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Some fundamental physics experiments using atomic clocks and sensors

Quelques expériences de physique fondamentale faisant appel aux horloges et capteurs atomiques

Christine Guerlin [a,*], Pacôme Delva [b], Peter Wolf [b]

[a] *Laboratoire Kastler Brossel, ENS-PSL Research University, CNRS, UPMC-Sorbonne Universités, Collège de France*
[b] *SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61, avenue de l'Observatoire, 75014 Paris, France*

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ABSTRACT

We present several experiments in fundamental physics that use atomic clocks and sensors together with high performance time/frequency transfer methods. Our account is far from being exhaustive and instead concentrates on a chosen subset of present and future experiments, whilst providing some theoretical background. We only give very brief overviews of the experiments and theories, but provide ample references for the interested reader.

RÉSUMÉ

Nous présentons plusieurs expériences en physique fondamentale qui utilisent les horloges et les capteurs atomiques en combinaison avec des méthodes de transfert en temps/fréquence de haute performance. Notre revue est loin d'être exhaustive et se concentre plutôt sur un sous-ensemble choisi d'expériences actuelles et futures, tout en fournissant un certain *background* théorique. Nous nous bornons à donner de brefs survols des expériences et des théories, mais fournissons d'amples références bibliographiques pour le lecteur intéressé par le sujet.

1. Introduction

In our present understanding, and at its most fundamental level, physics is based on two theories: the Standard Model of particle physics (SM) that describes electromagnetism and the (strong and weak) nuclear interactions, and General Relativity (GR) that accounts for all gravitational phenomena. In spite of the overwhelming success of these two theories in describing much of the observed universe, a number of open issues, both theoretical and experimental remain.

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[*] Corresponding author.
E-mail address: christine.guerlin@lkb.ens.fr (C. Guerlin).

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The assumed validity of GR at cosmological scales, together with a hypothesis of homogeneity and isotropy, have led to the "concordance model" of cosmology, referred to as the Λ-CDM model, which is in agreement with all present-day observations at large scales, notably the most recent observations of the anisotropies of the cosmic microwave background by the Planck satellite [1]. However, important difficulties remain, in particular the necessary introduction of dark energy, described by a cosmological constant Λ, and of cold dark matter, made of some unknown, stable particle, which is not accounted for in the SM.

On the theoretical side, the SM is a quantum field theory, whilst GR, as well as many other alternative theories of gravitation, are classical. As such, they are fundamentally incomplete, because they do not include quantum effects. Most physicists agree that GR and SM are only low-energy approximations of a more fundamental theory that remains to be discovered, and that would provide a unified description of all interactions. Most attempts at such a unified theory lead to tiny violations of the basic principles of GR and/or the SM, in particular the Einstein Equivalence Principle (EEP), at a, in general unknown, level of accuracy. It is the aim of high-accuracy fundamental physics experiments, like the ones described here, to search for first experimental hints of such modifications by making use of the outstanding performance provided by modern time/frequency metrology.

In this contribution we concentrate on some fundamental physics experiments that have been carried out over the last years, and are planned for the future, using atomic clocks and sensors together with time/frequency transfer at LNE–SYRTE and worldwide. After a short introduction in Section 2 (for more details, see, e.g., [2,3]), we give a brief description of some theoretical frameworks that allow the analysis and intercomparison of different experiments that test the EEP (Section 3), and then describe the experiments and their results in those frameworks (Sections 4 to 6). Due to the space limitations we cannot give details of the experiments and the reader is referred to the references for further reading. We also leave out some experiments for lack of space, such as tests of Lorentz invariance using the cryogenic oscillator at LNE–SYRTE [4–8], searches for position and boost dependence using the LNE–SYRTE fountains vs. H-maser comparisons [9], or tests that are described in the article entitled "Atomic fountains and optical clocks at SYRTE: status and perspectives" in the present volume (e.g., searches for the variation of fundamental constants).

2. The Einstein equivalence principle

The Einstein Equivalence Principle (EEP) is the foundation of all curved space–time or "metric" theories of gravitation, including of course GR. It divides gravitational theories into two classes: metric theories, those that embody EEP and non-metric theories, those that do not. This distinction is fundamental, as metric theories describe gravitation as a geometric phenomenon, namely an effect of curvature of space–time itself rather than a field over space–time, quite unlike any of the other known interactions. It might thus appear unnatural to use a metric theory for gravitation, so different from the formalisms of the other interactions, and indeed most unification attempts cast doubt on precisely this hypothesis and thus on the validity of the EEP.

Following Will [10,11] the EEP is generally divided into three sub-principles: the Weak Equivalence Principle (WEP) also known as the Universality of Free Fall (UFF), Local Lorentz Invariance (LLI), and Local Position Invariance (LPI) closely related to the Universality of Clock Rates (UCR). The EEP is satisfied if and only if all three sub-principles are satisfied. Below we describe these three sub-principles:

1. WEP (or UFF) states that if any uncharged test body[1] is placed at an initial event in space–time and given an initial velocity there, then its subsequent trajectory will be independent of its internal structure and composition. The most common test of WEP consists in measuring the relative acceleration of two test bodies of different internal structure and composition freely falling in the same gravitational field. If WEP is satisfied, that relative acceleration is zero;
2. LLI states that the outcome of any local non-gravitational test experiment is independent of the velocity and orientation of the (freely falling) apparatus. Tests of LLI usually involve a local experiment (e.g., the comparison of the frequency of two different types of clocks) whose velocity and/or orientation is varied in space–time. LLI is verified if the result of the experiment is unaltered by that variation;
3. LPI states that the outcome of any local non-gravitational test experiment is independent of where and when in the Universe it is performed. Tests of LPI usually involve a local experiment (e.g., the measurement of a fundamental constant, or the comparison of two clocks based on different physical processes) at different locations and/or times. In particular, varying the local gravitational potential allows for searches of some anomalous coupling between gravity and the fields involved in the local experiment. A particular version of LPI tests, known as test of the gravitational redshift, uses the same type of clock, but at two different locations (different local gravitational potentials) and compares them *via* an electromagnetic signal (Pound and Rebka type of experiment [12]). Then it can be shown (see Section 2.4c in Ref. [10]) that the measured relative frequency difference is equal to $\Delta U/c^2$ (where ΔU is the difference in gravitational potential) if and only if LPI is satisfied.

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[1] By uncharged test body is meant an electrically neutral body whose size is small enough that the coupling to inhomogeneities in the gravitational field can be neglected.

Although the three sub-principles seem very different in their phenomenological consequences, it was realized quite early that any self-consistent gravitational theory is very likely to contain connections between them. This has become known as Schiff's conjecture [13], formulated around 1960. Loosely stated, the Schiff conjecture implies that if one of the three sub-principles is violated, then so are the other two.

Schiff's conjecture has given rise to much debate, in particular concerning its empirical consequences and the relative merit of tests of the different sub-principles. Whilst it is true that any theory respecting energy conservation (e.g., based on an invariant action principle) must satisfy Schiff's conjecture, the actual quantitative relationship between violation of the sub-principles is model dependent and varies as a function of the mechanism used for the violation (see [2,3] for a more detailed discussion and examples). As a consequence, it is not known *a priori* which test (WEP, LLI, or LPI) is more likely to first detect a violation and the most reasonable approach is to perform all possible tests of the three sub-principles.

3. Alternative theoretical frameworks

To date, no violation of EEP and its sub-principles has been detected. However, each experiment gives a quantitative bound on the maximum allowed violation. In order to evaluate theoretical constraints given by an experiment, one needs to refer to a given theoretical framework that describes possible violations of fundamental principles. This also allows us to make quantitative comparisons between different types of experiments. Numerous types of theoretical frameworks have been developed; here we will present briefly three of them, which are commonly used for analyzing and comparing tests of one or several aspects of the Einstein Equivalence Principle, in particular with atomic clocks and sensors.

3.1. Modified Lagrangian framework

A very general, yet powerful formalism allowing deviations from GR and metric theories of gravity, but at the same time permitting a coherent analysis of various experiments is the "modified Lagrangian framework" [14,15,10,16,3]. We only summarize here the main phenomenological consequences in a simplified version (see, e.g., [3] for a recent, more detailed account).

The equation of motion of a massive test body in a Newtonian gravitational field U is to leading order

$$\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = \left(1 + \beta_X^{(a)}\right)\vec{\nabla}U \tag{1}$$

where $\beta_X^{(a)}$ is a dimensionless parameter that characterizes the violation of EEP, and $\vec{v}$ is the velocity. $\beta_X^{(a)}$ depends on the particular type of mass-energy or interaction that is assumed to behave anomalously in the presence of a gravitational field, e.g. it would be different for the electromagnetic or the nuclear interactions, with possible variations as a function of spin or the other internal properties of the body, here labeled by the superscript (a). Thus $\beta_X^{(a)}$ would depend not only on the type of internal energy X, but also on the type of body (a). More generally, and by symmetry, it would also depend on the composition of the source of the gravitational field (e.g., Earth, Sun, Moon). The immediate consequence is that typical WEP tests measure $\beta_X^{(a)} - \beta_X^{(b)}$ for two bodies a and b.

Typical LPI tests can be analyzed in the same framework using a cyclic Gedanken experiment based on energy conservation. This was done in Ref. [14], extending a famous argument by Einstein himself. The result for the fractional frequency shift z in a Pound and Rebka type experiment [12] is then

$$z = \left(1 + \alpha_X^{(a)}\right)\frac{\Delta U}{c^2} \tag{2}$$

where ΔU is the gravitational potential difference between the two clocks and the LPI-violating parameter $\alpha_X^{(a)}$ is again non-universal. The two parameters are not independent but related by:

$$\beta_X^{(a)} = \alpha_X^{(a)}\frac{E_X}{m c^2} \tag{3}$$

where E_X is the energy of type X in the body a. This allows comparing the relative merits of different types of experiments, but still depends on the model used i.e. the type of anomalous energy E_X and the employed materials or bodies (see [3] for some explicit examples). Therefore, clock comparison experiments can determine either the difference $\alpha_X^{(a)} - \alpha_X^{(b)}$ by comparing different types of clocks, co-located in a varying gravitational field (so-called null redshift tests), or individual $\alpha_X^{(a)}$ by comparing distant clocks at different U (see, e.g., Sections 5 and 6).

This type of framework can be further generalized to also allow for a dependence on velocity [10], thus including LLI tests with clocks like, e.g., [9].

3.2. The Robertson–Mansouri–Sexl framework

The Robertson–Mansouri–Sexl (RMS) framework [17–20] is a common kinematic framework for studying Lorentz violations. As in [17], let us postulate that there exists a "preferred" reference frame Σ in which light is propagated rectilinearly and isotropically in free space with constant speed c (in practice, often chosen to be the Cosmic Microwave Background rest frame). It is assumed that any observer at rest with respect to Σ may be supplied with two independent kinds of instruments, called *rods* and *clocks*, with which he can measure space and time intervals respectively. Independent means that the fundamental measurement of one kind of interval cannot be reduced to that of the other with the aid of the postulated constancy of the velocity of light. Then we assume that the physical geometry of the 3-dimensional space, as revealed by the measuring rods, is Euclidean. The observer may assign to an event E four coordinates $(T, \vec{X})$, consisting of a temporal coordinate and three spatial Cartesian coordinates, and define a line element:

$$\mathrm{d}\sigma^2 = c^2 \mathrm{d}T^2 - \mathrm{d}\vec{X}^2 \tag{4}$$

with the aid of which he can [17]:

1. measure proper time intervals $\mathrm{d}T = \mathrm{d}\sigma/c$ at any fixed point $\vec{X}$ in his space;
2. measure space intervals $\mathrm{d}\lambda = \sqrt{-\mathrm{d}\sigma^2}$ at any fixed time T;
3. characterize all beams of light passing through an event E as the generators of the cone $\mathrm{d}\sigma = 0$ with E as vertex.

Next we postulate the existence of a reference frame S that is moving with any constant velocity $\vec{w} \equiv \mathrm{d}\vec{X}/\mathrm{d}T$ of magnitude $w < c$, with respect to Σ.[2] Any observer in S may be supplied with rods and clocks of the same constitution as those of the observer in Σ, with which he can introduce coordinates $(t, \vec{x})$ consisting of a temporal coordinate and three spatial coordinates.[3] We further postulate that the physical geometry of the spatial subspace, as revealed by the measurement techniques, is Euclidean, where $\vec{x}$ are Cartesian coordinates. There is no assumption on the velocity of light or other physical law in S. Then the most general linear transformation from Σ to S is given by [18]:

$$T = a^{-1}(t - c^{-1}\vec{\epsilon} \cdot \vec{x}) \tag{5}$$

$$\vec{X} = d^{-1}\vec{x} - (d^{-1} - b^{-1})(\vec{w} \cdot \vec{x})\vec{w}/w^2 + \vec{w}T \tag{6}$$

where a, b and d are functions of w^2, and $\vec{\epsilon}$ is a w-dependent vector specifying the clock synchronization procedure in S. If one adopts Einstein synchronization by round-trip light signal in S, then $\vec{\epsilon} = -\gamma^2 ab^{-1}\vec{w}$, where $\gamma \equiv (1 - c^{-2}w^2)^{-1/2}$; if one synchronizes by slow transport of clock, then $\vec{\epsilon} = b^{-1}\nabla_{\vec{w}} a$. However, observables of the experiment should not depend on the choice of $\vec{\epsilon}$, i.e. should be independent of a specific synchronization procedure for the clocks. This can be shown explicitly. In Special Relativity, the functions a, b and d have the specific forms $a = b^{-1} = \gamma^{-1}$, $d = 1$, and $\vec{\epsilon}$ can be arbitrary; with either Einstein or transport synchronization, $\vec{\epsilon} = -\vec{w}$.

In the low velocity limit $w \ll c$, one can expand a, b and d by introducing the arbitrary parameters α^{RMS}, β^{RMS}, δ^{RMS} and α_2^{RMS}:

$$a(\vec{w}) = 1 + c^{-2}(\alpha^{\mathrm{RMS}} - 1/2)w^2 + c^{-4}(\alpha_2^{\mathrm{RMS}} - 1/8)w^4 + \mathrm{O}(c^{-6}w^6) \tag{7}$$

$$b(\vec{w}) = 1 + c^{-2}(\beta^{\mathrm{RMS}} + 1/2)w^2 + \mathrm{O}(c^{-4}w^4) \tag{8}$$

$$d(\vec{w}) = 1 + c^{-2}\delta^{\mathrm{RMS}}w^2 + \mathrm{O}(c^{-4}w^4) \tag{9}$$

Since this framework is purely kinematic (it does not include transformation laws for dynamics), it can be used only for a restricted set of experiment types, for example optical interferometry, birefringence, Doppler shifts, or time of flights. As we will see in Sections 5 and 6, remote high-precision atomic clocks allow one to test time of flights with high precision in varying spatial directions; these tests can be very conveniently analyzed in the RMS framework.

3.3. *Standard Model Extension*

One of the most comprehensive frameworks for analyzing possible phenomena originating from physics beyond the Standard Model and General Relativity is the Standard Model Extension (SME) developed by Kostelecky and co-workers over the last two decades. It is a phenomenological framework parameterizing in the Lagrangian of a system all possible departures from Lorentz symmetry (LLI) for all fields of the Standard Model and of General Relativity, including all particles [23,24], electromagnetic fields [25], and gravitation [26]. There are many corresponding "sectors" (proton, neutron, electron, photon, gravity), each of them parameterized by tens of parameters (see, e.g., [27] for a recent review article). In the minimal form of the SME describing the leading order effects of Lorentz violation, there are for example 19 parameters in the photon sector, and 44 per particle sector. The parameter space is consequently vast, while presenting the desirable quality of being exhaustive. This makes it a very attractive and efficient frame for analyzing an experiment without having to restrict to one

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[2] Here the discussion is limited to inertial frames. The discussion can be widened by using the approach developed in [21,22].

[3] In the RMS framework it is assumed that two measuring rods of different composition which agree in length in Σ also agree in length in S; and that two clocks that have the same period in Σ also do have the same period when brought into S. These assumptions are a bit constraining, as in all generality two clocks of different nature could have different periods in S if they have the same period in Σ, because of Lorentz violation. This can be taken into account in the Standard Model Extension (see Section 3.3).

specific underlying alternative theory, and for comparing between them experiments that can be very different in nature. To date, only a comparatively small part of the coefficient space has been explored.

The use of quantum sensor metrology for fundamental tests has allowed setting the presently most stringent constraints (and for some of them the only ones) on a number of combinations of SME parameters [28], by testing the dependence of observables on the orientation and boost of the experiment. In particular, the recent application of cold atom interferometers and clocks to Lorentz invariance tests, though restricted to few experiments yet, has already brought reference constraints in two new sectors: proton and gravity sectors. On Earth, analyzing clock frequencies of a Cs clock operated on different transitions between magnetized nuclear states has led to improving constraints of parameter combinations in the proton sector by more than ten orders of magnitude [29]; this experiment will be detailed in Section 4. More recently, another experiment has been able to set the most stringent constraints on several coefficients in one of the most sparsely tested sector, the pure gravity sector, using an atom free-fall gravimeter ([30], experiment, and [31], theory). Though emerging, the field of SME tests with atom interferometers and clocks has thus already proven to be extremely fruitful.

4. Test with spin-polarized states in a Cs fountain

4.1. Motivation

An important class of tests of Lorentz violation is the Hughes–Drever type of experiment: the transition frequency of a clock might depend on the orientation and boost of the clock frame in space. This violation can be more robustly investigated as a differential signal, by comparing two different co-located clock transitions, e.g., two transitions with opposite spin orientations. The SME framework is very efficient for giving a parameterized model of such an experiment, allowing the experiment to set measurements for the parameter values. In this framework, a Lorentz violation in the clock can be seen as arising from the interaction of clock species elementary particles with background expectation values of Lorentz tensor fields in vacuum, giving rise to shifts in the particle energies that depend on their physical properties, such as the spin, and on the boost magnitude and orientation. The Lorentz violating tensors introduced in SME are expected to have fixed coefficients in a nonrotating coordinate frame. Consequently by coordinate transformation, for clock comparisons in a rotating frame such as the lab frame on earth, periodic signals are predicted, at sidereal period $2\pi/\omega \simeq 23$ h 56 min and its harmonics. Atomic clocks have very high stability and accuracy, which allow long integration times leading to high-precision measurements. They therefore offer some of the most powerful tests of Lorentz violations. To present in more detail one of these tests in the SME framework, we have chosen here to focus on an experiment realized in 2006 with a cold atom ^{133}Cs fountain, that has allowed the first measurement of four proton SME parameters and improvements by 11 and 13 orders of magnitude on the determination of four others [29].

4.2. Lorentz violating energy shifts of clock states in SME

The SME framework is qualitatively predictive: it allows us to model the shape of the possible signals for Lorentz violation. Adjusting data to this model then allows experimental determination of its Lorentz violating coefficients, for any type of experiment usually described in the Standard Model. Appropriate SME models for clock transition frequencies on Earth and in space have been derived in [32,33], and [34]. A short approach to this derivation is presented hereunder.

In the matter sector for fermions, the Lorentz violating Lagrangian involves eight new tensors for each particle, labeled a_μ, b_μ, $c_{\mu\nu}$, $d_{\mu\nu}$, e_μ, f_μ, $g_{\lambda\mu\nu}$, and $H_{\mu\nu}$. To determine the leading-order effects of the Lorentz violation, a nonrelativistic Hamiltonian can be derived from this Lagrangian [35]. In order to estimate energy shifts for an atom, all individual nonrelativistic Hamiltonians associated with its nucleons and electrons have to be summed. Since all Lorentz violating effects are expected to be very small, a perturbative approach is sufficient. Energy shifts of atomic clock levels are thus calculated as the expectation value of the Lorentz violating perturbative Hamiltonian δh in the unperturbed states, usually well characterized by their total angular momentum $\vec{F}$. These states are thus labeled $|F, m_F\rangle$, with the two quantum numbers F and m_F characterizing respectively the norm of $\vec{F}$ and its projection along a quantization axis fixed by an applied magnetic field. Using Wigner–Eckart theorem, the expectation values $\langle F, m_F|\,\delta h\,|F, m_F\rangle$ are shown to depend on only five parameter combinations $\tilde{b}_3^w$, $\tilde{c}_q^w$, $\tilde{d}_3^w$, $\tilde{g}_d^w$ and $\tilde{g}_q^w$; these are the only combinations that can be bounded with clock comparisons experiments with ordinary matter (where $w = e, n, p$ for electron, neutron, proton). For example, a combination of interest for the experiment considered here as we will see, is

$$\tilde{c}_q^p = m_\mathrm{p}\,(c_{11}^p + c_{22}^p - 2c_{33}^p) \tag{10}$$

where indices 1 to 3 refer to the spatial reference frame of the lab, axis 3 being along the quantization axis, and m_p is the proton mass.

This derivation of the frequency shift is usually made in the approximation of the Schmidt nuclear model, a shell model in which the entire angular momentum of the nucleus is carried by a single nucleon. ^{133}Cs has an even number of neutrons (78) and odd number of protons (55); the Schmidt nucleon carrying the $I = 7/2$ spin of the nucleus is thus a proton. As a consequence, energy shifts of ^{133}Cs clocks are independent of neutron parameters. With this Schmidt nucleon and one valence electron, the frequency shifts for ground-state hyperfine transitions $|3, m_F\rangle \to |4, m_F\rangle$ can be derived explicitly following the method above:

$$\delta\nu = \frac{m_F}{14h}\sum_{w=p,e}(\beta_w\tilde{b}_3^w - \delta_w\tilde{d}_3^w + \kappa_w\tilde{g}_d^w) - \frac{m_F^2}{14h}(\gamma_p\tilde{c}_q^p) + m_F K_Z^{(1)}B + \left(1 - \frac{m_F^2}{16}\right)K_Z^{(2)}B^2 \tag{11}$$

The first two terms are Lorentz violating SME shifts; the last two describe the first and second order Zeeman frequency shifts where B is the applied magnetic field (neglecting B^3 and higher order terms). From this equation, we note that the usual non-polarized $m_F = 0$ clock states are insensitive to the Lorentz violation. The Lorentz violation in clocks thus relies on a non-zero spin state whose spin direction varies over time.

The coefficients for the Lorentz violation are supposed constant in an inertial reference frame; the usual frame of reference in which quantitative constraints are given is the Sun-centered frame (referenced in the following by indices T, X, Y, Z). The tensor coefficients in the lab frame (spatial indices 1 to 3), as appearing in the above expressions (10) and (11), are obtained from these fixed coefficients by a time-dependent boost and rotation with sidereal periodicity. Consequently, the frequency shift (11) can be decomposed in several time dependent components, with amplitudes being linear combinations of the Sun-centered SME coefficients, which can be directly fitted to clock comparison data.

4.3. Measurement sequence and model

Comparing, within the same clock, frequencies of Zeeman transitions ($m_F \neq 0$) to the frequency of the clock transition ($m_F = 0$) thus in principle gives access to the Lorentz violation terms. However the remaining first- and second-order Zeeman terms will limit the measurement precision, as they also exhibit, through their dependence on the magnetic field B, a time variation with diurnal and semi-diurnal components. To avoid this limitation, in [29] quasi-simultaneous measurements of the $m_F = 3$, $m_F = -3$ and $m_F = 0$ transitions are combined in the new observable

$$\nu_c = \nu_3 + \nu_{-3} - 2\nu_0 \tag{12}$$

exhibiting the following dependence:

$$\nu_c = \frac{1}{7h}K_p\tilde{c}_q^p - \frac{9}{8}K_Z^{(2)}B^2 \tag{13}$$

This observable is thus only sensitive to the second-order Zeeman shift, whereas it keeps one dependence on a Lorentz violating term, $\tilde{c}_q^p$ which involves the proton tensor $c_{\mu\nu}^p$ following expression (10).

In Cs fountains on Earth, the applied magnetic field, fixing the axis 3 of the lab frame, is vertical. This frame is thus rotating with sidereal period $2\pi/\omega$ around the Earth's rotation axis. Using the coordinate transformation from the Sun centered to the lab frame, one obtains from expression (13) the following time decomposition for the putative Lorentz violating signal:

$$\nu_c = A + C_\omega\cos(\omega T) + S_\omega\sin(\omega T) + C_{2\omega}\cos(2\omega T) + S_{2\omega}\sin(2\omega T) \tag{14}$$

In this expression, there are one offset and four amplitude parameters, each one depending on a specific combination of the SME parameters in the Sun centered-frame c_{IJ} with indices $I, J = T, X, Y, Z$ (see [34] for their explicit expressions in the case of a generic Earth-centered circular orbit). These coefficients actually appear in three types of linear combinations

$$\tilde{c}_Q = m(c_{XX} + c_{YY} - 2c_{ZZ}),\ \tilde{c}_- = m(c_{XX} - c_{YY}) \tag{15}$$

$$\tilde{c}_J = m|\epsilon_{JKL}|c_{KL} \tag{16}$$

$$\tilde{c}_{TJ} = m(c_{TJ} + c_{JT}) \tag{17}$$

respectively involving diagonal tensor coefficients (Eq. (15)), off-diagonal spatial elements (Eq. (16)), and off-diagonal time indices (Eq. (17)). Indices J, K, L run over spatial coordinates X, Y, Z. The totally antisymmetric tensor ϵ_{JKL} is defined with $\epsilon_{XYZ} = +1$. The index p indicating that all these coefficients are meant here for the proton has been omitted.

4.4. Experiment and sensitivity

For details of the experiment and experimental sequence, we refer to [29]; for a more recent description of the device, see also the article "Atomic fountains and optical clocks at SYRTE: status and perspectives" in the present volume. We focus here on the main results of [29].

In the chosen measurement sequence, the observable ν_c can be measured repetitively approximately every 400 s. Two data sets for ν_c measurements have been taken in 2005 at SYRTE on a ^{133}Cs fountain, with an overall measurement duration of 35 days. The complete raw data are shown in the inset of Fig. 1, each point representing a measurement sequence of ν_c. Fig. 1 also shows the frequency stability of a 10-day continuous stretch of data during the recording of one of the data sets. Essentially white noise behavior indicates that the experimental sequence successfully rejects the long-term variation of the magnetic field. Extrapolated to 35 days, this behavior allows us to reach a sensitivity of about 50 μHz.

A least square fit of the model (14) to the entire data set provides the five coefficients of the model and associated statistical uncertainties. Systematic uncertainties are also evaluated, being dominant only for the offset term. From this

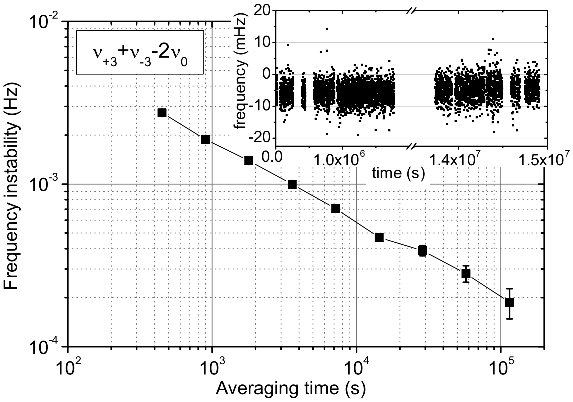

Fig. 1. Frequency stability (Allan deviation) of a $\simeq$ 10 days continuous measurement of ν_c. The inset shows the raw data as a function of time (from [29]).

Table 1
Orders of magnitude of limits (in GeV) on Lorentz violating parameters in the minimal SME proton sector measured in [29]. Previous limits, when available, are indicated in brackets [36].

Parameter	Limit
$\tilde{c}_Q$	$10^{-22(-11)}$
$\tilde{c}_X, \tilde{c}_Y$	10^{-25}
$\tilde{c}_Z, \tilde{c}_-$	10^{-25}
$\tilde{c}_{TJ}$	$10^{-21(-8)}$

set of constraints, the values of the eight SME parameters of Eqs. (15) to (17) are determined for the proton. They are all consistent with zero, indicating no Lorentz violation. The resulting uncertainties are given in Table 1. The coefficients on the second and the third line were previously unconstrained. Their uncertainty is limited by the statistical uncertainty, and would be improved with a longer measurement time. The constraint on the $\tilde{c}_Q$ coefficient has improved by 11 orders of magnitude compared to previous bounds [36]. Its uncertainty is mainly linked to the systematic effects affecting the constant term of the model. The constraints on the $\tilde{c}_{TJ}$ coefficients have been improved by 13 orders of magnitude; their uncertainty is limited by statistical uncertainty as for $\tilde{c}_J$ and $\tilde{c}_-$, but is higher by four orders of magnitude as they appear in boost suppressed effects, with an Earth boost $v/c \sim 10^{-4}$.

Based on these results, in the future, space clocks such as PHARAO in the planned ACES mission (see Section 5) will provide the possibility of carrying out similar experiments but with faster (90 min orbital period for ACES) modulation of the Lorentz violating model, and correspondingly faster data integration and higher resolution.

5. ACES/PHARAO

ACES/PHARAO (Atomic Clock Ensemble in Space/Projet d'horloge atomique par refroidissement d'atomes en orbite) is an international metrological space mission of the French and European space agencies (ESA and CNES). It is an international scientific and industrial collaboration with French lead (LKB and SYRTE) that aims at realizing a time scale of high stability and accuracy on board the International Space Station (ISS). Relative frequency stability (ADEV) should be better than $\sigma_y = 10^{-13} \times \tau^{-1/2}$, which corresponds to 3×10^{-16} after one day of integration; the time deviation (TDEV) should be better than $\sigma_x = 4.1 \times 10^{-14} \times \tau^{1/2}$, which corresponds to 12 ps after one day of integration. Absolute frequency accuracy should be around 10^{-16}. To achieve these performances, its payload includes the first cold atom clock in space, PHARAO, which is a Cs clock, and an H-maser.

The scientific objectives are:

- to demonstrate the high performance of the atomic clocks ensemble in the space environment and the ability to achieve high-stability space-ground time and frequency transfer;
- to perform space to ground clock comparisons with high resolution on a worldwide basis using a link in the microwave domain. The link stability should reach around 0.3 ps after 300 s of integration and around 7 ps after 1 day of integration;
- to perform tests of the Einstein Equivalence Principle (EEP: see Section 2). It will be possible to test Local Lorentz Invariance (LLI) and Local Position Invariance (LPI) to unprecedented accuracy by doing three types of tests: a test of the gravitational redshift contributes to the search for a variation of fundamental constants, LLI tests in the RMS and SME frameworks.

Besides these primary objectives, several secondary objectives can be found in [37]. For example, the measurement of gravitational redshifts can be used to measure gravitational potential differences between different clock locations, which is a new type of geodetic measurements using clocks called chronometric geodesy [38].

LKB and SYRTE are heavily involved in the experiment, from the conception of the cold atom clock to the development and the data analysis. SYRTE is an official ACES Data Analysis Center. Presently we develop a data analysis algorithm in order to process the mission raw data and extract the scientific products of the mission, which are mainly the desynchronization between clocks. In order to test our algorithm, we developed a full simulation of the raw observables, as they will be produced by the TimeTech modem and instrumentation.

A violation of LPI can be quantified as described in Section 3.1 by a factor $\alpha_X^{(a)}$ appearing in the standard formula of gravitational redshift (2), with X representing here the hyperfine energy. The most stringent limit from previous measurements comes from the 1976 NASA/SAO GP-A rocket experiment [39,40], yielding $|\alpha_X^{(H)}| \lesssim 1.4 \times 10^{-4}$ [41]. This test took advantage of the stability of the spaceborne and ground hydrogen maser clocks, connected by a continuous-wave microwave link, to measure the modulation of the gravitational redshift with altitude. On the contrary, the gravitational redshift in the ACES experiment will only be modulated to around 10%; therefore the high accuracy of the spaceborne (10^{-16}) and ground clocks are used, to measure the absolute redshift that will constrain $|\alpha_X^{(Cs)}| \lesssim 3 \times 10^{-6}$, an improvement by a factor 45 compared to the GP-A experiment.

High-accuracy comparisons of atomic frequency standards based on different atoms and ions can be interpreted as a test of the variation of fundamental constants. By combining the comparisons between different types of atomic clocks (e.g., Rb/Cs, $\mathrm{Al}^+/\mathrm{Hg}^+$, $\mathrm{Hg}^+/\mathrm{Cs}$, ...), it is possible to disentangle the contributions coming from three different fundamental constants: α the fine structure constant (electroweak interactions), $\mu = m_\mathrm{e}/m_\mathrm{p}$ the electron-to-proton mass ratio, and $m_\mathrm{q}/\Lambda_\mathrm{QCD}$ the quark mass scaled to the quantum chromodynamics mass scale Λ_QCD (strong interactions). The present limits can be found in [42] and in the article entitled “Atomic fountains and optical clocks at SYRTE: status and perspectives” in the present volume. The ACES experiment will improve these limits by increasing the number of possible inter-clock comparisons from distant laboratories.

Finally, the ACES experiment will test LLI by testing the independence of the clock synchronization procedure with the orientation of the microwave link. The expected sensitivity on the parameter α^{RMS} of the Robertson–Mansouri–Sexl framework (see Section 3.2) is 2×10^{-8}, which is the best present limit obtained from an Ives–Stilwell type of experiment [43]. In this experiment, one compares the rest transition frequency of an atom to its transition frequency when at high velocity as seen by an observer at rest. Both tests are complementary.

A test of LLI in the SME can also be done with PHARAO following the test realized on Earth in [29] detailed in Section 4. Beyond a faster integration due to the shorter orbital period as already mentioned, the time dependence of the signal will allow a more constraining set of measurements for SME coefficients: the quantization axis of PHARAO being along the ISS trajectory, over one orbital period its direction will be fully reversed twice, giving rise potentially to stronger modulation signals at this frequency.

6. STE–QUEST

The STE–QUEST (Space-Time Explorer and QUantum Equivalence Space Test) space mission is specifically designed for testing different aspects of the EEP and searching for its violation with high precision. It was proposed in the fall of 2010 in response to ESA's M3 call in the Cosmic Vision programme (with launch date in the 2022–2024 time interval). STE–QUEST, together with three other mission proposals, was pre-selected in early 2011 by ESA's advisory structure as a candidate mission, and went through a three-year assessment study of the satellite and payload (see the Assessment Study Report [2], also known as the “Yellow Book”, and [3]). It was not selected in the final selection, but will be re-proposed in the currently ongoing M4 call.

The primary science objectives of STE–QUEST is testing the different aspects of the Einstein Equivalence Principle with quantum sensors. The payload consists of a differential atom interferometer comparing the free propagation of matter waves of different composition under the effect of gravity and a frequency comparison link in the microwave domain for comparing atomic clocks on ground.

STE–QUEST performs a direct test of the Weak Equivalence Principle (WEP) by comparing the free fall of quantum objects of different composition. In the M4 version, the Eötvös ratio between the matter waves of ^{87}Rb and ^{41}K is measured in a differential atom accelerometer down to the 2×10^{-15} uncertainty level. While present limits on WEP tests involving classical objects reach an uncertainty of a few parts in 10^{13}, measurements performed on quantum objects (matter waves in states which have no classical counterpart, e.g., spatio-temporal quantum superpositions) are still at the level of a few parts in 10^7 [44–46]. From this point of view, STE–QUEST will explore the boundaries between gravitation and quantum mechanics, significantly improving existing measurements and complementing experiments such as μ-SCOPE, designed for a classical WEP test in space to the level 1×10^{-15}. In the framework described in Section 3.1, this corresponds to a limit of $|\beta_X^{(Rb)} - \beta_X^{(K)}| \leq 2 \times 10^{-15}$, where X is the WEP violating energy present in ^{87}Rb and/or ^{41}K quantum matter waves.

STE–QUEST will be able to compare distant ground clocks using the microwave link (MWL) in common-view mode at the 10^{-18} level in fractional frequency. This allows an LPI test in the gravitational field of the Sun as shown in Fig. 2. In this example the frequency ratio $\nu_\mathrm{T}/\nu_\mathrm{B}$ between two ground clocks in Turin and Boulder is measured (see [3] for more detail).

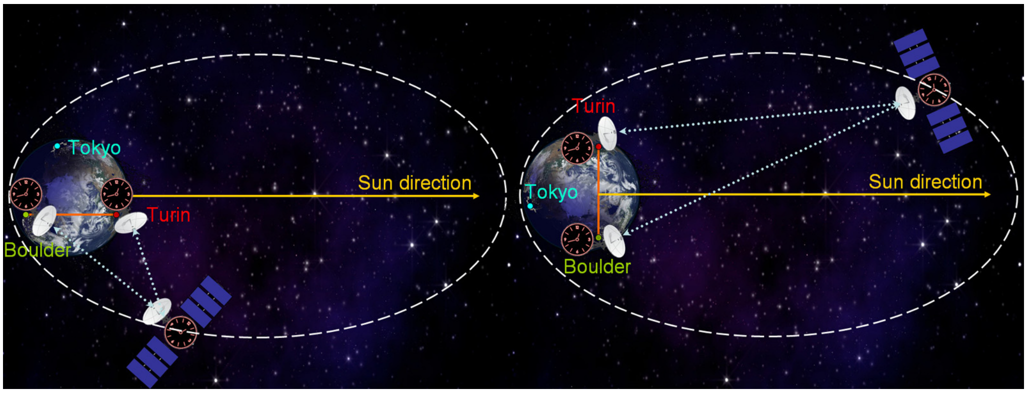

Fig. 2. (Color online.) Common-view comparison between Turin and Boulder for the test of LPI in the field of the Sun. The two panels show the different locations of the clocks in the field of the Sun as the Earth rotates, and their common-view comparison by STE–QUEST.

In the framework discussed in Section 3.1, we can consider a generalization in which the Sun acts as the source of the anomalous gravitational coupling. The measured frequency ratio of the two clocks can be written as

$$\frac{\nu_T}{\nu_B} = 1 - \frac{1}{c^2}\left[U_B^{\odot} - U_T^{\odot} + \frac{v_B^2 - v_T^2}{2} + \alpha_B^{\odot} U_B^{\odot} - \alpha_T^{\odot} U_T^{\odot}\right] + \Delta \tag{18}$$

where $U_B^{\odot}$ and $U_T^{\odot}$ are the solar Newtonian gravitational potentials at the locations of the ground clocks and v_B and v_T are the corresponding velocities in a solar-system barycentric reference frame. The LPI violating parameters $\alpha_B^{\odot}$ and $\alpha_T^{\odot}$ depend on the type of transition used in the respective clocks and possibly on the source of the gravitational field (here the Sun); Δ represents all corrections due to the other solar system bodies (including the Earth) assumed to behave normally, as well as higher-order correction terms.

An essential point to note is that, in the absence of an LPI violation ($\alpha_B^{\odot} = \alpha_T^{\odot} = 0$), the leading part in Eq. (18) is equal to zero (up to small tidal correction terms in Δ and constant terms from the Earth field). This is a direct consequence of the EEP, as the Earth is freely falling in the Sun field [47]. The LPI test in the Sun field is thus a null test, verifying whether the measured frequency ratio is equal to the expected value, i.e. $1 + \Delta$ in this example. In general, the types of clocks used at the different ground stations may be of different types, so $\alpha_B^{\odot} \neq \alpha_T^{\odot}$. We can assume for simplicity clocks of the same type, which simplifies the LPI violating term in (18) to $\alpha^{\odot}(U_B^{\odot} - U_T^{\odot})$, with the aim of the experiment being the measurement of $\alpha^{\odot}$, by searching for the sinusoidal signal at diurnal frequency resulting from $\alpha^{\odot} \neq 0$. In the baseline configuration, the measurement uncertainties of the MWL and the ground clocks should allow a detection of any non-zero value of the LPI violating parameter $\alpha^{\odot}$ in the Sun field that exceeds 2×10^{-6}, a roughly 10^4 fold improvement over present knowledge [48,49]. One can also carry out similar LPI tests in the field of the Moon or of other sources by searching for signals with the appropriate frequency and phase, in general different from the Sun signal.

When coupled to gravity, one finds that WEP/UFF tests can provide the best available sensitivity to certain types of Lorentz violation in the SME involving matter–gravity couplings [50]. In fact, several Lorentz-violating possibilities can only be tested using such precision gravitational experiments [51]. Hence, the WEP tests of the STE–QUEST mission would provide the best sensitivities to date on an additional set of coefficients for Lorentz violation in the matter sector (improvement of up to five orders of magnitude) [3]. Red shift tests between ground clocks can also be analyzed, as well as in ACES, to test the gravitational sector of SME [50]. The Microwave Link might also be used for a test of LLI, with a longer time of flight and thus a stronger possible frame-dependent signal than for ACES thanks to the much higher orbit altitude.

7. Conclusion

With the examples of fundamental physics experiments presented in our contribution, as well as in other parts of this volume (e.g., “Atomic fountains and optical clocks at SYRTE: status and perspectives”), we have shown that quantum sensor metrology, and in particular atomic clocks together with time/frequency transfer methods, are becoming an outstanding tool to explore the foundations of physics in the low energy domain (compared to particle accelerators or violent processes in the universe) but with ultimate accuracy. Furthermore, the quantum nature of the probes is not only a tool to achieve high accuracy, but also of interest in its own right, as it allows direct exploration of the interface between quantum mechanics and general relativity. Atomic clocks and sensors have opened a new field of fundamental physics in the laboratory, and are making their way into space where the unperturbed microgravity environment will bring new exciting results from experiments like ACES and STE–QUEST, which should provide first experimental glimpses of the new physics beyond General Relativity and the Standard Model of particle physics.

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