Atomic and optical tests of Lorentz symmetry

Neil Russell

Physics Department, Northern Michigan University, Marquette, MI, USA
E-mail: nrussell@nmu.edu

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Abstract
This paper reports on the Fourth Meeting on Lorentz and CPT Symmetry, CPT '07, held in August 2007 in Bloomington, IN, USA. The focus is on recent tests of Lorentz symmetry using atomic and optical physics. Results presented at the meeting include improved bounds on Lorentz violation in the photon sector, and the first bounds on several coefficients in the gravity sector.

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1. Introduction

The AMO community has played a major role in testing Lorentz symmetry over the last decade. Much of this is due to the innovative design work of experimentalists, who have steadily improved the attainable levels of precision in various experiments. Exquisite tests of Lorentz symmetry in AMO and other areas have been performed with optical and microwave cavities [1, 2], with atomic clocks and masers [3], with torsion pendula [4, 5] and with Penning traps confining electrons or protons [6]. These endeavors have vigorously sought to test whether nature is exactly Lorentz symmetric.

The creation in the 1990s of a broad theoretical framework for Lorentz violation is a major reason for the surge of interest in studies of Lorentz symmetry. This framework, which spans the spectrum of quantum and gravitational physics, is called the Standard-Model Extension (SME) [7]. It has opened numerous avenues to probe Planck-scale physics, where Lorentz violations may occur, without the need to attain the $10^{19}$ GeV energies at which the theories of particle physics and gravitation are expected to merge.

Lorentz violations are possible, for example, in string theory with spontaneous symmetry breaking. This idea, of using a potential to spontaneously break Lorentz symmetry, thus enforcing a nonzero vacuum value for a tensor field, was introduced by Kostelecký and Samuel [8]. Several models for such fields have been created as useful test cases, and include the ones known as the bumblebee field and the cardinal field [9]. It is remarkable that AMO experiments, such as the ones mentioned above, are able in principle to achieve sensitivity to the vacuum expectation values of these fields. Alternative approaches to Lorentz violation include ones involving spacetime-varying fields [10], noncommutative field theories [11], quantum-gravity [12], branes [13], supersymmetry [14] and many others [15].

The goal of this paper is to provide the background and details of experimental and theoretical work on Lorentz violation in the area of AMO physics presented at the Fourth Meeting on CPT and Lorentz Violation, held in Bloomington, Indiana, in August 2007 [16]. A number of new bounds on SME coefficients were presented at the meeting. A full listing of the experimental measurements of the SME coefficients in all sectors can be found in [17].

2. The SME

The SME is defined at the level of the effective field-theory action $S_{SME}$, with a variety of Lorentz-violating terms appearing in the Lagrangian density $\mathcal{L}_{SME}$:

$$S_{SME} = \int \mathcal{L}_{SME} \, dt \, \vec{x}.$$  (1)

One way of evaluating the content of the Lagrangian density $\mathcal{L}_{SME}$ is by separating the gravity and matter sectors:

$$\mathcal{L}_{SME} = \mathcal{L}_{\text{matter}} + \mathcal{L}_{\text{gravity}}.$$  (2)

Terms in the gravitational piece $\mathcal{L}_{\text{gravity}}$ are constructed only from the basic gravitational fields. The choice of these is guided by the need for a realistic description of nature, which must include particles with spin.
spacetimes incorporate spinors in curved spacetimes and can be constructed using the vierbein and the spin connection [18], these are the chosen basic fields. The familiar gravitational fields, such as the curvature and the torsion, can be expressed in terms of the vierbein and the spin connection. The matter piece $L_{\text{matter}}$ consists of all other terms. It includes ones constructed from the spinors $\psi$ describing ordinary matter (protons, neutrons and electrons), gauge fields such as $A^\mu$ for the photon, and the fields describing particles that are not ‘ordinary’, like muons, mesons, neutrinos and so on. The terms in $L_{\text{matter}}$ can include the basic gravitational fields together with these matter fields, whereas $L_{\text{gravity}}$ is ‘pure’, containing only gravitational fields.

Lorentz violation in the flat-spacetime (Minkowski) limit with no torsion has been studied extensively since the basic theoretical framework was introduced [7]. In this limit, the metric $g_{\mu\nu}$ has nonzero constant values on the diagonal only, there are no gravitational fields to consider, and the only Lagrangian density of relevance is $L_{\text{matter}}$. The Lorentz-preserving part of this Lagrangian density is the standard model of particle physics, whereas the Lorentz-violating part contains terms with coefficients that can be experimentally probed.

For more than a decade, experimental limits have been placed on coefficients for Lorentz violation in the torsion-free Minkowski limit of the SME. In the case of ordinary matter and radiation, relevant studies include the ones mentioned above, as well as others involving high-speed ions [19], cosmological birefringence [20, 21] and satellite-mounted oscillators [22]. For other particles and fields in the Minkowski limit of the matter sector, theoretical and experimental studies include ones looking at muons [23, 24], neutral mesons [25], neutrinos [26], the Higgs [27] and baryogenesis [28]. A variety of astrophysical processes involving both ordinary and other matter place limits on Lorentz violation [29].

In the case of nonzero torsion, the Minkowski limit of the matter sector has recently been studied. Several new bounds on components of the torsion tensor have been found [30] based on experiments in the AMO field.

In the pure-gravity sector, the Lorentz-preserving part of $L_{\text{gravity}}$ contains the conventional Einstein–Hilbert Lagrangian from which the Einstein field equations follow when torsion is zero and no other terms are present. The Lorentz-violating terms in $L_{\text{gravity}}$ provide a framework for a variety of experimental tests of Lorentz symmetry in the context of pure gravity [31]. The first experimental measurements of coefficients for Lorentz-violating terms in this sector were presented at CPT ’07 [32, 33].

The following sections provide an overview of recent experiments and theory in each of these sectors, with emphasis on results relating to AMO physics that were presented at CPT ’07.

3. AMO Lorentz tests of the Minkowski limit of the SME

3.1. Couplings of fermions with the SME background

Since Lorentz-violating background fields are known to be small, the analysis of effects that might occur is readily handled using the perturbation theory. For most applications with ordinary fermionic matter, the unperturbed system is obtained from the Dirac equation with solutions being the spinors $\psi$. Many of the principles encapsulated in the Dirac equation have recently been studied with emphasis on atomic-interferometry-based tests of basic principles including Lorentz symmetry, the universality of free fall, locality, and the superposition principle [34]. Other issues such as stability and causality have been researched in this context, as well as in field theory [35]. A variety of couplings of fermions with Lorentz-violating background fields have been studied. For example, one term appearing in the lagrangian density is [7]

$$L_{\text{matter}} \supset b_\mu \psi \gamma_5 \gamma^\mu \psi.$$ (3)

Distinct coefficients $b_\mu$ are used to quantify Lorentz violation for each fermion. Perturbative analysis of this term can be used to find the shifts in the spectra of electrons in Penning traps [6], hydrogen and antihydrogen [36], atomic clocks and masers [3], torsion pendula [5], and other systems. Many of these experiments involve the comparison of highly stable frequencies with each other [37].

In the neutron sector of the SME, the most stringent bounds on Lorentz violation have been obtained using a He–Xe dual maser at the Harvard–Smithsonian Center for Astrophysics. Limits on symmetry breaking among the rotational components of the Lorentz group are at the level of $10^{-31} \text{GeV}$ [38] and, on the boost components, at the level of $10^{-27} \text{GeV}$ [39]. An improvement in precision of about an order of magnitude is expected after current upgrades are completed. These include upgraded temperature controls, optimized noble gas pressures and cell geometries, increased Zeeman frequency, proper spatial definition of masing ensembles and improved stability of the double-tuned resonator [40].

A group at Princeton University has designed, built and operated a potassium–helium co-magnetometer with sensitivity to electron, proton and neutron coefficients for Lorentz violation. The potassium and helium atoms are confined within a glass cell and controlled using optical pumping techniques. Using data taken over a period of 15 months, this magnetometer, dubbed CPT-I, has achieved excellent sensitivity to a variety of effects including sidereal signals that would be expected from a fixed Lorentz-violating background. Preliminary results include a bound at the level of $10^{-30} \text{GeV}$ on the equatorial components of the proton $b_\mu$ coefficient [41]. A second-generation co-magnetometer, CPT-II, is currently being implemented to achieve yet higher sensitivities. This device is mounted on a turntable, making possible cycle times of much less than a day. This is expected to much improve the sensitivity to sidereal effects. Other innovations have been introduced to improve sensitivities in various ways. These include shorter optical path lengths, reduction of convection noise in the oven area, evacuation of air from the optical path, and improved magnetic shielding. CPT-II is expected to surpass the sensitivity of CPT-I by several orders of magnitude [42].

Experiments with antihydrogen have the potential to find signals of Lorentz violation that are not accessible with other systems. There are three groups working on
antihydrogen physics at CERN: the ‘Antihydrogen Laser Physics Apparatus’ (ALPHA) collaboration, the ‘Atomic Spectroscopy and Collisions using Slow Antiprotons’ (ASACUSA) collaboration and the ‘Antihydrogen Trap’ (ATRAP) collaboration. ALPHA and ASACUSA were represented at CPT ‘07.

The ASACUSA collaboration has conducted several precision experiments using the laser spectroscopy of antiprotonic helium. The group has measured the antiproton-to-electron mass ratio to a precision of 2 parts per billion [43], which is within an order of magnitude of the proton-to-electron mass ratio found using a Penning-trap comparison of a proton and an electron. Theoretical studies of Lorentz violation in antihydrogen have shown that unsuppressed signals could potentially occur in the studies of Lorentz violation in antihydrogen have shown that unsuppressed signals could potentially occur in the comparison of the hyperfine spectral lines of hydrogen and antihydrogen [36]. The ASACUSA collaboration plans to measure the hyperfine lines of antihydrogen in a Stern–Gerlach beam arrangement [44]. The expected resolution is at the level of $10^{-21}$ GeV.

The ALPHA collaboration aims to produce trapped antihydrogen with the eventual goal of conducting precise comparisons of the spectra of antihydrogen and hydrogen. The group demonstrated the trapping of antiprotons from the CERN antiproton decelerator in 2006. The design involves a Penning–Malmberg trap featuring a magnetic octopole configuration [45] to confine positrons and antiprotons in the same region. Methods of cooling and compressing the plasmas to enhance the rate of antihydrogen formation are being investigated.

The Eöt-Wash group at the University of Washington in Seattle has investigated couplings of spin with Lorentz-violating SME background fields [4]. The apparatus used for this consists of a spin-polarized torsion pendulum suspended by a 75 cm tungsten fiber. It has minimal magnetic and gravitational moments, and a net number of polarized spins of the order of $10^{23}$, making it highly sensitive to the coupling of these spins with the Lorentz-violating background field $b_\mu$ for the electron. The component of this background that is parallel to the rotation axis of the Earth has been bounded at the level of a few parts in $10^{-30}$ GeV by this experiment. The limits it places on the two components in the equatorial plane are an additional order of magnitude tighter.

Another system where large numbers of spin-polarized atoms may be able to amplify Lorentz-violating effects is the Bose–Einstein condensate. Since this involves atoms that are bosonic, the statistical properties can be expected to be very different from fermionic systems. Under suitable conditions, spin-polarized Bose–Einstein condensates may be sensitive to Lorentz-violating background fields at a level comparable to other existing tests [46].

Space-based experimental tests of fundamental physics are motivated by their potential to reach higher precisions than earth-based ones and to probe otherwise inaccessible observables. A number of proposals and projects at various stages of development exist in the European Space Agency and NASA communities. These include the Laser Interferometer Space Antenna (LISA), its precursor LISA Pathfinder (LISAPF), the Grand Unification and Gravity Explorer (GAUGE), the Laser Astrometric Test of Relativity (LATOR), the Astronomical Space Test of Relativity using Optical Devices (ASTROD), the Odyssey Mission aimed at exploring gravity in the Solar System and the Matter-Wave Explorer of Gravity (MWXG) [47]. Technological advances making such missions attractive for physics experiments include the ability to create drag-free platforms using systems such as micronewton thrusters, and precision capacitive, magnetic and optical sensing of proof-mass behavior. Other proposals for high-precision space tests include ones based on atomic-clock comparisons [22].

A recent muon experiment at the Brookhaven National Laboratory, while not directly in the field of AMO physics, may be of interest since it has many similarities to the Penning-trap system. The E821 experiment, run by the $g − 2$ collaboration, measured the anomaly frequency of positive and negative muons stored in the AGS ring. Analysis of sidereal variations in these frequencies limited the equatorial-plane $b_\mu$ coefficients for Lorentz violation at the level of $10^{-24}$ GeV [23]. Further analysis is expected to be able to place constraints on a variety of combinations of muon coefficients for Lorentz violation.

3.2. Couplings of photons with the SME background

In the Minkowski limit of the SME without torsion, the following photon-sector term has been the primary focus of a number of experiments:

$$\mathcal{L}_{\text{matter}} \supset -\frac{1}{4} \epsilon_{\kappa \lambda \mu \nu} F^{\kappa \lambda} F^{\mu \nu}.$$ (4)

to date, most of the tests in this sector have focused on propagating electromagnetic fields, although practical tests are possible in statics [48]. After accounting for symmetries there are 19 independent components for the coefficients $\epsilon_{\kappa \lambda \mu \nu}$. There are ten linear combinations of these that imply birefringence, and these have been constrained tightly using observations of distant cosmological sources [20]. The remaining nine have been studied extensively in laboratory experiments with microwave and optical cavity oscillators. Experiments have placed bounds on linear combinations of these nine coefficients, denoted by $\tilde{k}_{e} e$ and $\tilde{k}_{o} o$. Recent results from two such experiments were presented at CPT ‘07.

An experiment at the University of Western Australia involves two cryogenic sapphire oscillators, rotated about the vertical axis with a period of 18 s. By taking data over a timescale of about 1 year, measurements have been made of all eight independent $\tilde{k}_{e} e$ and $\tilde{k}_{o} o$ components without any noncancellation assumptions [49]. A second experiment by this group at the University of Western Australia consists of a Mach–Zehnder microwave interferometer mounted on a rotating platform. After completion of the development stages, it is expected to measure $\tilde{k}_{e}$ at competitive levels [49].

An order of magnitude improvement in sensitivity is expected in an experiment at the Humboldt University in Berlin, Germany. It compares the optical frequencies in two orthogonal cavities created in a single block of fused silica [50]. The system is maintained in a thermally insulated and vibration isolated vacuum chamber, which is mounted on a turntable with a period of 45 s. This and other experiments have utilized such rotating turntables to improve precisions over earlier versions that relied on the rotation of the earth to
seek anisotropies. The preliminary results of this experiment place some of the tightest constraints on a variety of the $\kappa_{\nu}^{\mu \lambda \nu}$ and $\kappa_{\nu}^{\mu \lambda \nu}$ coefficients for Lorentz violation [17] and are listed in Table 1.

The results from geographically distant experiments, such as the ones discussed above, can be combined to obtain additional information. Furthermore, coordinate and field redefinitions can be used for establishing various links between results in different sectors of the SME. Recent work along these lines has led to several results [2].

Theoretical considerations of precision Doppler-shift experiments show that sensitivity to some coefficients for Lorentz violation, such as the $\epsilon_{\mu \nu}$ for protons and electrons, is possible in principle [51]. An experiment at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, has conducted a test of special relativity by measuring the Doppler shifts of beams of lithium atoms traveling at speeds of about 3–6% of the speed of light [19]. One of the results of this experiment is

$$|\kappa_{\mu \nu}| < 8.4 \times 10^{-8},$$

a bound on Lorentz violation in the photon sector. Additional sensitivity, to components in the fermion sector, may be possible through the use of circularly polarized lasers.

Higher-order couplings constructed from the electromagnetic fields $A_{\mu}$ or $F_{\mu \nu}$, and derivatives, have been studied recently [21]. They include, for example, the term

$$L_{\text{matter}} \supset - \frac{1}{2} \epsilon_{\mu \nu \lambda \rho} \left( \kappa_{\nu}^{(5 \mu \lambda \nu)} \right)^{\mu} \nabla_{\lambda} F_{\mu \nu}.$$  

The constant coefficient $\left( \kappa_{\nu}^{(5 \mu \lambda \nu)} \right)^{\mu}$ has the dimension of inverse mass, which ensures that the full term is of dimension four in the mass. In general, there is an infinite number of terms constructed in this way by the inclusion of further derivatives. Effects of such terms include vacuum birefringence, and recent work has placed limits on the coefficients $\left( \kappa_{\nu}^{(5 \mu \lambda \nu)} \right)^{\mu}$ and higher-order coefficients by studying polarization data from observations of the cosmic microwave background [21].

### 4. AMO Lorentz tests in the gravitational sector

#### 4.1. Pure gravity sector

The first constraints on pure-gravity sector SME coefficients were presented at CPT '07 by two experimental groups, one working with lunar-laser ranging, and the other with atomic interferometry. The SME terms of interest in these experiments appear in the Lagrangian density in the form [31]

$$L_{\text{gravity}} \supset \frac{1}{16\pi G} F_{\mu \nu} R^{\mu \nu},$$

where $G$ is the universal gravitational constant. This term couples the traceless Ricci tensor $R^{\mu \nu}_{\text{traceless}}$, obtained by contraction of the curvature tensor $R_{\mu \nu \rho \sigma}$, to a Lorentz-violating background expressed as $s^{\mu \nu}$. The coefficients $s^{\mu \nu}$ have vacuum expectation values $\bar{s}^{\mu \nu}$ induced by spontaneous violation of local Lorentz symmetry. The fluctuations of fields like $s^{\mu \nu}$ about the vacuum expectation values $\bar{s}^{\mu \nu}$ have fascinating implications for physics [9]. The coefficients of interest at present are $\bar{s}^{\mu \nu}$, which are traceless and antisymmetric and so have nine independent values.

A group at Stanford University has used a highly sensitive atomic gravimeter to place bounds on combinations involving the $\bar{s}$ coefficients and photon-sector coefficients. The outstanding precision of gravimeters based on atom interferometry stems from the ability of neutral atoms to approach a freely falling reference frame with high accuracy, and the ability of lasers to interrogate the motion with fantastic precision. The Stanford group controls and measures the behavior of matter waves formed using clouds of Cs atoms. The device has resolved the acceleration of gravity more than three times better than the best previously reported value [33]. Their results are given in Table 2.

A Harvard group presented results of an analysis of more than 30 years of lunar laser-ranging data, constraining six independent combinations of $\bar{s}$ coefficients at the level of $10^{-8}$ and $10^{-11}$. These data were collected primarily at the McDonald Laser-Ranging Station in Texas, USA, and the Côte d’Azur station in Grasse, France, during the period spanning September 1969 and December 2003. Their results are reported in [32], and are summarized in Table 3. The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) [52] is expected to improve on these results by

### Table 1. Photon-sector results reported by the Humboldt University group [30]. The value of $\beta$ is $10^{-4}$.

| Combination | Result       |
|-------------|--------------|
| $(\kappa_{\nu})_{\nu}^{\mu \lambda \nu}$ | $(-0.1 \pm 0.6) \times 10^{-17}$ |
| $(\kappa_{\nu})_{\nu}^{\mu \lambda \nu}$ | $(-2.0 \pm 0.9) \times 10^{-17}$ |
| $(\kappa_{\nu})_{\nu}^{\mu \lambda \nu}$ | $(-0.3 \pm 1.4) \times 10^{-17}$ |
| $(\kappa_{\nu})_{\nu}^{\mu \lambda \nu}$ | $(-2.0 \pm 1.7) \times 10^{-17}$ |
| $(\kappa_{\nu})_{\nu}^{\mu \lambda \nu}$ | $(0.2 \pm 3.1) \times 10^{-17}$ |
| $\beta(\kappa_{\nu})_{\nu}^{\mu \lambda \nu}$ | $(2.5 \pm 2.5) \times 10^{-17}$ |
| $\beta(\kappa_{\nu})_{\nu}^{\mu \lambda \nu}$ | $(1.5 \pm 1.7) \times 10^{-17}$ |
| $\beta(\kappa_{\nu})_{\nu}^{\mu \lambda \nu}$ | $(1.0 \pm 1.5) \times 10^{-17}$ |

### Table 2. Pure-gravity sector results reported by the Stanford University group, using a Cesium-based atomic gravimeter [33]. The $\sigma$ coefficients are a combination of pure-gravity sector $s$ coefficients and photon-sector coefficients.

| Combination | Result       |
|-------------|--------------|
| $\sigma_{XY} - \sigma_{YX}$ | $(-5.6 \pm 2.1) \times 10^{-9}$ |
| $\sigma_{XY}$ | $(-0.9 \pm 79) \times 10^{-9}$ |
| $\sigma_{YX}$ | $(-13 \pm 17) \times 10^{-9}$ |
| $\sigma_{YY}$ | $(-61 \pm 38) \times 10^{-9}$ |
| $\sigma_{TT}$ | $(-2.0 \pm 4.4) \times 10^{-5}$ |
| $\sigma_{TX}$ | $(5.4 \pm 4.5) \times 10^{-5}$ |
| $\sigma_{TZ}$ | $(1.1 \pm 26) \times 10^{-5}$ |

### Table 3. Pure-gravity sector results reported by the Harvard–Smithsonian group, based on archival lunar laser-ranging data [32].

| Combination | Result       |
|-------------|--------------|
| $\bar{s}_{11}^{11} - \bar{s}_{22}^{12}$ | $(1.5 \pm 0.9) \times 10^{-10}$ |
| $\bar{s}_{12}$ | $(6.9 \pm 4.5) \times 10^{-11}$ |
| $\bar{s}_{02}$ | $(-5.2 \pm 4.8) \times 10^{-7}$ |
| $\bar{s}_{01}$ | $(-0.8 \pm 1.1) \times 10^{-5}$ |
| $\bar{s}_{\Omega_{\mu \nu}}$ | $(0.2 \pm 3.9) \times 10^{-7}$ |
| $\bar{s}_{\Omega_{\mu \nu}}$ | $(-1.3 \pm 4.1) \times 10^{-7}$ |
about an order of magnitude. The telescope at Apache Point in New Mexico, USA, can detect reflections from the lunar retroreflector arrays even in daylight conditions, and ranging can be achieved at the millimeter level.

4.2. Couplings of matter with gravitational fields

Terms in $\mathcal{L}_{\text{matter}}$ that couple matter to gravitational fields are currently being studied [53] since they offer the possibility of obtaining new sensitivities to Lorentz violation in, for example, the fermion sector. One approach is to start from the relativistic theory using the spin connection and the vierbein [18] as the basic gravitational objects, and the Dirac fermion $\psi$ and the photon field $A^\mu$ as the basic nongravitational objects. One can then extract the nonrelativistic limit using, for example, a Fouldy–Wouthuysen transformation, to obtain a formalism appropriate for direct experimental analysis. Another approach of interest is the classical theory involving point-particles rather than wave functions. Results are expected to provide the first direct sensitivities to the $a_\mu$ coefficients for the proton, neutron and electron [53].

Torsion is a basic field in Riemann–Cartan theories of gravity, giving twisting degrees of freedom that are distinct from curvature. This field $T^T_{ab\mu}$, which has 24 independent components, can be nonzero even in the Minkowski flat-spacetime limit. Couplings of fermions and other particles with this field have similarities to couplings of fermions with Lorentz-violating background fields in the SME. This fact has been exploited recently to deduce new bounds on 15 of the torsion components and the most stringent bounds on the four minimally coupled torsion components [30]. The latter four bounds, on the axial components $A^\mu = e^{\Phi T}_a T_{ab\mu}/6$, are

$$|A_T| < 2.9 \times 10^{-27} \text{ GeV}, \quad |A_X| < 2.1 \times 10^{-31} \text{ GeV},$$

$$|A_Y| < 2.5 \times 10^{-31} \text{ GeV}, \quad |A_Z| < 1.0 \times 10^{-29} \text{ GeV}.$$

These results are based on experiments with a spin-polarized torsion pendulum [4], and with a helium–xenon dual maser [39].

5. Closing

The SME is an umbrella framework for tests of Lorentz symmetry in nature. By setting up a general coefficient space for all Lorentz violations it has allowed new tests of Lorentz symmetry to be identified across the sectors of physics, and made possible the comparison of Lorentz tests from vastly differing systems. Experiments, many of them in the sphere of AMO physics, have delved into the SME coefficient space for the last decade. On the theoretical front, recent research has focused on the gravitational sector of the SME. This paper reports primarily on AMO Lorentz-symmetry tests featured in presentations made at the CPT ’07 meeting held in Indiana in August 2007 [16]. Included are bounds on a number of coefficients measured for the first time in the pure gravity sector. This sector of the SME is likely to generate further experimental activity as a number of unexplored regions offer the alluring prospect of finding Lorentz violations.

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