. The many proposed investigations that remain to be completed, which could extend existing limits, are summarized in Sec. 3. Unless otherwise stated, bounds on combinations of coefficient components assume all other SME coefficients are zero.

2. Constraints

Concurrent with the development of experimental and observational predictions, several constraints were placed using the published results of experiments. Constraints were placed on 4 combinations of the 12 $\alpha(\bar{a}_{\text{eff}}^w)_\mu$ coefficient components, and 4 constraints were placed on previously unconstrained combinations of $(\bar{c}^w)_{\mu\nu}$.³ Four of these constraints are from precession of the perihelion of bodes based on existing data,⁸

$$\begin{aligned} & | -0.97(\bar{a}_{\text{eff}}^\circ)_X + 0.15(\bar{a}_{\text{eff}}^\circ)_Y + 0.18(\bar{a}_{\text{eff}}^\circ)_Z | \lesssim 10^{-6} \text{ GeV (Mercury),} \\ & | -0.97(\bar{c}^n)_{TX} + 0.15(\bar{c}^n)_{TY} + 0.18(\bar{c}^n)_{TZ} | \lesssim 10^{-5} \quad \text{(Mercury),} \\ & | -0.97(\bar{a}_{\text{eff}}^\circ)_X - 0.21(\bar{a}_{\text{eff}}^\circ)_Y - 0.10(\bar{a}_{\text{eff}}^\circ)_Z | \lesssim 10^{-6} \text{ GeV (Earth),} \\ & | -0.97(\bar{c}^n)_{TX} - 0.21(\bar{c}^n)_{TY} - 0.10(\bar{c}^n)_{TZ} | \lesssim 10^{-5} \quad \text{(Earth),} \end{aligned} \quad (1)$$

where $(\bar{a}_{\text{eff}}^\circ)_J = \alpha[(\bar{a}_{\text{eff}}^e)_J + (\bar{a}_{\text{eff}}^p)_J + 0.1(\bar{a}_{\text{eff}}^n)_J]$. Note that the $(\bar{c}^n)_{\Xi\Sigma}$ constraints above are simplified using existing constraints⁹ on other combinations of $(\bar{c}^w)_{\Xi\Sigma}$. The other 2 constraints on $\alpha(\bar{a}_{\text{eff}}^w)_\Xi$ are from torsion pendulum measurements of WEP based on data from Ref. 10,

$$|\alpha(\bar{a}_{\text{eff}}^n)_T| \lesssim 10^{-10} \text{ GeV}, \quad |\alpha(\bar{a}_{\text{eff}}^e)_T + \alpha(\bar{a}_{\text{eff}}^p)_T| \lesssim 10^{-10} \text{ GeV}, \quad (2)$$

and the final constraints are based on combined results from torsion pendulum WEP measurements and falling corner-cube WEP measurements¹¹

$$|(\bar{c}^n)_Q| \lesssim 10^{-8}, \quad |(\bar{c}^e)_{TT} + (\bar{c}^p)_{TT} - (\bar{c}^n)_{TT}| \lesssim 10^{-8}, \quad (3)$$

though other WEP tests could be used if sufficient sensitivity is available.

Following Refs. 2,3, weak constraints have been achieved on 4 additional combinations of $\alpha(\bar{a}_{\text{eff}}^w)_\mu$ coefficients:

$$\begin{aligned} & |\alpha(\bar{a}_{\text{eff}}^n)_X + 0.83\alpha[(\bar{a}_{\text{eff}}^p)_X + (\bar{a}_{\text{eff}}^e)_X]| \leq 0.2 \text{ GeV,} \\ & |\alpha(\bar{a}_{\text{eff}}^n)_Y + 0.83\alpha[(\bar{a}_{\text{eff}}^p)_Y + (\bar{a}_{\text{eff}}^e)_Y]| \leq 0.2 \text{ GeV,} \end{aligned} \quad (4)$$

using a torsion-strip balance,¹² and

$$\begin{aligned} & |\alpha[(\bar{a}_{\text{eff}}^e)_X + (\bar{a}_{\text{eff}}^p)_X + (\bar{a}_{\text{eff}}^e)_X]| = 0.44 \pm 0.28 \text{ GeV,} \\ & |\alpha[(\bar{a}_{\text{eff}}^e)_Y + (\bar{a}_{\text{eff}}^p)_Y + (\bar{a}_{\text{eff}}^e)_Y]| = 0.04 \pm 0.24 \text{ GeV,} \end{aligned} \quad (5)$$

via a reinterpretation¹³ of He/K comagnetometer b_μ results.¹⁴ Computational work on $\alpha(\bar{a}_{\text{eff}}^w)_J$ has also been done associated with the Cassini mission.¹⁵ Additional work has been done associated with the separation of $\alpha(\bar{a}_{\text{eff}}^w)_T$ and $(\bar{c}^w)_{TT}$ as well resulting in the independent constraints¹⁶ on $(\bar{c}^p)_{TT}$ and $(\bar{c}^n)_{TT}$ at the 10^{-6} level, $\alpha[(\bar{a}_{\text{eff}}^c)_T + (\bar{a}_{\text{eff}}^p)_T]$ and $(\bar{a}_{\text{eff}}^n)_T$ at the level of 10^{-6} GeV, and much stronger constraints on $(\bar{c}^e)_{TT}$ via nongravitational experiments. Ref. 9 summarizes all constraints discussed.

3. Outstanding proposed analysis

To date, 8 combinations of the 12 components of the $\alpha(\bar{a}_{\text{eff}}^w)_\mu$ coefficient have been constrained, and 4 of those constraints are weak. Existing experiments could improve the weak constraints by up to 6 orders of magnitude. Proposed experiments could improve these constraints by up to 11 orders of magnitude, and some could gain sensitivity to unconstrained combinations.

Analysis of existing data from the following experiments could provide up to the indicated order of magnitude improvement in sensitivities to spatial components of $\alpha(\bar{a}_{\text{eff}}^w)_\Xi$: torsion pendulum WEP,¹⁰ 6 orders of magnitude; super-conducting gravimeters,¹⁷ 6 orders; lunar laser ranging,¹⁸ 5 orders; Cassini data,¹⁵ 5 orders; and atom interferometry,^{11,19} 4 orders. If performed, the following proposed experiments could provide even greater improvement as indicated: space-based WEP,²⁰ up to 11 orders; Earth-based WEP,^{21,22} up to 10 orders; and gravimeters,²² up to 9 orders.

Gravitational tests with special types of matter could obtain sensitivity to additional unconstrained combinations. The 4 unconstrained combinations of $\alpha(\bar{a}_{\text{eff}}^w)_\Xi$ components for ordinary matter could be accessed with charged-matter tests.²³ Tests with higher-generation matter²⁴ of type w would attain sensitivity to many unconstrained associated coefficient components of $\alpha(\bar{a}_{\text{eff}}^w)_\Xi$. Tests with antimatter²⁵ also have the ability to separate special combinations³ of coefficients if sufficient sensitivity can be reached.

The above possibilities offer excellent prospects for improved tests of Lorentz symmetry, and provide the opportunity for significant progress in the ongoing search for new physics at the Planck scale.

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