Title: Laboratory search for temporal variations of fundamental constants with optical clocks

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Abstract: Optical frequency standards based on forbidden transitions of trapped and laser-cooled ions have now achieved significantly higher stability and greater accuracy than primary cesium clocks. At PTB we investigate an optical clock based on the electric quadrupole transition $S_{1/2} \rightarrow D_{3/2}$ at 688 THz in the 171Yb$^+$ ion and have shown that the frequencies realized in two independent ion traps agree to within a few parts in 1016. Results from a sequence of precise measurements of the transition frequency are now available that cover a period of seven years. Combined with data obtained at NIST on the quadrupole transition in Hg$^+$, this allows to derive a model-independent limit for a temporal drift of the fine structure constant. We prepare to observe two more optical transitions that will provide increased sensitivity to alpha variations: The electric-octupole transition $S_{1/2} \rightarrow F_{7/2}$ of Yb$^+$ at 642 THz offers a sub-hertz frequency resolution. The ratio of the 688 THz and 642 THz frequencies in Yb$^+$ can be measured as a dimensionless number with a femtosecond laser frequency comb. Repeated measurements of this quantity permit to search for temporal variations of alpha with a sensitivity factor $\approx 7$, the highest in any of the available combinations of optical frequency standards. Much higher sensitivity (of order 104) may be obtained in the study of the 7.6 eV nuclear transition between the two lowest states of Th-229. We have developed a concept for a highly accurate nuclear clock based on this transition and describe first steps towards the experimental realization. This work is supported by DFG, FQXi and QUEST.
Laboratory search for temporal variations of fundamental constants with optical clocks

Ekkehard Peik

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Time and Frequency Department
Braunschweig, Germany
Outline

- Motivation: Optical Clocks
- Single-Ion Optical Frequency Standards with $^{171}\text{Yb}^+$
- Limits on Temporal Variations of Fundamental Constants
- Outlook: $^{171}\text{Yb}^+$ Octupole Transition
  $^{229}\text{Th}^3+$ Nuclear Clock
Optical Frequency Standard or Clock

Atomic Reference

forbidden" transition of trapped laser-cooled atoms

Laser

locked to atomic resonance, short-term stabilized to Fabry-Perot resonator

fs-Comb Generator

"optical clockwork", provides radiofrequency output and means for comparison with other optical frequencies
Stability of atomic frequency standards

\[ \sigma_y(\tau) \approx \frac{\Delta \nu}{\nu_0} \sqrt{\frac{T_c}{N\tau}} \]

\(\Delta \nu\): observed linewidth \quad (Fourier limited)
\(\nu_0\): reference frequency
\(N\): atom number (projection noise limited detection)
\(T_c\): cycle time

microwave \quad \longrightarrow \quad \text{optical frequency}
\(\nu_0\) increases by 5 orders of magnitude
Accuracy, systematic frequency shifts

some shifts are proportional to the frequency:
  2nd order Doppler: $\delta v \sim T v$

some shifts have absolute order of magnitude and are relatively less important in the optical range:

<table>
<thead>
<tr>
<th></th>
<th>relative shift for:</th>
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<tbody>
<tr>
<td></td>
<td>Cs 9.19 GHz</td>
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<tr>
<td>quadratic Zeeman shift at 1 $\mu$T</td>
<td>4.7 E-12</td>
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<tr>
<td>blackbody AC Stark shift at 300 K</td>
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Measurement of optical frequency ratios with a frequency comb

\[ \nu_{SH} / \nu_0 = 2.000 \ 000 \ 000 \ 000 \ 000 \ 000 \ 000 \ 001 \ (1 \pm 7 \cdot 10^{-19}) \]

Demonstrated instabilities of frequency comparisons
Reference Systems

laser-cooled neutral atoms in optical traps:
Sr, Yb, Hg, Ca ...

single trapped laser-cooled ions:
Hg\(^+\), Sr\(^+\), Yb\(^+\), In\(^+\), Al\(^+\)...

„simple“ atoms:
H, He...

molecules:
I\(_2\), CH\(_4\), OsO\(_4\)...

nuclei:
\(^{229}\)Th
Optical Frequency Standards with a Laser-Cooled Ion in a Paul Trap

- Lamb-Dicke confinement with small trap shifts
- unlimited interaction time
- single ion: no collisions
- stability: use high-Q transition
Yb$^+$ single-ion optical frequency standard

$^{171}$Yb$^+$ level scheme

Advantages of Yb$^+$
- all diode laser system
- long trapping time (months)
**Yb\(^+\) single-ion optical frequency standard**

171\(^1\)Yb\(^+\) level scheme

- \( ^2\)P\(_{1/2} \) F=1  
- \( ^2\)P\(_{1/2} \) F=0  
- \( ^2\)D\(_{3/2} \) F=2  
- \( ^2\)D\(_{3/2} \) F=1  
- \( ^2\)S\(_{1/2} \) F=1  
- \( ^2\)S\(_{1/2} \) F=0  

- 935.2 nm \( \rightarrow \) \([3/2]_{1/2} \)  
- 638.6 nm \( \rightarrow \) \([5/2]_{5/2} \)  
- 435.5 nm, \( \delta v_{\text{nat}} = 3.1 \text{ Hz} \)

Measurement cycle

- Cooling laser off/on  
- Probe laser on/off  
- Magnetic field: \(~400 \mu \text{T}\) \( \longrightarrow \) \(~1 \mu \text{T}\)

Advantages of Yb\(^+\)

- All diode laser system  
- Long trapping time (months)
High resolution spectroscopy of the quadrupole transition at 688 THz

Pi-Pulse
\(\tau(\text{pulse}) = 1\,\text{ms}\)
1 kHz linewidth

„standard operation“
\(\tau(\text{pulse}) = 30\,\text{ms}\)
30 Hz linewidth

Close to the resolution limit
\(\tau(\text{pulse}) = 90\,\text{ms} \approx 2\cdot\tau(\text{Yb}^+)\)
10 Hz linewidth

(a) \(t_p = 1\,\text{ms}\)
(b) \(t_p = 30\,\text{ms}\)
(c) \(t_p = 90\,\text{ms}\)
Frequency comparison between two trapped $^{171}\text{Yb}^+$ ions
Frequency comparison between two trapped $^{171}$Yb$^+$ions

For nominally unperturbed conditions in both traps we observe a frequency difference of 0.26(42) Hz, comparable to the best relative agreement between cesium fountain clocks.

$6 \times 10^{-16}$

Setup for absolute optical frequency measurements

Cs fountain

\( \nu_{\text{Yb}^+} \text{ in units of SI Hertz} \)

5 MHz

H Maser

Femtosecond frequency comb generator

100 MHz

688 THz
(435.5 nm)

Laser frequency servo, time constant: 10...30 s

Yb\(^+\) trap

344 THz (871 nm)

Clock laser

Reference cavity
Results of absolute frequency measurements 2000-2006

$^{171}\text{Yb}^+ \ S_{1/2} - D_{3/2}$:
688 358 979 309 307.5(1.4) Hz

Main contributions to the uncertainty budget of the measurements in 2005 and 2006:

$u_A = 0.40 \text{ Hz} \quad \text{(continuous measurements up to 36 h)}$

$u_B (\text{Cs}) = 0.83 \text{ Hz}$

$u_B (\text{Yb}^+) = 1.05 \text{ Hz} \quad \text{(quadrupole shift, blackbody AC Stark shift)}$
Testing the Constancy Of Fundamental Constants
Search for variations of the fine structure constant in atomic clock comparisons

\[ \frac{\partial \ln f}{\partial t} = \frac{\partial \ln \text{Ry}}{\partial t} + A \cdot \frac{\partial \ln \alpha}{\partial t} \]

Simple, model-independent parametrization
(no model for cesium clock (hyperfine structure) required)

\[ A \text{ is related to the relativistic level shift, } \frac{(Z\alpha)^2}{n*} \left( \frac{1}{j + 1/2} \right) \]

can be calculated with relativistic Hartree-Fock
V. Flambaum, V. Dzuba, et al.
Remote comparison of single-ion clocks NIST-PTB, 2000-2006

$^{199}$Hg$^+$, S - D at 1064 THz (NIST Boulder)

$^{171}$Yb$^+$, S - D at 688 THz (PTB)

A(Yb) = 0.88

A(Hg) = -3.19

E. Peik et al., physics/0611088
Combination of available data from optical clocks (spring 2008)

\[
\frac{\partial \ln \{Ry\}}{\partial t} = (1.9 \pm 3.8) \times 10^{-16} \text{ yr}^{-1}
\]

\[
\frac{\partial \ln \alpha}{\partial t} = (-1.6 \pm 2.3) \times 10^{-17} \text{ yr}^{-1}
\]

Al+/Hg+: T. Rosenband et al., Science 319, 1808 (2008)
New project: $^{171}\text{Yb}^+$ 467 nm octupole transition

Resolution only limited by laser linewidth and by heating rate of trapped ion

Single-ion clock of high stability

Driven by a frequency doubled diode laser
(needed: 1 mW power 0.1 Hz linewidth)

(& repumping at 935 nm, 638 nm, 370 nm HFS)

Pioneering work at NPL: see e.g.
$^{171}\text{Yb}^+$, prospects for $d\alpha/dt$ measurements

- higher $\Delta A$ than in any other combination of optical frequency standards
  (S. Lea, NPL; V. Dzuba and V. Flambaum, UNSW)

- can be done in ONE trap

- frequency ratio measurement by comb generator; independence from Cs clocks, long-distance transfer,....

- measurements with $1 \times 10^{-16}$ uncertainty, performed over one year, would lead to a sensitivity of $(1/\alpha)(d\alpha/dt) \approx 2 \times 10^{-17}$/yr
Th-229: A Nuclear Optical Clock?
The Thorium Isomer at 7.6 eV: An Optical Mössbauer Transition

The lowest-lying known excited state of a nucleus is an isomer of Th-229. This nucleus can be excited by the absorption of VUV light.

\begin{align*}
\frac{3}{2}^+ [631] & \rightarrow \frac{5}{2}^+ [633] \\
\Delta E & = 7.6 \text{ eV} \\
M1 \text{ transition} & \\
\tau & = 10^4 \text{ s}
\end{align*}

**Measurements of \( \Delta E \)**

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*R. Helmer and C. Reich, Idaho

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" B. Beck et al., LLNL
Detection of the Nuclear Excitation in Nuclear-Electronic Double-Resonance

Nucleus in the ground state; laser-induced fluorescence from the shell.

Laser excitation of the nucleus; change of hyperfine structure detected in intensity or polarisation of fluorescence.
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\begin{align*}
\frac{3^+}{2}[631] & \quad 2^{29m}{\text{Th Isomer}} \\
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Possibility for a single-ion frequency standard with a nuclear excitation as the reference transition.
- Th\(^{3+}\) has suitable level scheme for laser cooling
- Promises a further reduction of systematic line shifts

Field-induced shifts of the nuclear resonance frequency

\[ \text{total energy} = \text{energy of the bare nucleus} + \]
\[ + \text{energy of electron shell in coulomb potential} + \text{hyperfine structure} \]
Field-induced shifts of the nuclear resonance frequency

total energy = energy of the bare nucleus +
+ energy of electron shell in coulomb potential + hyperfine structure

Nuclear ground state, I=5/2

HFS

Energy of electronic ground state

\[ ^2F_{5/2} \]  \[ ^2F_{3/2} \]  \[ F=5 \]  \[ F=3 \]  \[ F=1 \]  \[ F=0 \]  \[ F=0 \]
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total energy = energy of the bare nucleus +
+ energy of electron shell in coulomb potential + hyperfine structure

Nuclear ground state, $I=5/2$

Isomer, $I=3/2$

HFS

$^2F_{5/2}$

F=5

F=0

Isom. shift

HFS

$^2F_{5/2}$

F=4

F=1

Energy of electronic ground state (Th$^{3+}$)
Field-induced shifts of the nuclear resonance frequency

\[
\text{total energy} = \text{energy of the bare nucleus} + \\
+ \text{energy of electron shell in coulomb potential} + \text{hyperfine structure}
\]

Nuclear ground state, \( I = \frac{5}{2} \)

Isomer, \( I = \frac{3}{2} \)

HFS

\( ^2F_{5/2} \)

\( F = 5 \)

\( F = 0 \)

\( ^2F_{5/2} \)

\( F = 4 \)

\( F = 1 \)

Not only nuclear moments, but also electronic moments may contribute to Zeeman and Stark effect, if the shift depends on \( F \) or \( I \).
Expected systematic shifts in a trapped-ion Th-229 frequency standard

- relativistic Doppler ✓
- quadratic Zeeman ✓
- quadratic Stark (scalar) ✓
- blackbody AC Stark collisions ✓
- quadratic Stark (tensor) ✓
- quadrupole shift (E field grad.) ✓

✓: controllable to the level $10^{-18}$

Use electronic $S_{1/2}$ state: all effects ✓

Remains: hyperfine Stark shifts (like in Cs clock)
Scaling of the $^{229}$Th transition frequency $\omega$ in terms of $\alpha$ and quark masses:


$$\frac{\delta \omega}{\omega} \approx 10^5 \left( 4 \frac{\delta \alpha}{\alpha} + \frac{\delta X_q}{X_q} - 10 \frac{\delta X_s}{X_s} \right)$$

where $X_q = m_q/\Lambda_{QCD}$ and $X_s = m_s/\Lambda_{QCD}$

$10^5$ enhancement in sensitivity to variations results from the near perfect cancellation of two $O(\text{MeV})$ contributions to the nuclear level energies.

Comparing the Th nuclear frequency to present atomic clocks will allow to look for temporal variations at the level $10^{-20}$ per year.

See also:
Field-induced shifts of the nuclear resonance frequency

total energy = energy of the bare nucleus +
+ energy of electron shell in coulomb potential + hyperfine structure

Nuclear ground state, \( I=5/2 \)  
Isomer, \( I=3/2 \)

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Energy of electronic ground state \( \text{Th}^{3+} \)

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See also:
Production of $^{229}$Th

$^{229}$Th is radioactive and is produced in the decay chain of $^{233}$U. In 2% of the decays of $^{233}$U the isomer $^{229m}$Th is produced and the decay chain should proceed with the emission of a UV photon.

$^{233}$U (1.592x$10^5$ yr.)
- $\alpha$ decay

$^{229}$Th (7880 yr.)
- $\alpha$ decay

$^{225}$Ra (14.9 day)
- $\beta^-$ decay

$^{225}$Ac (10.0 day)
- $\alpha$ decay

$^{221}$Fr (4.9 min.)
Production of $^{229}$Th

$^{229}$Th is radioactive and is produced in the decay chain of $^{233}$U. In 2% of the decays of $^{233}$U the isomer $^{229m}$Th is produced and the decay chain should proceed with the emission of a UV photon.

But:
Nobody has unambiguously detected this light.

The experimental challenge: precise measurement of the wavelength.
The experimental challenge:
direct observation of the optical nuclear transition,
precise measurement of the wavelength

Experimental approaches at PTB:

- Fluorescence detection after broadband excitation of the isomer
- Detection in forward scattering of broadband light
- Recoil isomers from the U-233 alpha decay
- Direct VUV emission from U-233
- Multiphoton laser excitation of trapped Th ions
The experimental challenge:

direct observation of the optical nuclear transition,
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Experimental approaches at PTB:

• Fluorescence detection after broadband excitation of isomer

  Failed; search range: $\lambda > 200$ nm

• Detection in forward scattering of scattered light

• Recoil isomers from the U-233 alpha decay

• Direct VUV emission from U-233

• Multiphoton laser excitation of trapped Th ions
The experimental challenge:
direct observation of the optical nuclear transition,
precise measurement of the wavelength

Experimental approaches at PTB:

• Fluorescence detection after broadband excitation of isomer
Failed; search range: \( \lambda > 200 \text{ nm} \)

• Detection in forward scattering of subband light

• Recoil isomers from the U-233 alpha decay

• Direct VUV emission from U-233

• Multiphoton laser excitation of trapped Th ions

Work in progress
Acknowledgements

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QUEST

PTB
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\( ^2F_{5/2} \)

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$\frac{3}{2}^+ [631]$

$\Delta E = 7.6 \text{ eV}$

M1 transition

$\tau = 10^4 \text{ s}$

$^{229}\text{Th Ground State}$

$\frac{5}{2}^+ [633]$

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