The Mercury-ion Optical Clock

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Overview

An optical frequency standard based on a single trapped ^{199}Hg$^+$ ion

Why optical clocks?

- Higher frequency ⇒ higher stability, for given averaging time.

Quantum limit to stability: $\frac{\Delta\nu}{\nu} \approx \frac{1}{2\pi\nu_0\sqrt{N T_R \tau}}$

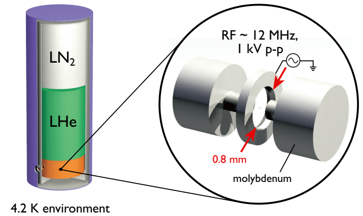
examples:

Cs fountain: $N = 10^6$ atoms, $\nu_0 = 9$ GHz, $T_R = 1$ s
$\Longrightarrow \Delta\nu/\nu \sim 2\times10^{-14}\tau^{-\frac{1}{2}}$

Hg+ optical clock: $N = 1$ ion, $\nu_0 = 10^{15}$ Hz, $T_R = 30$ ms
$\Longrightarrow \Delta\nu/\nu \sim 1\times10^{-15}\tau^{-\frac{1}{2}}$

- High accuracy possible with single ion
- Absolute frequency measurements possible with femtosecond comb.

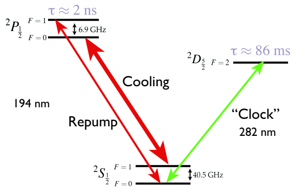
Cryogenic spherical rf (Paul) trap



4.2 K environment
High environmental isolation
Storage time: months (in principle)

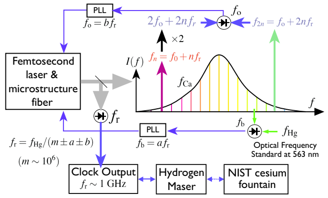
Secular frequency: ~ 1 MHz

Relevant ^{199}Hg$^+$ energy levels



- Clock transition Q ≈ 5 10^{14}
- Structure enables quantum jump spectroscopy

Femtosecond frequency comb

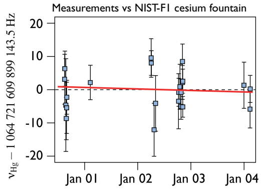


- Enables comparison with other optical and microwave frequency standards

S.A. Diddams, *et al.*, Science **293** 825 (2001).

Absolute frequency measurements

Measurements vs NIST-F1 cesium fountain



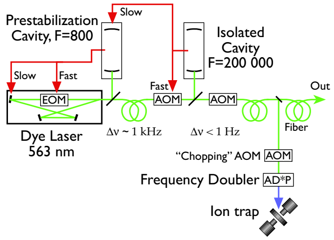
Linear fit to data : -0.5 ± 1.1 Hz/yr
Consistent with zero drift

(Statistical error bars only) S. Bize *et al.*, PRL **90** 150802 (2003).

Stable light source

Probe laser for 282 nm clock transition

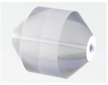
Low-noise 282 nm source



Isolated high-finesse cavities

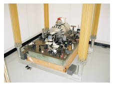
- Long-term stability due to ion
- Short-term laser stability derives from isolated, high-finesse Fabry-Perot cavity

High-finesse cavity: *F*~200 000
ULE cavity spacer ~ 25 cm

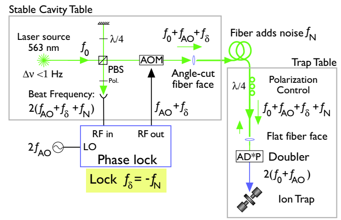


Thermal and seismic isolation:

Temperature-controlled vacuum chamber; suspended from ceiling by latex tubing

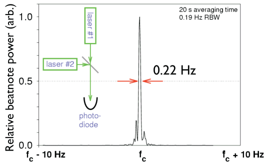


Fiber noise cancellation



L.-S. Ma, P. Jungner, J. Ye, and J. L. Hall, Opt. Lett. **19**, 1777 (1994).
J. C. Bergquist, et al., Frontiers of Laser Spectroscopy, North Holland, 1994, p. 359.
B. C. Young, et al., Proc. of the 14th Int. Conf. on Laser Spectroscopy, World Scientific, 1999, p. 61.

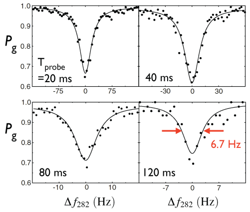
Beatnote between laser sources



Beatnote between two 563 nm laser sources stabilized with independent cavities

Clock transition lineshapes

- Quantum-jump spectroscopy
  - Rabi excitation
  - Transform-limited linewidth
- Lock to ion by stepping across transition



R. J. Rafac *et al.*, PRL **85** 2462 (2000).

Systematic frequency shifts

Evaluating the accuracy of the mercury clock

Major contributions to uncertainty

Effect	Correction (Hz at 1.06 PHz)	Uncertainty (Hz)
2nd order Zeeman (B-field uncertainty)	1700, (typ., daily)	2.8
2nd order Zeeman (coefficient uncertainty)	0	2.6
$^2D_{\frac{5}{2}}$ quadrupole shift	*Not evaluated*	10
H-maser frequency		4

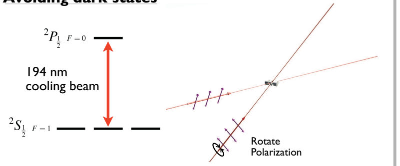
Total fractional uncertainty: 10^{-14}

Negligible contributions (at this level):
ac stark shifts (laser and rf trap), fs comb noise, background collision shifts (helium), and 2nd-order Doppler (micromotion, thermal)

All effects except quadrupole should reduce below 10^{-18}

W. M. Itano, J. Res. NIST **105**, 829 (2000).

Avoiding dark states

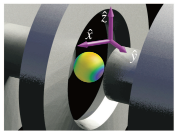


- Dark states for any polarization, limit fluorescence rate
- Destabilize dark states with magnetic bias field or (now) polarization modulation

See D. J. Berkeland and M. G. Boshier, PRA **90** 033413 (2002).

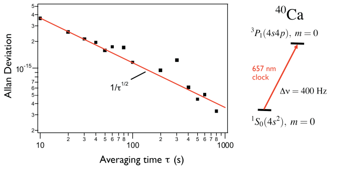
The quadrupole shift

- Shift due to coupling of $^2D_{5/2}$-state electric quadrupole moment with stray E-field gradients
- Quadrupole shift averages to zero over three orthogonal quantization axes [W. M. Itano, J. Res. NIST **105**, 829 (2000).]



- No shift in an ideal spherical rf trap
- Total shift expected to be under 1 Hz
- Need a stable flywheel for the measurement!
- Can determine mercury ion quadrupole moment by measuring frequency shift due to a *known* electric-field gradient.

Stability vs calcium optical clock



Data vs Ca optical clock (G. Wilpers and C.W. Oates)

- May provide "flywheel" for accuracy evaluation

Prospects for immediate future

Effect	Correction (Hz at 1.06 PHz)	Uncertainty (Hz)
2nd order Zeeman (B-field uncertainty)	10, (typ., daily)	0.15
2nd order Zeeman (coefficient uncertainty)	0	0.01
$^2D_{\frac{5}{2}}$ quadrupole shift	*In progress*	???
H-maser frequency		1

Total fractional uncertainty <10^{-16} soon?

- Magnetic shifts reduced with polarization scrambling; shielding will further reduce uncertainty.
- Quadrupole shift evaluation is in progress: Correction is likely to be under 1 Hz.
- Lower H-maser uncertainty by running simultaneously with cesium fountain.

Application to fundamental constants

Motivation

- Astrophysical data suggest $\alpha = e^2/4\pi\varepsilon_0\hbar c$ may have changed in cosmological time (10^{10} years ago)

$$\Delta\alpha(\text{past})/\alpha = -(0.54 \pm 0.12)\times10^{-5}\ ?$$

M.T. Murphy, et al., astro-ph/0306483
(Astrophysical model assumptions)

- Geological data from Oklo reactors ($2\cdot10^9$ years ago)

$$\Delta\alpha(\text{past})/\alpha = -(0.36 \pm 1.44)\times10^{-8}$$

Y. Fujii, et al., Nuc. Phys. B **573**, 377 (2000).
(Assumptions about reactor operating conditions)

- What about present-day variation?

Transition frequencies

- Clock comparisons may provide the best test of present-day changes in physical constants.

For Hg vs Cs, express transition frequencies as:

$$\nu_{Hg} \approx R_\infty c F_{Hg}(\alpha),$$
$$\nu_{Cs} \approx g_{Cs}(m_e/m_p)\alpha^2 R_\infty c F_{Cs}(\alpha)$$

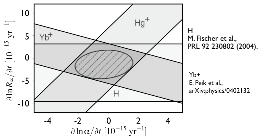
$$\alpha\frac{\partial}{\partial\alpha}(\ln F_{Hg}(\alpha)) \approx -3.2$$
$$\alpha\frac{\partial}{\partial\alpha}(\ln F_{Cs}(\alpha)) \approx +0.8$$
$$\Longrightarrow \frac{\nu_{Cs}}{\nu_{Hg}} \approx g_{Cs}(m_e/m_p)\alpha^{6.0}$$

Test stability of this ratio

V.A. Dzuba, V.V. Flambaum, and J. K. Webb, PRA **59**, 230 (1999).

S. Bize *et al.*, PRL **90**, 150802 (2003).

Limits with other standards



H
M. Fischer et al., PRL 92 230802 (2004).

Yb+
E. Peik et al., arXiv:physics/0402132

$$\frac{\partial \ln\alpha}{\partial t} = (-0.3 \pm 2.0)\times10^{-15}\ \text{yr}^{-1} \qquad \frac{\partial \ln R_\infty}{\partial t} = (-1.5 \pm 3.2)\times10^{-15}\ \text{yr}^{-1}$$

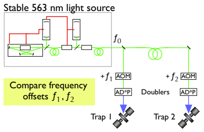
- Results consistent with zero drift
- Improvements to evaluated accuracy of mercury ion clock will tighten limits

Future Steps

Accuracy evaluation

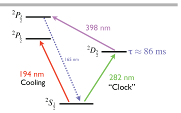
- Complete measurements of quadrupole moment and quadrupole shift
- Add magnetic shielding to trap
- Comparisons with other optical standards: Ca, 2nd Hg+ system, and others coming on line: Al+, Yb, and Sr.

Comparison of two Hg ion clocks



Improvements to stability

- Quench *D* (excited) state of clock transition, to reduce dead time during measurement cycle.



Acknowledgments & References

Other contributing members of NIST ion storage group:

S. Bize
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R. E. Drullinger
T. Rosenband
U. Tanaka
D. J. Wineland

References:

R. J. Rafac *et al.*, PRL **85** 2462 (2000).
W. M. Itano, J. Res. NIST **105**, 829 (2000).
S.A. Diddams, *et al.*, Science **293** 825 (2001).
S. Bize *et al.*, PRL **90** 150802 (2003).

Additional publications available at
http://www.boulder.nist.gov/timefreq/ion/

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