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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

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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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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.

[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.