Cold Atom Clocks

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Cold atom fountains have now ten years of existence. We will review recent progress on microwave clocks using laser cooled neutral atoms.

With an ultra-stable cryogenic sapphire oscillator as interrogation oscillator, a cesium fountain operates at the quantum projection noise limit [1]. With 6 10^5 detected atoms, the relative frequency stability $\delta\nu/\nu$ is 4 10^{-14} $\tau^{-1/2}$ where τ is the integration time in seconds. This stability is comparable to that of hydrogen masers. At $\tau = 2\ 10^4$ s, the measured stability reaches 6 10^{-16}. Equally important is the accuracy of the frequency standard since ^{133}Cs is the primary reference for the definition of the time unit, the second. The accuracy of our cesium fountain FO1 is presently 1.1 10^{-15}, currently the best reported value [2].

A ^{87}Rb fountain has also been constructed [3] and the ^{87}Rb ground-state hyperfine energy has been compared to the Cs primary standard with a relative accuracy of 2.5 10^{-15}. Comparing the hyperfine energies of atoms with different atomic numbers Z, one can search for possible variations of the fine structure constant $\alpha = e^2/\hbar c$ with time [4]. Two measurements of the ratio $\nu(^{87}Rb)/\nu(^{133}Cs)$ spread over an interval of 12 months indicate no change at a level of 4 10^{-15}/year, placing a new upper limit for $1/\alpha(d\alpha/dt)$. The second attractive feature of ^{87}Rb fountains is the smallness of the frequency shift induced by the mean field interaction between atoms [5]. This shift is found to be two orders of magnitude below that of cesium [6, 7].

We then will describe a transportable cesium fountain [2], which has recently been used as a primary frequency reference for a new measurement of the $1s \rightarrow 2s$ transition frequency in atomic hydrogen with an accuracy of 1.8 10^{-14} [8]. Finally, the interest of the microgravity of space for cold atom experiments will be outlined. A space mission, ACES, carrying ultra-stable clocks, will be presented. ACES has been selected by the European Space Agency to fly on the International Space Station in 2004 [9, 10].

[1] Santarelli G., Laurent P., Lemonde P., Clairon A., Mann A., Chang S., Luiten A., and Salomon C., Phys. Rev. Lett., **82**, 4619 (1999).

[2] Laurent P., Lemonde P., Santarelli G., Abgrall M., Kitching J., Sortais Y., Bize S., Santos M., Nicolas, C., Zhang S., Schehr G., Clairon A., Mann A., Luiten A., Chang S., and Salomon C., Proc. of the 14^{14} Int. Conf. on Laser Spectroscopy, World Scientific, p.41 (1999).

[3] Bize S., Sortais Y., Santos M., Mandache C., Clairon A., and Salomon C., Europhys. Lett., **45**,

558 (1999).
[4] Prestage J., Tjoelker R., and Maleki L., Phys. Rev. Lett., **74**, 3511 (1995).
[5] Kokkelmans S., Verhaar B., Gibble K., and Heinzen D., Phys. Rev. A, **56**, R4389 (1997).
[6] Sortais Y., Bize S., Nicolas C., Santos M., Mandache C., Santarelli G., Salomon C., and Clairon A., Proc of the IEEE 1999 EFTF and FCS joint symposium, p. 34 (1999) Europhys. Lett., **45**, 558 (1999).
[7] Fertig C., Legere R., Süptitz, and Gibble K., ibid., p.39.
[8] Niering M., Holzwarth R., Reichert J., Pokasov P., Udem T., Weitz M., Hänsch T., Lemonde P., Santarelli G., Abgrall M., LaurentP., Salomon C., and Clairon A., Phys. Rev. Lett., in press,(2000).
[9] Salomon C. and Veillet C., *ESA symposium proc. on "Space Station Utilisation"*, SP 385, 295 (1996).
[10] Salomon C., Lemonde P., Laurent P., Simon E., Santarelli G., Clairon A., Dimarcq N., Petit P., Audoin C., Gonzalez F.,and Jamin-Changeart F., *ibid* p. 289.