# Optical clocks with trapped ions and the search for variations of fundamental constants

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# Outline

- Laboratory limits on temporal variation of the fine structure constant
- The electric octupole transition in $^{171}Yb^{+}$
- The optical nuclear transition in $^{229}Th^{+}$

# Scaling of transition frequencies with fundamental constants

| Transition | | Energy scaling | Refs. |
|---|---|---|---|
| Atomic | Gross structure | Ry | H spectroscopy |
| | Fine structure | $\alpha^2$Ry | [24] |
| | Hyperfine structure | $\alpha^2(\mu/\mu_B)$Ry | Cs + Rb fountain clocks |
| Molecular | Electronic structure | Ry | [25] |
| | Vibrational structure | $(m_e/m_p)^{1/2}$Ry | [25] |
| | Rotational structure | $(m_e/m_p)$Ry | [25] |
| Relativistic corrections | | Function of $\alpha^2$ | [22,23] |

M. Savedoff, 1956

R. Thompson, 1975

J. Prestage, 1995
V. Flambaum et al.

Optical clocks with heavy ions or atoms

From: S. G. Karshenboim, E. Peik (eds.)
Astrophysics, Clocks and Fundamental Constants,
Lect. Notes in Physics **648** (2004)

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

S. G. Karshenboim
physics/0311080

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

common-mode shift → $\frac{\partial \ln Ry}{\partial t}$

transition-specific shift → $\frac{\partial \ln \alpha}{\partial t}$

Simple 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

# Optical Frequency Standard with a Laser-Cooled Ion in a Paul Trap

→ Very low uncertainty is possible (to $10^{-18}$)
proposed by Hans Dehmelt 1975

Experiments with $Hg^+$ (NIST), $Yb^+$ (PTB, NPL),
$Sr^+$ (NRC, NPL), $Ca^+$(Mars., Innsb.,...), $Al^+$ (NIST), ...

Measurements of optical transition frequencies using
cesium fountains and femtosecond-laser frequency combs:

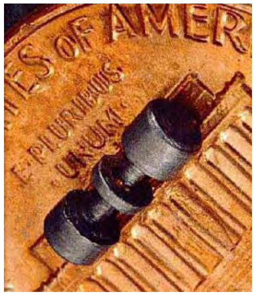
| | | |
|---|---|---|
| $^{199}Hg^+$ $S_{1/2}$ - $D_{5/2}$: | 1 064 721 609 899 144.94(97) Hz | NIST |
| $^{171}Yb^+$ $S_{1/2}$ - $D_{3/2}$: | 688 358 979 309 306.62(73) Hz | PTB |
| $^{88}Sr^+$ $S_{1/2}$ - $D_{5/2}$: | 444 779 044 095 484.2(1.7) Hz | NPL |

These standards are listed as „secondary representations
of the *second*“ in the optical frequency domain.

Precision data is available from about 2000 on.

Next generation exp.: optical frequency ratios

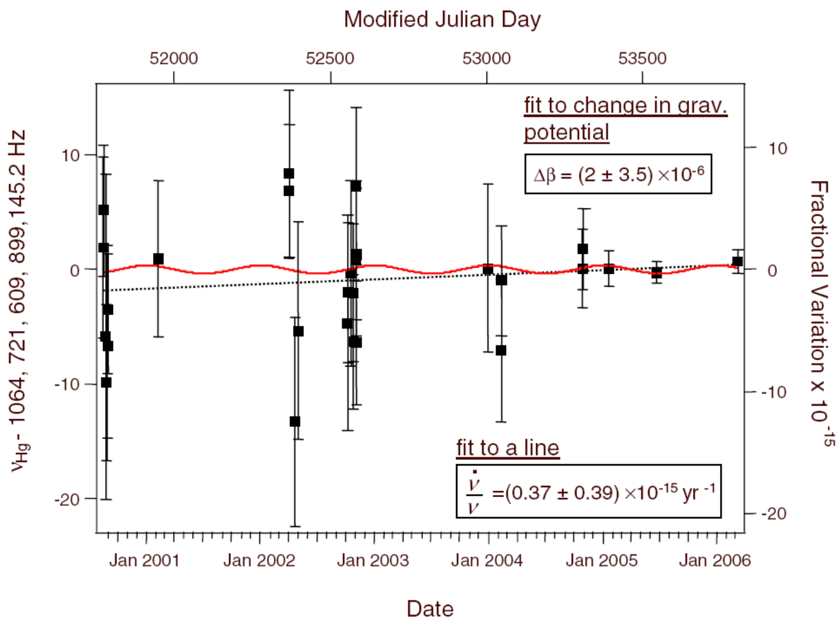
# Remote comparison of single-ion clocks NIST-PTB, 2000-2008

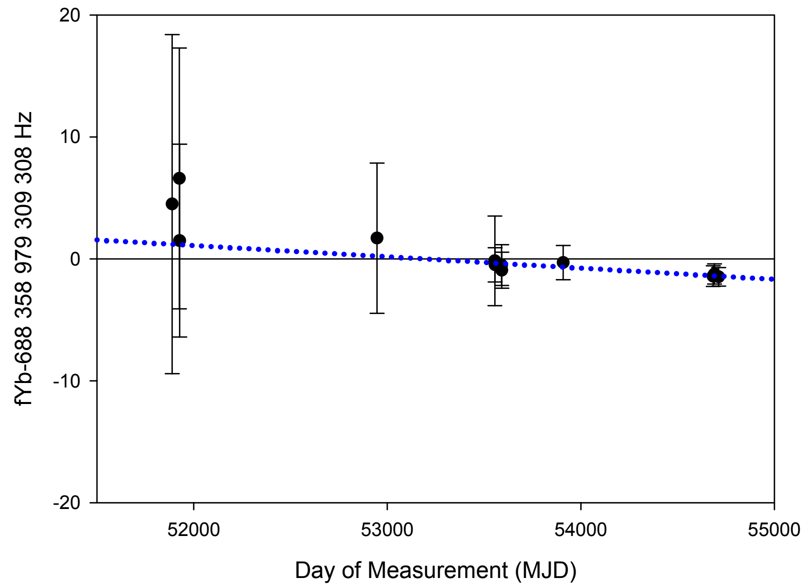


$^{199}Hg^{+}$, S - D at 1064 THz
(NIST Boulder)

A(Yb)= 1.00
A(Hg)=−3.19

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

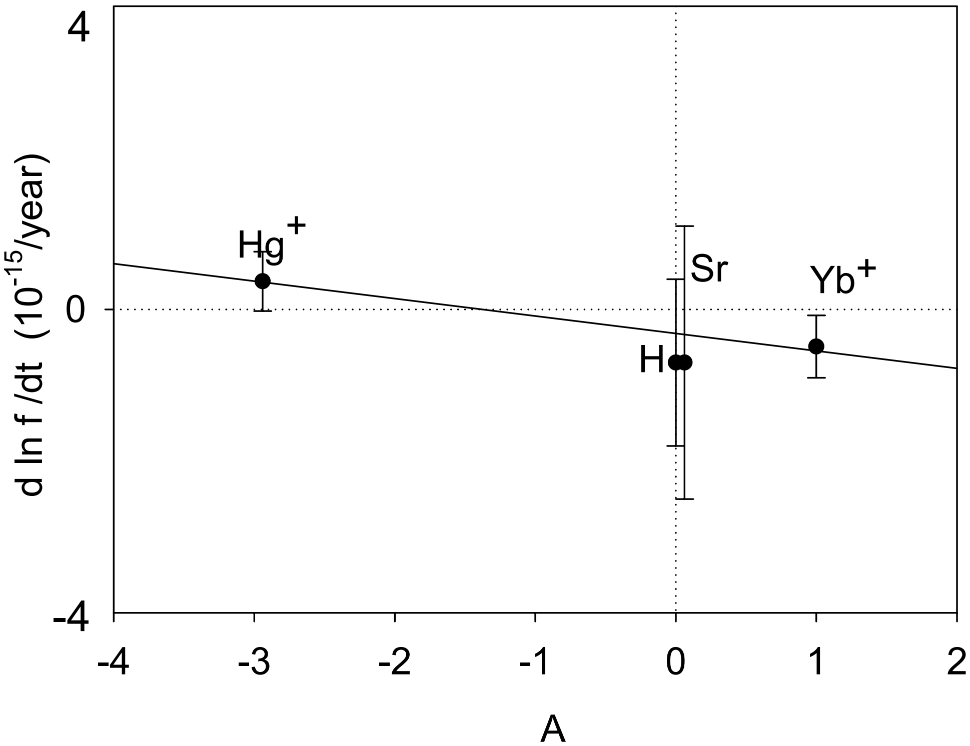



T. Fortier et al., Phys. Rev. Lett. **98**, 070801 (2007)

First analysis of this kind: E. Peik et al., Phys. Rev. Lett. **93**, 170801 (2004)

# Measured frequency drifts (against Cs clocks) versus sensitivity factor A




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

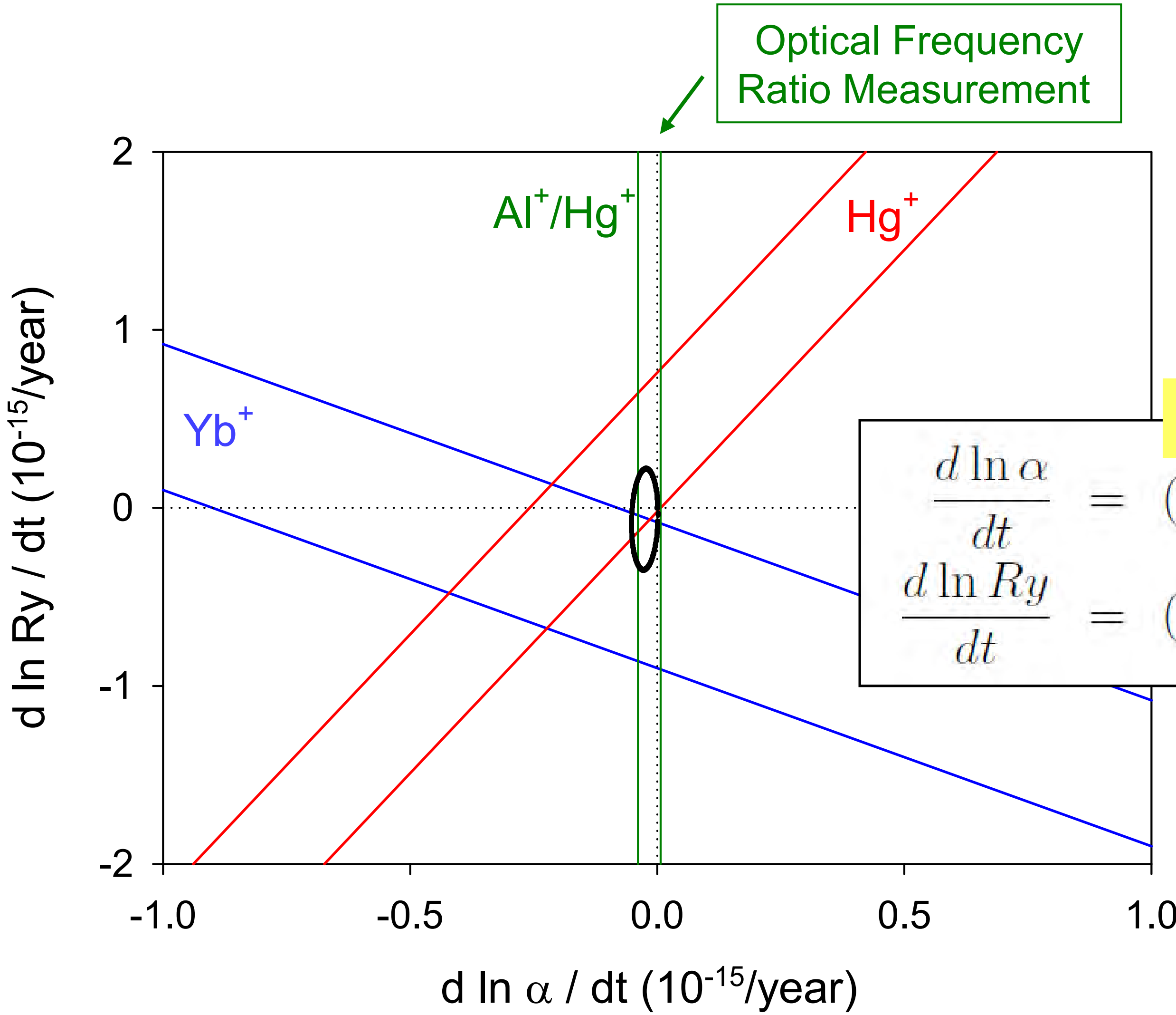
Hg+: NIST
Yb+: PTB
Sr: Boulder, Paris, Tokyo, PRL 100, 140801 (2008)
H: MPQ (ICAP 2010)

From the slope of a weighted linear regression:

d ln $\alpha$ / dt = (-2.3 ± 1.4)×$10^{-16}$ /yr

# Limits for Temporal Variations of Fundamental Constants: Combination of available data from optical clocks (fall 2008)

$Al^+/Hg^+$: T. Rosenband et al., Science **319**, 1808 (2008)
$Hg^+$: T. Fortier et al., Phys. Rev. Lett. **98**, 070801 (2007)
$Yb^+$: Chr. Tamm et al., Phys. Rev. A **80**, 043403 (2009)




combined

$$\frac{d \ln \alpha}{dt} = (-2.5 \pm 2.7) \cdot 10^{-17}\ \mathrm{yr}^{-1}$$

$$\frac{d \ln Ry}{dt} = (-0.6 \pm 2.9) \cdot 10^{-16}\ \mathrm{yr}^{-1}$$

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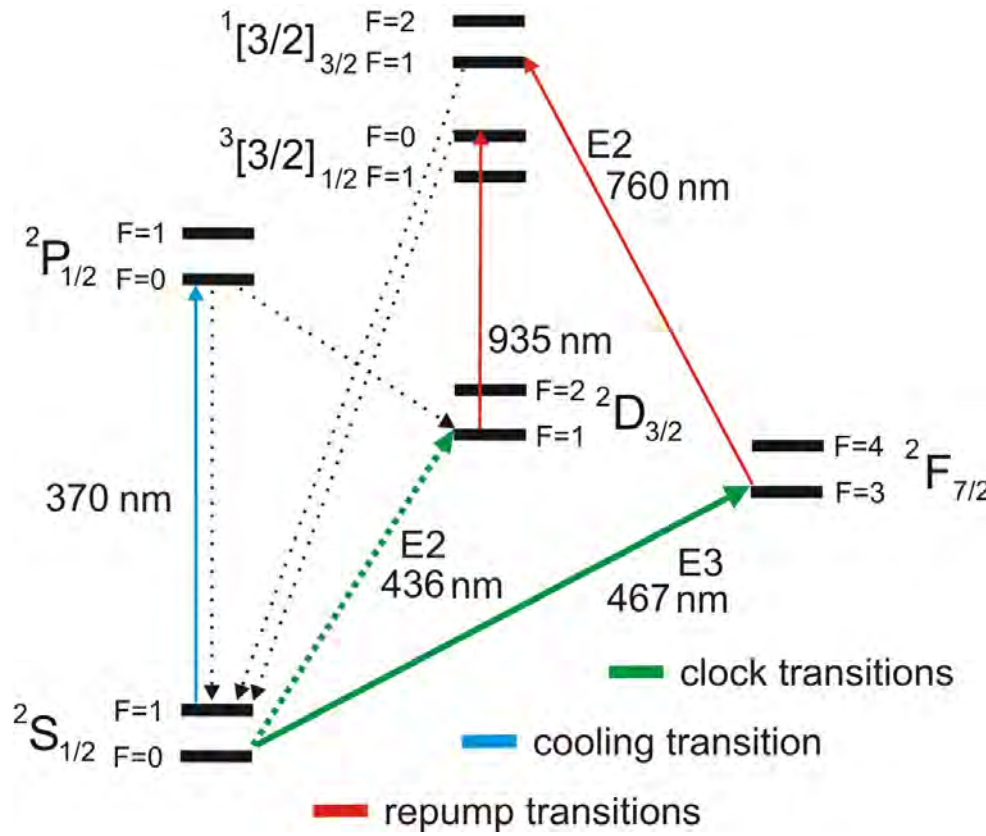
# Clock Transitions in $^{171}Yb^+$

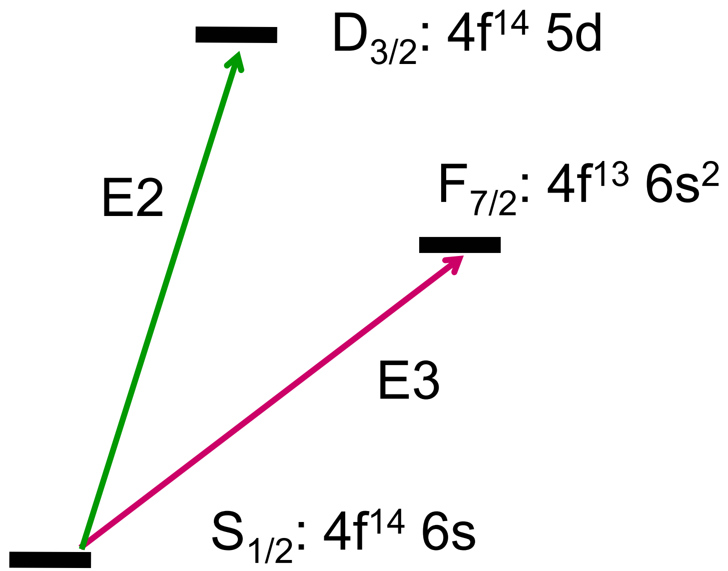
Advantages of $Yb^+$
- all transitions driven by diode lasers
- long storage time (months)
- $^{171}Yb^+$: nuclear spin 1/2




Quadrupole Transition S-D
- secondary representation of the second
- syst. uncertainty ≈ $5\times10^{-16}$ (PTB)
- resolution limited by natural linewidth

Octupole Transition S-F
- Pioneering work at NPL (M. Roberts, PRL 78, 1876 (1997))
- F-state has lower quadrupole moment than D-state
- smaller blackbody shift than E2 transition
- nHz natural linewidth
- large nonresonant light shift from clock laser

Electronic configurations for the two clock transitions in $Yb^+$:




Octupole transition opens the closed 4f shell.

Relativistic contributions to level energies are big and different in D and F state.

E2/E3 frequency ratio has high sensitivity to value of the fine structure constant.

$$Y = \frac{f_{Quad}}{f_{Okt}} \qquad \frac{d \ln Y}{dt} = 7.0 \frac{d \ln \alpha}{dt}$$

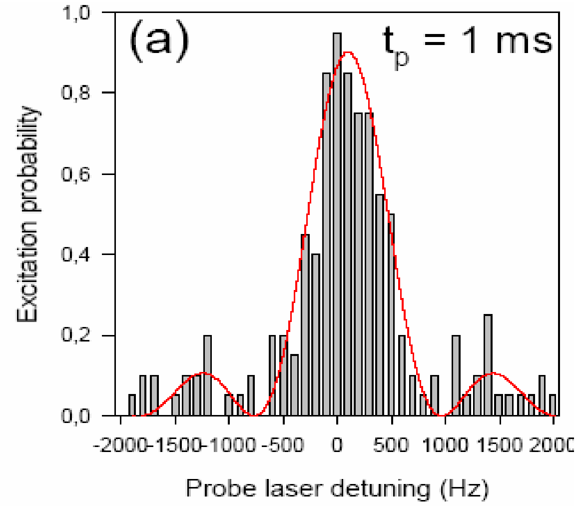
V. V. Flambaum, V. A. Dzuba arXiv:0805.0462
S. N. Lea, Rep. Prog. Phys. **70**, 1473 (2007)

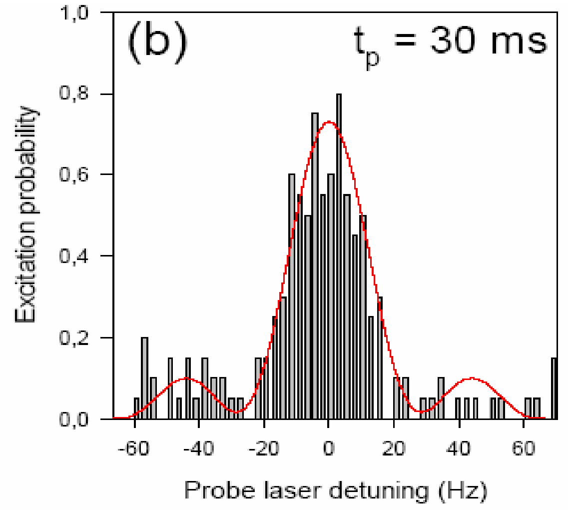
# High resolution spectroscopy of the quadrupole transition at 688 THz

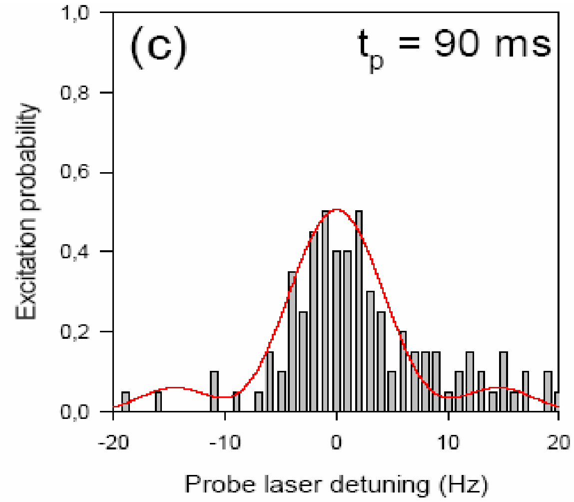
Pi-pulse
$\tau(\text{pulse}) = 1$ ms
1 kHz line width

„standard-operation“
$\tau(\text{pulse}) = 30$ ms
30 Hz line width

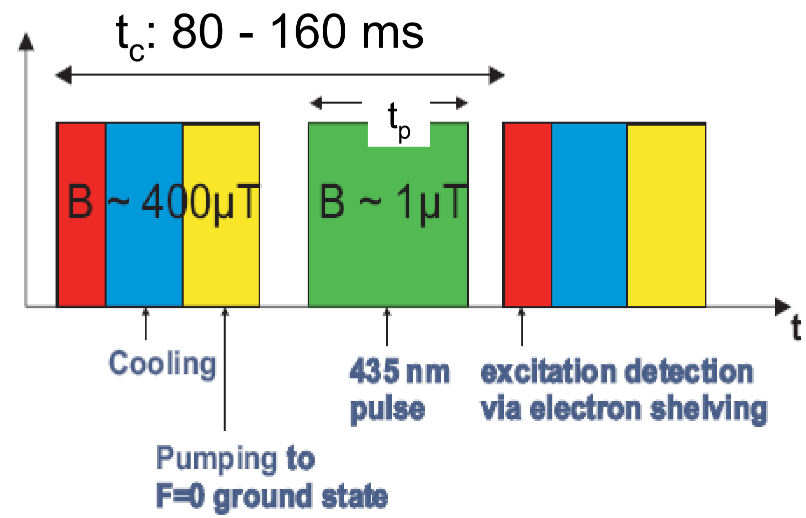
Closer to the resolution limit
$\tau(\text{pulse}) = 90 \text{ ms} \approx 2 \cdot \tau(Yb^+)$
10 Hz line width




Measurement cycle:



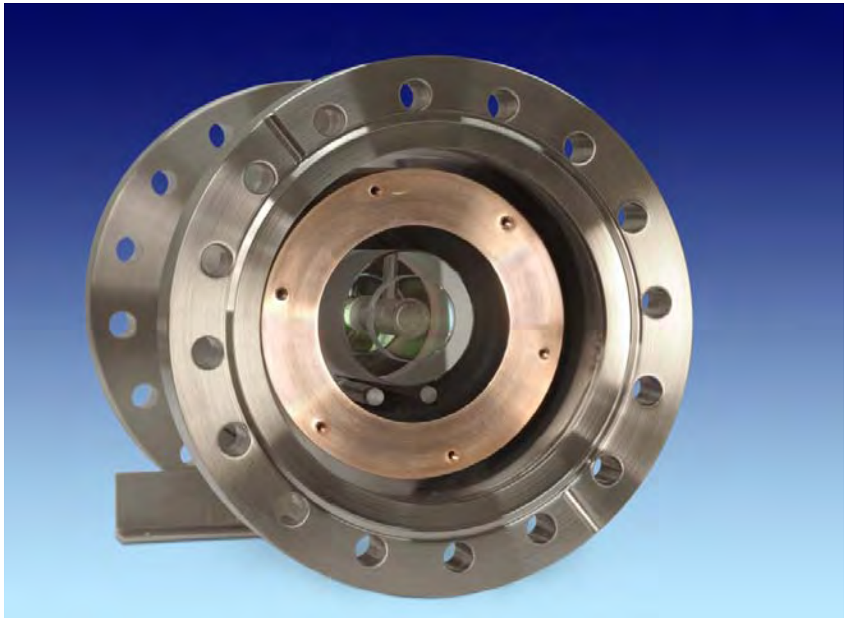
# Frequency-stable laser for 467 nm

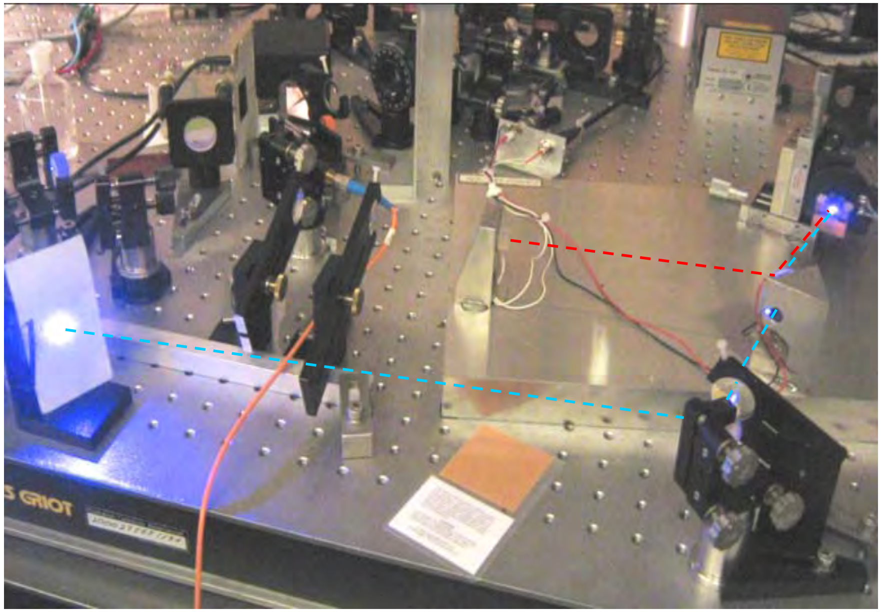
Laser excitation of the octupole transition:

- Resolution only limited by laser linewidth
- 10 ms $\pi$–pulse requires ≈ 1 kW/cm$^2$
- strong nonresonant light shift: Intensity has to be stable

Our approach:
934 nm master extended cavity diode laser, stabilized to a ULE cavity,
SHG in a semimonolithic cavity, 467 nm slave laser diode

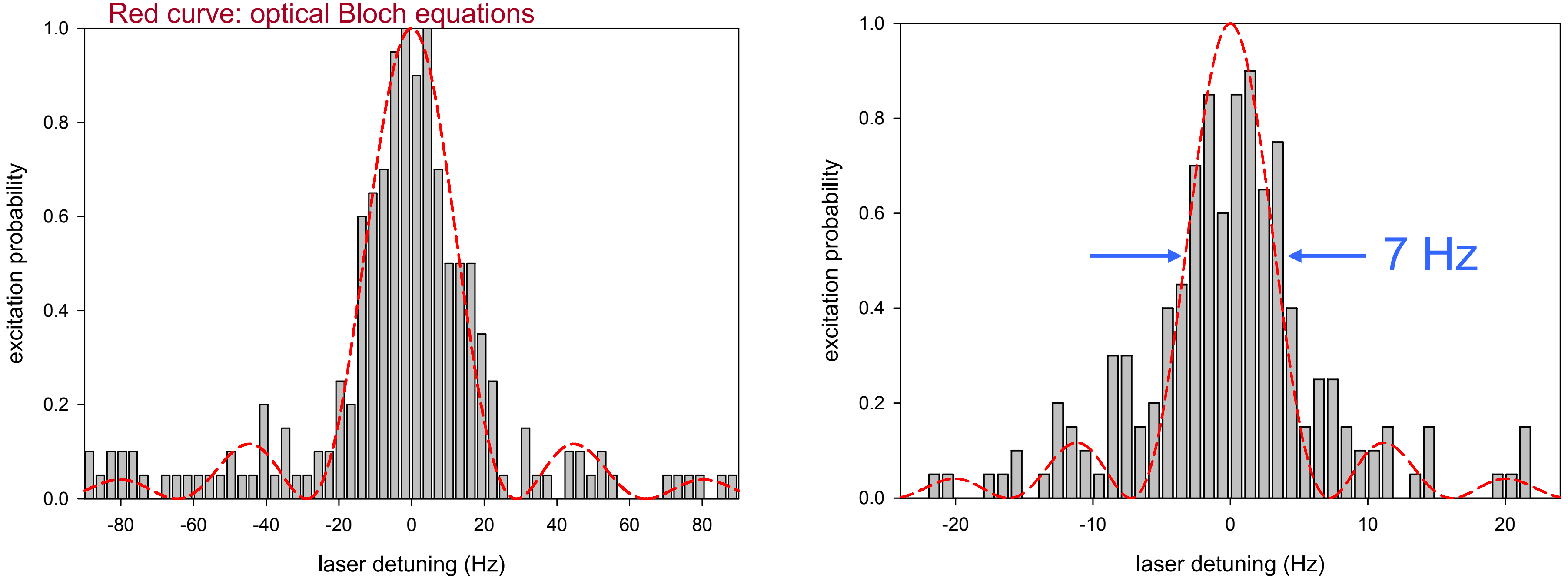
ULE resonator with thermal shield





# Spectroscopy of the $Yb^+$ S → F electric octupole transition

Grey: experiment, 20 cycles per frequency step
Red curve: optical Bloch equations




pulse duration: 30 ms

pulse duration: 120 ms
laser power: 0.5 mW

First results:
I. Sherstov, M. Okhapkin, B. Lipphardt, Chr. Tamm, E. Peik,
Phys. Rev. A **81**, 021805(R) (2010)
Improved results shown here:
N. Huntemann et al.

# Main contributions to the $Yb^+$ uncertainty budget (quadrupole, 688 THz)

Chr. Tamm, S. Weyers, B. Lipphardt, E. Peik, Phys. Rev. A **80**, 043403 (2009)

| effect | $Yb^+$ now | $Yb^+$ achievable |
|---|---|---|
| quadratic Zeeman shift | $0.07 \cdot 10^{-15}$ | $0.01 \cdot 10^{-15}$ |
| quadrupole shift & tensor Stark-shift | $0.3 \cdot 10^{-15}$ | $0.01 \cdot 10^{-15}$ |
| scalar Stark shifts (blackbody, laser) | $0.3 \cdot 10^{-15}$ | $0.02 \cdot 10^{-15}$ |
| servo error | $0.15 \cdot 10^{-15}$ | $0.01 \cdot 10^{-15}$ |

The octupole transition requires additional attention to the light shift.

$Yb^+$ should provide two optical frequency references with $\approx 10^{-17}$ uncertainty

I. Sherstov, M. Okhapkin, B. Lipphardt, Chr. Tamm, E. Peik,
Phys. Rev. A **81**, 021805(R) (2010)

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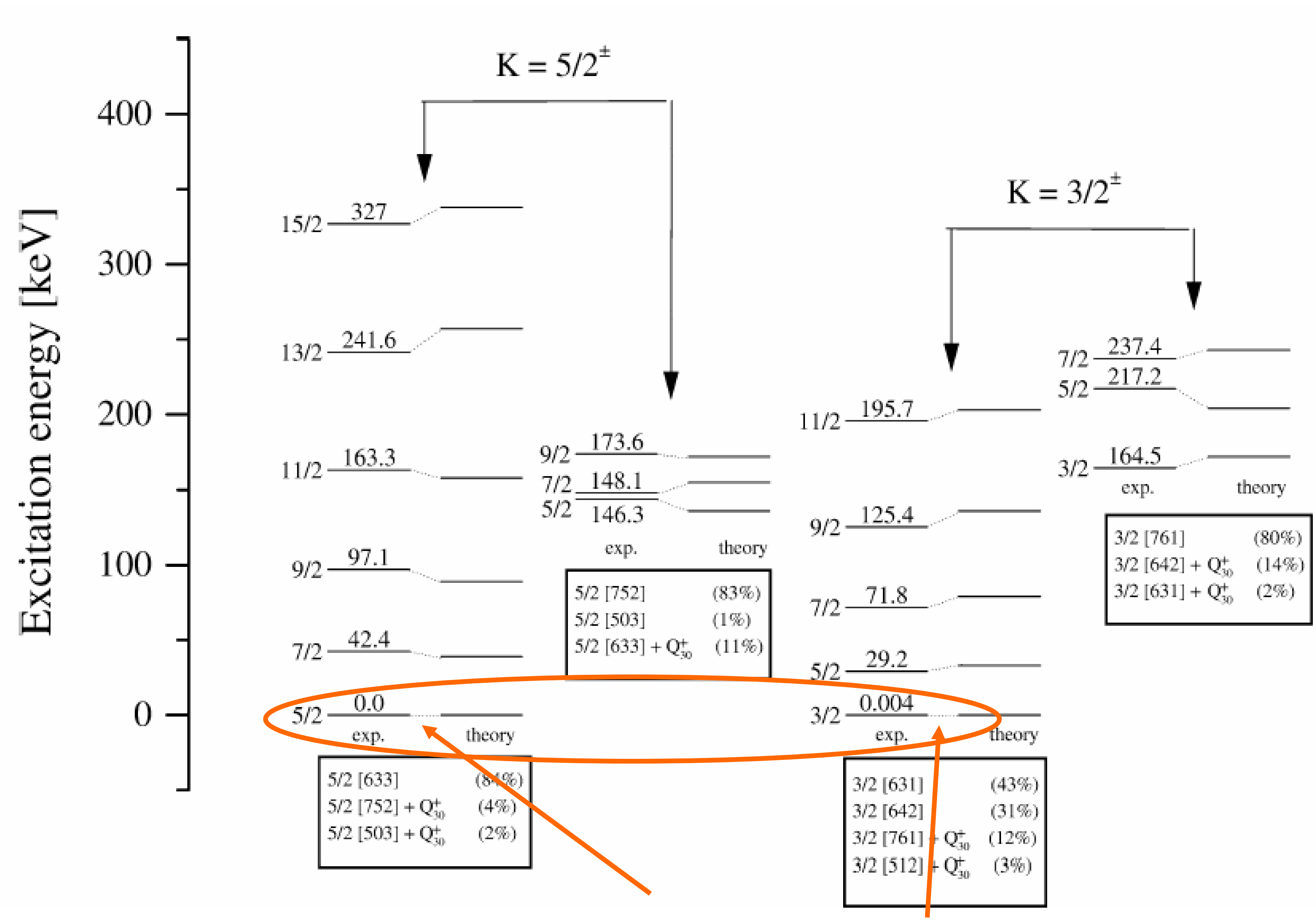
# The nuclear structure of $^{229}$Th




Two close-lying band-heads: ground state and isomer

# A single-ion high precision nuclear clock

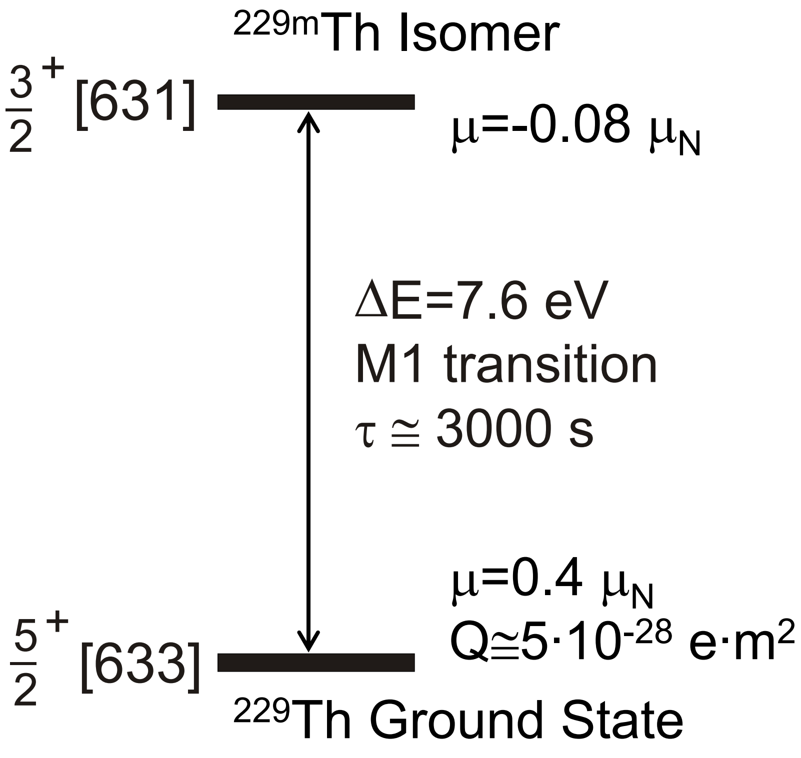
Nuclear moments are small.
Field induced systematic frequency shifts can be smaller than in an (electronic) atomic clock.

Consider hyperfine coupling, shielding and anti-shielding.
Select suitable electronic state for the nuclear excitation.

Analyzed for the $Th^{3+}$ system in:

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

Chr. Tamm, T. Schneider, E. Peik,
Lect. Notes Phys. **648**, 247 (2004)



# Th-229: the most sensitive probe in a search for variations of the fundamental coupling constants

Scaling of the $^{229}$Th transition frequency $\omega$ in terms of $\alpha$ 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 $X_q = m_q/\Lambda_{\rm QCD}$ and $X_s = m_s/\Lambda_{\rm QCD}$

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

**But: it depends a lot on nuclear structure!**

>10 theory papers 2006-2009

See for example:

A. C. Hayes, J. L. Friar, P. Möller, Phys. Rev. C **78**, 024311 (2008) ($|A|<\approx 10^3$)

E. Litvinova et al., Phys. Rev. C **79**, 064303 (2009) ($|A|<\approx 4\times10^4$)

Solution: Use measurements of isomer shifts and atomic structure calculations

J. C. Berengut, V. A. Dzuba, V. V. Flambaum, S. G. Porsev, PRL **102**, 210808 (2009)

Possible experimental realisations:

- 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.

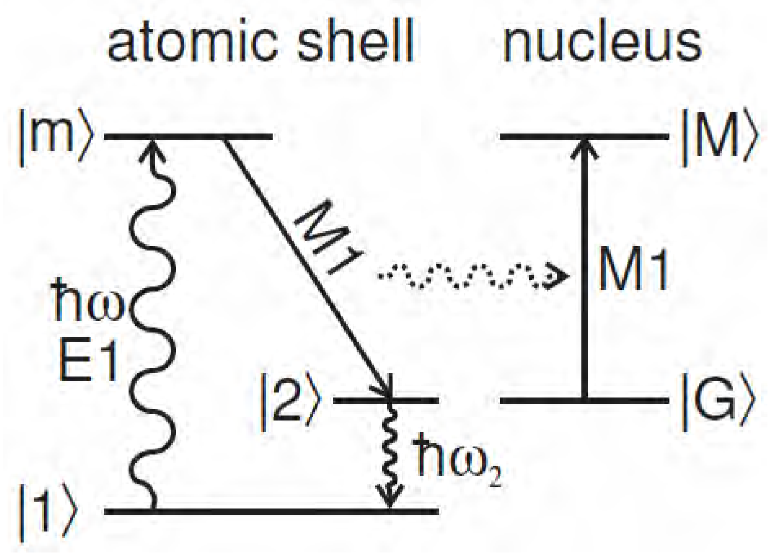
# Our „search“ strategy: Nuclear excitation via an „electron bridge“

- NEET (Nuclear Excitation by Electron Transition): Transfer of excitation from the electron shell to the nucleus

- Excitation of the shell in a 2-photon process, no tunable laser at ≈ 160 nm required

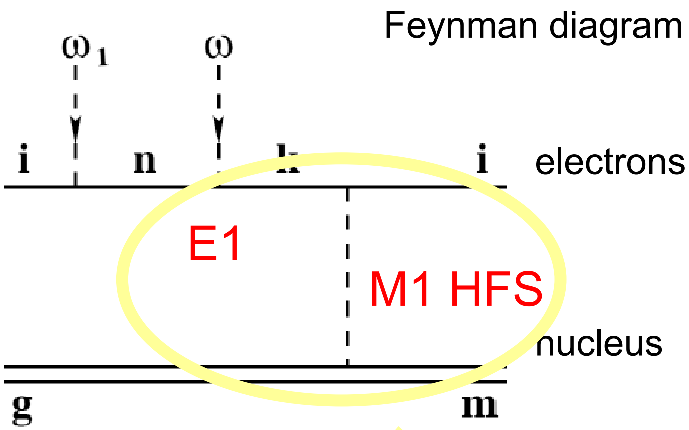
- Excitation rate may be strongly enhanced at resonance between electronic and nuclear transition frequency

- Detection of the nuclear excitation via fluorescence of change in hyperfine structure



# Two-photon electron bridge excitation rate

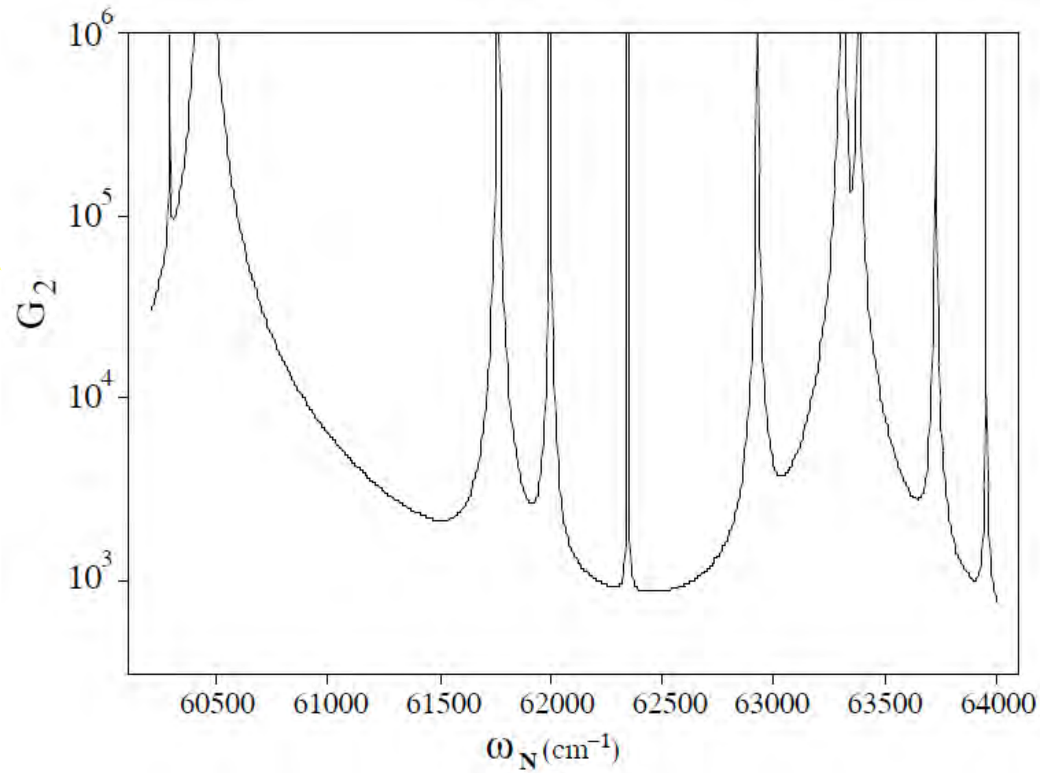
S. G. Porsev, V. V. Flambaum, E. Peik, Chr. Tamm, arXiv:1006.3324




$\omega_1$: resonance line at 402 nm

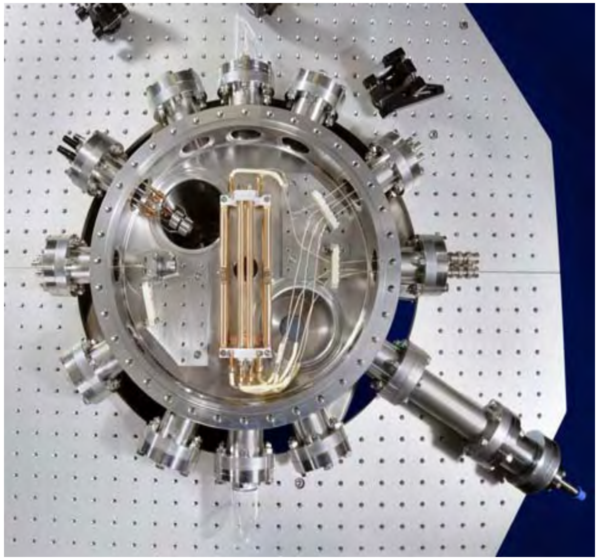
$\omega$: tunable laser to search for nuclear resonance

Excitation rate as a function of nuclear resonance frequency (electronic levels from ab-initio calculations

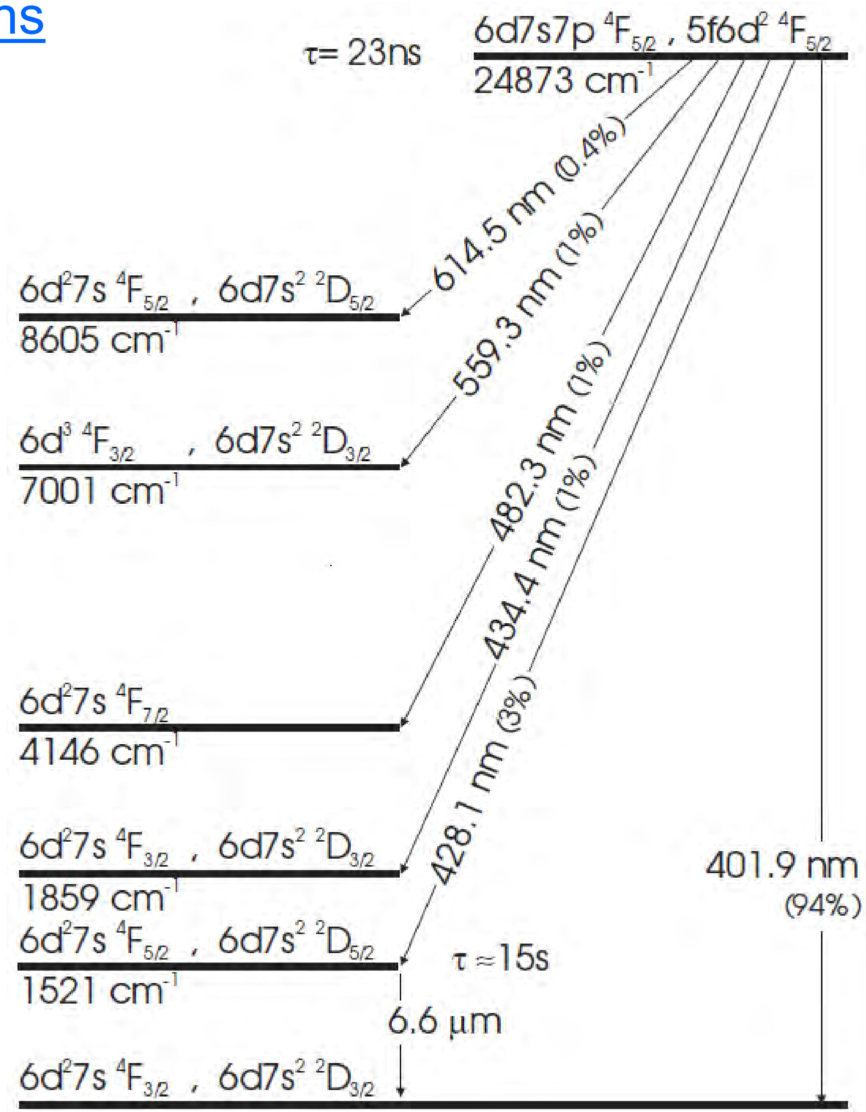



→ excitation rate of at least $10\ s^{-1}$ with conventional laser parameters

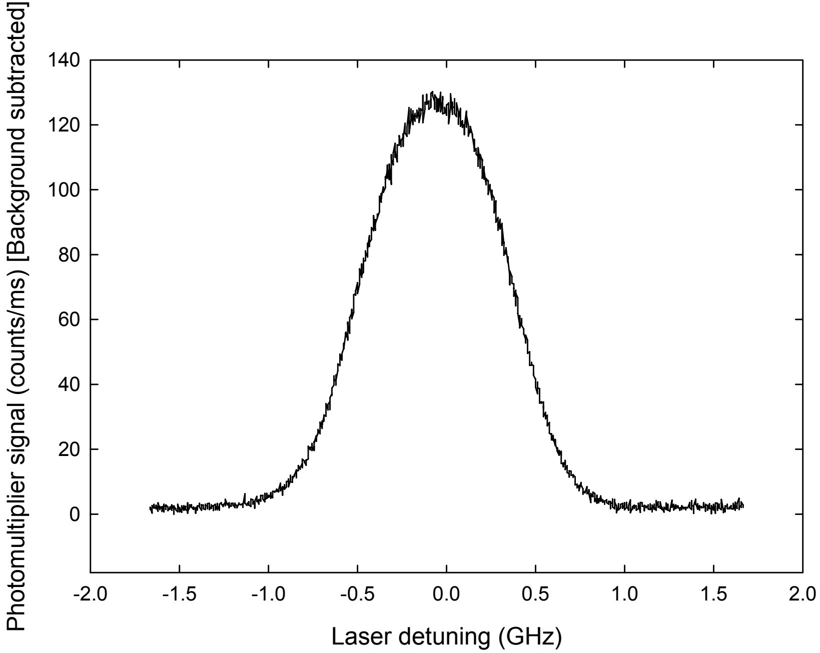
# Laser spectroscopy of trapped $Th^+$ ions



UHV chamber with linear Paul trap

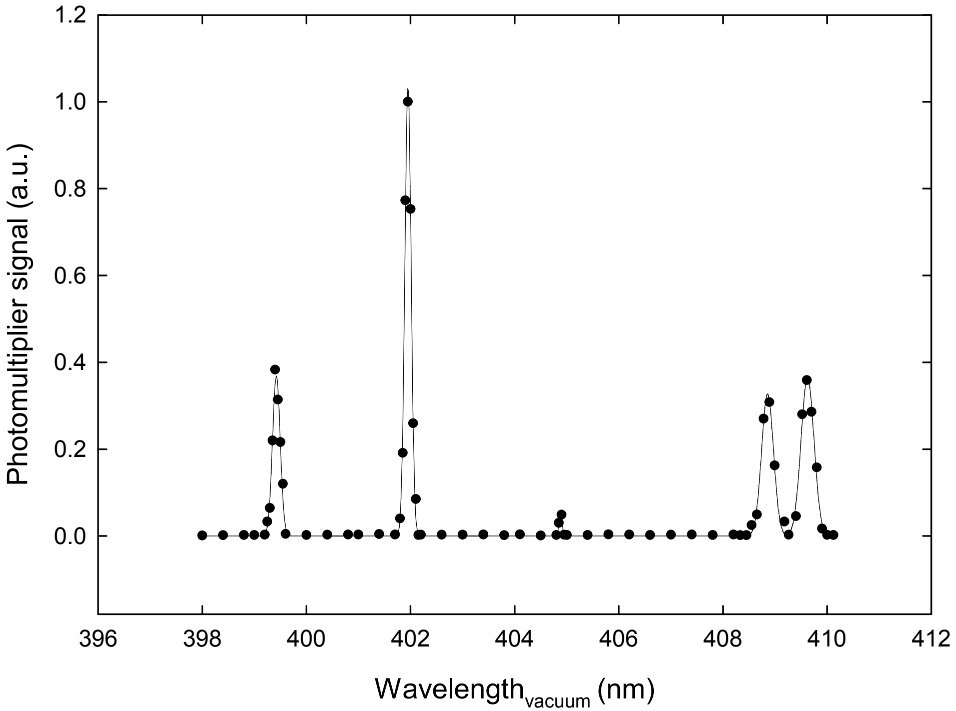



$Th^+$ resonance line at 402 nm has most favorable branching to the ground state.
Collisional quenching of metastables with buffer gas.




Excitation spectrum of a $^{232}Th^{+}$ ion cloud (≈$10^5$ ions) with an ECDL at 402 nm (0.05 mW)

Excitation spectrum with the second harmonic of a ps-Ti:Sa laser.



# Conclusion and Outlook

- Development of high precision optical clocks allow sensitive tests of fundamental physics

- Limit on $d\ln\alpha/dt$ from optical clocks now at a few $10^{-17}$/ yr (NIST, $Al^+/Hg^+$) and improving

- $Yb^+$: sensitive system for optical frequency ratio measurement of two forbidden transitions, should also provide $10^{-17}$/ yr

- Measurements on several transitions will be required to interpret and verify a positive detection $d\ln\alpha/dt \neq 0$

- Nuclear laser spectroscopy of $^{229}Th$ ions promises to provide the most sensitive probe for variations ($10^{-20}$/ yr ?) and may open a new field of research between atomic and nuclear physics

## Acknowledgements


Chr. Tamm
M. Okhapkin
B. Lipphardt
S. Weyers

I. Sherstov
N. Huntemann Yb+ octupole

K. Zimmermann
O. A. Herrera Sancho Th+ nuclear spectroscopy

S. Karshenboim, VNIIM and MPQ Theory
S. G. Porsev, St. Petersburg and UNSW
V. V. Flambaum, UNSW

Funding:
DFG
FQXi
QUEST
DAAD
TEC


**Conference Announcement: WE-Heraeus Seminar „Astrophysics, Clocks and Fundamental Constants“, ACFC 2011**
**18. – 21. July 2011, Bad Honnef, Germany**
organized by Savely Karshenboim, Michael Kramer and E.P.