Microwave and optical spectroscopy in r.f. traps Application to atomic clocks

Microwave spectroscopy for hyperfine structure measurements

Energy of a hyperfine state

$$W_F = \frac{1}{2} hAK + hB \frac{\frac{3}{2}K(K+1) - 2I(I-1)J(J+1)}{2I(2I-1)2J(2J-1)}$$

$$K = F(F+1) - I(I+1) - J(J+1)$$

Hyperfine coupling constants:
A: magnetic dipole interaction
B: Electric quadrupole interaction

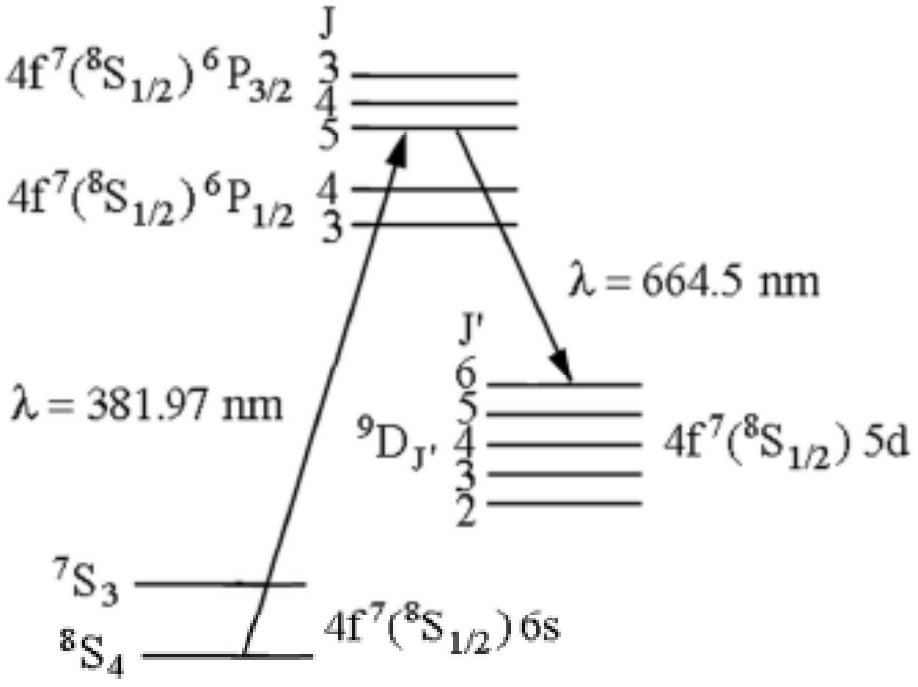
$$A_s = -\frac{1}{h}\frac{16\pi}{3}\frac{\mu_0}{4\pi}\mu_B^2 g_I \mid \Psi_s(0) \mid^2$$

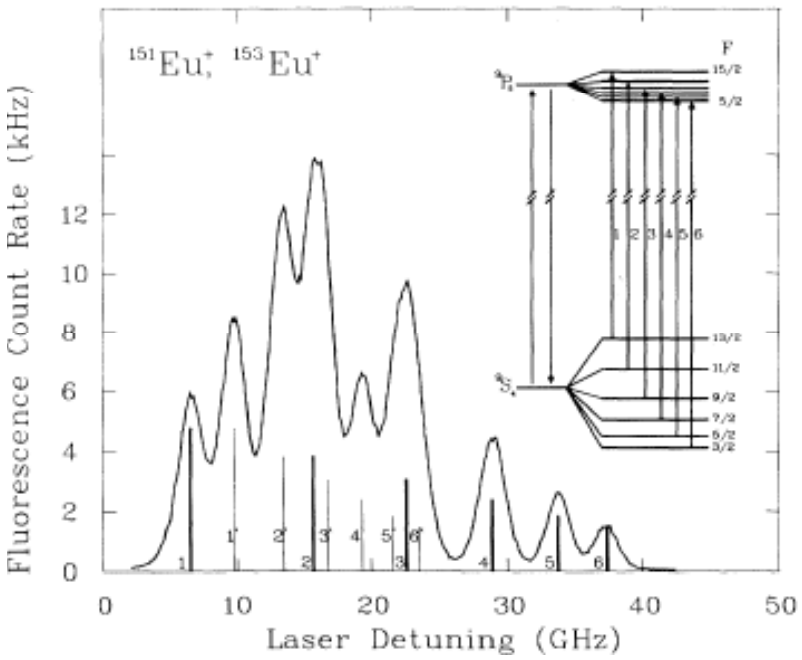
$$B = \frac{1}{h}\frac{e^2}{4\pi\varepsilon_0}\frac{2J-1}{2J+2} < r^{-3} >_{nl} Q$$

Features of microwave spectroscopy:

- No first order Doppler effect because of Dicke effect (ion oscillation amplitude < wavelength of radiation)
- Stable and accurate radiation sources available
- State preparation by laser or spectral lamp
- Resonance detection by flourescence light

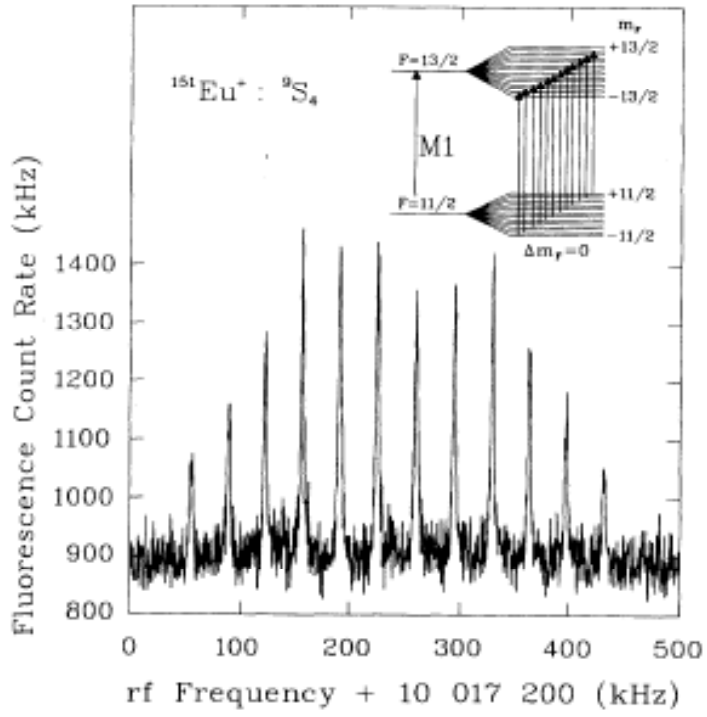
Example I: Eu+

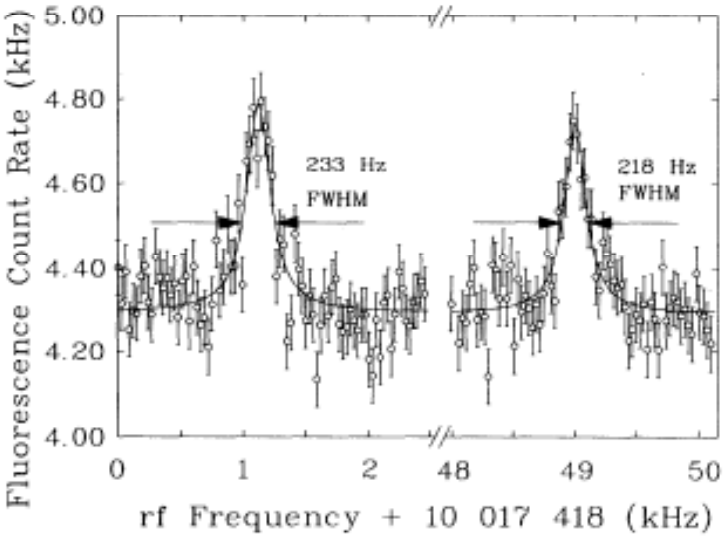




Optical spectrum
of stable
Eu+ isotopes 151, 153

Induced hyperfine transitions with Zeeman splitting





Uncertainty of resonances: 20 Hz in 10 GHz

Results for Eu isotopes

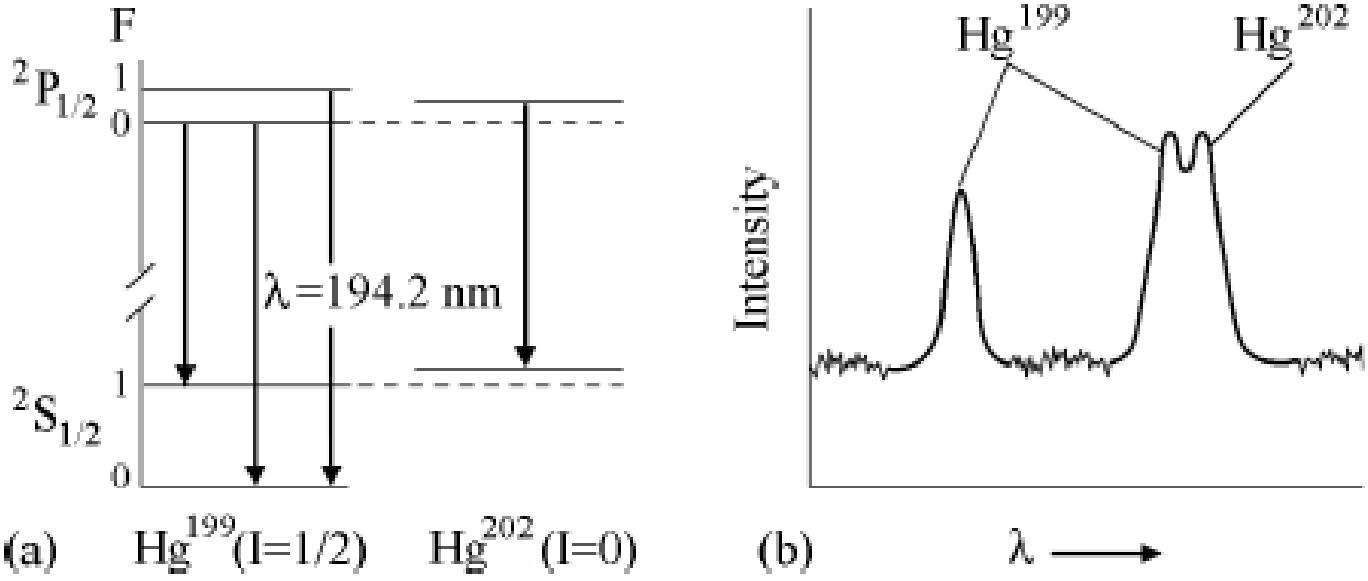
	I		A [MHz]	B [kHz]
$^{148}Eu^{+}$	5	$6\,^{9}S_{4}$	517.281 950 (150)	-292.63 (1.00)
$^{148}Eu^{+}$	5	$6\,^{7}S_{3}$	-561.647 (100)	
$^{149}Eu^{+}$	5/2	$6\,^{9}S_{4}$	1 585.450 570 (250)	-534.85 (1.90)
$^{150}Eu^{+}$	5	$6\,^{9}S_{4}$	599.010 680 (200)	-839.73 (3.00)
$^{150}Eu^{+}$	5	$6\,^{7}S_{3}$	-650.334 (2)	
$^{151}Eu^{+}$	5/2	$6\,^{9}S_{4}$	1 540.297 394 (13)	-660.862 (2.31)
$^{151}Eu^{+}$	5	$6\,^{7}S_{3}$	-1 672.457 109 (266)	-599.4 (3.1)
$^{153}Eu^{+}$	5/2	$6\,^{9}S_{4}$	684.565 993 (9)	-1 752.868 (84)
$^{153}Eu^{+}$	5	$6\,^{7}S_{3}$	-743.183 577 (82)	2 448.35 (8)

First step towards systematic study of Bohr-Weisskopf effect (distribution of magnetization over nuclear volume)

$$\Delta(1,2)=1-(A_1/A_2)(g_{I2}/g_{I1})$$

Need to measure nuclear g factors

Example II: Hg+

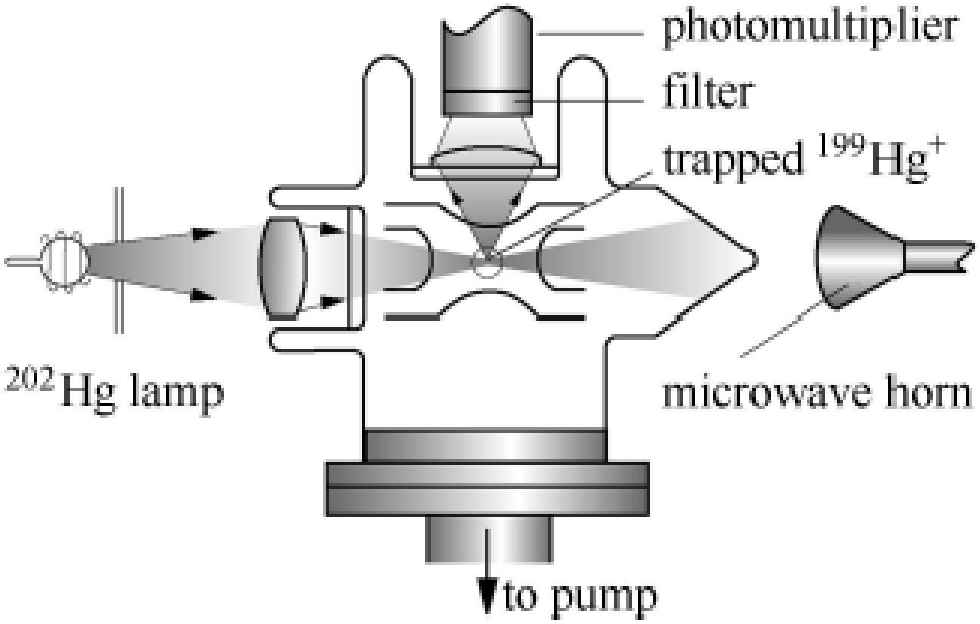


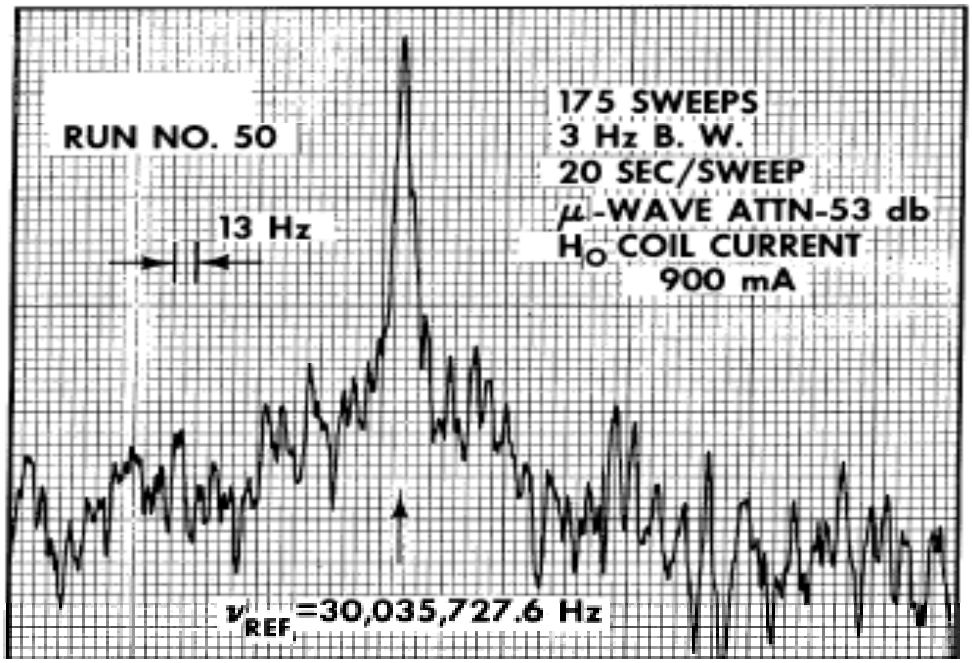
Level diagram of Hg+ isotopes

Optical spectrum of 199 Hg+ and 202Hg+

Optical pumping of one ground state hyperfine level of 199Hg+ by accidental coincidence of 202Hg+ line with one hyperfine component

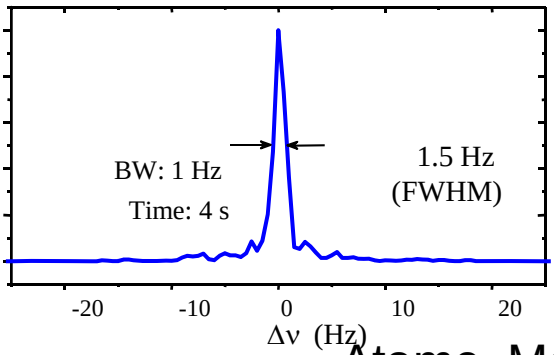
Microwave transition between 199Hg+ hyperfine levels monitored by change in fluorescence intensity



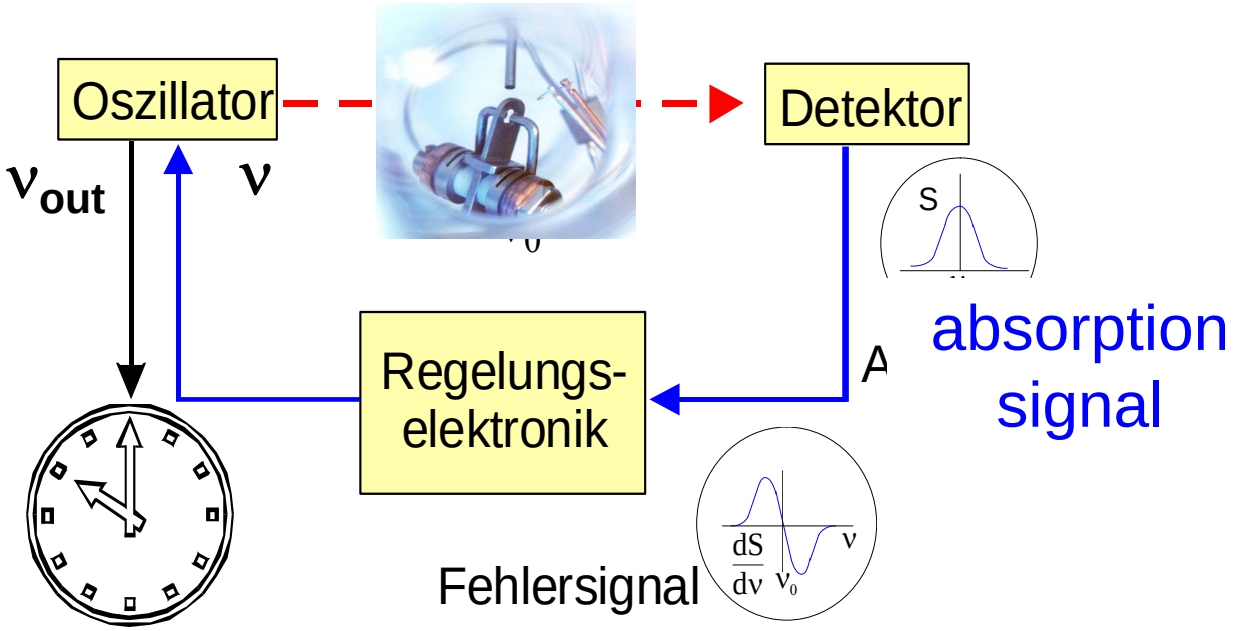


Major, Werth (1973)

Principle of Atomic Clocks



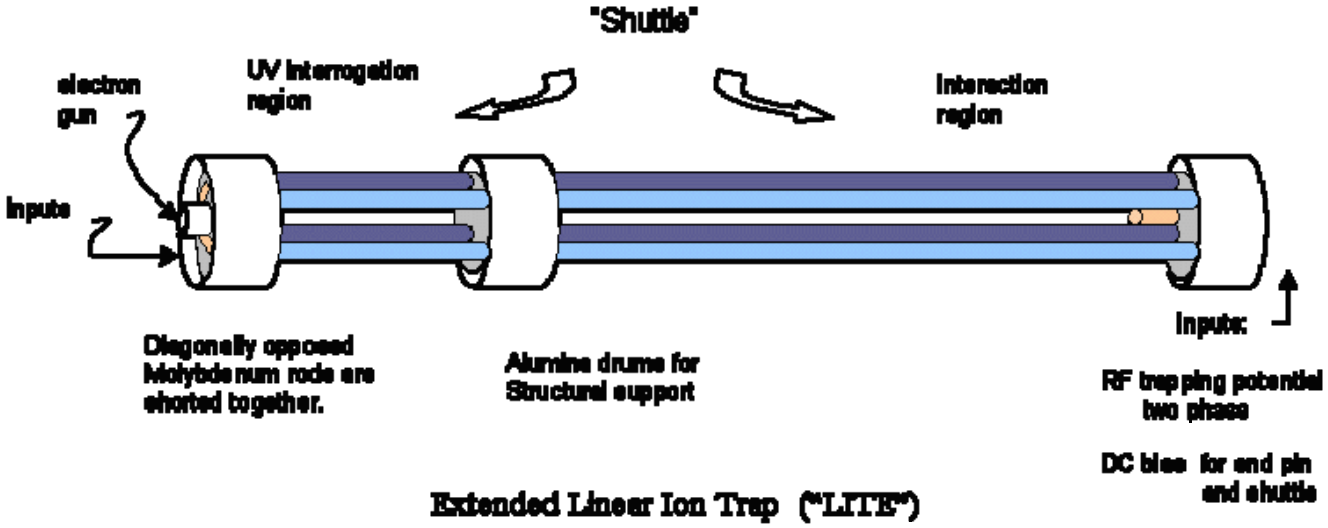
Atome, Moleküle oder Ionen



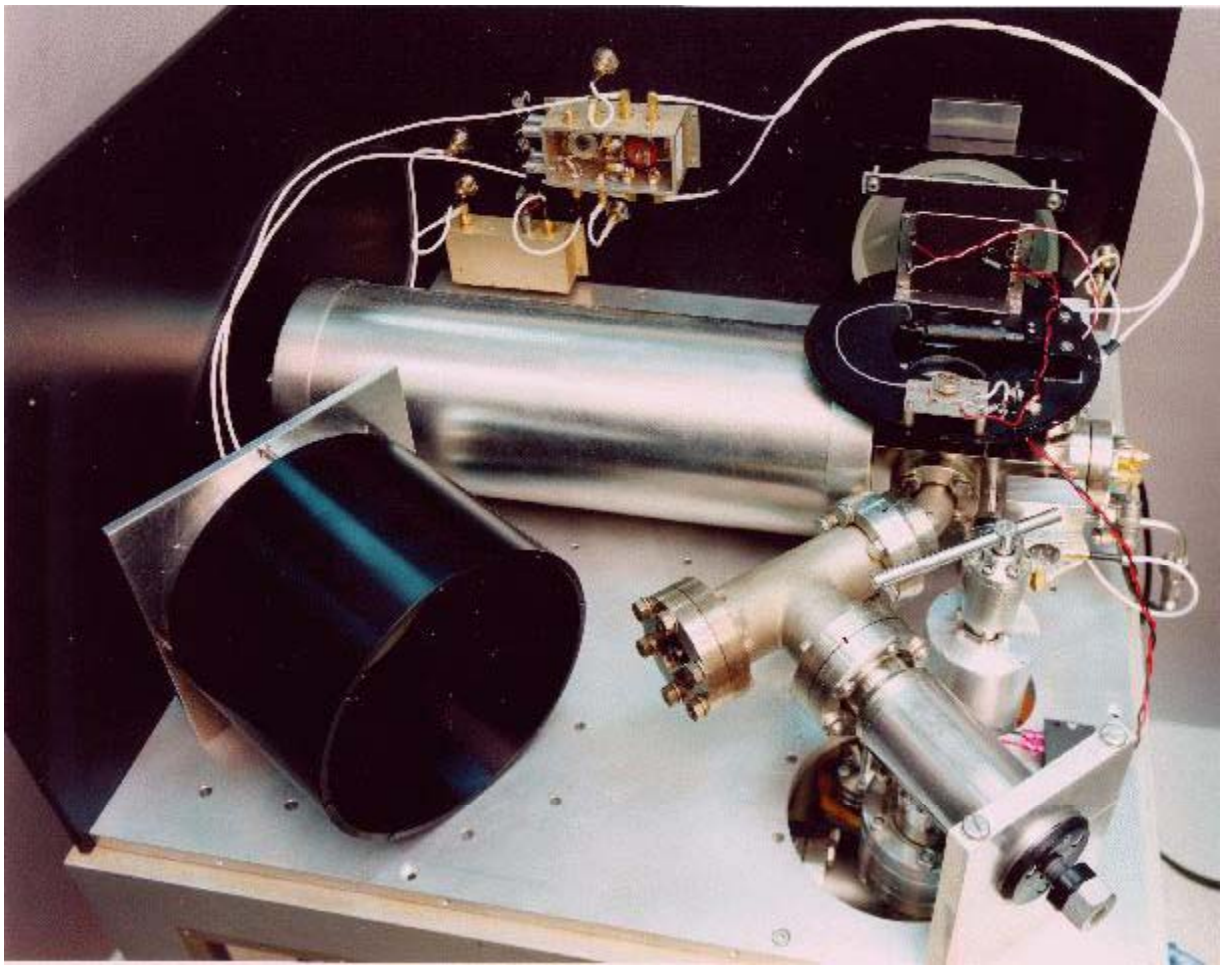
Accuracy: How accurately agrees ν_{out} with ν_0?

Stability: To what extent fluctuates ν_{out} around ν_0?

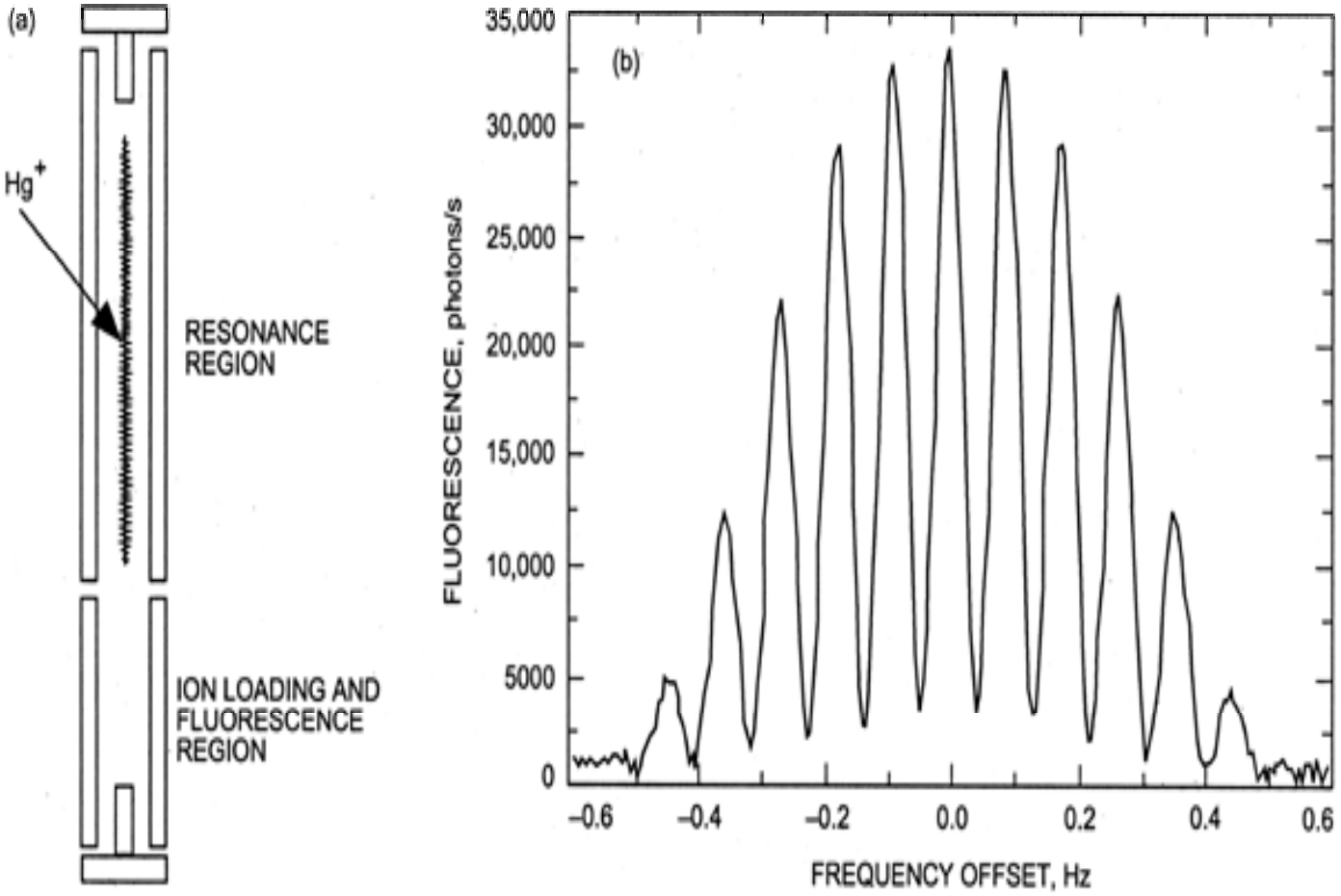
Linear ion trap at JPL
for microwave frequency standard



Extended Linear Ion Trap ("LITE")



40.9 GHz hyperfine transition in $^{199}Hg^{+}$
Ramsey fringes with 11,1 s interrogation time



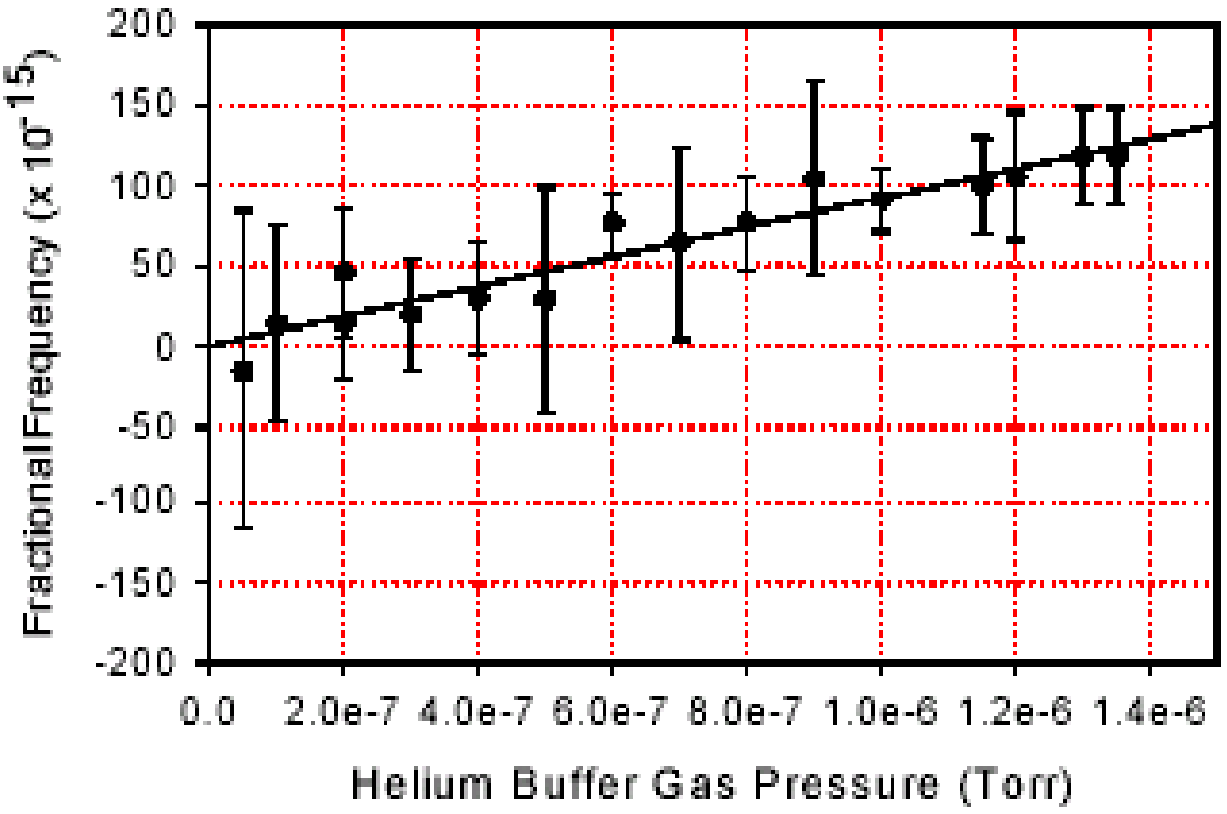
J. Tjoelker et al.,
JPL

$^{199}Hg^{+}$ microwave clock Uncertainty and stability

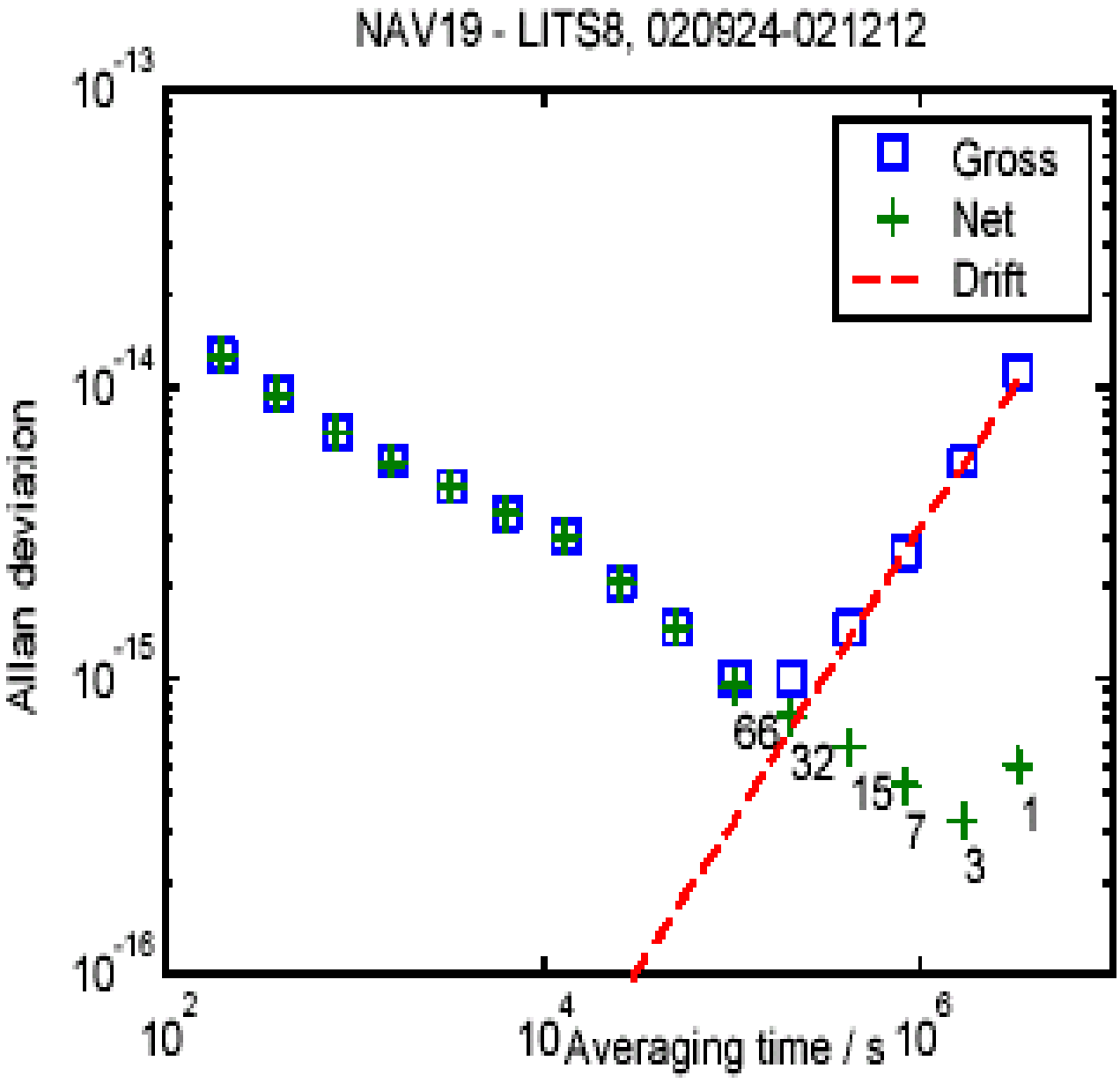
	LITS Frequency Offsets & Stability		
Frequency Offsets	Magnitude	Uncertainty ($x10^{-15}$)	Stability ($x10^{-15}$)
DC Magnetic (at 0.08G)	1×10^{-11}	0.1	<0.2
Shielding (24,000)			<.002 / mG
2nd Order Doppler			
Thermal (300K)	2×10^{-13}	<10	<0.2
Number Dependent	5×10^{-14}	<1	<0.1
Collision (pressure)			
Helium ($6x10^{-6}$ Torr)	10^{-13}	<10	<0.2
Mercury(10^{-9} Torr)	?	?	?
Other (<$2x10^{-9}$ Torr)	?	?	?
Blackbody	$< 10^{-16}$	< 0.1	<0.01
Gravitational Redshift	10^{-16}/m	< 0.2	

J. Tjoelker et al., Proc. 2003 Frequ. Contr. Symp

$^{199}Hg^{+}$ hyperfine frequency shifts with He buffer gas pressure



Frequency stability of $^{199}Hg^{+}$ microwave standard
H-maser as reference



Red line: H-maser drift

J. Tjoelker et al, Prov. 2003 Frrqu. Contr. Symp.

Optical spectroscopy

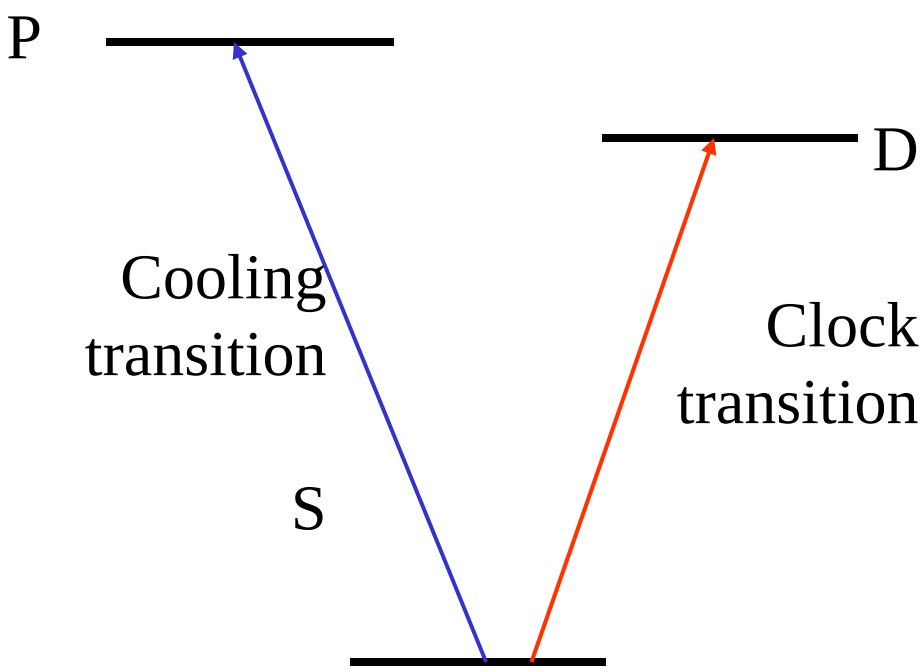
High resolution requires:

- Cooling into Dicke regime
- Long lived metastable states
- Lasers of high spectral purity

Optical clocks:
Laser stabilization on narrow transition to long lived metastable state,
Measurement of laser frequency

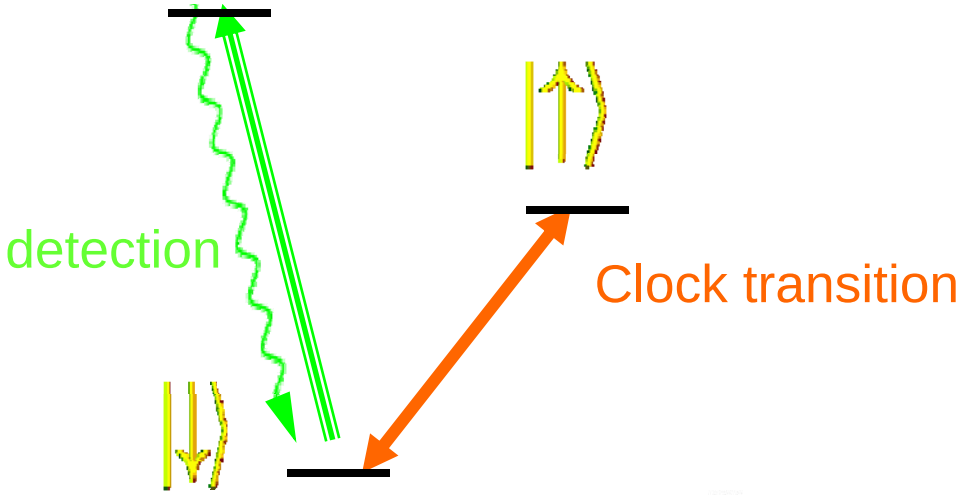
Required level diagram

Requirement to level scheme:
Fast E1 cooling transition
Narrow „clock“ transition

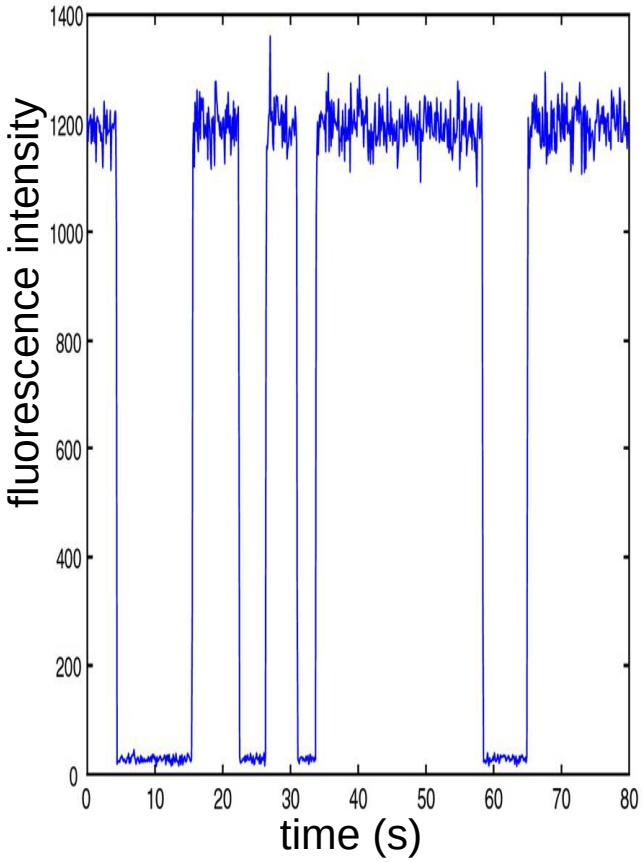


Candidate ions: Hg^+, Yb^+, Sr^+, Ca^+, In^+

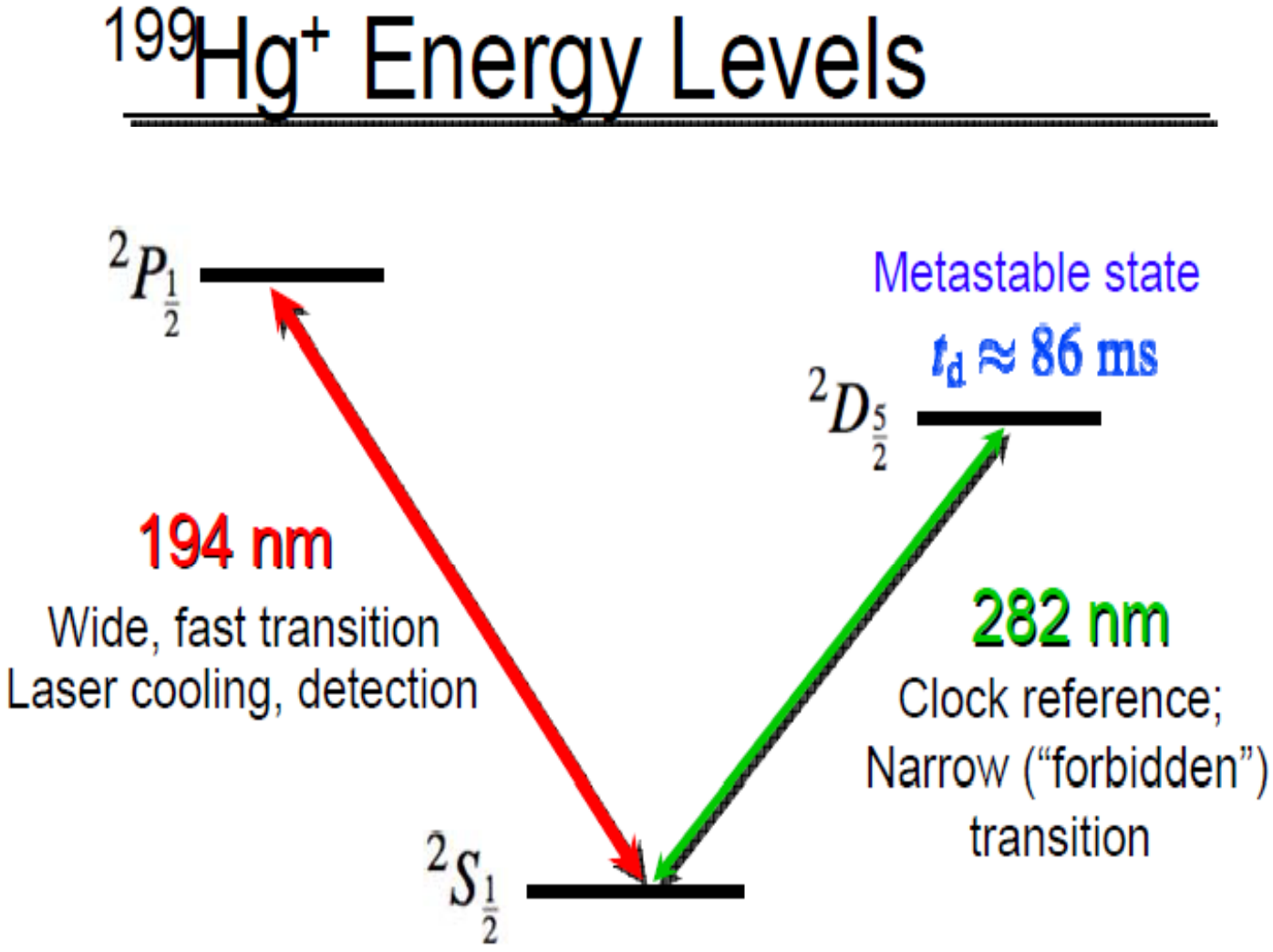
State detection using electron shelving



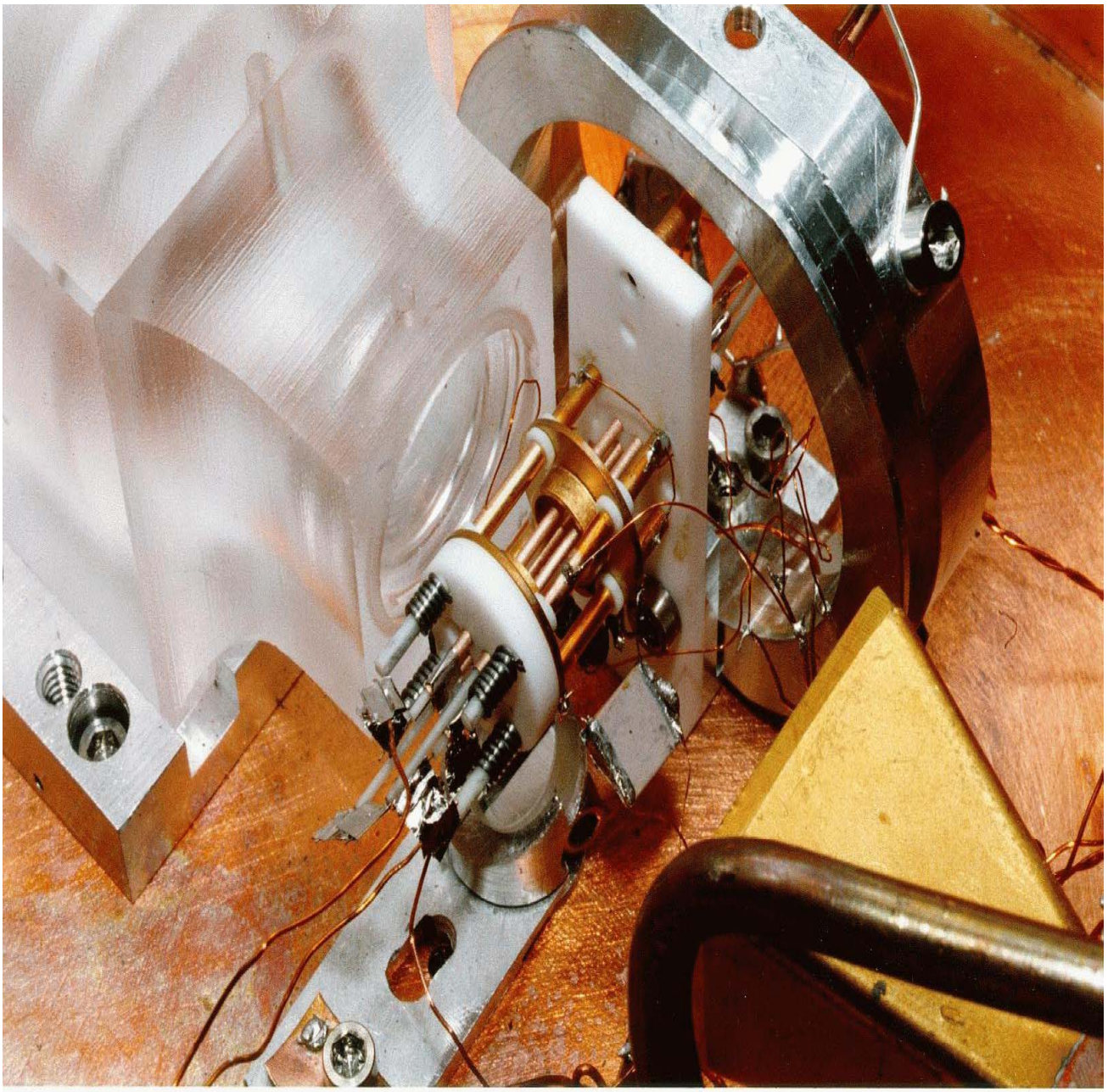
observe quantum jumps online



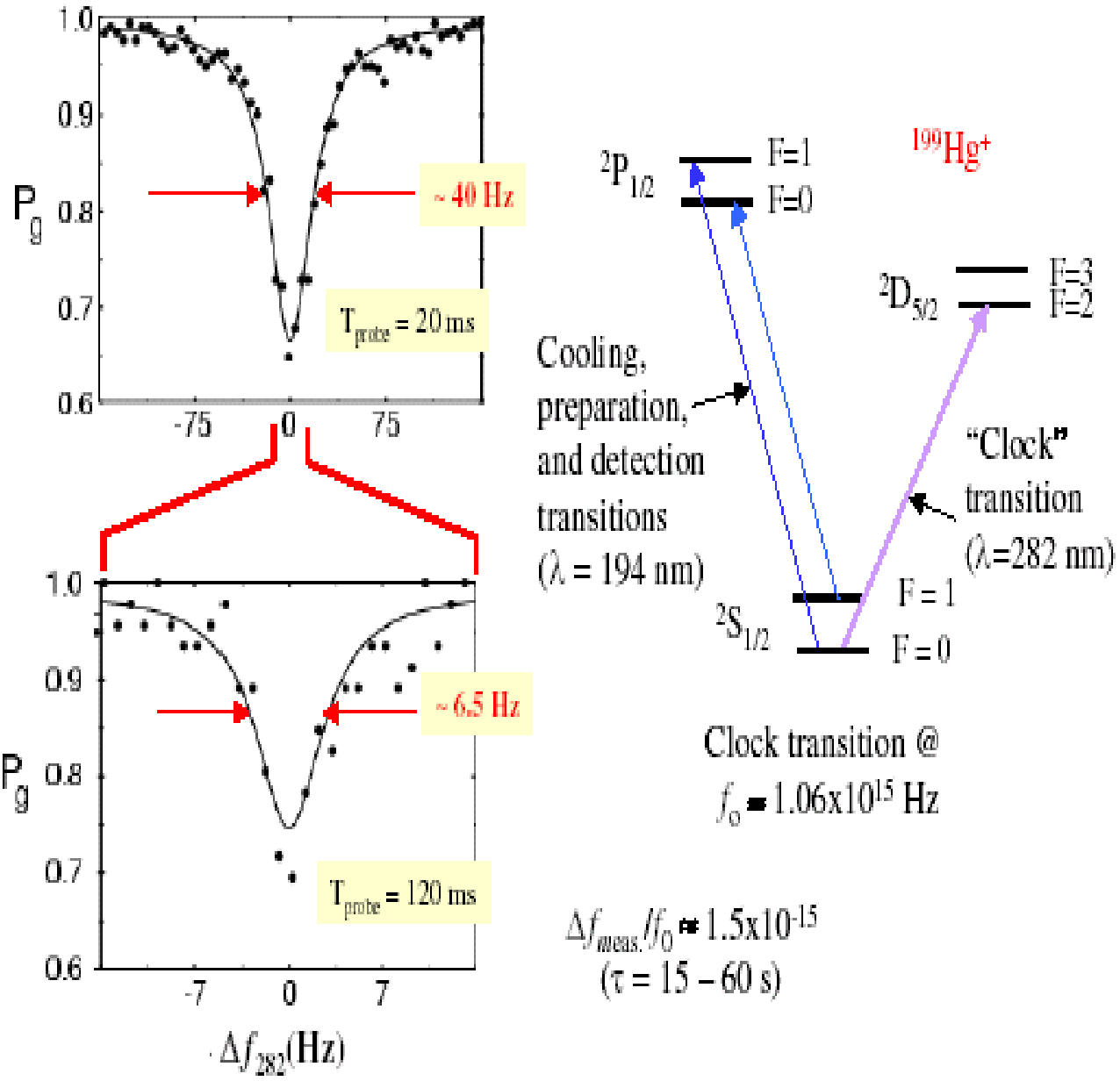
Example: 199 Hg+



Linear ion trap at NIST for Hg^+ optical clock

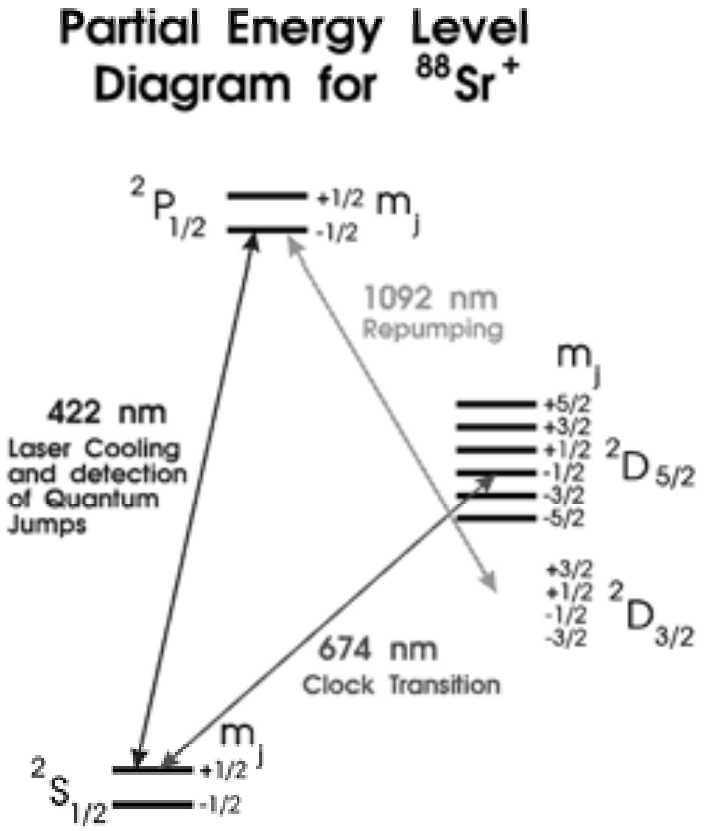


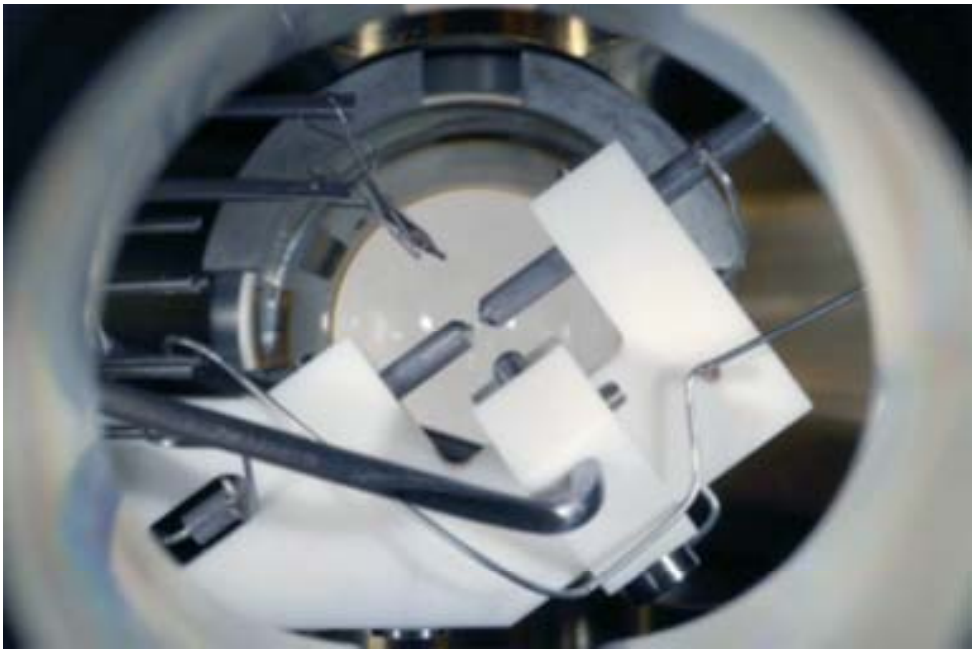
Quantum-jump absorbtion spectra of the $^2S_{1/2}(F=0)$ - $^2D_{5/2}(F=2)$ transition in $^{199}Hg^+$



J. Bergquist et al. (2002)

Work at NRC Canada: single Sr+ optical clock

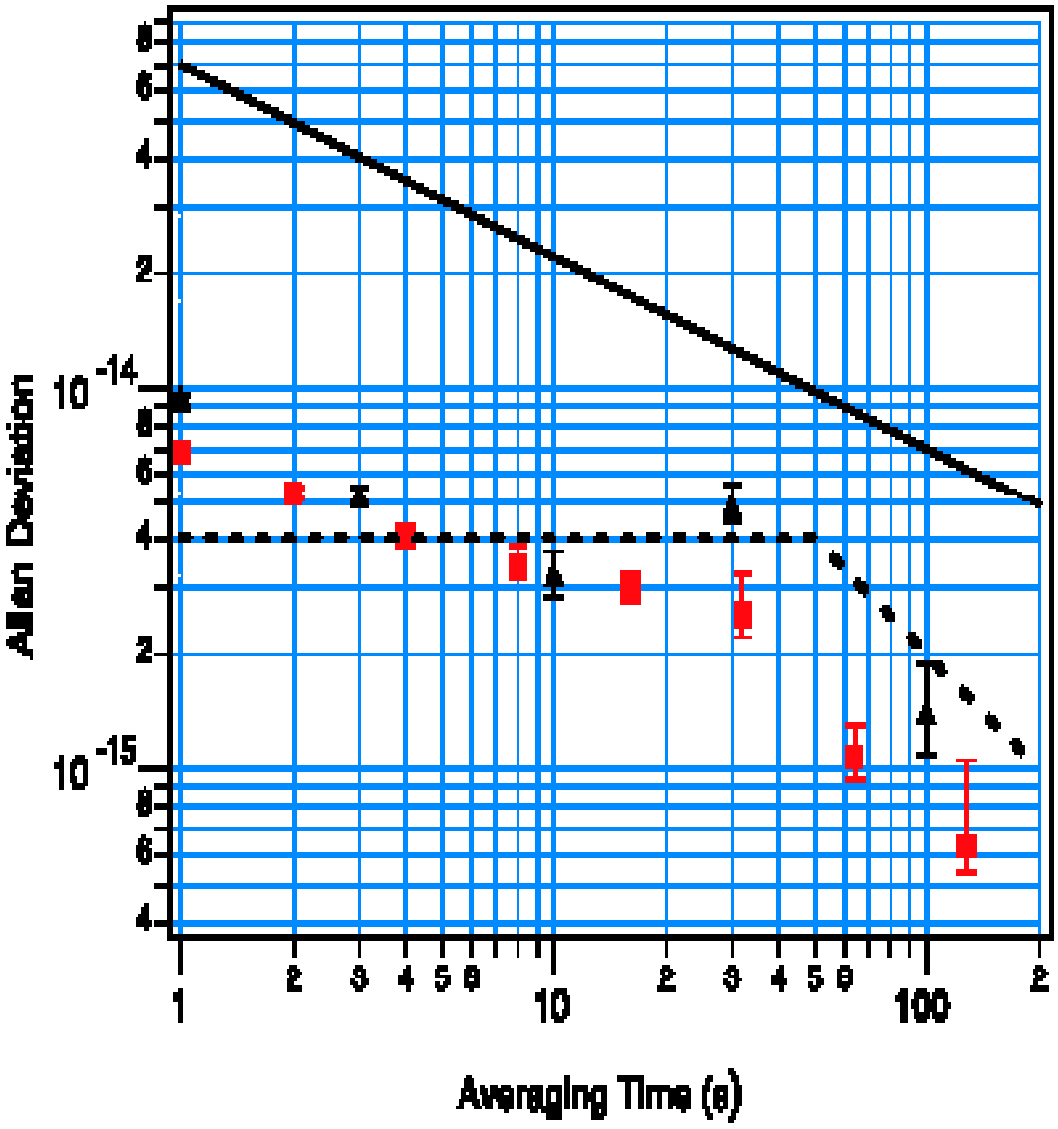




Sources of uncertainty in single ion Sr+ clock

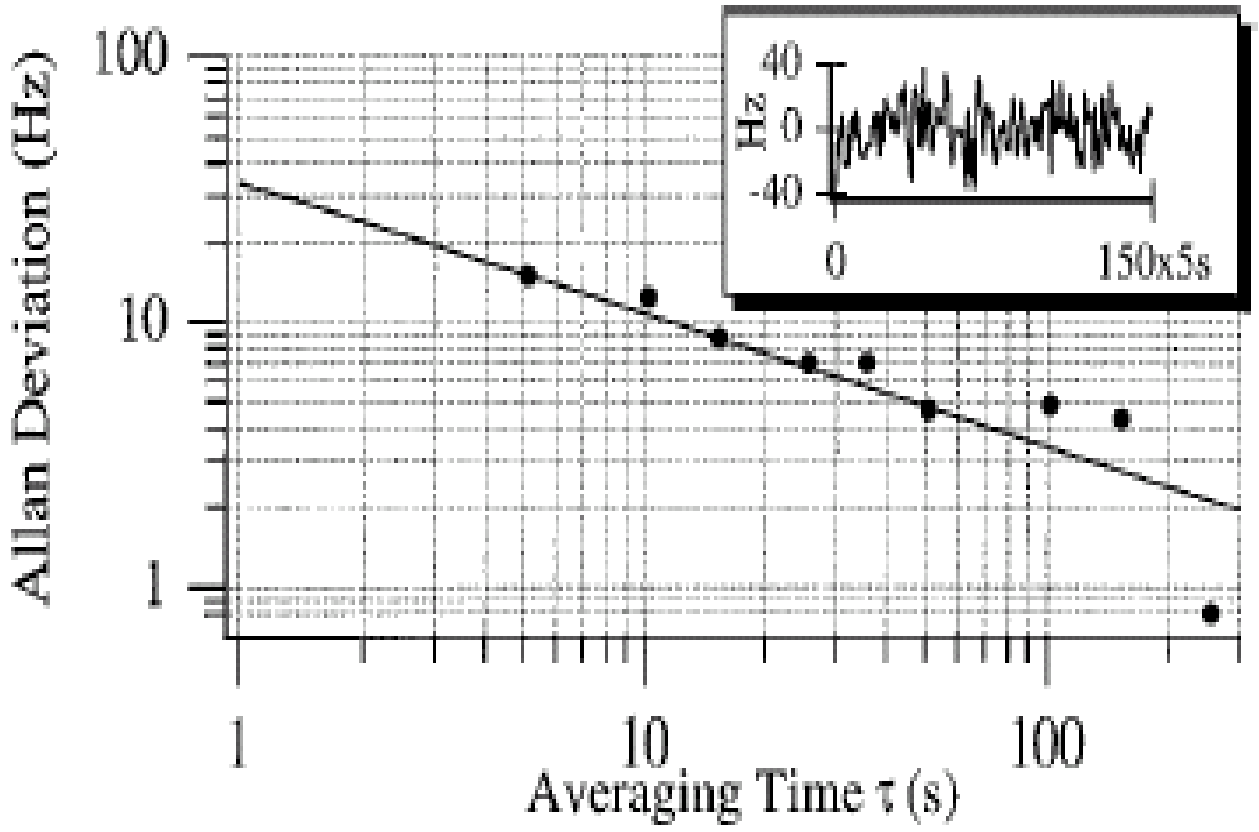
Source	Shift of line center	Magnitude
Second order Doppler effect	0.13 Hz	3×10^{-16}
Quadratic Stark shift	0.2 Hz	5×10^{-16}
Electric quadrupole shift of $4d\,^2D_{5/2}$ level	<0.5 Hz	$<1 \times 10^{-15}$
Blackbody ac Stark shift	0.16 Hz	4×10^{-16}
ac magnetic fields	<0.2 Hz	$<5 \times 10^{-16}$
Quadratic Zeeman shift (static field)	15 mHz	3×10^{-17}
Collisions	<10 mHz	$<2 \times 10^{-17}$

Measured stability of a single Hg^+ optical standard
Cs standard (solid line) for comparison



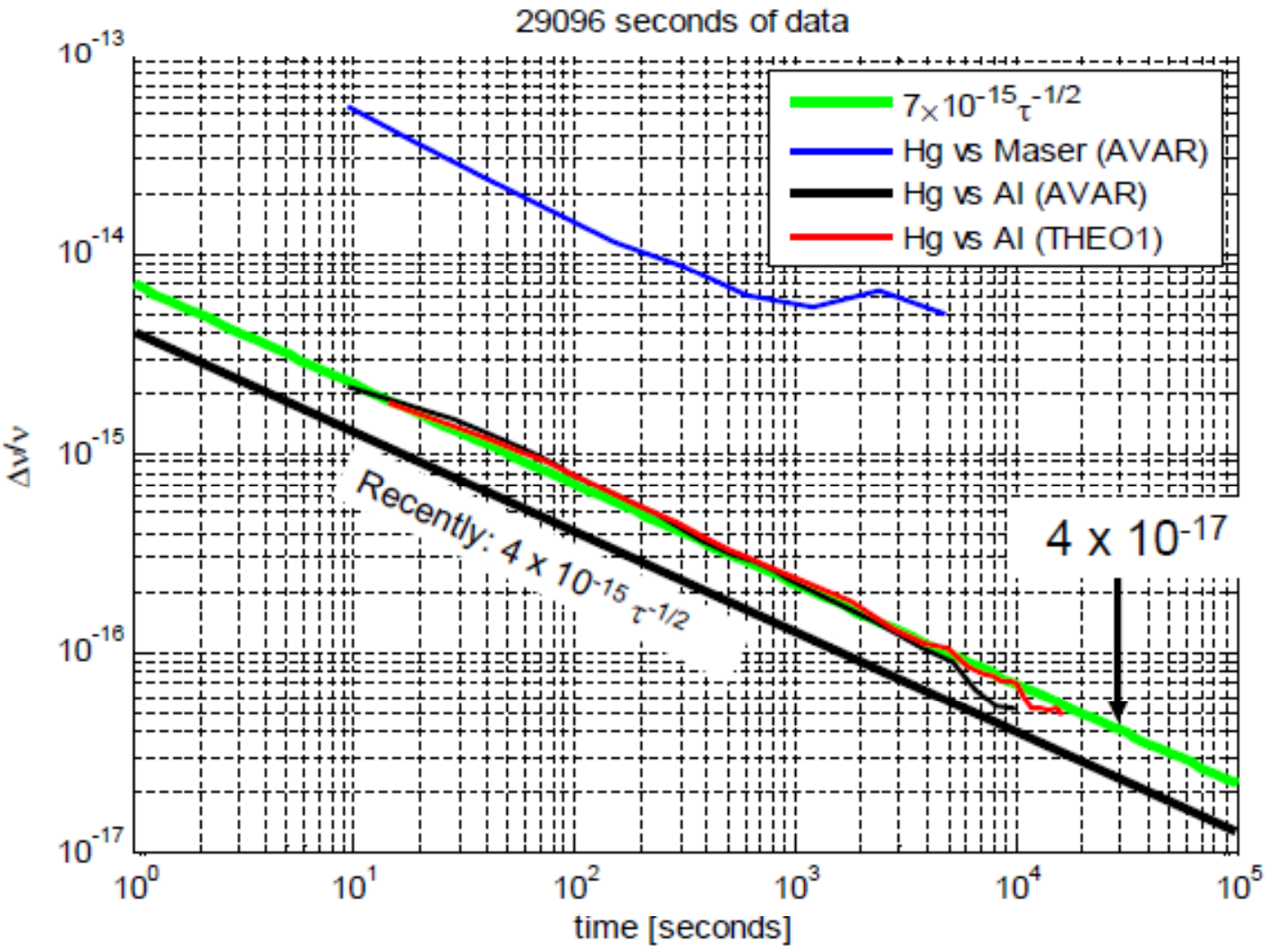
S. Diddams et al., Science 293, 825 (2001)

Frequency stability of Hg^+ optical standard vs. Ca standard
(K.R. Vogel et al., Opt. Lett. 26,102 (2001))



$\sigma(\tau) = 6.4\ 10^{-14}\ \tau^{-1/2}$

Al^+/Hg^+ Stability



Systematic Frequency Shifts

- The immediate future:
  Begin averaging over quadrupole shift

Error budget:

Estimated partial error budget for the near future

Effect	Correction (Hz) (at 1.06 PHz)	Fractional uncertainty $\Delta f/f_0$ (10^{-15})
Second-order Zeeman (B field uncertainty)	1.19	<0.01
$^2D_{\frac{5}{2}}$ quadrupole shift	0	0.01
Gravitational redshift	0.55	0.01
Micromotion shifts	0	0.01

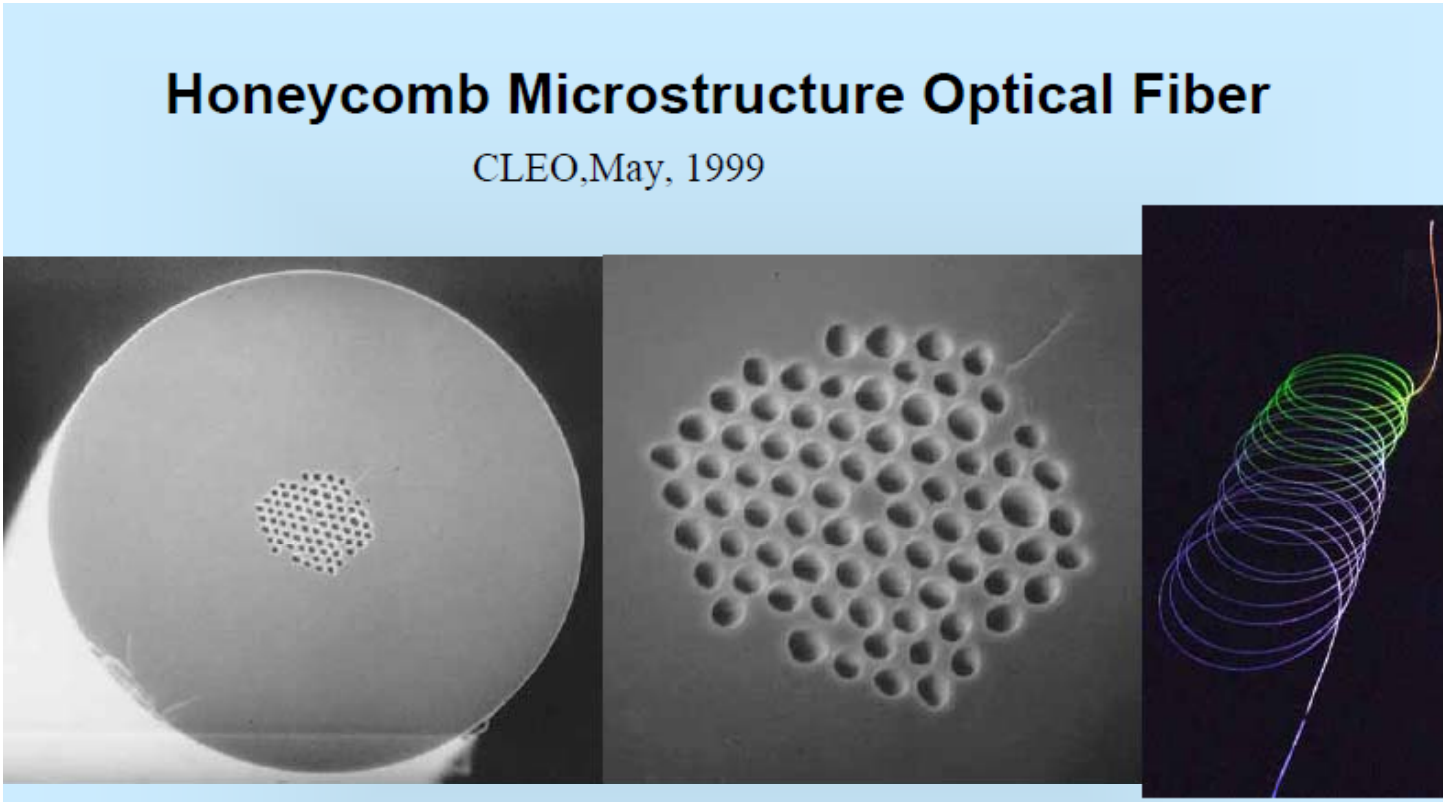
Expected fractional systematic uncertainty: ~2 x 10^{-17}

Measuring the frequency of optical transitions

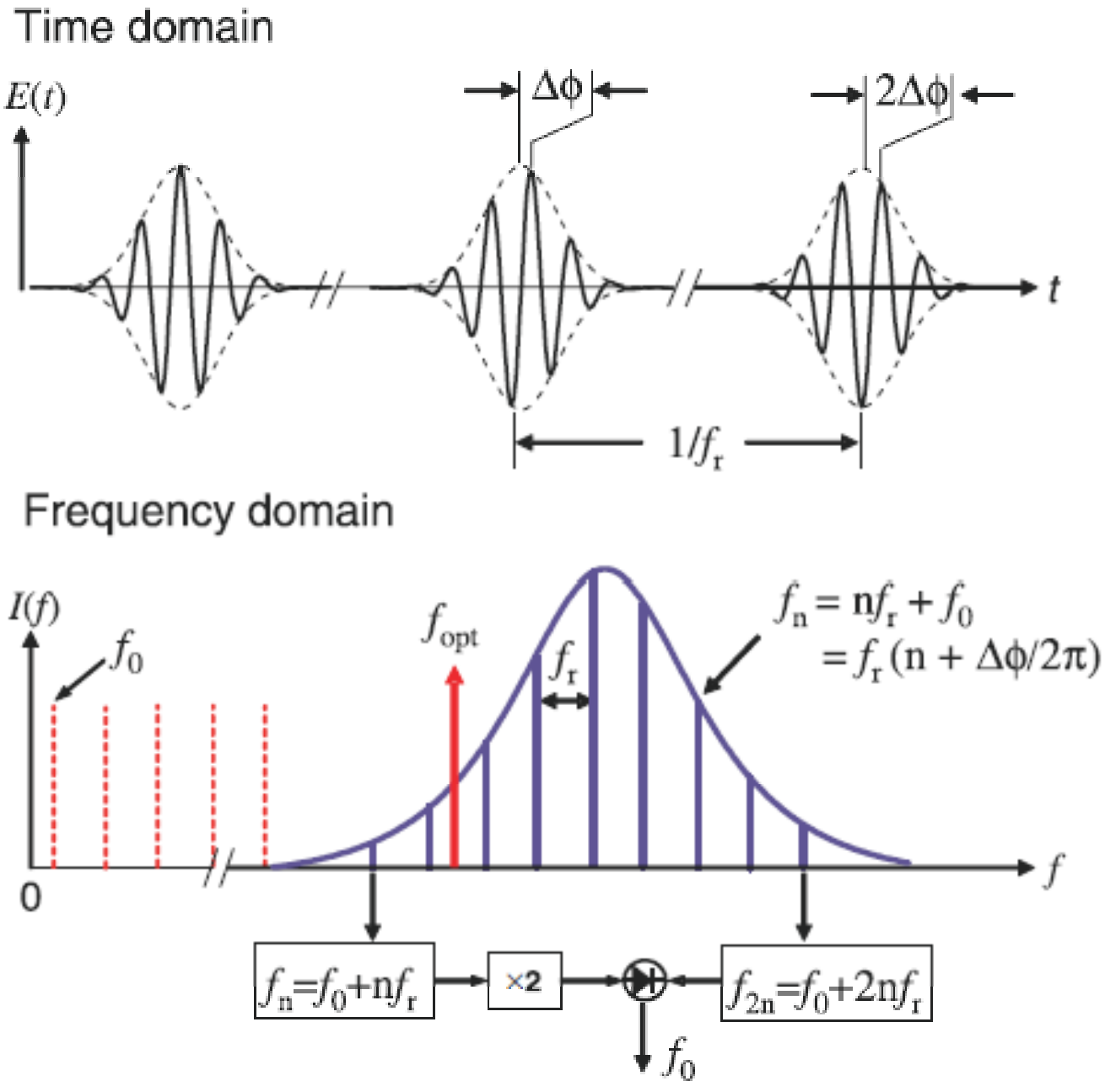
Frequency comb technique

Hänsch, Hall: Nobelprize 2005

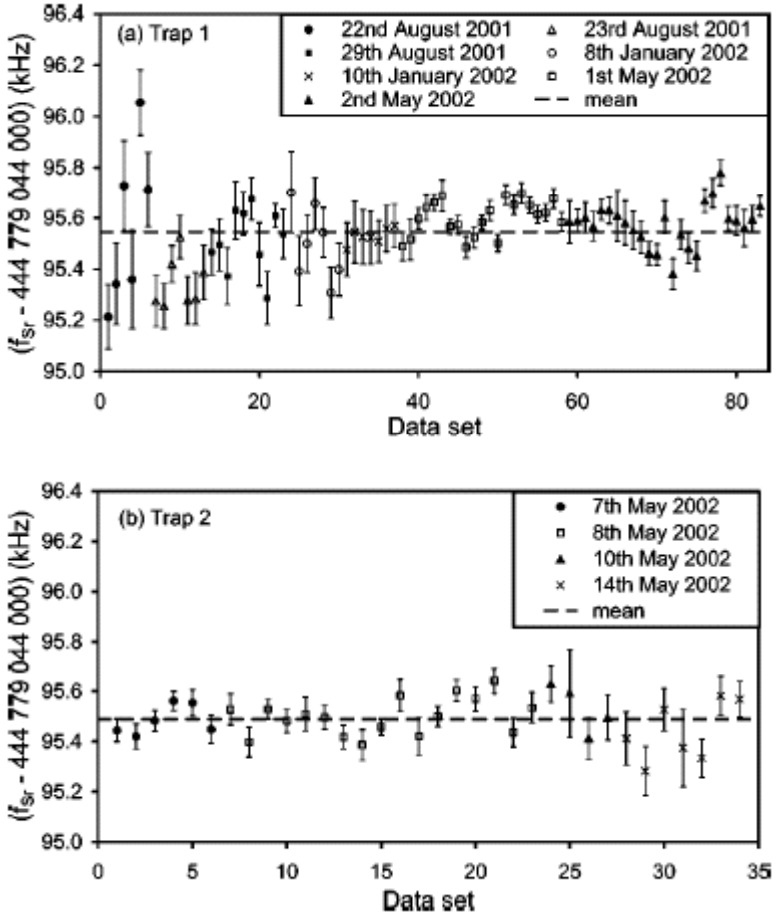
Femtosecond Laser into photonic fiber



Output of optical fiber:
Discrete wavelength pulses
at interval of laser repetition frequency



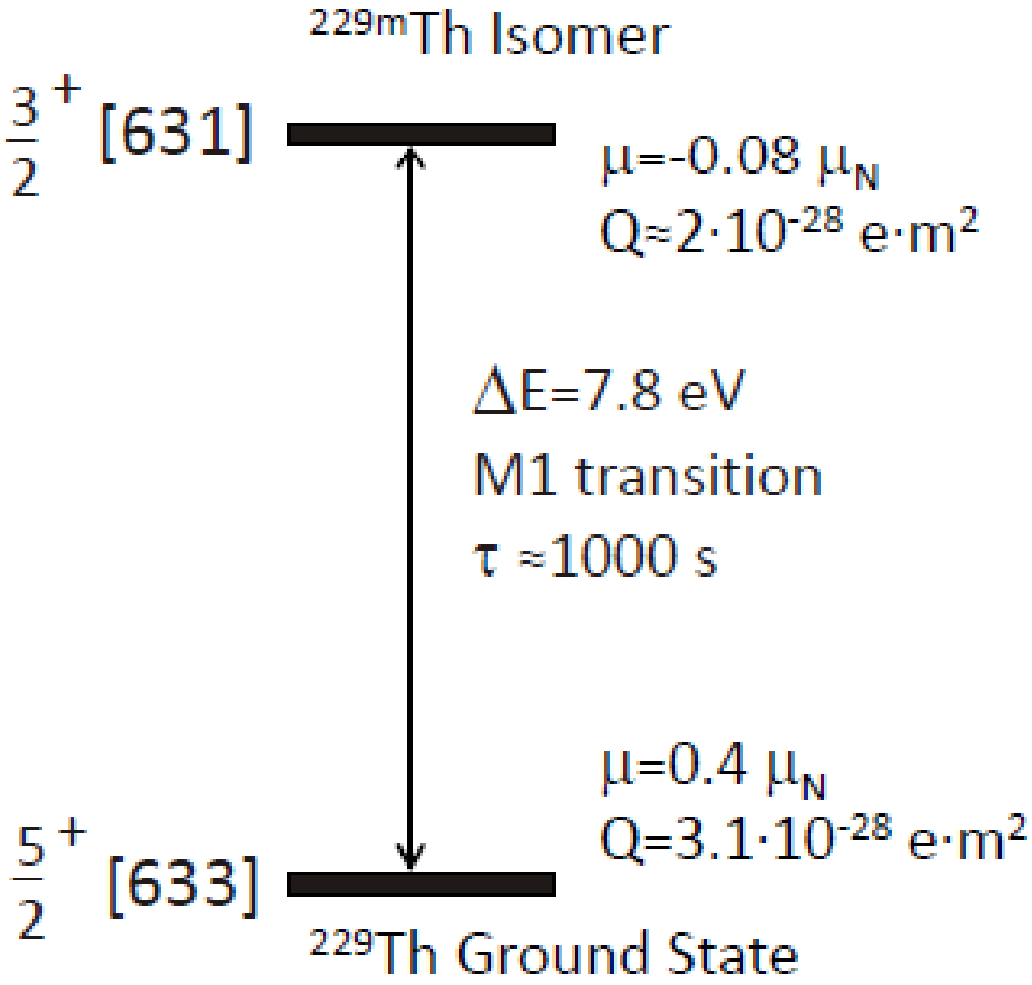
The frequency of the $^{88}Sr^{+}$ S-D transition measured in two different traps (NPL, 2003)



Systematic frequency shifts [Hz]

Source	Trap 1 Correction	Trap 1 Uncertainty	Trap 2 Correction	Trap 2 Uncertainty
Reproducibility		152		104
422 nm ac Stark shift	−48	60	0	0
1092 nm ac Stark shift	0	<3	0	<3
Servo errors	−3	3	−12	12
Other frequency shifts	0	<1	0	<1
Maser frequency	0	11	0	11
Total uncertainty for each trap		164		105

Potential future nuclear clock with 229Th



The only known isomer with an excitation energy in the optical range and in the range of outer shell electronic transitions.

- Studied by C.W. Reich et al. at INL since the 1970s,
  established the low energy isomer,
  from γ-spectroscopy: 3.5 ± 1.0 eV, published in 1994
- Theoretical work by E.V. Tkalya, F.F. Karpeshin, and others
  isomer lifetime, coupling to electronic excitations (τ ~ few 1000 s)
- False detections of optical emission in the U-233 decay chain in 1997/98
- Proposal of nuclear laser spectroscopy and nuclear clock
  E. Peik and Chr. Tamm, published in 2003
- Unsuccessful search for optical nuclear excitation or decay
- More precise energy measurement from γ-spectroscopy at LLNL:
  7.6 ± 0.5 eV, published in 2007
- 2011: still no direct detection of the optical transition;
  experimental efforts in several groups worldwide

Possible realizations of Th-229 nuclear clocks:
- Laser-cooled Th^{3+} in an ion trap
- Th ions as dopant in a transparent crystal (like CaF_2, LiCAF etc.)

Experimental problem:
Transition energy known only to ≈ 10% uncertainty,
not a system for high resolution spectroscopy yet.

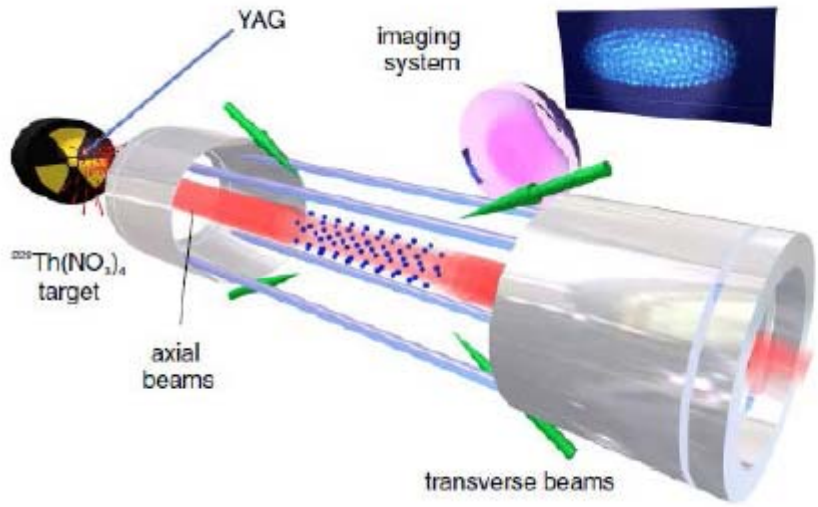
Nuclear clock with laser cooled $^{229}Th^{3+}$

- Th^{3+} possesses a much more simple level scheme (single valence e^-)
- can be laser-cooled using diode lasers & detected via resonance fluorescence in the red or NIR
- electronic and nuclear resonances are separated in energy

Estimates for long term frequency stability:

$\mathbf{10^{-19}}$

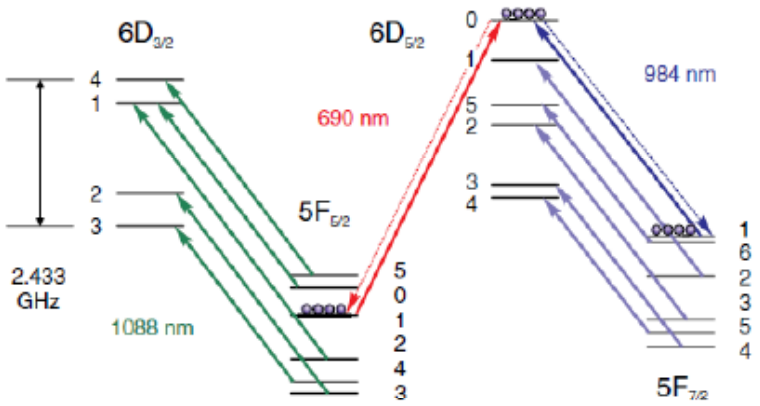
Experiment at PTB Braunschweig



- Loading via laser ablation with ns pulsed Nd:YAG (tripled)
- Trap L = 188 mm r = 3.3 mm, taylored for efficient loading of ablation plume
- Trapping and cooling 10^3 – 10^4 Th^{3+} ions (Th-229 & Th-23
  (enhanced loading efficiency with initial buffer gas cooling)

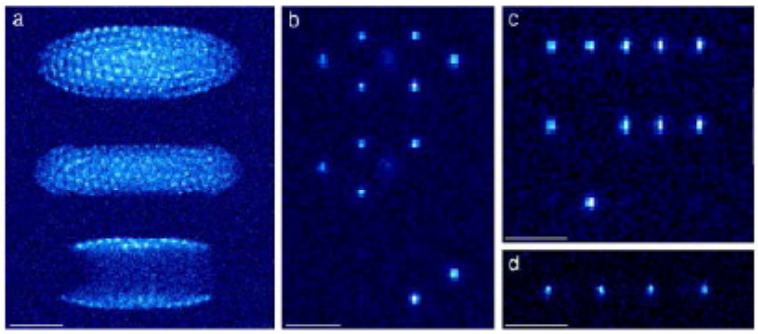
Campbell et al., Phys. Rev.Lett **106**, 223001 (2011)

Low lying energy levels in $^{229}Th^{3+}$:



- cooling on 1088 nm line to tens of K
- cooling to tens of mK on lambda scheme
- sympathetic cooling on even isotope (**no HF!**) for lowest temperatures

Laser cooled ion crystals:

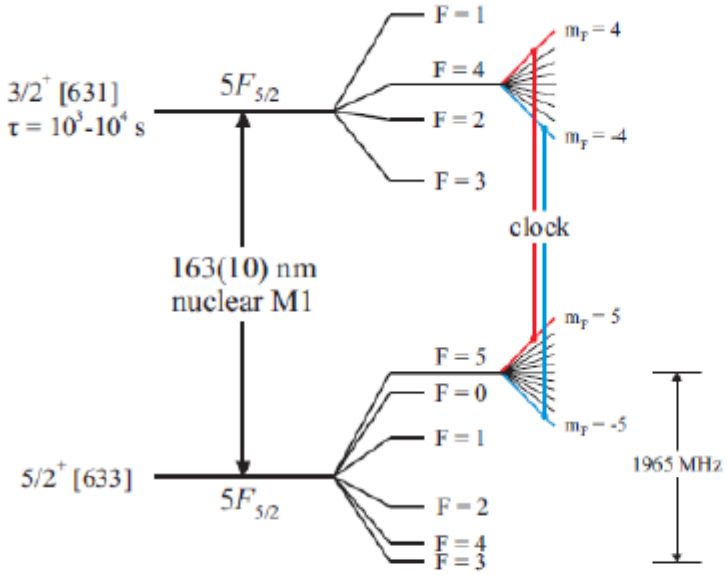


$^{229}Th^{3+}$

$^{232}Th^{3+}$

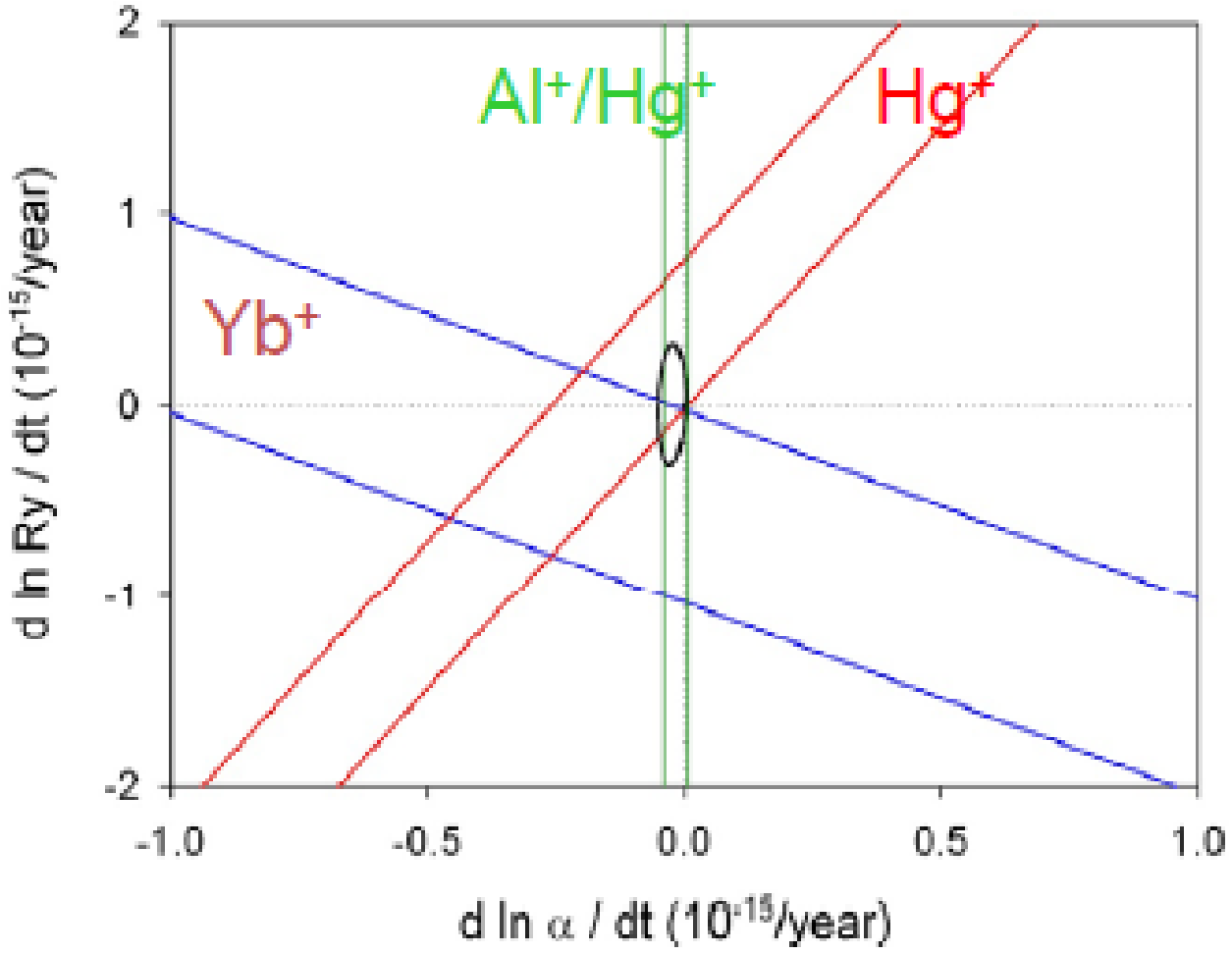
Campbell et al., Phys. Rev.Lett **106**, 223001 (2011)

Clock transition from ground state ($5F_{5/2}$):



With laser cooled and trapped i
fractional frequency inaccura
as low as
10^{-19}
should be possible!

Search for variation of the finestructure constant α in time by clock comparison



Present status:

$$\frac{\partial \ln \alpha}{\partial t} = (-2.4 \pm 2.7) \cdot 10^{-17}\ \mathrm{yr}^{-1}$$

$$\frac{\partial \ln Ry}{\partial t} = (0.0 \pm 3.2) \cdot 10^{-16}\ \mathrm{yr}^{-1}$$

Summary

Ion trap frequency standards operate in the microwave domain and optical domain

Stabilities below the 10^{-15} level have been reached in both cases

Optical frequency measurements have reached high precision

Further progress is expected with potential nuclear clock