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

Date: Jul 16, 2008 11:20 AM

URL: http://pirsa.org/08070018

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 S1/2 â€“ D3/2 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 S1/2 - F7/2of 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 â‰ˆ7, 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.

Perimeter Institute, Waterloo, July 14 - 18, 2008

Laboratory search for temporal variations of fundamental constants with optical clocks

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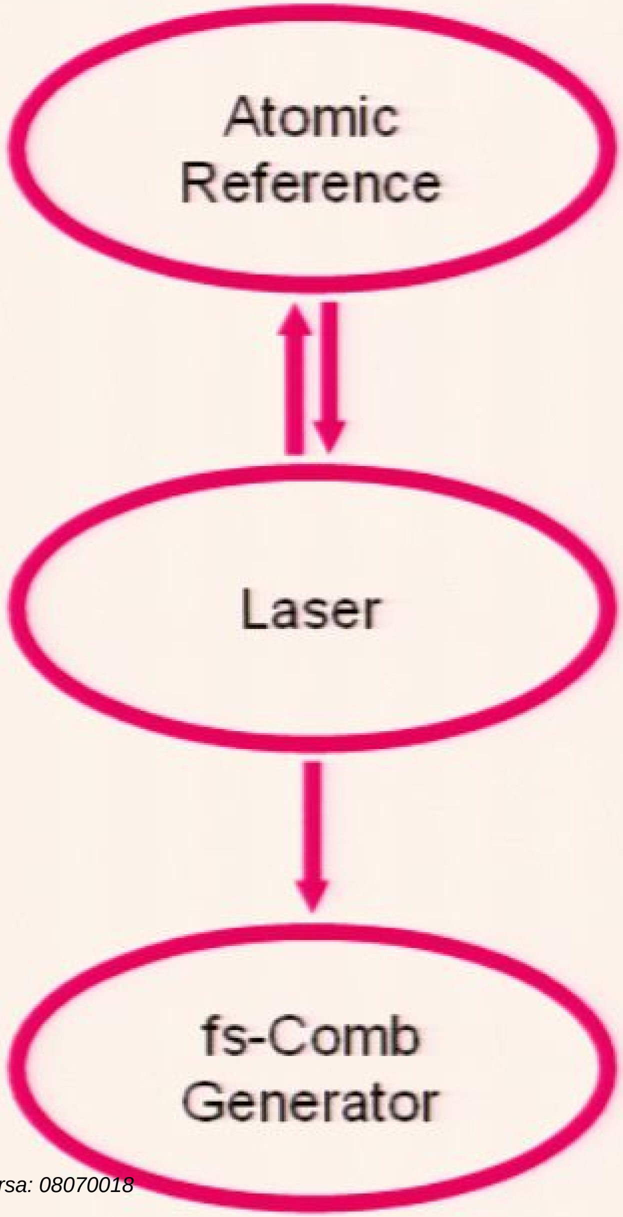
SFB 407 fq(x) quest PTB

Outline

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

Allan deviation $$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T_c}{N\tau}}$$

$\Delta\nu$: observed linewidth (Fourier limited)

ν_0: reference frequency

N: atom number (projection noise limited detection)

T_c: cycle time

microwave ⟶ optical frequency

ν_0 increases by 5 orders of magnitude

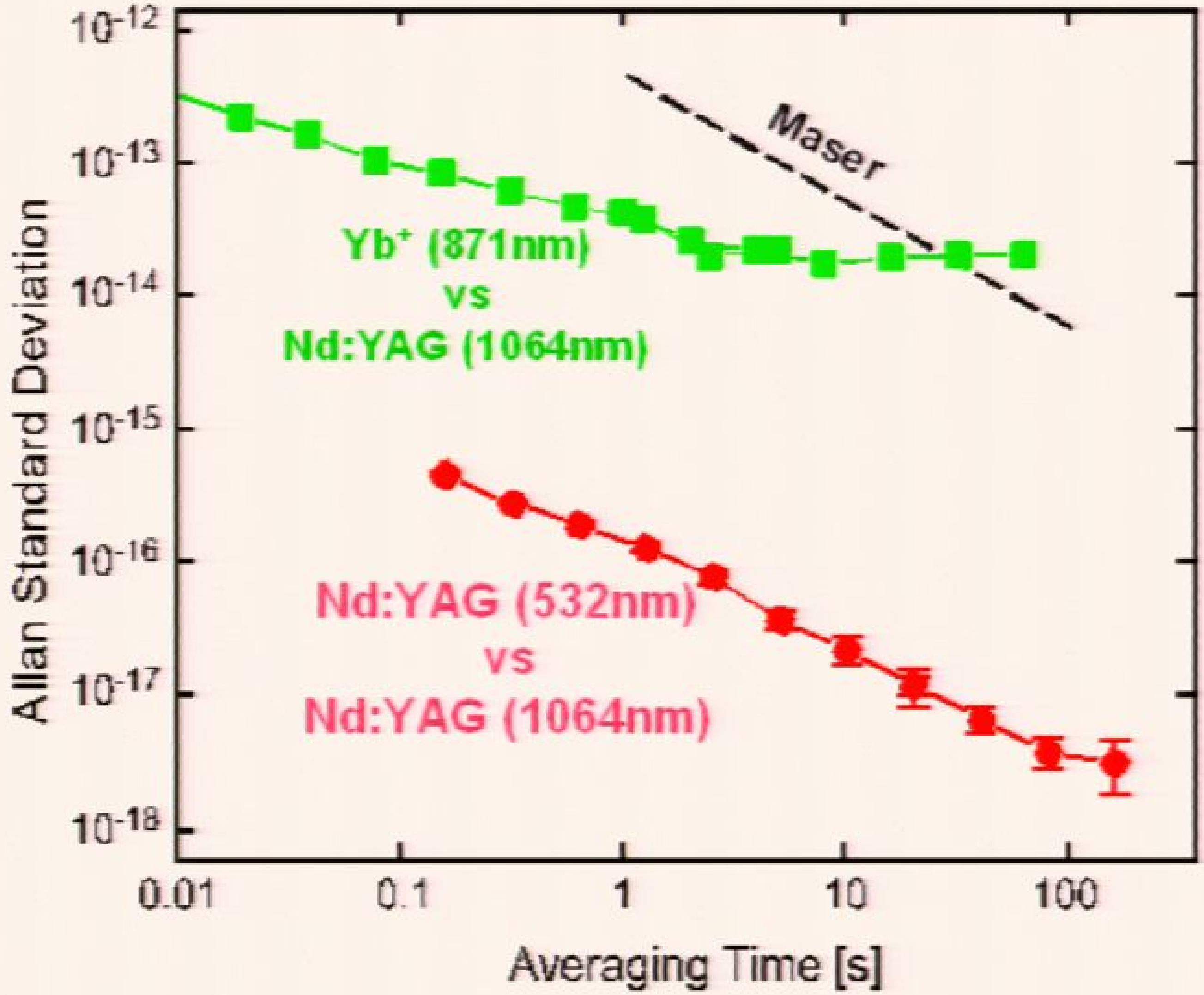
Accuracy, systematic frequency shifts

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

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

	relative shift for:	
	Cs 9.19 GHz	Yb^+ 688 THz
quadratic Zeeman shift at 1 μT	4.7 E-12	7.6 E-17
blackbody AC Stark shift at 300 K	-1.7 E-14	-5.8 E-16

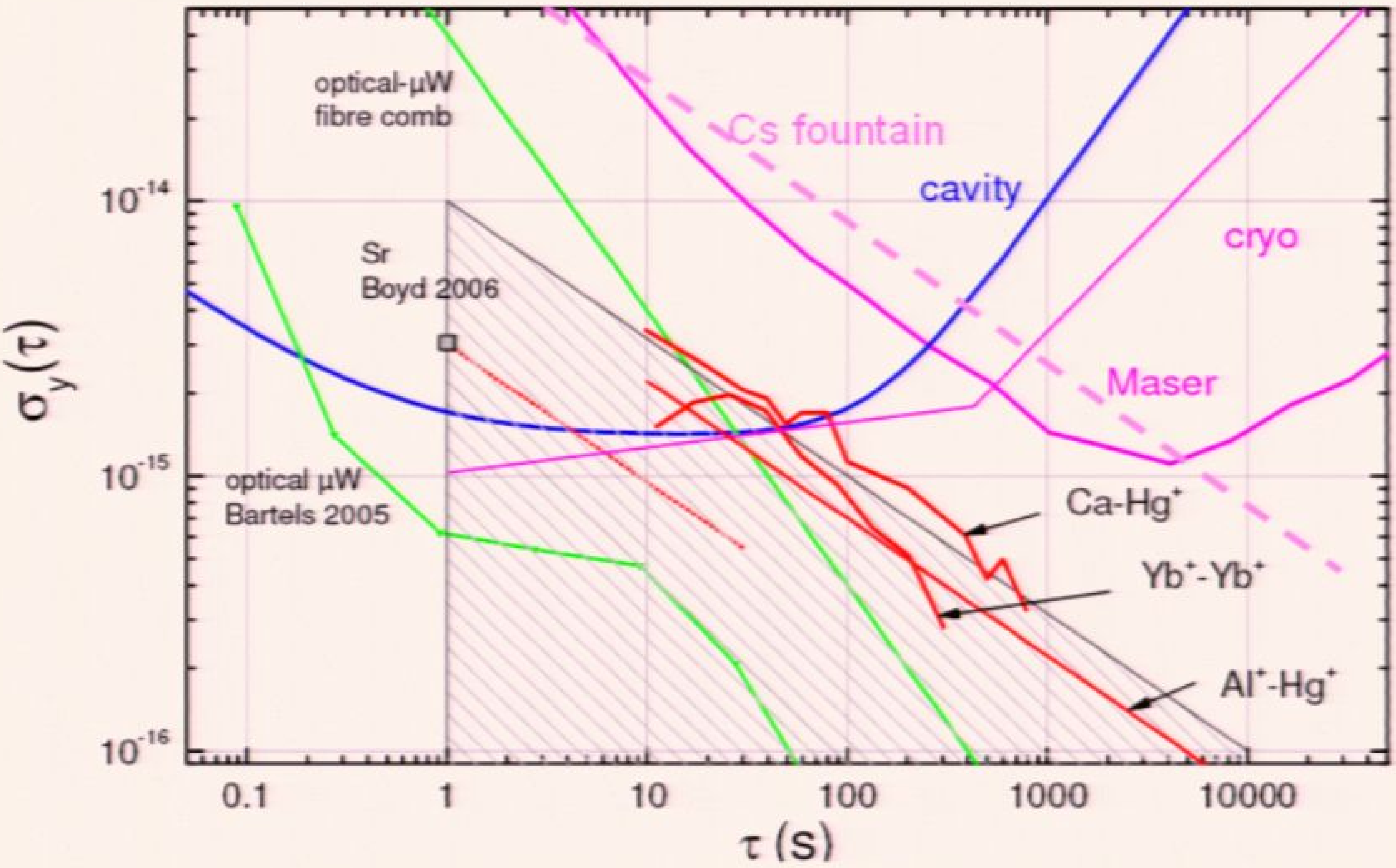
Measurement of optical frequency ratios with a frequency comb



$$\nu_{SH} / \nu_0 = 2.\ 000\ 000\ 000\ 000\ 000\ 001 \ \cdot (1 \pm 7 \cdot 10^{-19})$$

J. Stenger et al. Phys. Rev. Lett. **88**, 073601 (2002)

Demonstrated instabilities of frequency comparisons



Reference Systems

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

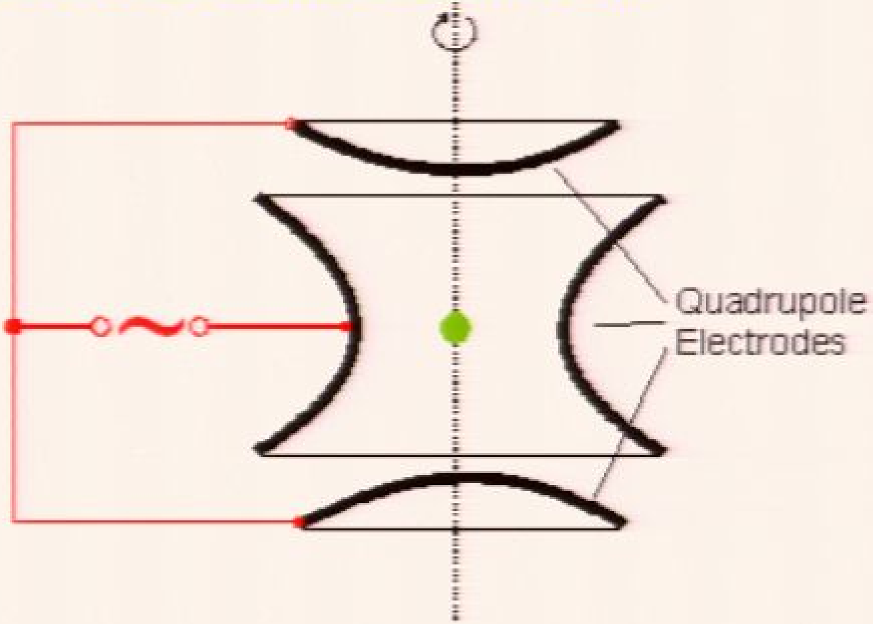
single trapped
laser-cooled ions:
Hg^+, Sr^+, Yb^+, In^+, Al^+…

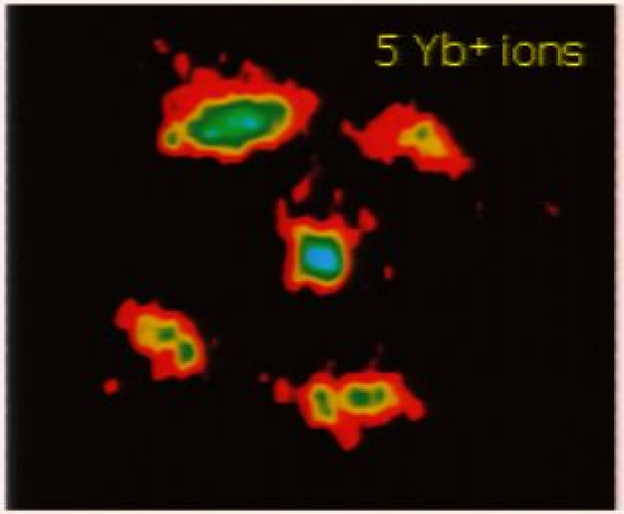
„simple“ atoms:
H, He...

molecules:
I_2, CH_4, OsO_4...

nuclei:
^{229}Th

ptical Frequency Standards with a aser-Cooled Ion in a Paul Trap

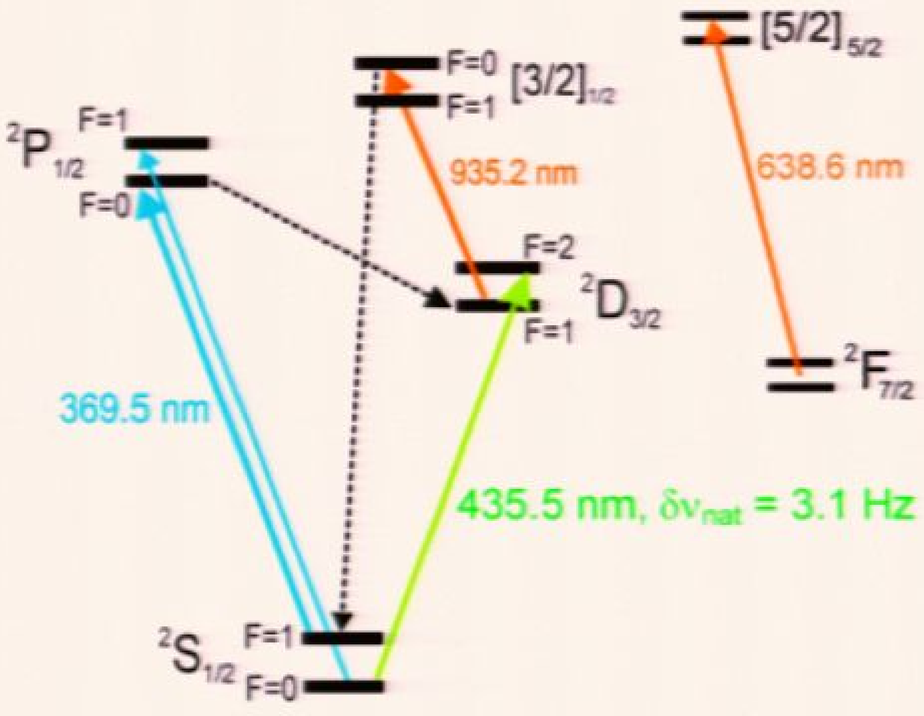




- Lamb-Dicke confinement with small trap shifts
- unlimited interaction time
- single ion: no collisions
- stability: use high-Q transition

Yb⁺ single-ion optical frequency standard

^{171}Yb⁺ level scheme



Advantages of Yb⁺
- all diode laser system
- long trapping time (months)

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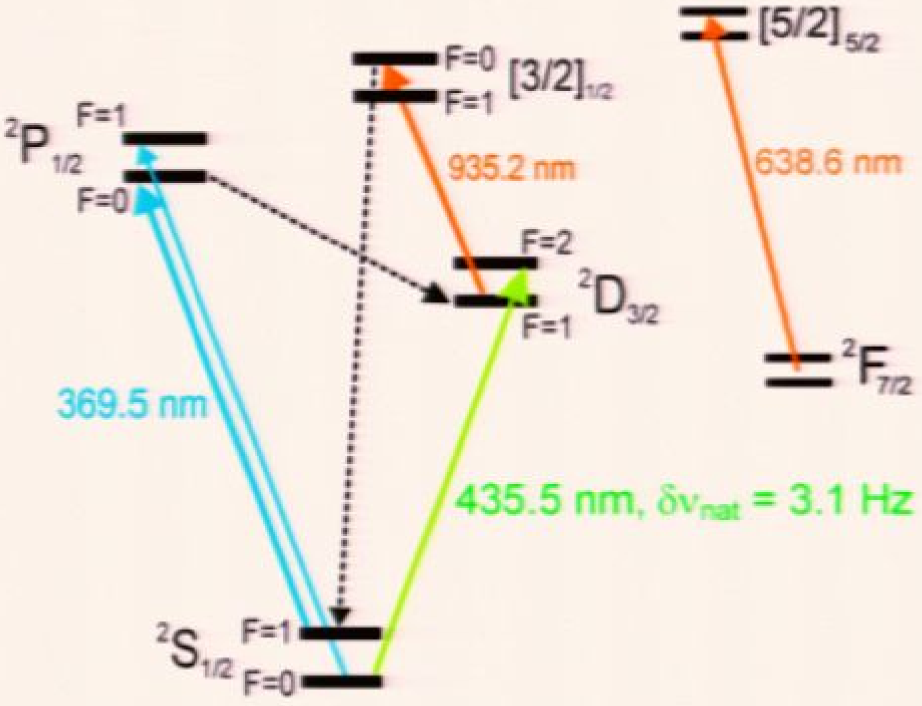
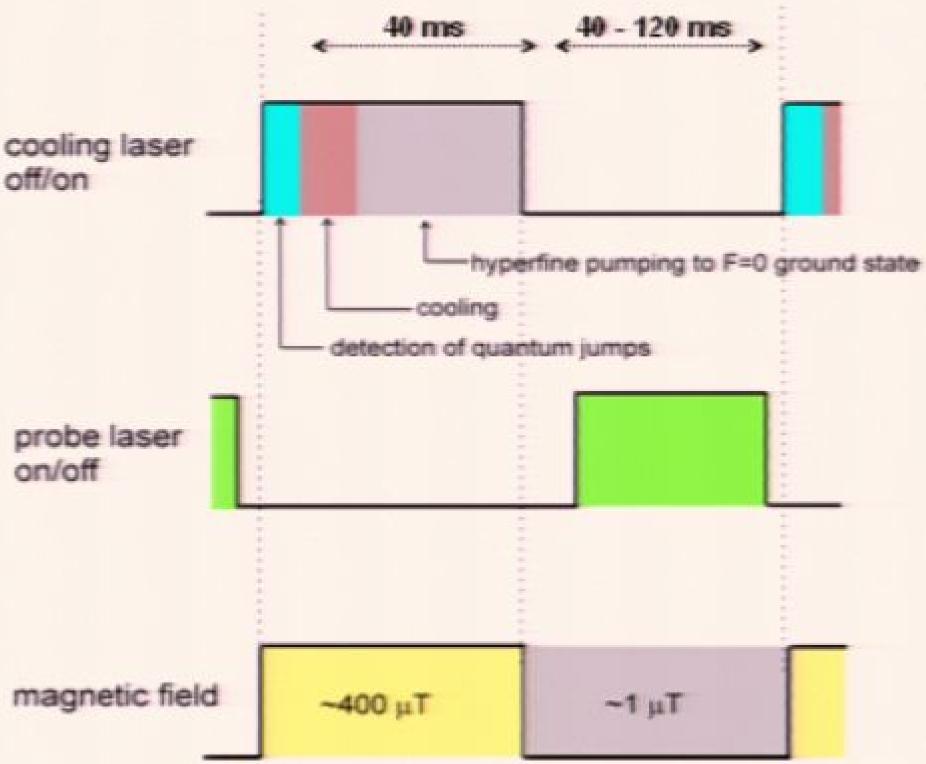


Measurement cycle



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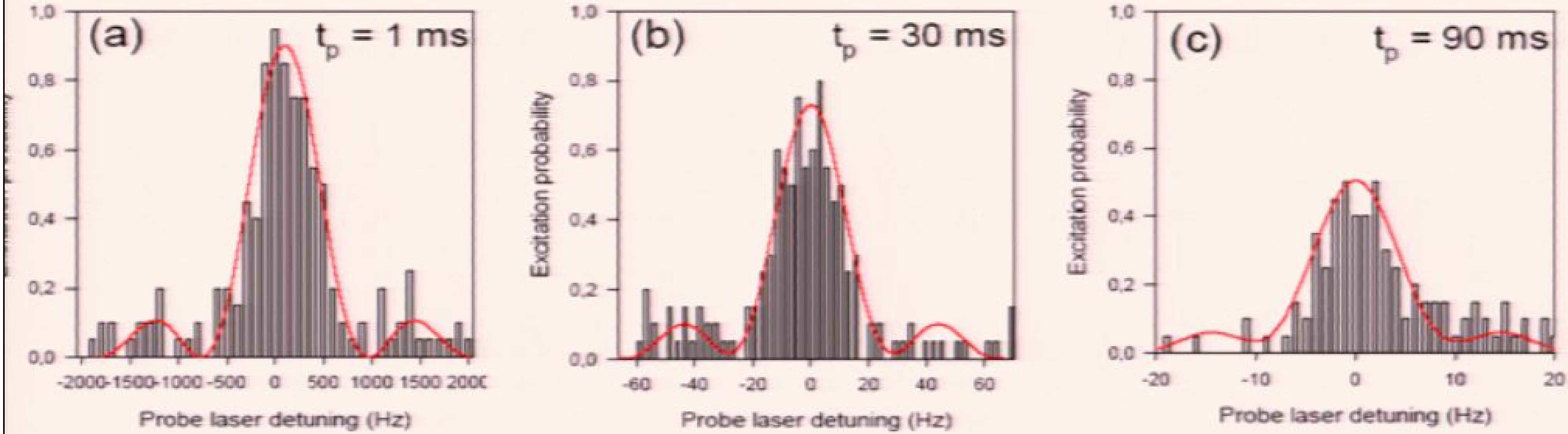
- all diode laser system
- long trapping time (months)

High resolution spectroscopy of the quadrupole transition at 688 THz

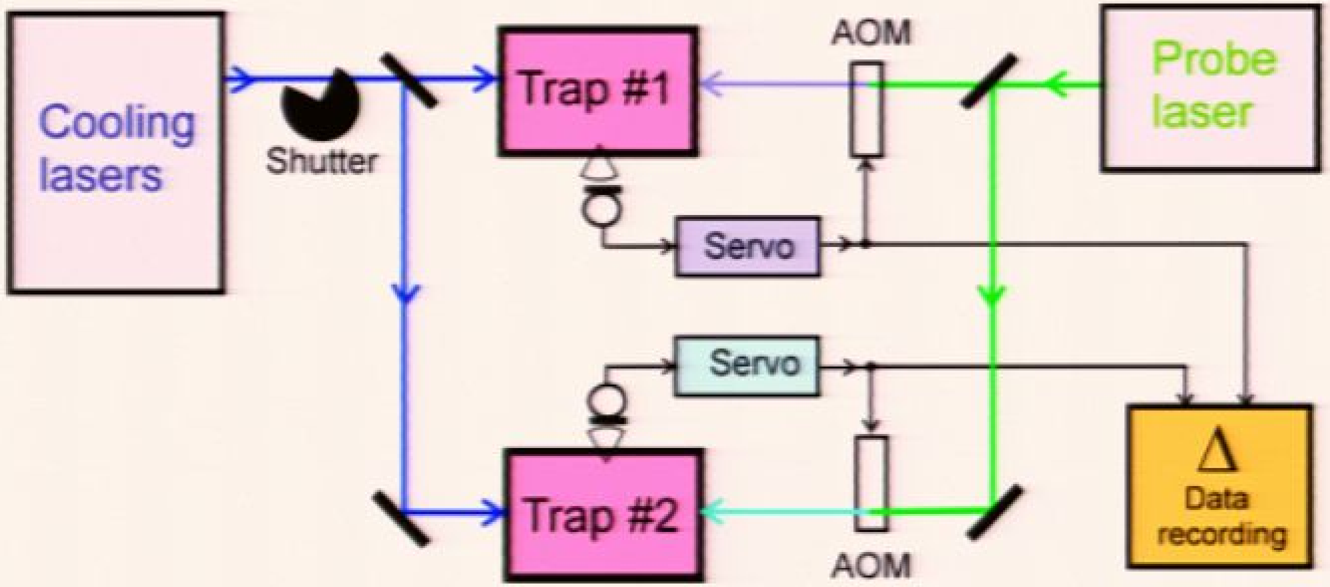
Pi-Pulse
τ(pulse)=1 ms
1 kHz linewidth

„standard operation“
τ(pulse)=30 ms
30 Hz linewidth

Close to the resolution limit
τ(pulse) = 90 ms ≈ 2·τ(Yb$^+$)
10 Hz linewidth



Frequency comparison between two trapped ^{171}Yb^{+}ions



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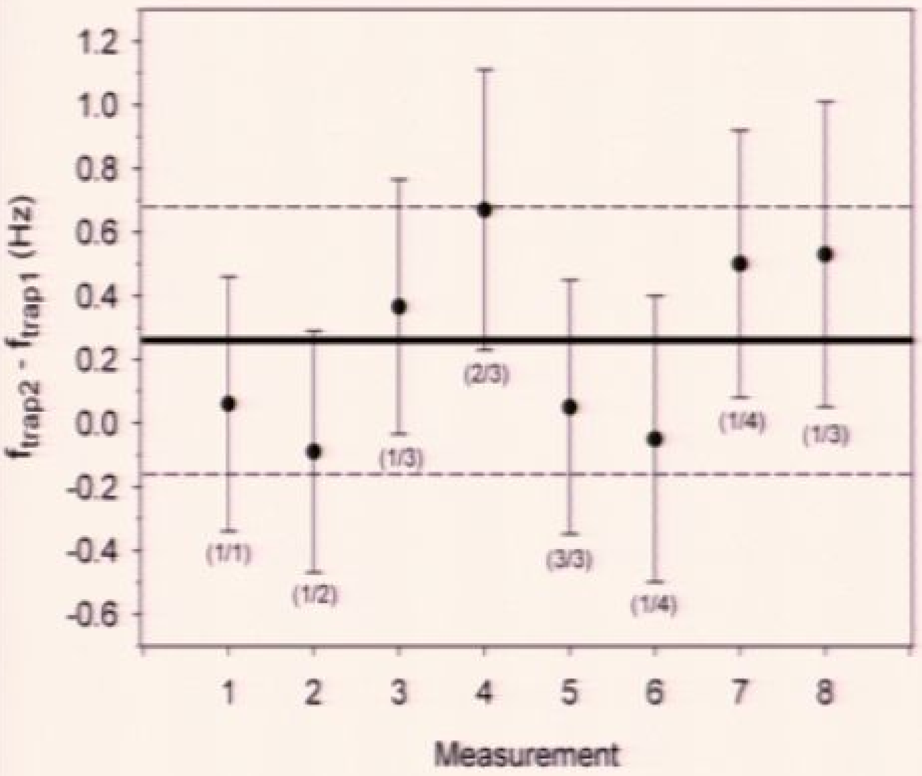
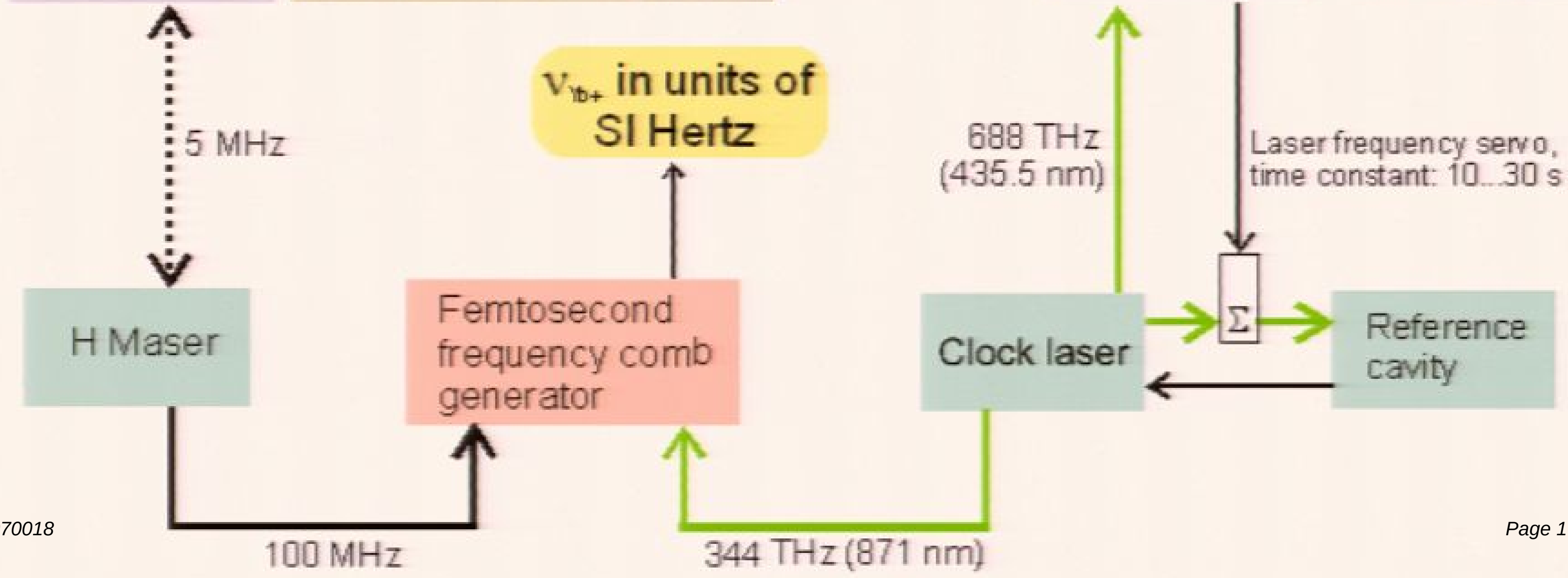


For nominally unperturbed conditions in both traps we observe a frequency difference of 0.26(42) Hz,
comparable to the best relative agreement between cesium fountain clocks.

6×10^{-16}

T. Schneider, E. Peik, Chr. Tamm,
Phys. Rev. Lett. **94**, 230801 (2005)

Setup for absolute optical frequency measurements



Cs fountain

Yb$^+$ trap

5 MHz

ν_{Yb+} in units of SI Hertz

688 THz (435.5 nm)

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

Σ

H Maser

Femtosecond frequency comb generator

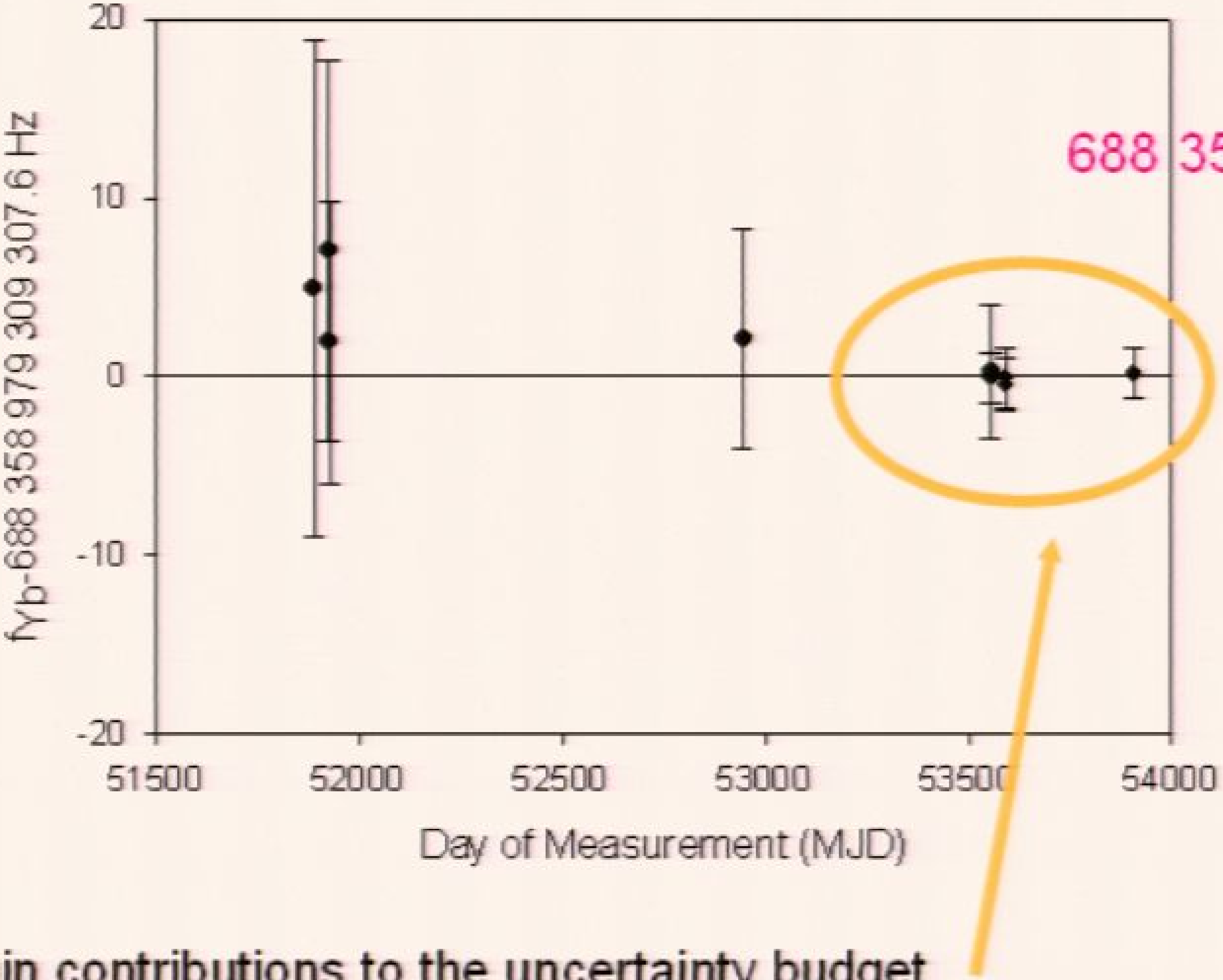
Clock laser

Reference cavity

100 MHz

344 THz (871 nm)

Results of absolute frequency measurements 2000-2006

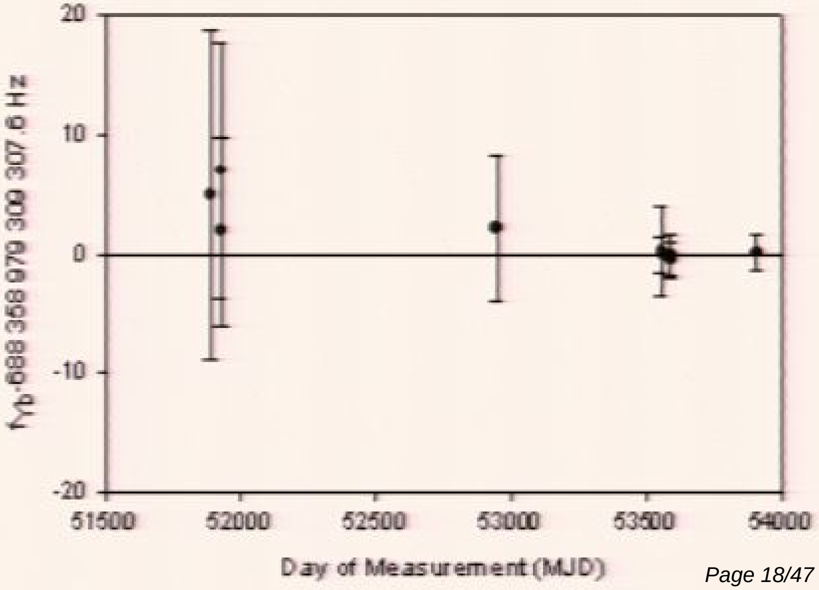


$^{171}Yb^{+}\ S_{1/2} - D_{3/2}$:
688 358 979 309 307.5(1.4) Hz

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

u_A=0.40 Hz (continuous measurements up to 36 h)
u_B(Cs)=0.83 Hz
$u_B(Yb^{+})$=1.05 Hz (quadrupole shift, blackbody AC Stark shift)

Testing the Constancy
Of Fundamental Constants



Search for variations of the fine structure constant in atomic clock comparisons

S. G. Karshenboim
physics/0311080

common-mode shift

$$\boxed{\frac{\partial \ln f}{\partial t} = \frac{\partial \ln Ry}{\partial t} + A \cdot \frac{\partial \ln \alpha}{\partial t}}$$

transition-specific shift

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

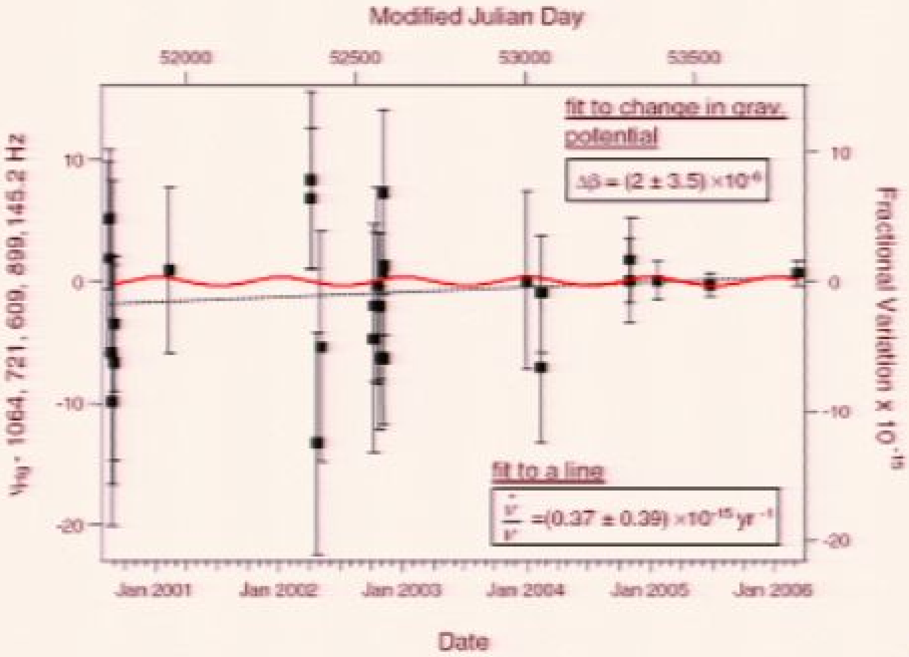
A is related to the relativistic level shift, $\frac{(Z\alpha)^2}{n_*} \frac{1}{j+1/2}$

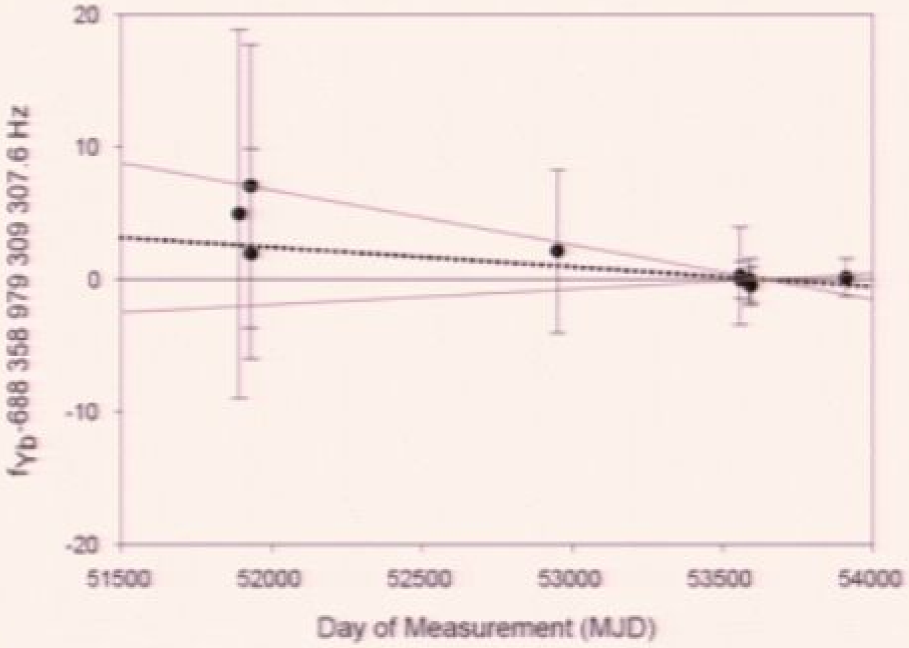
can be calculated with relativistic Hartree-Fock
V. Flambaum, V. Dzuba, et al.

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)



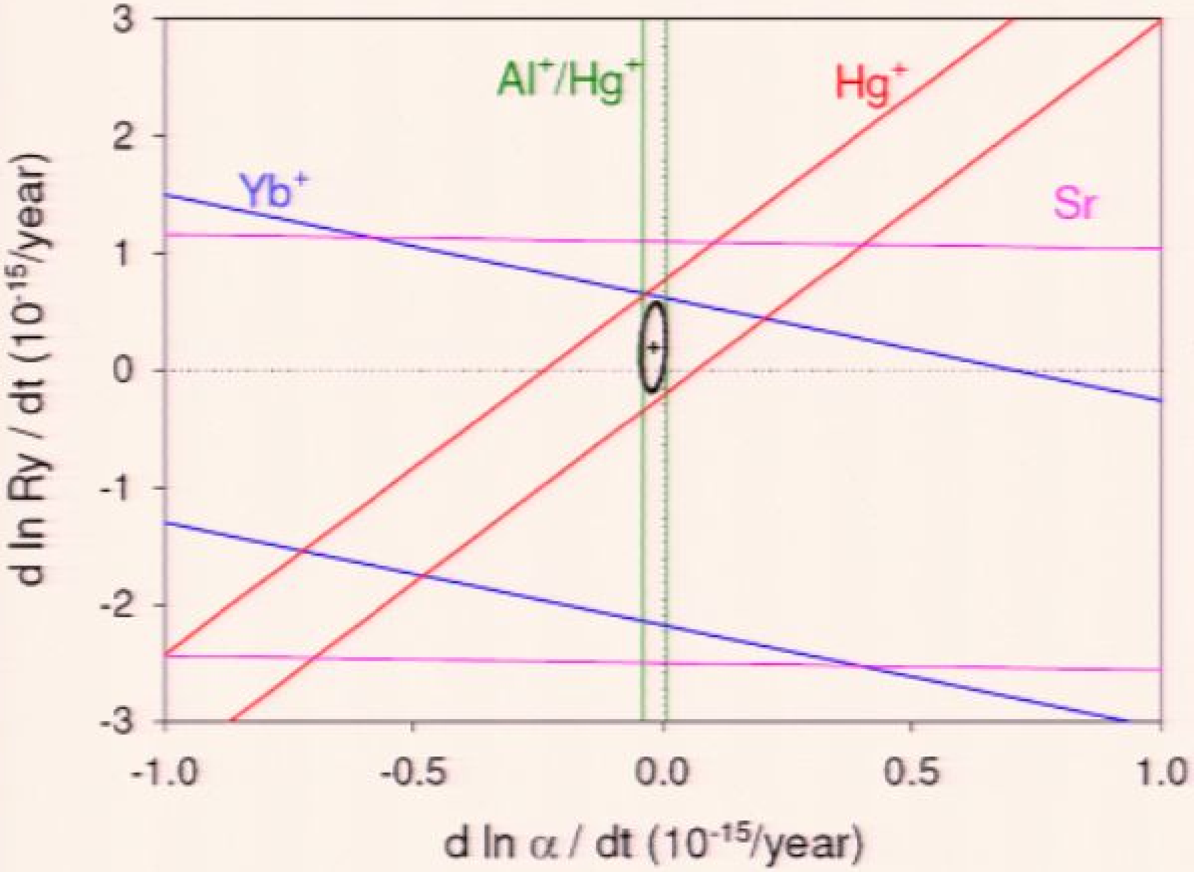


T. Fortier et al., Phys. Rev. Lett. **98**, 070801 (2007)

A(Yb)= 0.88
A(Hg)=−3.19

E. Peik et al., physics/0611088

Combination of available data from optical clocks (spring 2008)

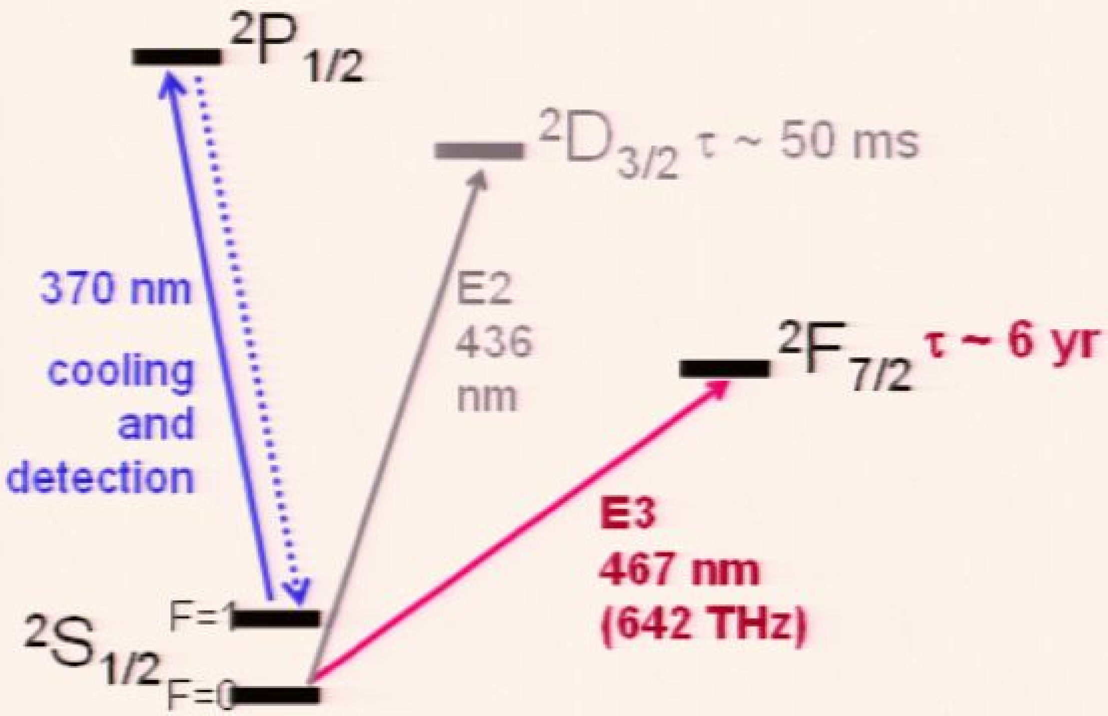


$$\frac{\partial \ln\{Ry\,c\}}{\partial t} = (1.9 \pm 3.8) \times 10^{-16}\,\mathrm{yr}^{-1}$$

$$\frac{\partial \ln \alpha}{\partial t} = (-1.6 \pm 2.3) \times 10^{-17}\,\mathrm{yr}^{-1}$$

Al^+/Hg^+: T. Rosenband et al., Science **319**, 1808 (2008)
Sr: S. Blatt et al., Phys. Rev. Lett. **100**, 140801 (2008)

New project: ^{171}Yb^{+} 467 nm octupole transition



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

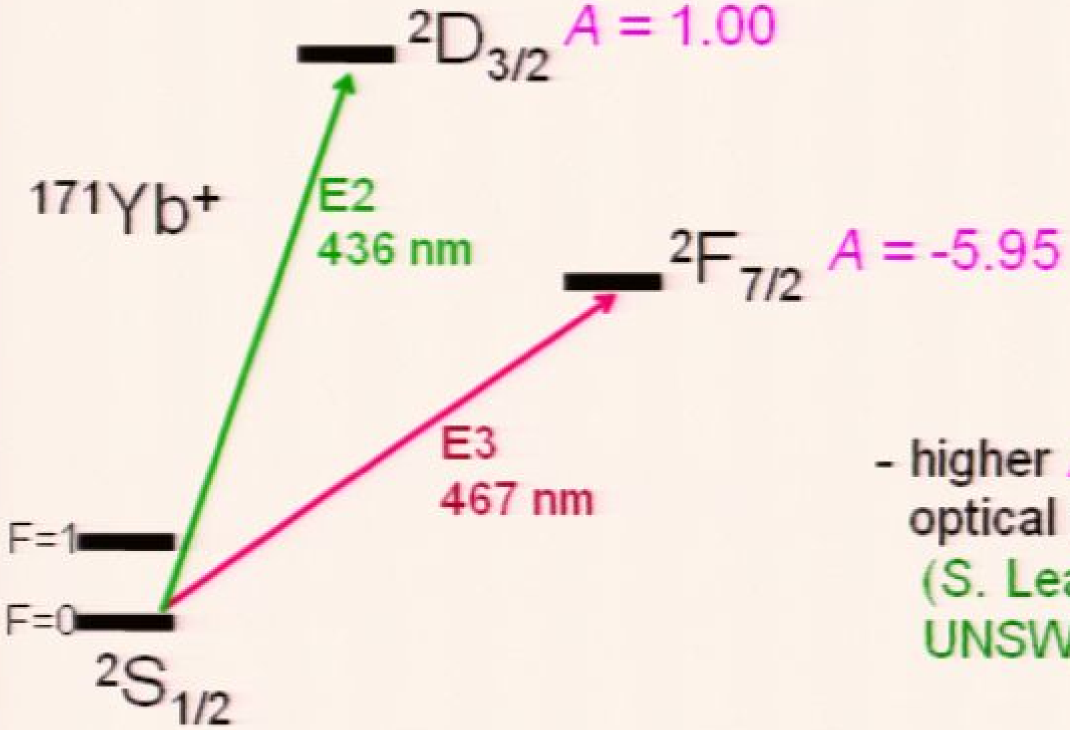
Resolution only limited by laser linewidth and by heating rate of trapped ion

Single-ion clock of high stability

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

Pioneering work at NPL: see e.g.
P.J. Blythe et al., Phys. Rev. A **67**, 020501 (2003)

^{171}Yb^{+}, prospects for $d\alpha/dt$ measurements



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

- can be done in ONE trap

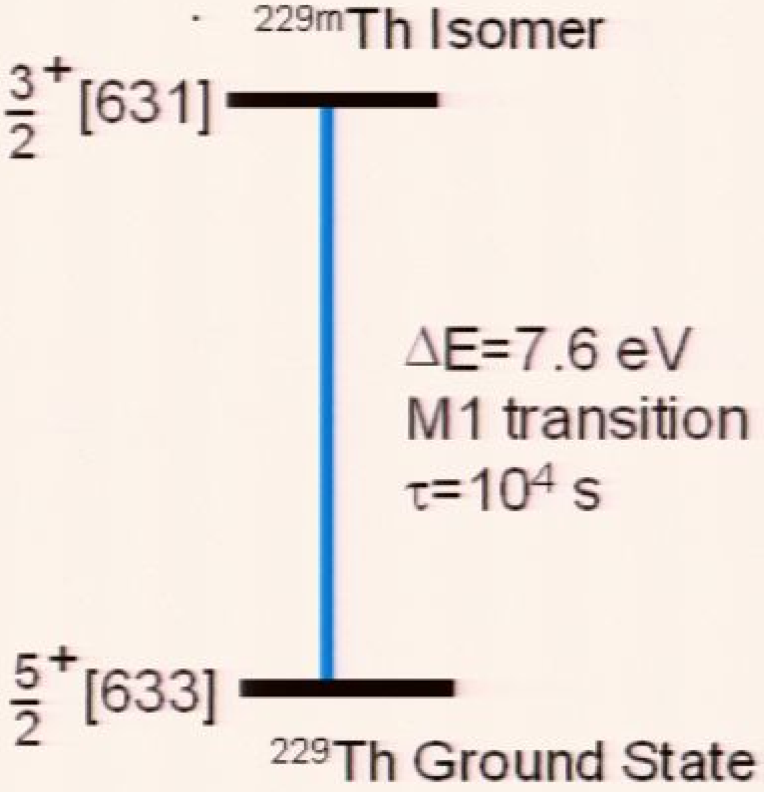
- frequency ratio measurement by comb generator; independence from Cs clocks, long-distance transfer,....

- measurements with $1\cdot10^{-16}$ uncertainty, performed over one year, would lead to a sensitivity of $(1/\alpha)(d\alpha/dt) \approx 2\cdot10^{-17}$ / 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.



^{229m}Th Isomer

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

ΔE=7.6 eV

M1 transition

τ=10^{4} s

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

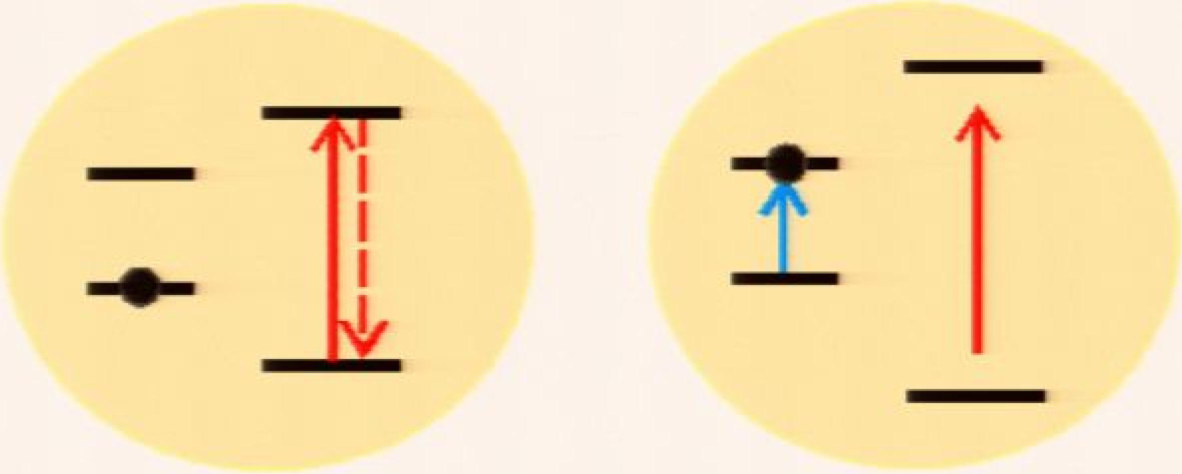
^{229}Th Ground State

Measurements of ΔE

ΔE [eV]	Year	Method
<100	1976	γ-Spectr.
-1 (4)	1990	“
<5	1990	d-Scatt.
3.5 (1.0)	1994	γ-Spectr*
3.4 (1.8)	2003	“
7.6 (0.5)	2007	“

*R. Helmer and C. Reich, Idaho
“ V. Barci et al., Nice
“ 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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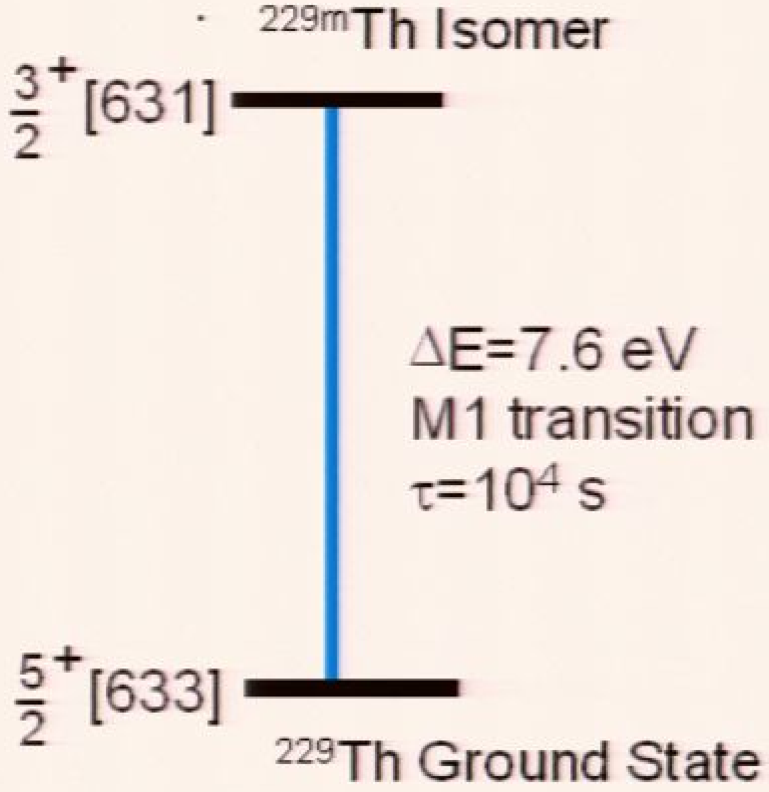

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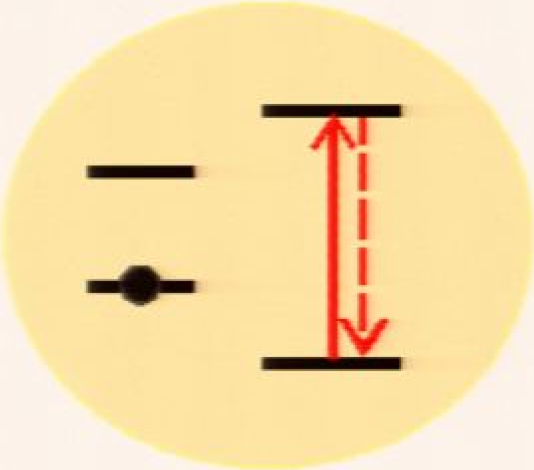
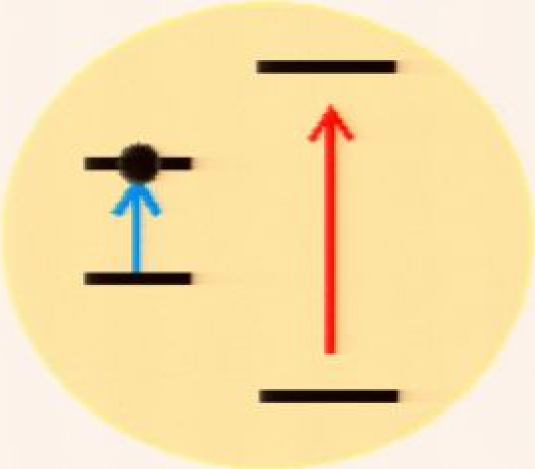
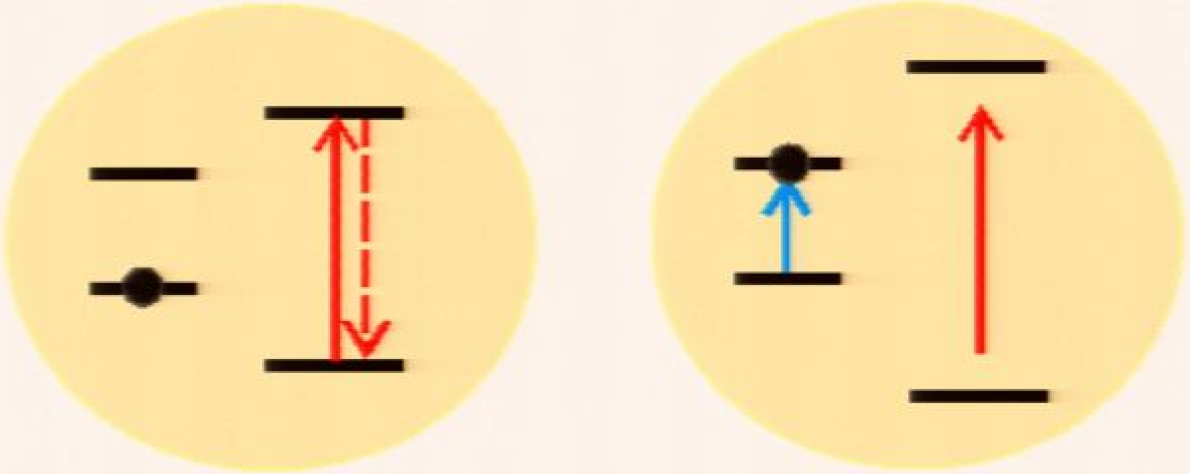


Nucleus in the ground state; laser-induced fluorescence from the shell.



Laser excitation of the nucleus; change of hyperfine structure detected in intensity or polarisation of fluorescence.

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.

→ 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

E. Peik, Chr. Tamm, Europhys. Lett. **61**, 181 (2003)

Field-induced shifts of the nuclear resonance frequency

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

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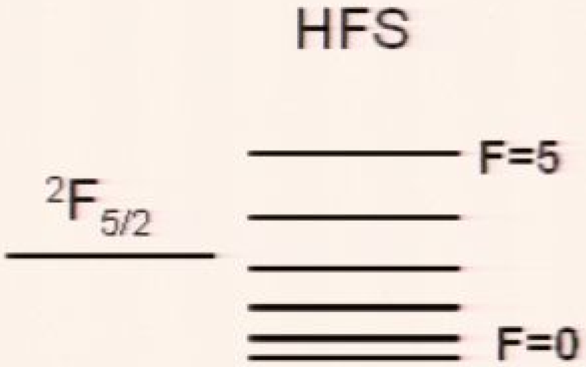
Nuclear ground state, I=5/2



Energy of
lectronic
round state
Th^{3+})

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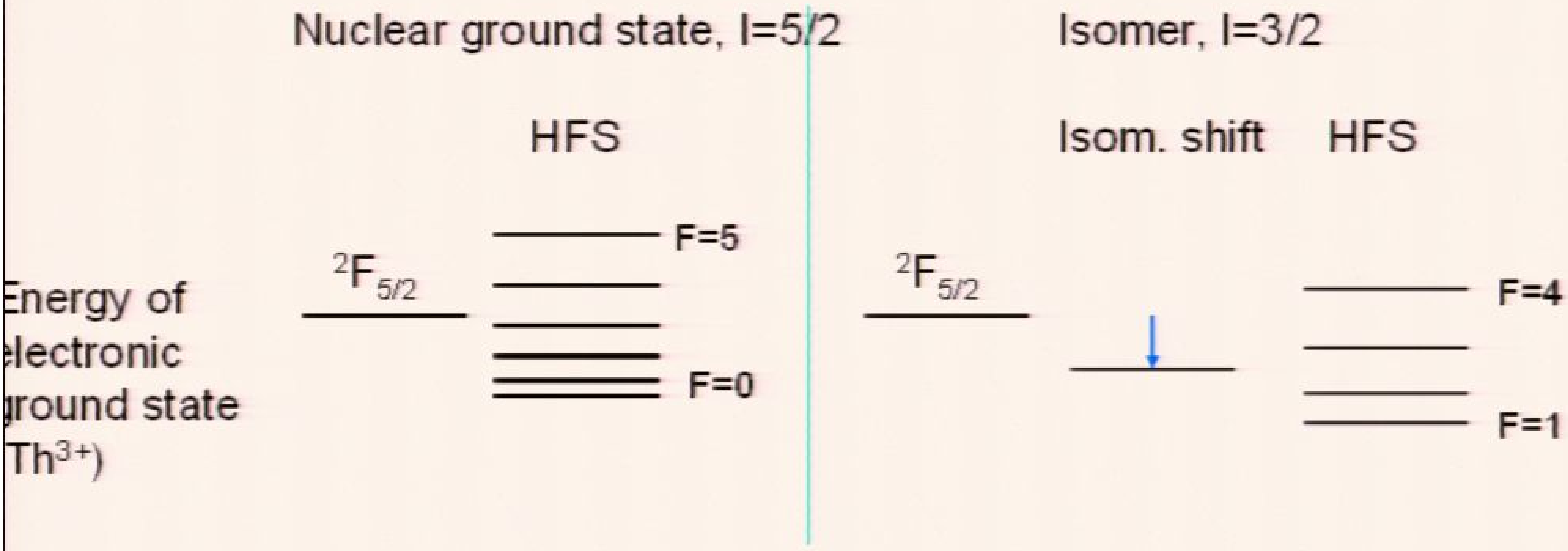

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Isomer, I=3/2

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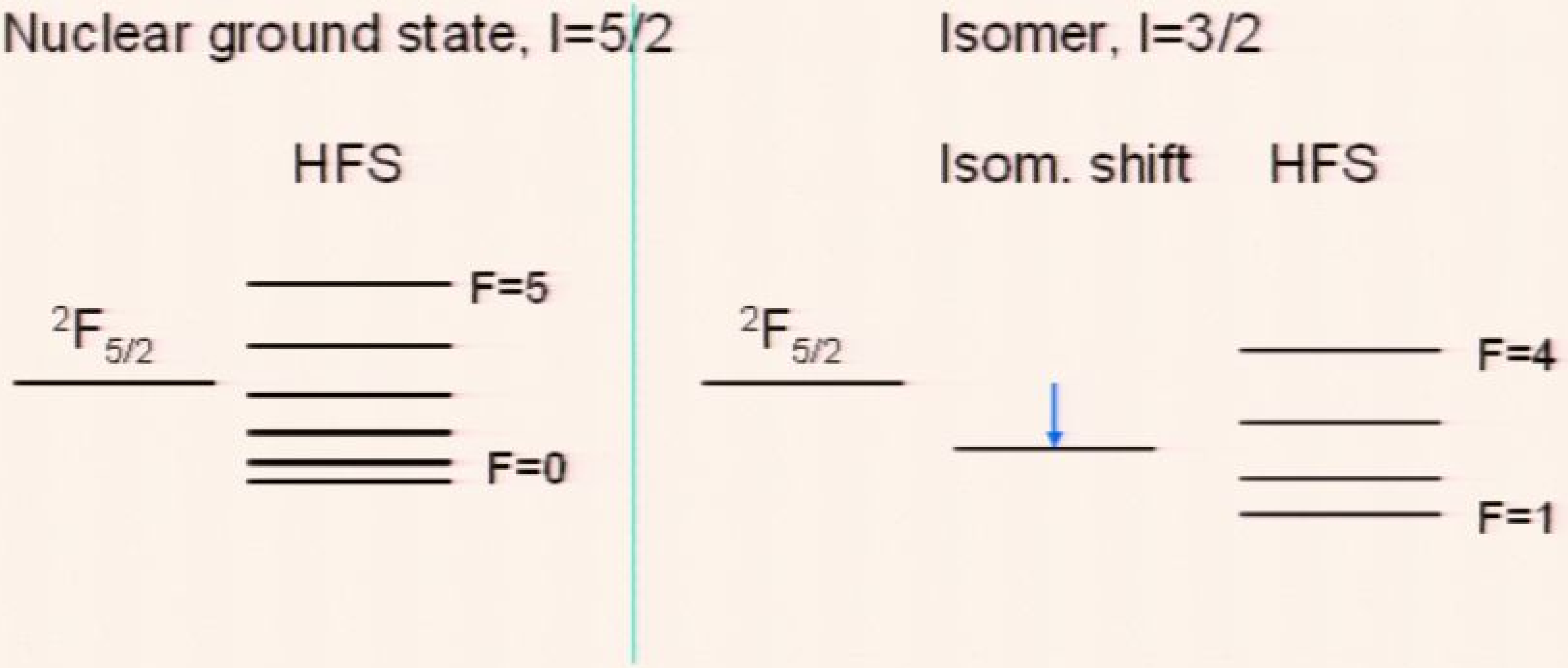

Nuclear ground state, I=5/2

Isomer, I=3/2

HFS

Isom. shift HFS

$^2F_{5/2}$

F=5

F=0

$^2F_{5/2}$

F=4

F=1

Energy of
lectronic
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Th^{3+})

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 ✓	(laser cooling)
quadratic Zeeman ✓	(m_F=0-0)
quadratic Stark (scalar) ✓	(independent from F and I)
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 ω in terms of α and quark masses:

V. Flambaum: Phys. Rev. Lett. **97**, 092502 (2006)

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

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

10^5 enhancement in sensitivity to variations results from the near perfect cancellation of two O(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:

X. He, Z. Ren, J. Phys. G. **34**, 1611 (2007)

A. C. Hayes, J. L. Friar, nucl-th/0702048, Phys. Lett. B **650**, 229 (2007)

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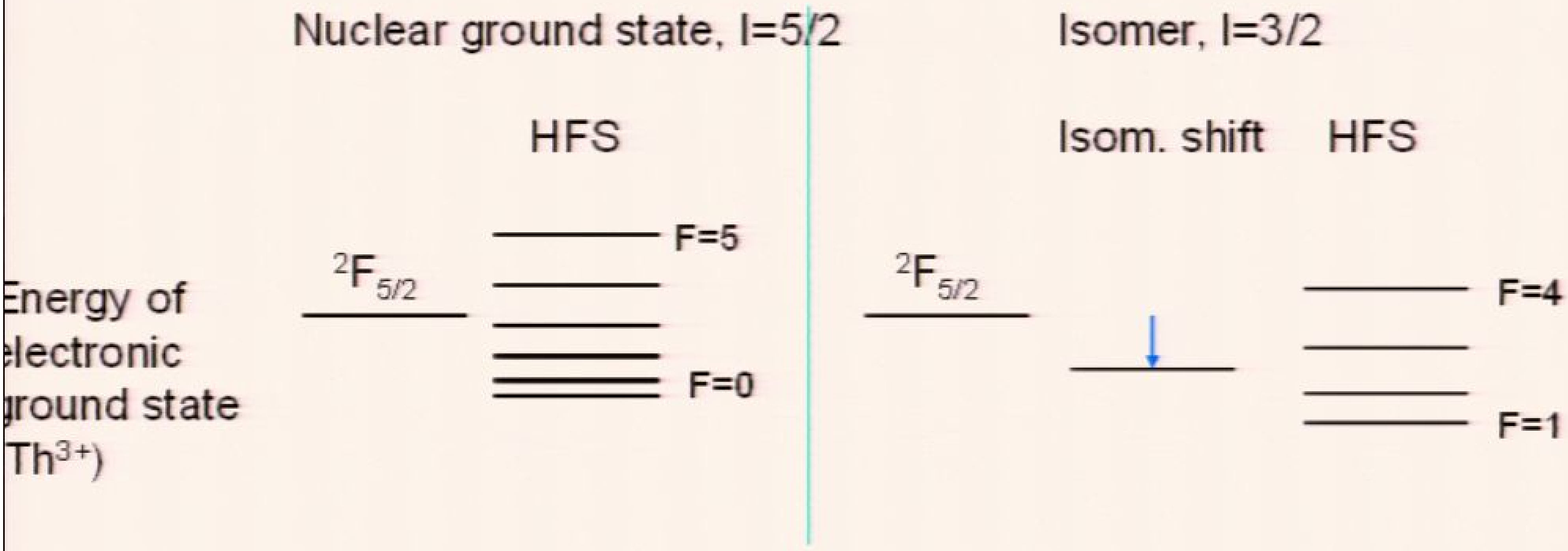

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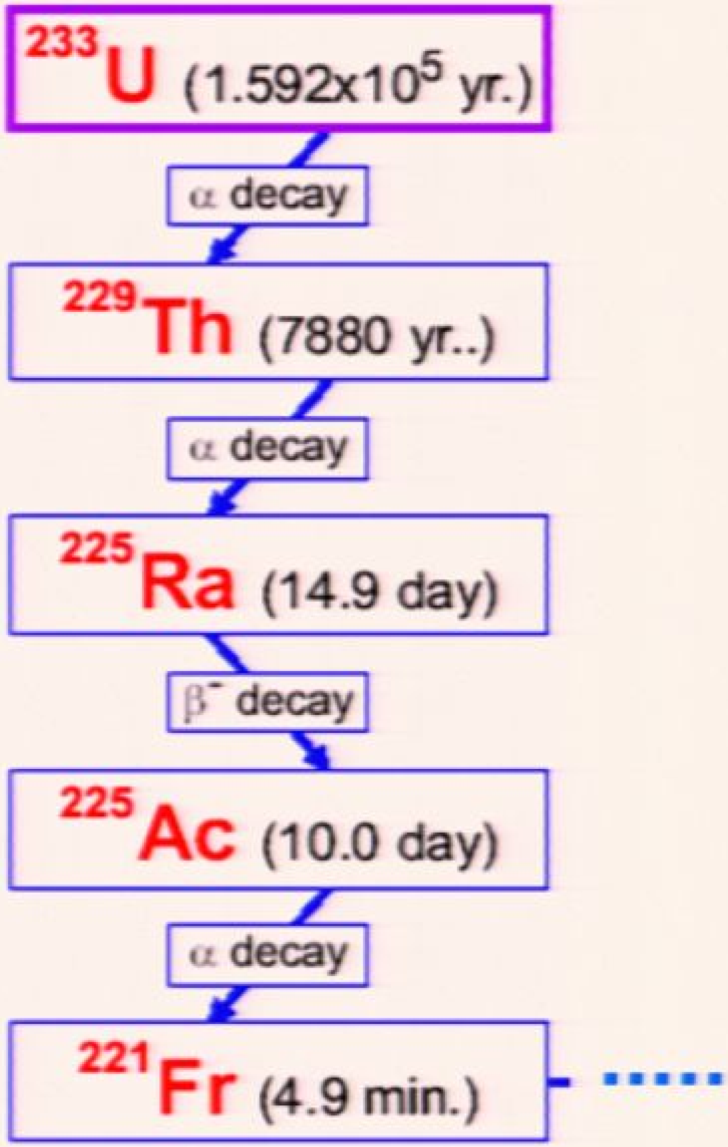
Production of ^{229}Th

^{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 (1.592x10^5 yr.)

α decay

^{229}Th (7880 yr..)

α decay

^{225}Ra (14.9 day)

β^- decay

^{225}Ac (10.0 day)

α decay

^{221}Fr (4.9 min.)

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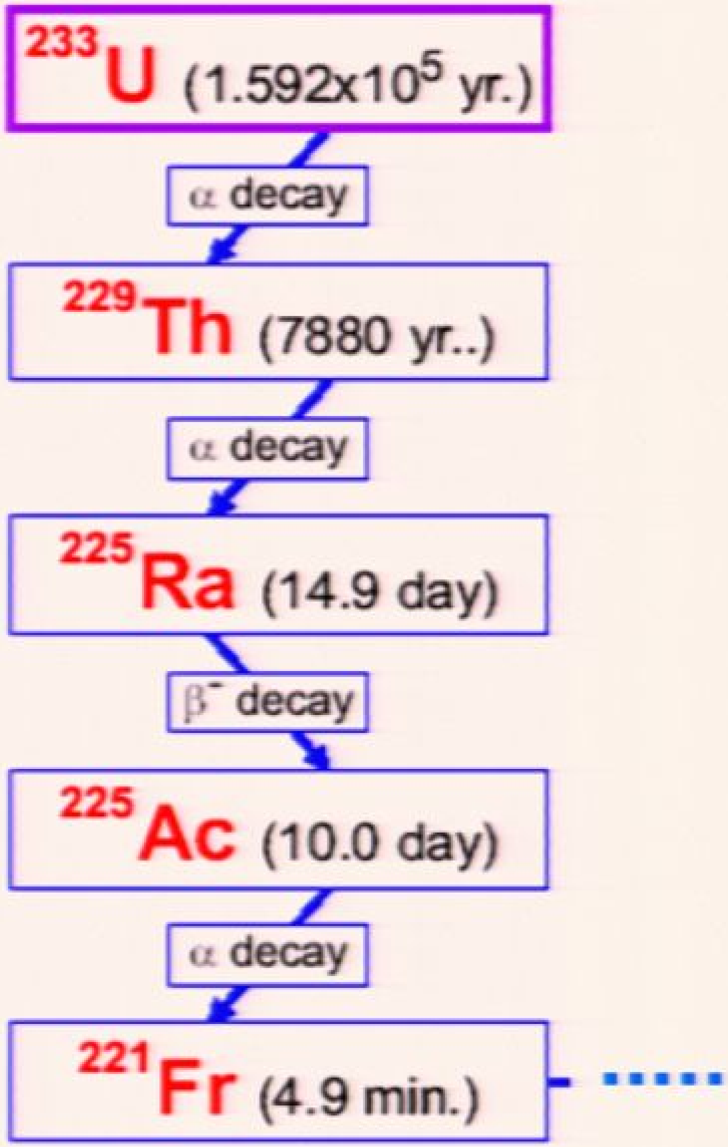

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α decay

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β^{-} decay

^{225}**Ac** (10.0 day)

α decay

^{221}**Fr** (4.9 min.) ……

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

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Failed; search range: λ>200 nm

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- 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

Chr. Tamm

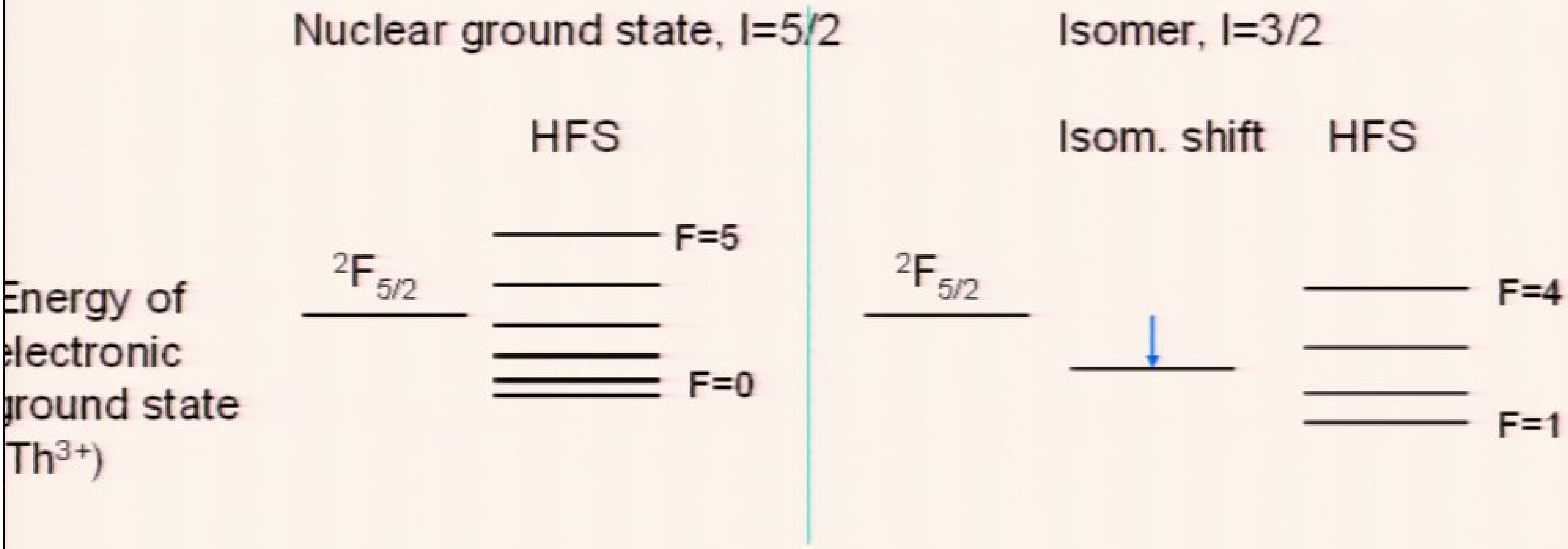
D. Griebsch
B. Lipphardt
T. Mehlstäubler
M. Okhapkin
H. Schnatz
T. Schneider
I. Sherstov
B. Stein
S. Weyers
R. Wynands
K. Zimmermann

S. Karshenboim, VNIIM and MPQ

Funding:
DFG
FQXi
QUEST

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

HFS

Isom. shift

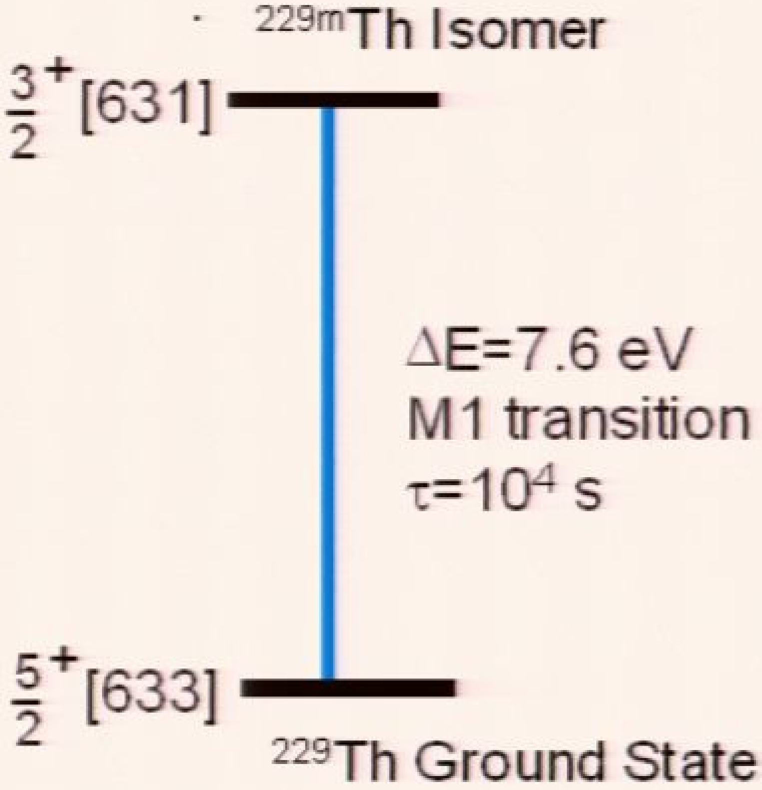
HFS

nergy of
lectronic
round state
Th^{3+})

Not only nuclear moments, but also electronic moments may contribute to Zeeman and Stark effect, if the shift depends on F or I.

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.

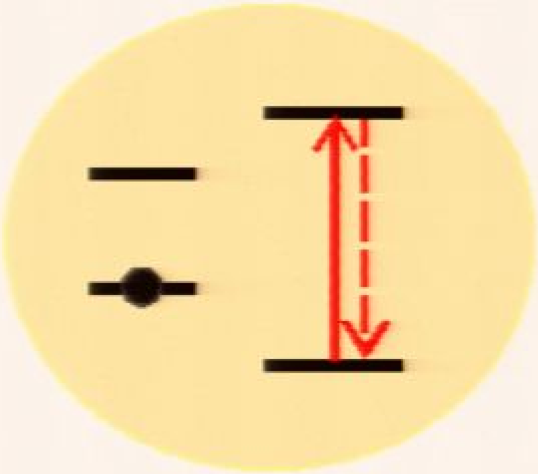


Measurements of ΔE

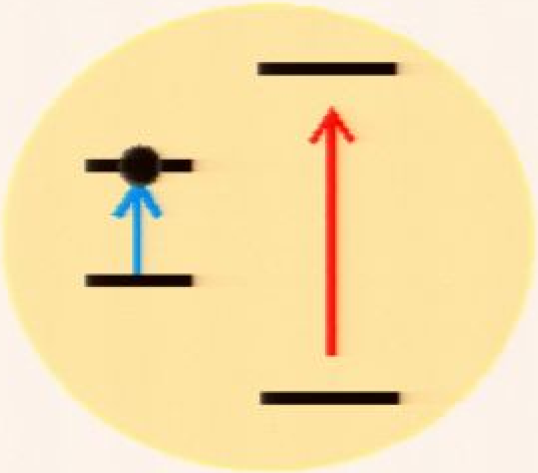
ΔE [eV]	Year	Method
<100	1976	γ-Spectr.
-1 (4)	1990	“
<5	1990	d-Scatt.
3.5 (1.0)	1994	γ-Spectr*
3.4 (1.8)	2003	“
7.6 (0.5)	2007	“

*R. Helmer and C. Reich, Idaho
“ V. Barci et al., Nice
“ B. Beck et al., LLNL

Detection of the Nuclear Excitation in Nuclear-Electronic Double-Resonance



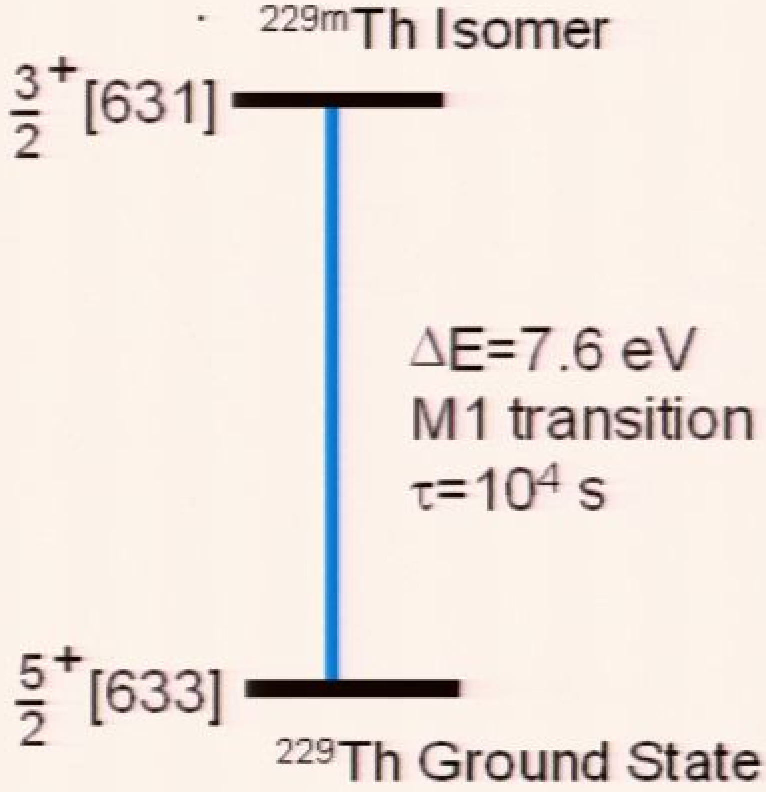
Nucleus in the ground state;
laser-induced fluorescence
from the shell.



Laser excitation of the nucleus;
change of hyperfine structure detected in
intensity or polarisation of fluorescence.

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.



^{229m}Th Isomer

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

ΔE=7.6 eV
M1 transition
$\tau=10^4$ s

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

^{229}Th Ground State

Measurements of ΔE

ΔE [eV]	Year	Method
<100	1976	γ-Spectr.
-1 (4)	1990	“
<5	1990	d-Scatt.
3.5 (1.0)	1994	γ-Spectr*
3.4 (1.8)	2003	“
7.6 (0.5)	2007	“

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