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Tests de physique fondamentale avec un ensemble d’horloges à atomes froids à l’Observatoire de Paris / *Fundamental physics tests with a cold-atom clock ensemble at Observatoire de Paris*

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Résumé/Abstract

Une application scientifique stimulante des horloges atomiques aux incertitudes extrêmes est de contribuer aux tests de physique fondamentale et à la recherche de physique au-delà du modèle standard de la physique des particules. La fréquence d’une transition atomique dépend des paramètres des interactions fondamentales (électrofaible et forte), tels que la constante de structure fine α, et des propriétés fondamentales des particules comme par exemple la masse de l’électron. Des comparaisons répétées d’horloges atomiques de haute précision peuvent être exploitées pour rechercher une variation temporelle, ou encore une variation avec le potentiel de gravité, des rapports de fréquences atomiques, et, via des calculs de structure atomique et nucléaoire, variations des constantes fondamentales. Les horloges atomiques fournissent des tests de laboratoire indépendants de modèle cosmologique qui mettent des limites aux théories alternatives de gravitation et de mécanique quantique, contribuant ainsi à la recherche d’une théorie unifiée des interactions fondamentales. Nous présentons notre contribution à cette recherche en exploitant des comparaisons de haute précision de différents types d’horloges et oscillateurs menées à l’Observatoire de Paris sur les deux dernières décennies.

One exciting scientific application of atomic clocks with extreme uncertainties is to contribute to testing fundamental physical laws and searching for physics beyond the Standard Model of particle physics. The frequency of an atomic transition relates to parameters of fundamental interactions (strong interaction, electro-weak interaction), such as the fine-structure constant α, and to fundamental properties of particles like for instance the electron mass, me. Repeated highly accurate atomic clock comparisons can be used to look for a putative variation with time or with gravitational potential of atomic frequency ratios, and, via suitable atomic structure calculations, of natural constants. Clocks provide laboratory tests, independent of any cosmological model, that constrain alternative theories of gravity and quantum mechanics, thereby contributing to the quest for a unified theory of the three fundamental interactions. We present our contribution to this quest by exploiting repeated accurate comparisons of different types of atomic clocks and oscillators performed over the last two decades at Observatoire de Paris.

1 Introduction

Einstein equivalence principle (EEP) is one of the founding principle of General Relativity. Many experiments have been dedicated to test the validity of this principle [1]. Several of them search for variations of fundamental constants, either on cosmological timescales using astronomical and geochemical data, or in our present epoch by exploiting highly stable and accurate atomic clocks. Such variations would violate Local Position Invariance (LPI), one of the three components of EEP. The possibility that dimensionless fundamental constants might change in time or space is allowed or predicted by alternative theories aimed at unifying gravitation with the other fundamental interactions; hence the strong interest in this search which could reveal physics beyond general relativity and the standard model of particle physics. Besides, some of these alternative theories predict the existence of new scalar fields that would lead to a space-time dependence of fundamental constants via their coupling to standard matter. Such scalar fields, with non-zero mass, could be a candidate for dark matter or dark energy needed to explain some galactic and cosmological observations. Atomic clocks are best suited devices to search for variation of constants at the present epoch in laboratory-based experiments whose interpretation is fully independent of any cosmological model.

In this paper we present an overview of our contribution to these tests by exploiting the cold atom clock ensemble and high performance oscillators developed at Observatoire de Paris during the last decades. We will report more specifically on highly accurate Rb/Cs frequency comparisons performed with atomic fountains over more than 15 yr. We will also present repeated accurate measurements of the frequency ratios Sr/Cs which complement similar measurements performed in other laboratories.

2 The cold atom clock ensemble at Observatoire de Paris

Since the early nineties, SYRTE (Systèmes de Référence Temps Espace) at Observatoire de Paris is developing an ensemble of high performance atomic clocks comprising three laser-cooled atomic fountain clocks [2], three optical lattice clocks and ultra-stable microwave and optical oscillators including optical frequency combs. Figure 1 gives a schematic overview of this ensemble. Our last report on the developments of this clock ensemble is given in Ref. [3]. The main application of this ensemble is time and frequency metrology. Besides, such an ensemble provides many possibilities for testing fundamental physical laws, relying on the high accuracy and stability of these devices.

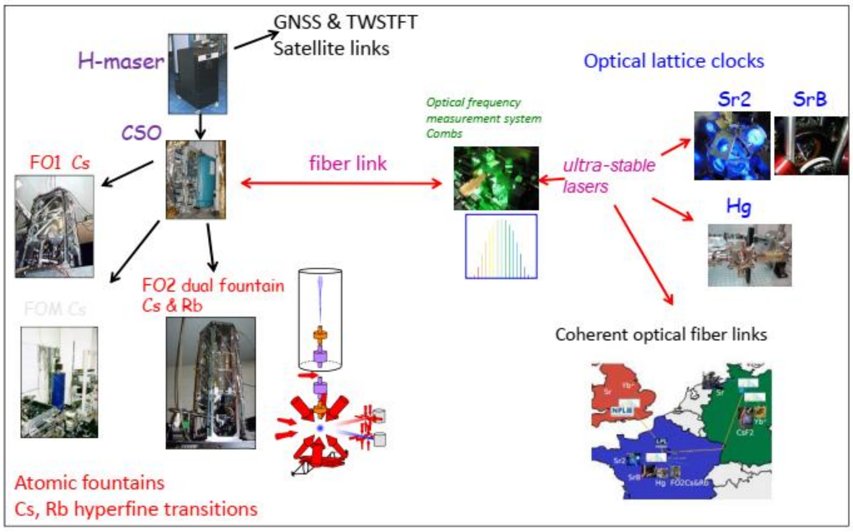

Figure 1: Overview of the LNE-SYRTE atomic clock ensemble at the Observatoire de Paris.

Atomic fountains are the first generation of the laser-cooled atomic frequency standards. They use the fountain geometry where spectroscopy of the clock transition is performed onto a free-falling sample of laser-cooled atoms which is beforehand launched upwards vertically (see, for instance, [2] and references therein). One of our three fountains called FO2 is a dual fountain operating simultaneously with rubidium and cesium atoms. The clock transitions are the ^{87}Rb and ^{133}Cs ground state hyperfine frequencies in the microwave domain. All three Cs fountains are primary frequency standards, the Rb part of FO2 is a secondary frequency standard and all four provide among the most accurate realizations of the SI second thus participating to the accuracy of the international atomic time, with uncertainties at the level of a few 10^{-16}.

To surpass atomic fountain performances, three optical lattice clocks (OLC), two using strontium atoms and one using mercury atoms, are currently under development at SYRTE (right side of fig. 1). The neutral atoms are dipole-trapped in an optical lattice and are interrogated by an ultra-stable “clock” laser in the optical part of the spectrum (1S0 - 3P0 in ^{87}Sr and ^{199}Hg). The uncertainties reached by the SYRTE strontium OLCs is a few 10^{-17}.

The link between the fountains and the optical clocks is performed via optical frequency combs spanning across the optical and microwave domains.

3 Tests of space-time variation of fundamental constants

The frequency of an atomic transition is a function of three constants, parameters of fundamental interactions (electro-weak and strong interactions): the fine-structure constant α, the ratio μ of the electron-to-proton mass m_e/m_p and the quark mass scaled properly. The ratio of two atomic transition frequencies is by definition independent on the unit of frequency and therefore its value depends only on these constants. We use repeated highly accurate atomic clock comparisons to look for a putative variation with time or with gravitational potential of atomic frequency ratios, and, via suitable atomic structure calculations, of natural constants [4]. Our comparisons between ^{87}Rb and ^{133}Cs hyperfine frequencies since the very first in 1998 are shown in Fig. 2. Since

2009, these comparisons are almost continuous using the dual Rb/Cs fountain FO2 alone. The measurements set a stringent limit to a putative variation with time of the Rb/Cs fractional frequency ratio at a level of a few 10^{-17} yr^{-1} (Fig.2, left). They also set the first limit to a fractional variation of the frequency ratio with gravitational potential (Fig. 2 right), providing a new stringent differential redshift test: difference in gravity redshift between Cs and Rb less than 4×10^{-7}. This test relies on exploiting the yearly modulation of the gravitational potential of the Sun due the eccentricity of the Earth orbit.

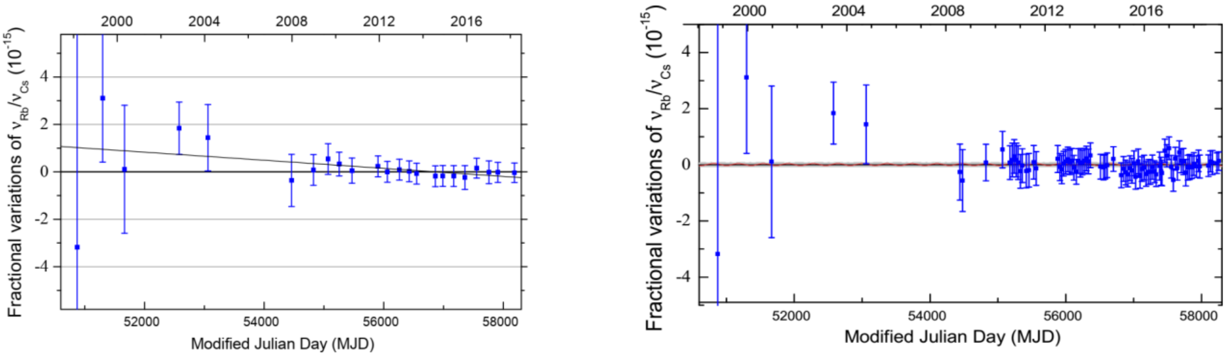

Figure 2: Temporal record of fractional variations of the Rb/Cs hyperfine frequency ratio. The error bars are the total 1σ uncertainties, dominated by the systematic uncertainties. Left: The solid red line is the weighted fit to a line. Right: Same data fitted by a modulation synchronized with the Earth's orbit around the Sun.

Frequency ratios between optical and microwave clocks offer a different sensitivity to natural constants than hyperfine frequency ratios. Repeated measurements of the frequency ratio between the strontium clock transition and the microwave Cs primary and Rb secondary frequency standards have been performed at SYRTE [5]. They are shown in Fig.3, together with other absolute frequency measurements of strontium optical lattice clocks against Cs fountain primary frequency standards over a decade. They give the linear drift with time of the Sr/Cs clock frequency ratio and a fit of its possible variation with the gravitational potential.

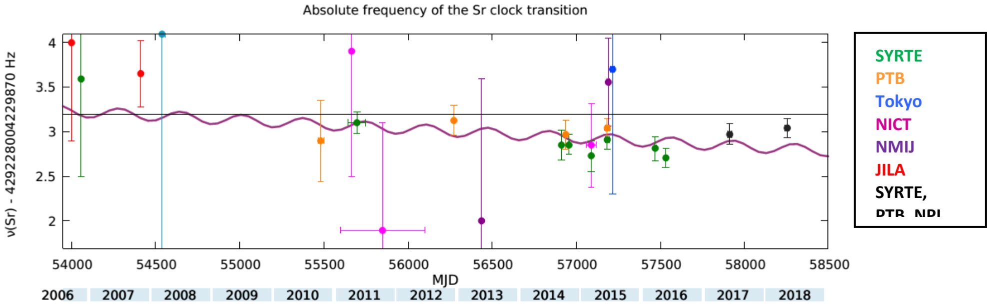

Figure 3: International comparisons of the Sr/Cs clock frequency ratio. A fit shows an upper bound on a drift of this ratio, and on a variation synchronized with the Earth's orbit around the Sun. Courtesy of J. Lodewyck.

Combining with other available highly accurate clock comparisons, we can extract independent constraints on the putative temporal variations of the three constants α, $\mu = m_e/m_p$ and scaled quark mass, at the present epoch, and on their putative couplings to gravity.

4 Search for scalar dark matter

We use 6 years of the hyperfine frequency comparison data of the dual rubidium and caesium fountain FO2 (data spanning November 2009 to February 2016) to search for a massive scalar dark matter candidate [6]. Such a scalar field can induce harmonic variations of the fine structure constant, of the mass of fermions, and of the quantum chromodynamic mass scale, which will directly impact the rubidium/caesium hyperfine transition frequency ratio. We find no signal consistent with a scalar dark matter candidate but provide improved constraints on the coupling of the putative scalar field to standard matter (Figure 4). Our limits are complementary to previous results that were sensitive to the fine structure constant only [7] and improve them by more than an order of magnitude when only a coupling to electromagnetism is assumed. They still provide the best present day constraints in a specific model of ultra-light ($< 10^{-10}$ eV) dark matter.

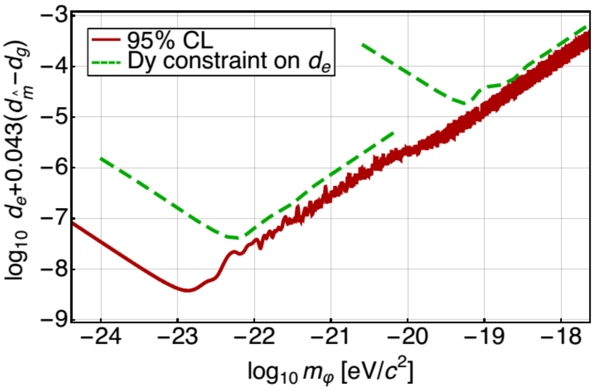

Figure 4: Upper limit on the linear combination of coupling constants d_i *between a light scalar field and standard matter fields as a function of scalar field mass. Green dashed line: upper bound from Dy atoms [7].*

5 Test of Lorentz Invariance in the matter sector

The SYRTE FO2 fountain has been used to perform a test of the Lorentz invariance postulate of general relativity entering the category of Hughes-Drever experiments [1]. In this experiment [8], the fountain sequence in tailored to probe opposing Zeeman transitions in ^{133}Cs in order to test for a putative variation of their frequencies when the orientation of the quantization axis changes (here, due the Earth rotation) with respect to a supposedly preferred frame, such as the frame of the Cosmic Microwave Background. The experiment was interpreted within the framework of the Lorentz violating Standard Model Extension (SME), where it is sensitive to proton parameters corresponding to a largely unexplored region of the SME parameter space. Several orders of magnitude were gained in constraining 4 parameters which were already constrained by other experiments and new parameters were constrained for the first time. A recent reinterpretation of the data is given in [9]. We recently repeated the measurements on opposing Zeeman transitions with FO2 fountain in the dual Rb/Cs configuration to improve and complement the early experiment.

6 Conclusion

We have presented valuable contributions of the atomic clock ensemble at Observatoire de Paris to various tests of fundamental physics, searches for variations of the fundamental constants at the present epoch and variations with respect to gravity, and search for dark matter fields. Clock tests in laboratories complement tests performed at higher redshift using astrophysical and geological data, providing inputs for developing unified theories. Future improved tests are foreseen by exploiting advanced remote comparison methods: coherent optical fiber links for long distance clock comparison [10] and ground-to-ground comparisons via the ACES/PHARAO space mission [11].

7 Acknowledgments

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