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EMRP European Metrology Research Programme ▶ Programme of EURAMET

Publishable JRP Summary for Project T1 J2.1 OCS. Optical clocks for a new definition of the second

- **New clocks for a new definition of the second**

To guarantee that no application is limited by the definition of a physical unit, it is mandatory that this definition be based on the state-of-the-art of the involved technologies. In the field of time and frequency metrology, ultra-high performance optical clocks now outperform the best standards based on the clock transition of cesium atoms which is presently used to define the SI second. It is therefore anticipated that a new definition of the second will be needed within a few years. In the present JRP which started in April 2008, we perform a detailed investigation of one of the most promising candidate atomic transitions for this new definition: the $^1S_0$-$^3P_0$ transition of atomic strontium. The principle underlying the operation of the clocks is the use of an optical lattice to freeze the atomic motion. Atoms are strongly confined in a series of potential wells formed by the interference of lasers. This confinement to the so-called Lamb-Dicke regime leads to a cancellation of motional frequency shifts which set a severe limit to atomic clocks using atoms in free flight. Though the lattice relatively strongly perturbs the atomic levels it is designed in such a way that the energy shift of both states forming the clock transition exactly match. This results in a null shift of the reference transition. In addition, by using a large number of atoms simultaneously, this type of clocks called optical lattice clocks has a superior potential in terms of ultimate frequency stability, presumably below 10^{-16} for one second of averaging, and better than 10^{-18} after one day of integration. We anticipate a control of the systematic frequency shifts at a level better than 10^{-16} in fractional units in the new clocks and plan to perform at least three independent measurements of the transition frequency by comparison with state of the art primary frequency standards.

- **Key achievements to date**

    - Experimental study of the frequency shift due to cold collisions in a clock with ^{88}Sr atoms.
    - Development of a new ultra-stable reference cavity with relative frequency stability better than 10^{-15}.
    - Demonstration of a non-destructive detection method of the atoms for the optimization of the clock frequency stability.
    - Demonstration of a frequency stability of 10^{-16} at 1000 s averaging time.

- **Key physical effects: blackbody radiation shift, cold collisions, atomic motion and related issues**

An important part of the project aims at tackling and controlling the relevant potential frequency shifts of the clock transition. The goal in terms of control of these systematic effects is to reach an uncertainty in the 10^{-17} range. The main identified potential issues are the frequency shift due to the blackbody radiation of the vacuum chamber surrounding the atoms and effects related to the atomic confinement in the lattice: imperfect cancellation of the lattice light shift, frequency shift due to collisions between confined cold atoms. We initiated studies to perform an accurate measurement of the atomic properties that determine the sensitivity to blackbody radiation shift, the investigation of techniques to allow the use of a cryogenic environment, the study of the collisional properties of bosonic and fermionic isotopes of Sr and the related trade-off associated to the different structure of the atomic transition for the different kinds of isotopes. Altogether the project will facilitate a huge step forward in the understanding of these effects.

The first phase of the project concentrates on the blackbody radiation shift. The design of two blackbody radiators allowing operation at high temperature or at cryogenic temperatures is underway. A new technique has been demonstrated allowing the transport of atoms from the region where they are captured to inside these radiators.

The measurement of physical effects associated to the other frequency shifts has also started. Atomic resonances of bosonic Sr atoms in a lattice were observed with a record linewidth of the order 20 Hz. This allowed performing an unprecedented experimental study of the effect of collisions between cold ^{88}Sr atoms in the lattice. Inelastic loss, line broadening and line shifts from collisions could be observed and for the first time quantitatively described by a density-matrix model. The data allows estimating operational parameters for a ^{88}Sr clock in a1-D optical lattice. They show, that even with as many as 10^4 atoms it should be possible to achieve a linewidth of one Hertz and a small collisional shift that can be extrapolated to zero density with an uncertainty of less than 10^{-16}. The possibility to compare two Sr lattice clocks locally is also underway for the accurate measurement of lattice based shift and collisional shift between polarized ^{87}Sr atoms.

- **Ultra-stable lasers**

The potential frequency stability of the new clocks would outperform existing devices by more than one order of magnitude. This requires limiting the excess noise in the interrogation process due to the frequency fluctuations of the laser used to probe the clock transition. Two decisive parameters are relevant here, the noise properties of the laser itself, and also the conversion efficiency of this noise by the interrogation (known as the Dick effect).

A new design of ultra-stable cavity using an ultra-low expansion (ULE) glass spacer and fused silica mirrors was studied and implemented. This differs from the "standard" design for which both the mirrors and the spacer are made of ULE. The main advantage of the new configuration is a significant reduction of the thermal noise limit of the cavity. An actual reduction of the thermal noise by a factor of 3 was experimentally demonstrated using this new design. A drawback of using fused silica mirrors is that the effective coefficient of thermal expansion of the reference cavity increases by two orders of magnitude, compared to an all-ULE case. An original method for compensating this effect has been proposed and experimentally validated.

In addition, a new method for detecting the atoms in the lattice clock has been demonstrated, exhibiting shot-noise limited performance. It is based on the detection of a phase shift on the probe laser instead of the standard fluorescence detection technique. This new technique allows keeping most of the atoms for several cycles of the clock operation therefore strongly reducing the time required at each cycle for capturing new atoms. By combining this technique and the new ultra-stable cavities, a significant improvement of the clock frequency stability towards the quantum limit is anticipated. In a first implementation of these techniques, a record frequency stability of 10^{-16} after 1000 s of averaging has been demonstrated.

- **Development of new atomic optical frequency standards, impact on fundamental physics and metrology**

By leading to the development of new frequency standards, this JRP will have a significant impact in the field of atomic physics: collisions between cold atoms, atomic motion in the quantum regime, atom-field interaction are scientific fields in themselves. An improved knowledge of these effects will result from our work. Other branches in physics will be impacted such as fundamental metrology and fundamental physics. A topical example which concerns both aspects is the possibility of a refined test of the stability of fundamental constants, the latter being a direct consequence of local position invariance (LPI). It is now well established that the repeated comparison of various kinds of atomic frequency standards allows performing such a test. The three Sr lattice clocks available to the consortium will be used as a common reference to repeatedly measure the other clock transitions under investigation in the involved NMIs. This test obviously impacts fundamental physics, LPI being at the heart of general relativity, but also fundamental metrology. If what we presently call fundamental constants are found to vary, the philosophy underlying today's definition of the second (and more generally of the whole SI) would need to be rethought: a single specific atomic transition could then not be used as a satisfactory definition. This would constitute a true revolution in science. On the other hand, if no deviation is found, the confidence in our present system would be dramatically strengthened.

- **Technological impact on future space science and other applications**

Optical frequency standards are at the heart of several future space missions. In the frame of "cosmic vision", the latest ESA call for scientific mission, two projects aim at flying optical clocks, one for testing general relativity in earth orbit (the EGE mission), the other for testing gravitation at the solar system scale (the SAGAS project). The present project includes several technological developments that will expedite the feasibility demonstration of these missions. We initiated the design of a compact optical lattice clock with strontium atoms and are investigating the associated difficulties in terms of reliability, size and mass, and power consumption. The progress on these aspects will be a first step on the way from bulky laboratory devices to flyable systems. Other domains will also be impacted by this development, such as satellite orbit control.

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