Lorentz and CPT Tests with Low-Energy Precision Experiments

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Ultrahigh-precision measurements in small experiments performed at low energies are currently experiencing a surge in importance for probing the boundaries of the established laws of physics. This surge can partly be attributed to a rapid gain in sensitivity, which may in some circumstances be considered to provide access to the Planck scale. Lorentz- and CPT-invariance studies form a large component of such efforts: these symmetries underpin essential physics features of numerous systems, they allow comparative tests, and departures from these symmetries are accommodated in various theoretical approaches to underlying physics. The last two decades have witnessed a significant rise in experimental and theoretical activity in this field, and ongoing and proposed endeavors as well as open questions point to a future increase in the vitality of this research. This Letter highlights some of the recent developments and promising opportunities for Lorentz and CPT tests in the coming years.

Basics. Experimental research in fundamental physics is often associated with the idea that new degrees of freedom may become excited when the energy scale of the physics processes in question is raised. The discovery potential, e.g., at accelerators, is therefore tied to the rate at which the center-of-mass energy can be increased. Alternatively, fundamental physics can also be uncovered via indirect effects at lower energies without necessarily exciting new degrees of freedom, but with the requirement of ultrahigh sensitivities. The current rate at which these sensitivities are being increased far outpaces the energy gains possible with colliders. Low-energy high-precision experimentation therefore represents a truly promising and burgeoning, complementary avenue in the pursuit of more fundamental physics.

Lorentz and CPT symmetry are particularly well suited for exploration in this context: they represent fundamental principles in established physics, departures from these principles are possible in various approaches to new physics [1, 2], and a majority of low-energy high-precision measurements are sensitive to such effects. Many theoretical and experimental efforts along these lines are based on the Standard-Model Extension (SME) [3, 4]. This effective-field-theory framework incorporates both the usual Standard Model and General Relativity as limiting cases and therefore permits the identification, analysis, and comparison of virtually all Lorentz and CPT tests. With hundreds of past experimental constraints on Lorentz and CPT violation [5], this topic has been on a climbing trajectory and is poised to gain further momentum in the coming decade. Below are brief descriptions of physical systems with demonstrated impact on the field and substantial future promise for record sensitivities.

Antihydrogen measurements. The availability of cold antiprotons at CERN's Antiproton Decelerator has paved the way for unprecedented studies of antihydrogen. One class of these is concerned with antihydrogen precision spectroscopy: the ALPHA and ASACUSA experiments are designed for such antihydrogen measurements, including 1S–2S, 1S–2P, and hyperfine spectroscopy, and compare these to the corresponding frequencies in ordinary hydrogen for a direct CPT test [6]. These efforts are well underway with the completion of various extraordinary milestones, such as a 1S–2S measurement just three orders of magnitude shy of the corresponding accuracy in hydrogen. Interpreted in terms particle–antiparticle absolute mass differences, this measurement exceeds, for the first time, the precision attained in neutral-kaon interferometry, a system considered the particle-physics standard for CPT tests [7, 8]. Another class of antihydrogen experiments seeks to study the interaction of antimatter with gravity. For example, AEgIS, ALPHA-g, and G-BAR at CERN will be employing complementary methods to measure the rate of free fall of antihydrogen in the gravitational field [6], and a proposal for a further antimatter gravity experiment at Fermilab exists [9]. Both spectroscopic and free-fall efforts are currently straining at the leash to resume antihydrogen studies when the new Extra-Low Energy Antiproton Ring ELENA goes into operation at CERN in 2021. The community will then be within striking distance for qualitatively novel Lorentz and CPT tests within effective field theory.

Clock comparisons. Some of the sharpest Lorentz-violation bounds for protons, neutrons, electrons, and photons, which can reach sensitivities of up to 10^{-29} for certain types of light-speed anisotropies, stem from atomic clocks, atom magnetometry, and other precision spectroscopy experiments [10–21]. Clock comparisons involve performing high-precision comparative measurements of at least two transitions in atomic clocks as the Earth rotates: anisotropies arising from violation of Lorentz symmetry are predicted to produce orientation dependence in the difference between the two clock frequencies [22]. On the other hand, clock-comparison experiments performed in space aboard an orbiting platform, such as the International Space Station, with a laboratory frame that is both rotating and boosted provide sensitivities to forms of Lorentz breaking that are not readily testable in terrestrial laboratories [23]. The last decade has witnessed remarkable improvements in optical clocks and trapped-ion control that were utilized for numerous Lorentz-symmetry tests with extraordinary precision [11, 12, 15, 17]. In the future, this trend is expected to pick up pace with novel measurement schemes specifically designed to improve clock comparisons by orders of magnitude [24] and rapid improvements in clock precision and the development of new clock technologies [25].

Cold neutrons. Due its unique combination of physical properties, such as neutrality, small Compton wavelength, low polarizability, and high matter-penetration power, the neutron has long been employed as an indispensable tool in experimental research including Lorentz and CPT tests. For example, ultrahigh sensitivities to SME coefficients have been attained via measurements involving neutron-spin motion [26], neutron–antineutron oscillations [27], and gravitationally bound neutrons [28]. With various prospective nEDM measurements at different laboratories, such as PSI [29], ILL [30], TRIUMF [31], and SNS [32], current constraints on neutron SME coefficients can be improved by up to about two orders of magnitude, and previously unexplored SME observables can be measured. Likewise, the planned NNbar experiment at ESS will provide unprecedented sensitivity to neutron–antineutron oscillations [33].

Matter-wave interferometry. Lorentz breakdown can also deform the interaction of gravity with matter [34–37]. The ensuing physical effect can therefore be explored with experimental techniques such as superconducting gravimeters and space-based missions [38–40], which continue to increase in sensitivity, and proposals for gravitational measurements with exotic systems, such as ones involving antimatter or higher generations [41–43], exist. Gravitational phenomena are also amenable to studies with matter-wave interferometers [44] and have already placed bounds on Lorentz violation when used as gravimeters [45] and as equivalence-principle tests [46]. Future atom-interferometer methods are expected to compete with these recent advances [44, 47]. In particular, capabilities such as large wave-packet separation in both space and momentum [48, 49] as well as simultaneous multispecies operation [47, 50, 51], promise leaps in both sensitivity and versatility of SME tests [52]. Extrapolating such developments, matter interferometry will be positioned at the forefront of probing Lorentz symmetry at the interface of matter and gravity in the coming years.

Muon physics. The history of Lorentz tests involving muons dates back almost 80 years to a measurement establishing relativistic time dilation. At present, muon systems are again scrutinized for new physics including Lorentz and CPT breakdown [41, 53]. One of these systems is muonium: its theoretical tractability and experimental accessibility have stimulated clean spectroscopic Lorentz and CPT tests with unique sensitivities to SME coefficients [54]. The future ground-state hyperfine spectroscopy by MuSEUM at J-PARC [55], the proposed determination of the 1S–2S transition frequency by Mu-MASS at PSI [56], and proposals for gravity measurements with muonium [42, 43] are clear indications for the growing vitality of the field in the coming years. Muon-spin precession represents a further experimental avenue in this context because spin motion is affected by various SME coefficients. This idea has already provided the basis for past analyses of muon $g-2$ data [41, 53, 57]. Future studies of μ^+ spin motion, such as Muon $g-2$ at Fermilab [58] and E34 at J-PARC [59], are in an exquisite position to sharpen existing Lorentz and CPT tests and access unconstrained SME observables [60]. An additional μ^- run at the Fermilab experiment would permit a direct CPT test, further broadening the scope of such efforts.

Penning-trap tests. Penning traps permit the isolation and investigation of individual charged particles and antiparticles. Lorentz and CPT tests with such devices are typically based on two types of measurements: sidereal time variations in the cyclotron and anomaly frequencies of trapped particles as the Earth rotates about its axis and instantaneous anomaly-frequency comparisons between particles and antiparticles. Numerous past studies have contributed to bounds on Lorentz and CPT violation that can be considered as probing the Planck regime [61–71]. Efforts in this field are bound to gain even further momentum in the future. For example, prospective upgrades at the BASE experiment, such as quantum-logic based spin readout [72] and a portable antiproton trap [73], will allow access to a much enlarged set of Lorentz- and CPT-breaking observables as well as substantial gains in sensitivity.

Resonant cavities. Lorentz tests with electromagnetic resonant cavities are modern versions of the classic Michelson–Morley experiment [74] and provide high sensitivities to the photon's SME coefficients. They typically compare the resonant frequencies of two cavities at different orientations and look for variations as the cavities are rotated or boosted. To date, experiments utilizing microwave cavities [75–77], optical cavities [78, 79], ring resonators [80–83], and acoustic cavities [84] have placed tight constraints on deviations from perfect Lorentz invariance. The LIGO interferometer has also been used to perform a more traditional Michelson–Morley experiment [85]. The last two decades have seen sensitivities in cavity experiments improve by orders of magnitude and an ever expanding reach into different forms of Lorentz violation [77, 82, 83]. This trend is expected to continue in future experiments, including those performed in space [86].

Short-range-interaction studies. Precision measurements set up to probe the gravitational inverse-square law and search for novel interactions typically exhibit intrinsic geometrical orientations, such as specific arrangements of test bodies. This feature makes them also ideal candidates for Lorentz and CPT tests: laboratory motion, such as sidereal revolution about the Earth's axis, typically changes this orientation, opening the possibility to detect fundamental anisotropies in the physics of the system under investigation [87]. This idea has produced some of the best experimental constraints on the SME's gravity sector [88], and planned experimental upgrades [89] provide further impetus for future efforts along these lines. An additional idea in this context concerns experiments with a spin-polarized torsion pendulum [90]. The corresponding measurements have placed stringent limits on spatial-anisotropy coefficients [91–93], and the ongoing improvement of such methods [94, 95] bodes well for continued activity in this field in the coming decade.

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