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New Tests of General Relativity

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The last decade has seen a rapid increase in the number of precision tests of relativity. This research has been motivated by the intriguing possibility that tiny deviations from relativity might arise in the underlying theory that is widely believed to successfully mesh General Relativity (GR) with quantum physics [1, 2]. Many of these tests have been analyzed within an effective field theory framework which generically describes possible deviations from exact relativity [3] and contains some traditional test frameworks as limiting cases [4]. One part of the activity has been a resurgence of interest in tests of relativity in the Minkowski-spacetime context, where Lorentz symmetry is the key ingredient. Numerous experimental and observational constraints have been obtained on many different types of relativity deviations involving matter [1]. Another part, which has developed more recently, has seen the effective field theory framework extended to include the curved spacetime regime [5], and recent theoretical work within this framework has shown that there are many unexplored ways in which the foundations of GR can be tested [6, 7]. Qualitatively new signals for deviations from local Lorentz symmetry involving lunar laser ranging observations [8] and atom interferometry experiments [9] have already been analyzed within this framework, and many exciting new possibilities exist for future work including proposed Weak Equivalence Principle (WEP) tests.

In the context of effective field theory in curved spacetime, relativity violations of these types can be described by an action that contains the usual Einstein-Hilbert term, a matter action, plus a series of terms describing Lorentz violation for gravity and matter. One useful limiting case of this construction has an action of the form

$$S_g = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}\; R \;+\; \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}\; s_{\mu\nu}R_T^{\mu\nu} \;+\; S'. \tag{1}$$

In this expression the first term is the conventional Einstein-Hilbert action for GR, while the second term is the leading "pure-gravity" Lorentz-violating coupling to the traceless Ricci tensor $R_T^{\mu\nu}$, which is controlled by 9 coefficient fields denoted $s_{\mu\nu}$. The last term S' includes possible dynamical terms for the coefficient fields $s_{\mu\nu}$. Lorentz violation in the classical point-mass limit of the matter sector is described by the action

$$S_M = \int d\lambda \left(-m\sqrt{-(g_{\mu\nu}+2c_{\mu\nu})u^\mu u^\nu} - a_\mu u^\mu \right), \tag{2}$$

where $u^\mu = dx^\mu/d\lambda$ is the worldline tangent and $c_{\mu\nu}$ and a_μ are the coefficient fields that control local Lorentz violation for matter. In contrast to $s_{\mu\nu}$, these coefficients depend on the type of point mass (particle species) and so they can also violate WEP. Perfect local Lorentz symmetry for gravity and matter is restored when the coefficients $s_{\mu\nu}$, $c_{\mu\nu}$, and a_μ vanish.

It turns out that consistency with Riemann geometry imposes the requirement that these relativity violations arise via so-called spontaneous Lorentz-symmetry breaking [5]. In this scenario, tensor fields in the underlying theory spontaneously acquire background values through a dynamical process. In the context of the pure-gravity and matter-gravity couplings in 1 and 2, the coefficient fields $s_{\mu\nu}$, $c_{\mu\nu}$, and a_μ can then be expanded around their background values $\bar{s}_{\mu\nu}$, $\bar{c}_{\mu\nu}$, and $\bar{a}_\mu$. The spontaneous breaking of Lorentz symmetry leaves a modified spacetime metric $g_{\mu\nu}$ and modified point-particle equations of motion. These results have been obtained in the linearized gravity limit and the results rely only on the vacuum values $\bar{s}_{\mu\nu}$, $\bar{c}_{\mu\nu}$, and $\bar{a}_\mu$. Calculations of observables in the post-newtonian limit can then reveal the dominant signals for Lorentz violation controlled by these coefficients.

Several novel features of the post-newtonian limit arise in this effective-field framework. Some of the effects can be matched to the well-established PPN formalism [11], but others lie outside it [6, 10]. Thus the effective-field formalism complements and extends the large body of analysis that exists within the PPN framework, revealing new directions to explore via the $\bar{s}_{\mu\nu}$, $\bar{c}_{\mu\nu}$, and $\bar{a}_\mu$ coefficients. The matter coefficients $\bar{c}_{\mu\nu}$ and $\bar{a}_\mu$, which can depend on particle species, contribute terms directly to the post-newtonian metric. This implies, for example, that two (chargeless) point-like sources with the same total mass but different composition yield gravitational fields of different strength. The coefficients for Lorentz violation $\bar{c}_{\mu\nu}$ and $\bar{a}_\mu$ also modify the equations of motion for matter, thus implying that they also control WEP violations.

From the post-newtonian metric and the standard geodesic equation for test bodies, the primary effects due to the nine coefficients $\bar{s}_{\mu\nu}$ can be obtained. Tests that can measure these coefficients include Earth-laboratory tests with gravimeters, torsion pendula, and short-range gravity experiments. Space-based tests include lunar and satellite laser ranging, studies of the secular precession of orbital elements in the solar system and with binary pulsars, and orbiting gyroscope experiments. In addition, classic effects such as the time delay and bending of light near a massive body are affected.

Constraints on the $\bar{s}_{\mu\nu}$ coefficients have already been reported. The main observable effects of Lorentz violation in the Earth-Moon orbit are oscillations in the lunar range. For example, one such unconventional oscillation occurs at a frequency of twice the mean orbital frequency, and can be traced to the violation of the conservation of angular momentum for the two-body system. Using lunar laser ranging data spanning over three decades, Battat, Chandler, and Stubbs placed constraints on 6 combinations of the $\bar{s}_{\mu\nu}$ coefficients at levels of 10^{-7} to 10^{-10} [8]. The local acceleration on the Earth's surface becomes modified in the presence of the $\bar{s}_{\mu\nu}$ accelerations, leading to 7 measurable coefficients in Earth-laboratory experiments. These coefficients were measured by Müller *et al.* using an atom interferometer as a (vertical) gravimeter, resulting in 7 constraints at the level of 10^{-6} to 10^{-9} [9]. The novel effects of the coefficients $\bar{s}_{\mu\nu}$ would also result in a horizontal acceleration modulated by the Earth's sidereal rotation frequency and its orbital frequency. A suitable interferometer can potentially measure this effect and may be used for future work.

For bodies interacting gravitationally, modifications to the standard geodesic equations of motion result from the coefficients $\bar{c}_{\mu\nu}$ and $\bar{a}_\mu$, which violate Lorentz symmetry and WEP [7]. Ground-based gravimeter, atom interferometry, and WEP experiments are among the existing and proposed tests that can probe these coefficients. Lunar and satellite laser ranging observations as well as measurements of the perihelion precession of the planets are also potentially of interest.

Space-based WEP tests are among the most sensitive tests for probing the $\bar{c}_{\mu\nu}$ and $\bar{a}_\mu$ coefficients. The relative acceleration of two test bodies of different composition is the observable of interest for these tests. Some novel time-dependent effects arise when the relative acceleration is calculated in the satellite reference frame in the presence of the coefficients $\bar{c}_{\mu\nu}$ and $\bar{a}_\mu$. In the effective field theory approach to describing Lorentz violation, the standard reference frame for reporting measurements is the Sun-centered celestial equatorial reference frame or SCF for short. Oscillations in the relative acceleration occur at a number of different frequencies including multiples and combinations of the satellite's orbital and rotational frequencies, as well as the Earth's orbital frequency, upon relating the satellite frame coefficients to the SCF. The extraction of Lorentz-violating amplitudes independent of the standard tidal effects can be acheived with this time dependence, and up to 9 independent combinations of the coefficients $\bar{c}_{\mu\nu}$ and $\bar{a}_{\mu}$ can be measured, which goes beyond the commonly used $\delta a/a$ parameterization for WEP tests. Future tests of particular interest are the STEP [12], MicroSCOPE [13], and Galileo Galilei [14] experiments. These tests offer sensitivities ranging from 10^{-7} GeV to 10^{-16} GeV for $\bar{a}_{\mu}$ coefficients and 10^{-9} to 10^{-16} for $\bar{c}_{\mu\nu}$ coefficients.

In conclusion, recent theoretical work within an effective field theory framework has revealed many new possibilities for testing GR. This framework systematically categorizes different types of local Lorentz violations for gravity and matter, including some types that also violate WEP. Calculations of observables in this framework have been performed and they reveal measurable signals for deviations from perfect local Lorentz symmetry controlled primarily by the coefficients $\bar{s}_{\mu\nu}$, $\bar{c}_{\mu\nu}$, and $\bar{a}_{\mu}$. For ordinary matter consisting of protons, neutrons, and electrons, there are 39 independent quantities in $\bar{c}_{\mu\nu}$ and $\bar{a}_{\mu}$, while $\bar{s}_{\mu\nu}$ contains 9 quantities. Already, 8 of the 9 coefficients in $\bar{s}_{\mu\nu}$ have been measured and the results are so far consistent with GR. However, future tests probing the coefficients $\bar{s}_{\mu\nu}$, $\bar{c}_{\mu\nu}$, $\bar{a}_{\mu}$ may reveal minuscule deviations from GR that would provide a signal from an underlying unified theory of physics.

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