Questionnaire previous to the 2006 meeting of the CCL/CCTF Joint Working Group

Summary of the previous meetings

The CCTF on its 16th meeting in April 2004 recommended that the unperturbed ground-state hyperfine quantum transition of ^{87}Rb may be used as a secondary representation of the second with a frequency of f_{Rb}= 6 834 682 610.904 324 Hz and an estimated relative standard uncertainty (1σ) of 3 x 10^{-15}, and submitted this recommendation to the CIPM.

The 2005 CCL/CCTF JWG adopted three optical frequency standards for recommendation to the CCTF as secondary representations of the second:

> The trapped and cooled mercury ion $^{199}Hg^{+}$, $5d^{10}\ 6s\ ^2S_{1/2}$ (F = 0) — $5d^9\ 6s^2\ ^2D_{5/2}$ (F = 2), Δm_F = 0 transition for which the value f = 1 064 721 609 899 145 Hz with a relative standard uncertainty of 3 x 10^{-15}, applies to the unperturbed quadrupole transition.
>
> The trapped and cooled strontium ion $^{88}Sr^{+}$, $5s\ ^2S_{1/2}$ – $4d\ ^2D_{5/2}$ transition for which the value f = 444 779 044 095 484.6 Hz with a relative standard uncertainty of 7 x 10^{-15}, applies to the radiation of a laser stabilized to the unperturbed transition and to the centre of the Zeeman multiplet.
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> The trapped and cooled ytterbium ion $^{171}Yb^{+}$, $6s\ ^2S_{1/2}$ (F = 0, m_F = 0) — $5d\ ^2D_{3/2}$ (F =2, m_F = 0) transition for which the value f = 688 358 979 309 308 Hz with a relative standard uncertainty of 9 x 10^{-15}, applies to the unperturbed quadrupole transition.

1. Frequency sources in the microwave domain

   1.1. Have you made or are you aware of new absolute frequency measurements of the Rb hyperfine transition?

   No

   If yes, please list the values and uncertainties obtained and refer to the publication in which they may be found. Please be sure to include measurements made in other laboratories.

   1.2. Are you aware of absolute frequency measurements of other microwave standards that should be proposed as secondary representations of the second?

No

If yes, please list the values and uncertainties obtained and the method used and refer to the publication in which they may be found. Please be sure to include measurements made in other laboratories in your country.

1.3. Are you currently developing new frequency sources in the microwave domain?

No

If yes, please give a brief description of your experiment.

2. Frequency sources in the optical domain

2.1. Have you made or are you aware of new absolute frequency measurements of the three optical transitions adopted by the 2005 CCL/CCTF JWG?

No

If yes, please list the values and uncertainties obtained and refer to the publication in which they may be found. Please be sure to include measurements made in other laboratories.

2.2. Have you made or are you aware of new absolute optical frequency measurements suitable to serve as secondary representations of the second?

Yes

If yes, please list the values and uncertainties obtained and refer to the publication in which they may be found.

Report on the frequency measurement of the $^1S_0$ - $^3P_0$ transition of ^{87}Sr

1- Experimental setup

We have performed the frequency measurement of the $^1S_0$ - $^3P_0$ transition of ^{87}Sr in an optical lattice clock. The apparatus is described in details in Ref. [1,2]. The clock frequency is measured relative to the Cs atomic fountain FO2 using a self-referenced optical frequency comb. The fractional frequency stability of this comparison is $6\ 10^{-14}\ t^{-1/2}$ with t the averaging time in seconds, so that individual measurement with 1 Hz ($2\ 10^{-15}$) statistical uncertainty are performed within about 15 minutes.

2- Results

The measured frequency of the transition is **429 228 004 229 879 (5) Hz**. In fractional units the uncertainty is 1.2 10^{-14}. The details of the experiments performed for this evaluation are given in Ref. [2]. This value is in excellent agreement with the one reported by the JILA group which is 10 Hz smaller with an error bar of 19 Hz [3]. It should be stressed here that there are significant differences between both experimental setups which strongly assess their mutual independence:

- The spectral width of the atomic resonances differ by a factor of 4 (50 Hz vs 200 Hz)
- In our measurement the probe laser was locked to the atomic resonance while the JILA one was based on fits of atomic resonances.
- the depth of the lattice in our experiment is up to one order of magnitude larger than in the JILA one.
- The time sequence of operation of both clocks differ significantly
- In both experiments an important contributor to the final error bar is the uncertainty on the first order Zeeman effect. The evaluation of this effect has been performed differently in both cases: JILA explored the effect of an intentional additional magnetic field, while we studied the dependence of the clock frequency on the probe laser polarization and on the width of the frequency modulation used to lock the probe laser to the atoms.

Finally, a third group at Tokyo university published a measurement of the same transition which is in disagreement with the two measurements of SYRTE and JILA. The reported value is 73 Hz larger with an error bar of 15 Hz [4]. Very recently this group presented a value in agreement with both JILA and SYRTE (3 Hz smaller with an error bar of 5 Hz) [5].

3- Prospects

The main contributor to the present uncertainty is by far the first order Zeeman effect. Relatively simple modifications of the experimental setup will allow to dwarf this contributor. We expect to be able to remeasure this atomic transition with an uncertainty in the low 10^{-15} range in 2007.

References

[1] A. Brusch, R. Le Targat, X. Baillard, M. Fouché and P. Lemonde, Phys. Rev. Lett. **96**, 103003 (2006).

[2] R. Le Targat et al., arXiv:physics/0605200.
[3] A. D. Ludlow et al., Phys. Rev. Lett. **96**, 033003 (2006).
[4] M. Takamoto, F-L. Hong, L. Higashi and H. Katori, Nature, **435**, 321 (2005).
[5] T. Akatsuka et al., 2006 IEEE international Frequency Control Symposium, Miami, USA.

2.3. Are you currently developing new frequency sources in the optical domain?

Yes

If yes, please give a brief description of your experiment.

<u>Neutral mercury: an interesting candidate for an optical lattice clock</u>

One interesting candidate for an optical lattice clock is neutral mercury (Hg). Hg has an alkaline-earth like electronic structure with a $^1S_0$-$^3P_0$ intercombination transition which is totally forbidden for bosonic natural isotopes and weakly allowed by hyperfine mixing for fermions. The wavelength of this transition is 265.6 nm. The natural linewidth of the transition has been calculated and measured to be in the 100 mHz range for fermions [1]. As for other proposed neutral atoms (Ca, Sr, Yb), bosonic isotopes can also be used for an optical clock provided a quenching scheme is used [2]. One possible foreseeable limitation of the accuracy of optical lattice clock, when accuracy below 10^{-17} is targeted, is the blackbody radiation shift. In this respect, Hg is an interesting candidate with an estimated blackbody radiation shift of 2×10^{-16}, between 10 and 100 times smaller than other alkaline-earth atoms [3,4]. Hg also possesses 6 abundant isotopes (2 fermions and 4 bosons, natural abundance >6%) and 1 relatively rare, although probably usable, bosonic isotope (^{196}Hg) with a 0.15% natural abundance. All isotopes have no more than F=3/2 (^{201}Hg) total spin in the ground state.

Two other important considerations to make Hg a reasonable candidate is the feasibility of laser cooling and of an non-perturbing lattice trap. Unlike other alkaline-earth candidate, the strongly allowed $^1S_0$-$^1P_1$ transition is not practical (185 nm) and has a very high Doppler cooling temperature. On the other hand, the $^1S_0$-$^3P_1$ transition at 254 nm with a natural linewidth of 1.2 MHz should lead to efficient magneto-optical trapping together with a low Doppler cooling temperature of 30 μK. Unlike the 185 nm radiation, the 254 nm wavelength can be accessed with sufficient power using available technologies. Similarly, it has been shown, that Hg possesses at least one useable “magic wavelength” for the non-perturbing dipole trap [5,6] at 342 nm.

To conclude, Hg is an interesting candidate for an optical lattice clock. One interesting metrological feature is the smallness of the blackbody radiation shift. Also, Hg has a high sensitivity to α variation [7]. One of the challenging aspects of using Hg for an optical clock is the necessity to generate and use UV laser light with relatively high power.

Development of an optical lattice clock based on mercury at SYRTE

Based on the above considerations, SYRTE has started developing an optical lattice clock based on Hg. This project has started in 2005 with the financial support coming most notably form LNE, the French NMI. Initial developments concerning the vacuum system, the clock laser at 265.6 nm have been completed in 2005-2006 (resonant frequency doubling of an alpha-DFG diode laser at 1062.4 nm using a PPKTP crystal leading to more than 100mW at 531.2 nm which should lead sufficient power at 265.6 nm for all envisioned experiments). Most definition studies for all main sub-systems have also been completed. In 2006, we have started developing the laser source for laser cooling, based on a commercial frequency doubled disk laser at 1014.9 nm delivering ~3 W at 507 nm. More than 700mW have been observed at 254 nm after resonant frequency doubling with BBO crystal. Saturated absorption spectroscopy of a Hg vapor has been performed in order to stabilized this laser source. Despite a recent failure in the disk laser system, these results clearly demonstrate the feasibility of a suitable laser source for laser cooling of Hg. The construction of the vacuum chamber and of the ultra stable reference laser at 1062.4 nm is now underway. With reasonable optimism, we are targeting to observe laser cooling by the beginning of 2007 and to probe the clock transition for the first time in 2007. 2007 will also be devoted to the development of the optical lattice trap (laser sources, build-up cavity, and modified vacuum chamber).

[1] M.C. Bigeon, Journal de Physique **28**, 51 (1967)
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[2] A. V. Taichenachev, V. I. Yudin, C. W. Oates, C. W. Hoyt, Z. W. Barber, and L. Hollberg, Phys. Rev. Lett. **96**, 083001 (2006)
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[3] V. Pal'chikov, private communications (2004)

[4] Sergey G. Porsev, Andrei Derevianko, ArXiv:physics/0602082 (2006)
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P.S.: In your response please would you attach a pdf copy of the publication, preprint or internal report which describes the relevant information to assess the final values and uncertainties provided, as this is extremely useful for the JWG deliberation.

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