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HIGH-PERFORMANCE TRAPPED Hg^+ FREQUENCY STANDARDS*

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Abstract

We have demonstrated a new frequency standard, accurate to 3.4×10^{-15}, based on the 40.5 GHz ground state hyperfine transition in cooled and trapped $^{199}Hg^+$. We are also developing an optical frequency standard based on $^{199}Hg^+$. The spectral width of the 563 nm laser used in this standard is less than 6 Hz.

Introduction

Trapped and cooled ions can be the basis of stable and accurate frequency standards, since their transition frequencies can be relatively unperturbed by external fields and Doppler effects, and because the statistical precision of frequency measurements using such ions can be very high. We are using trapped and cooled $^{199}Hg^+$ to develop both a microwave and an optical frequency standard.

Figure 1 shows the relevant energy levels of Hg^+ [1]. We cool the ions using the $^2S_{1/2} \rightarrow {}^2P_{1/2}$ electric dipole transitions at 194 nm. Transition p is the primary cooling transition because it is nearly a cycling transition. However, because the ions can be optically pumped into the $^2S_{1/2}$, $F = 0$ state, a second light source weakly drives the repumping transition r. The ground state hyperfine transition at 40.5 GHz is used as the clock transition for the microwave frequency standard. The electric quadrupole transition at 282 nm will be the basis for an optical frequency standard.

Microwave Frequency Standard

Figure 2 shows a schematic of the linear Paul trap used for the microwave frequency standard, and a linear crystal of ions confined along the trap axis [2]. The oscillating electric potential V_0 applied between the trap rods creates a pseudopotential to confine the ion radially. A static potential U_0 applied to the two cylindrical endcaps at either end of the trap confines the ions axially. Typically, the ion crystals consist of five to fifteen ions with an inter-ion spacing of about 10 μm. Two 194 nm laser beams intersect the ions at angles of ±20°, and are used to cool the ions and to determine their internal states.

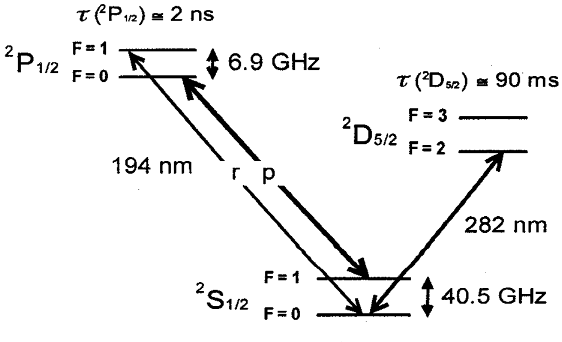

Figure 1: Energy level diagram of Hg^+.

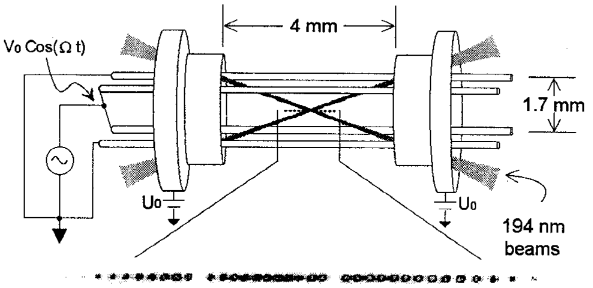

Figure 2: Linear Paul trap and a linear crystal of Hg ions. The gaps in the crystal are likely isotopes of Hg whose transition frequencies are not resonant with the 194 nm laser light.

We lock the frequency of a microwave synthesizer [3] to the central fringe of the Ramsey spectrum obtained in the following way. First, we cool the ions by driving both transitions p and r. Next, only transition p is driven, optically pumping the ions into the $^2S_{1/2}$, $F = 0$ state. The hyperfine transition is then driven using Ramsey's method of separated oscillatory fields [4], with a free precession time T_R which we vary from 2 to 100 s. Finally, transitions to the $^2S_{1/2}$, $F = 1$ state are detected by driving only transition p while counting the number of detected scattered photons.

The frequency stability of the microwave synthesizer when it is locked to the transition is $3.3\ (2) \times 10^{-13}\ \tau^{-1/2}$ for measurement times $\tau < 2$ h, when we use seven ions and a free precession time T_R of 100 s. This frequency stability is comparable to those of the Cs beam standard NIST-7, for which $\sigma_y(\tau) \cong 8 \times 10^{-13}\ \tau^{-1/2}$ [5], and the Cs fountain standard, for which $\sigma_y(\tau) \cong 2 \times 10^{-13}\ \tau^{-1/2}$ [6].

We have also evaluated the standard for possible systematic frequency shifts [1], and find that the fractional accuracy of the standard is 3.4×10^{-15}. This uncertainty from systematic effects is approximately equal to the best values reported, from a cesium beam clock (5 parts in 10^{15}) [7], and a cesium fountain clock (2 parts in 10^{15}) [8]. It is dominated by the uncertainty in the measurement of the ac Zeeman shift caused by currents in the trap electrodes at the frequency of the trap's electric field, and by slow fluctuations in the static magnetic field. Future experiments are expected to sharply reduce these sources of uncertainty.

Optical Frequency Standard

We are developing an optical frequency standard based on the 1.7 Hz wide $^2S_{1/2} \rightarrow {}^2D_{5/2}$ electric quadrupole transition at 282 nm. To take advantage of the small width of this transition, the bandwidth of the laser light at 282 nm must be on the order of a few Hz or less. Such a narrow frequency source is provided by locking the frequency of a dye laser at 563 nm to the resonance frequency of a highly stabilized reference cavity [9]. The light at 563 nm is then frequency-doubled to 282 nm.

The reference cavity has a finesse of over 50 000, and is suspended by two thin wires in an evacuated, thermally isolated chamber. The intra-cavity power is controlled to 0.1% to avoid fluctuations in the cavity spacing caused by variations in light pressure and heating of the mirror coatings. The vacuum chamber is placed on a frame suspended by many vertical strands of rubber tubing to isolate it from floor and ceiling vibrations. The entire system is enclosed in a box lined with thin layers of foam and lead to reduce vibrations from acoustical noise.

Figure 3 shows the spectrum of the beat note between two laser beams stabilized to two independent cavities such as that described above. The width of the spectrum at its half-power point is 8 Hz. Assuming the frequencies of both laser beams are similar, this means that a single beam has a frequency width of less than 6 Hz at 563 nm, or fractionally 1.1×10^{-14}. We believe that this is the narrowest optical frequency spectrum recorded.

We are now constructing a Paul-Straubel trap [10] in a cryogenic environment. A frequency-doubled laser locked to the 282 nm transition in a single ion by using a free precession time of 30 ms would have a theoretical frequency stability of about $1 \times 10^{-15}\ \tau^{-1/2}$.

Summary

We have evaluated a microwave frequency standard at 40.5 GHz, and found that its frequency stability is $3 \times 10^{-13}\ \tau^{1/2}$ for $\tau < 2$ h when there are seven ions and the free precession time is 100 s. The fractional accuracy of this standard is 3.4×10^{-15}. We are also developing an optical frequency standard based on the 282 nm $^{199}\mathrm{Hg}^+$ electric quadrupole transition. The laser used to drive this transition is stabilized to less than 6 Hz at 563 nm.

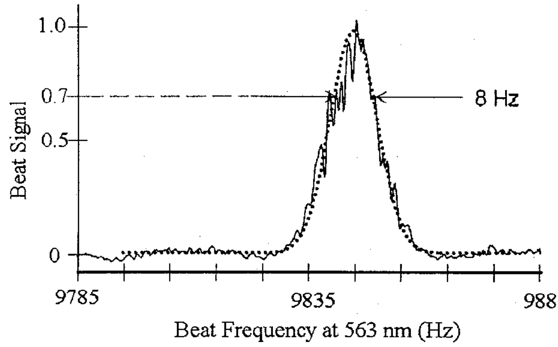

Figure 3: Beat between two laser beams stabilized to two independent cavities. The dotted line is meant to guide the eye.

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References

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[1] D.J. Berkeland, J.D. Miller, J.C. Bergquist, W.M. Itano, and D.J. Wineland, "Laser-Cooled Mercury Ion Frequency Standard," to be published in Phys. Rev. Lett..

[2] M.E. Poitzsch, J.C. Bergquist, W.M. Itano, and D. J. Wineland, "Cryogenic Linear Ion Trap for Accurate Spectroscopy," Rev. Sci. Instrum. **67**, 129-134 (1996).

[3] C.W. Nelson, F.L. Walls, F.G. Ascarrunz, and P.A. Pond, "Progress on Prototype Synthesizer Electronic for $^{199}\mathrm{Hg}^+$ at 40.5 GHz," Proc. 1992 IEEE Freq. Control Symp., 64-68 (1992).

[4] N.F. Ramsey, *Molecular Beams*, pp. 124-134 (Oxford Univ. Press, London, 1956).

[5] W.D. Lee, J.H. Shirley, J.P. Lowe, and R.E. Drullinger, "The Accuracy Evaluation of NIST-7," IEEE Trans. Instrum. Meas. **44**, 120-123 (1995).

[6] A. Clairon, S. Ghezali, G. Santarelly, Ph. Laurent, S.N. Lea, M. Bahoura, E. Simon, S. Weyers and K. Szymaniec, "Preliminary Accuracy Evaluation of a Cesium Fountain Frequency Standard," in Proc. of the Fifth Symp. Freq. Standards and Metrology, ed. James C. Bergquist, World Scientific, p. 49-59, (1996).

[7] R.E. Drullinger, J.H. Shirley and W.D. Lee, "NIST-7, The U.S. Primary Frequency Standard: New Evaluation Techniques" in 28th Ann. PTTI Appl. And Planning Mtg., 255-264 (1996).

[8] E. Simon, P. Laurent, C. Mandache and A. Clairon, "Experimental Measurement of the Shift of Cs Hyperfine Splittings Due to a Static Electric Field," in 11th Eur. Freq. And Time Forum Neuchatel, 43-45 (1997).

[9] J.C. Bergquist, W.M. Itano, and D.J. Wineland, "Laser Stabilization to a Single Ion," in Frontiers in Laser Spectroscopy, 357-376 (1994).

[10] N. Yu, W. Nagourney, and H. Dehmelt, "Demonstration of a New Paul-Straubel Trap for Trapping Single Ions," J. Appl. Phys. **69**, 3779-3781 (1991).