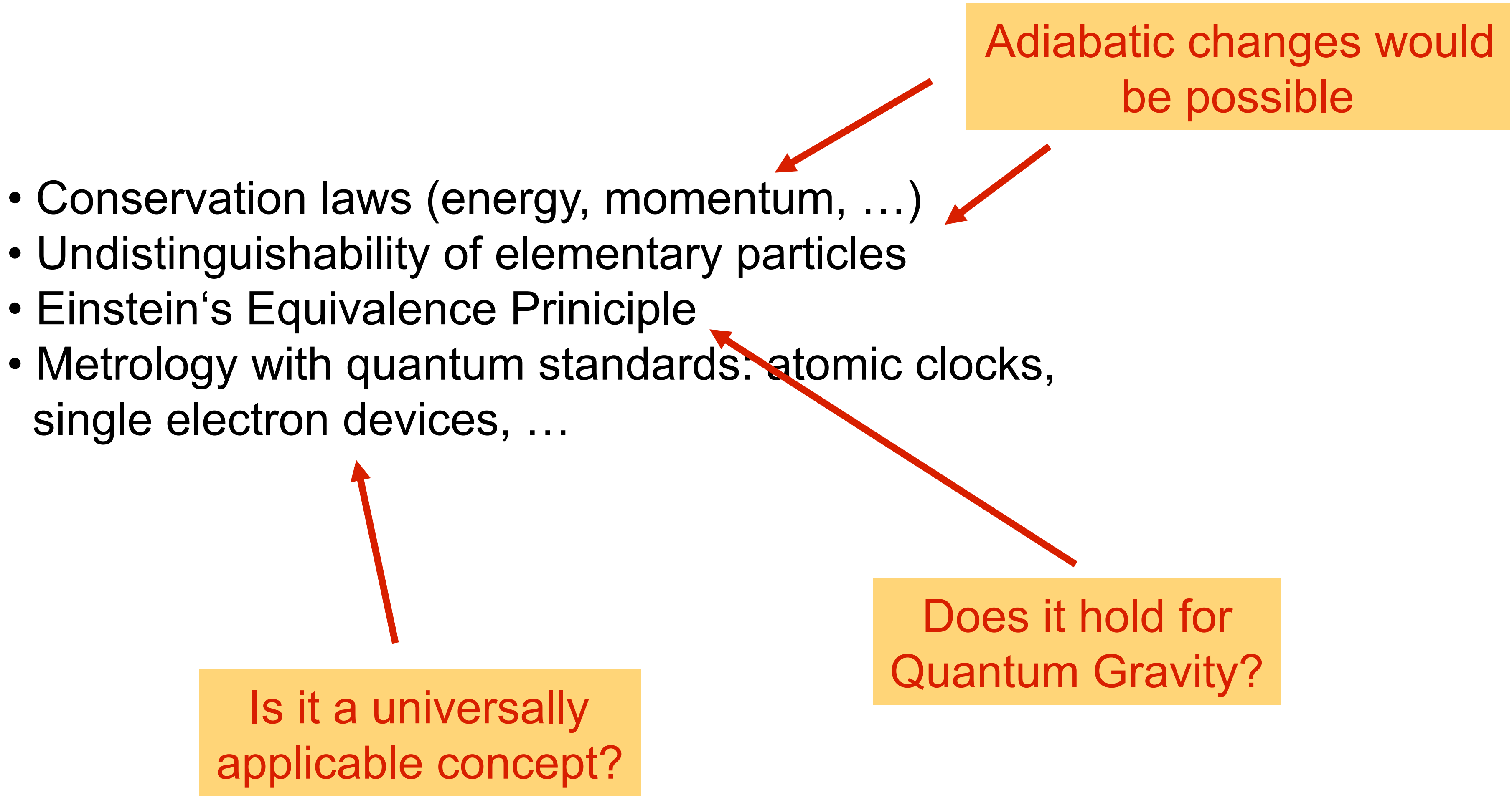
Laboratory Tests on Variations of Fundamental Constants

Ekkehard Peik

Physikalisch-Technische Bundesanstalt
Time and Frequency Department
Braunschweig, Germany

Fundamental Constants are ***constant*** ?



Adiabatic changes would be possible

- Conservation laws (energy, momentum, …)
- Undistinguishability of elementary particles
- Einstein‘s Equivalence Priniciple
- Metrology with quantum standards: atomic clocks, single electron devices, …

Does it hold for Quantum Gravity?

Is it a universally applicable concept?

Importance of dimensionless numbers

If variations in a dimensional quantity (c, ħ, etc.) would be detected, there is no clear way to distinguish between a change of the quantity and a change of the unit (or meter).

The SI system has fixed certain quantities by definition:

speed of light:	$c=299\,792\,458$ m/s
Cs hyperfine frequency:	$f_{Cs}=9\,192\,631\,770$ Hz

Most important test cases in a search for variations:

Sommerfeld's fine structure constant $\alpha=1/137.035999679(94)$
(electromagnetic force; relativistic contributions to atomic and molecular energies)

Mass ratio of proton and electron $\mu=1836.15267247(80)$
(sensitive to quark masses, strong force)

Problem in devising a test:

Isolate variability of one fundamental constant
if we have to expect all of them to vary.

Scaling of transition frequencies with fundamental constants

Transition		Energy scaling	Refs.	
Atomic	Gross structure	Ry		H spectroscopy
	Fine structure	α^2Ry	[24]	M. Savedoff, 1956
	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]	R. Thompson, 1975
	Rotational structure	(m_e/m_p)Ry	[25]	
Relativistic corrections		Function of α^2	[22,23]	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)

Laboratory experiments on variations of fundamental constants

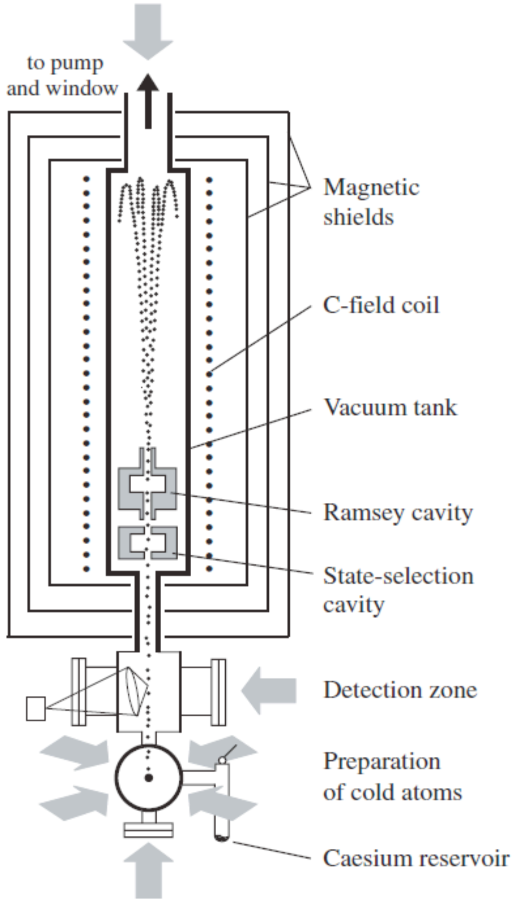
- spectral reference data for astrophysical observations

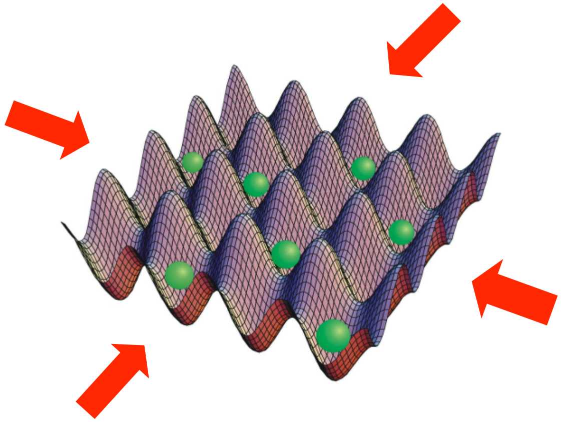
- tests on short timescales (years) ***with high-precision***: atomic clocks
  - Hyperfine structure (microwave clocks)
  - electronic structure (optical clocks)

- tests on selected systems ***with high sensitivity***:

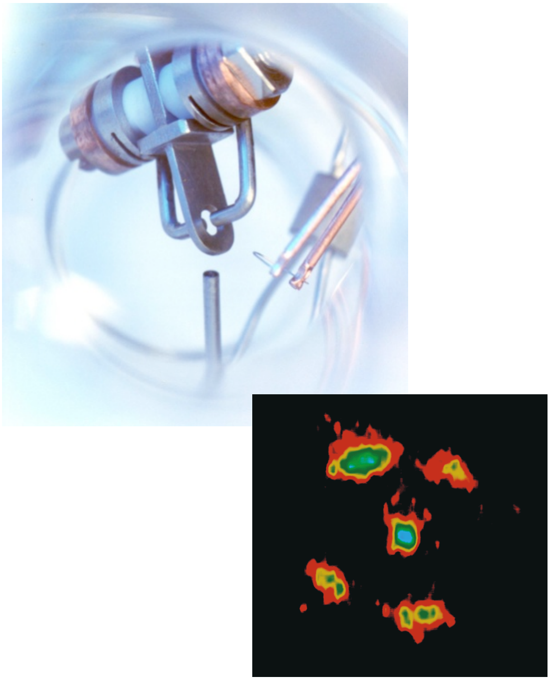
  accidental degeneracies:
  - electronic states in Dy
  - in molecular structure (electronic, vibration, rotation), tunneling transitions
  - nuclear levels (Th-229)

Atomic Clocks with laser-cooled atoms and ions





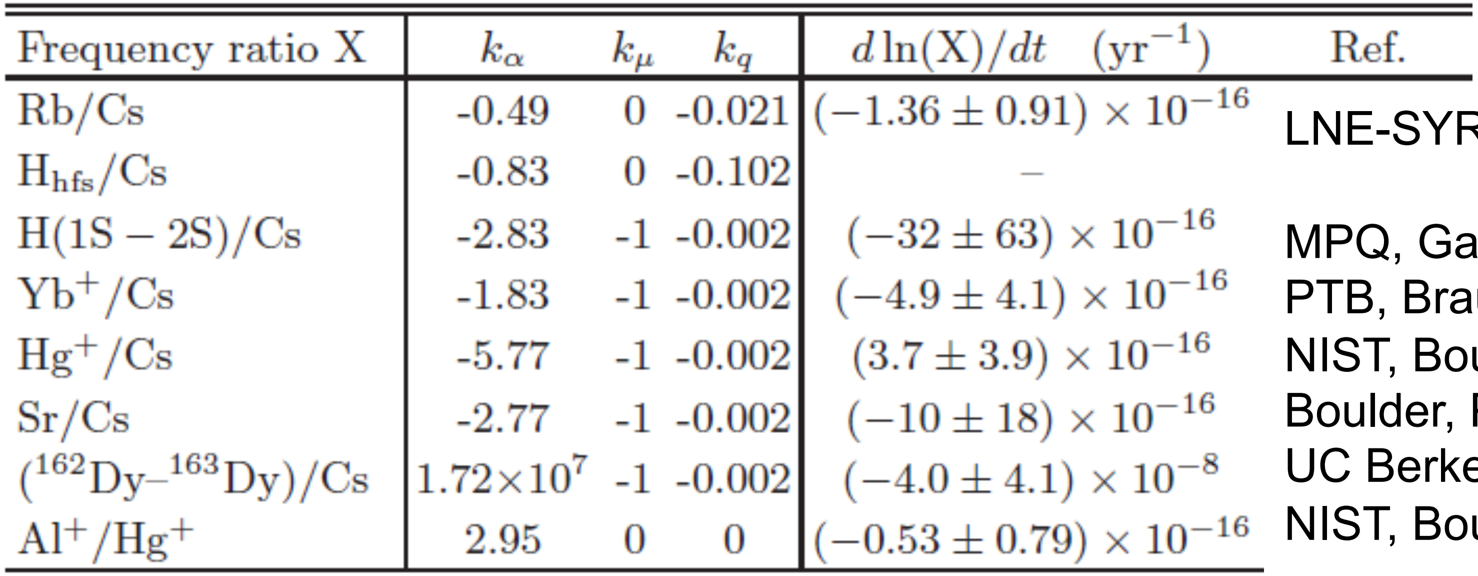
Optical lattice clocks:
Neutral atoms in an optical trap
at the „magic“ wavelength,
Best systematic uncertainty: low 10^{-17}



Atomic Fountain:
Primary caesium clock,
realization of the SI second,
Best systematic uncertainty: low 10^{-16}

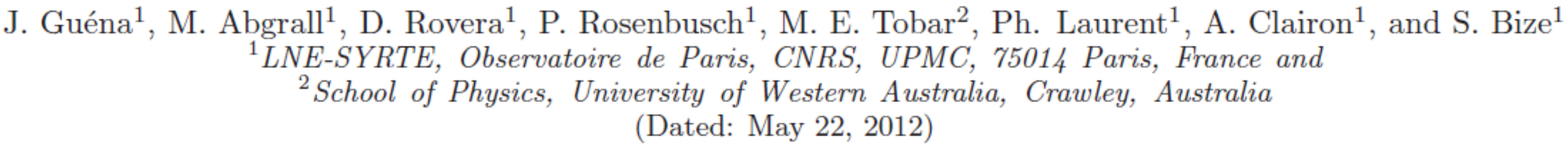
Single trapped ion:
Quantum limited control and very
small perturbations,
Best systematic uncertainty: upper 10^{-18}

Laboratory limits on variations of atomic frequency ratios



Frequency ratio X	k_α	k_μ	k_q	$d\ln(X)/dt$ (yr^{-1})	Ref.
Rb/Cs	-0.49	0	-0.021	$(-1.36 \pm 0.91) \times 10^{-16}$	LNE-SYRTE, Paris
H_{hfs}/Cs	-0.83	0	-0.102	–	
H(1S – 2S)/Cs	-2.83	-1	-0.002	$(-32 \pm 63) \times 10^{-16}$	MPQ, Garching
Yb^+/Cs	-1.83	-1	-0.002	$(-4.9 \pm 4.1) \times 10^{-16}$	PTB, Braunschweig
Hg^+/Cs	-5.77	-1	-0.002	$(3.7 \pm 3.9) \times 10^{-16}$	NIST, Boulder
Sr/Cs	-2.77	-1	-0.002	$(-10 \pm 18) \times 10^{-16}$	Boulder, Paris, Tokyo
$(^{162}\text{Dy}-^{163}\text{Dy})$/Cs	1.72×10^7	-1	-0.002	$(-4.0 \pm 4.1) \times 10^{-8}$	UC Berkeley
Al^+/Hg^+	2.95	0	0	$(-0.53 \pm 0.79) \times 10^{-16}$	NIST, Boulder

Sensitivities to α, μ and m_q/Λ_{QCD}



J. Guéna[1], M. Abgrall[1], D. Rovera[1], P. Rosenbusch[1], M. E. Tobar[2], Ph. Laurent[1], A. Clairon[1], and S. Bize[1]
[1] *LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 75014 Paris, France and*
[2] *School of Physics, University of Western Australia, Crawley, Australia*
(Dated: May 22, 2012)

arXiv 1205:4235

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

S. G. Karshenboim
physics/0311080

common-mode shift

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

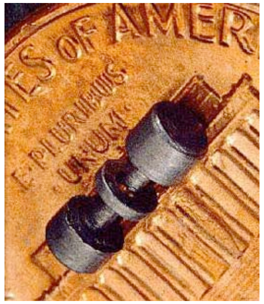
transition-specific shift

Simple parametrization
(no model for caesium 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.

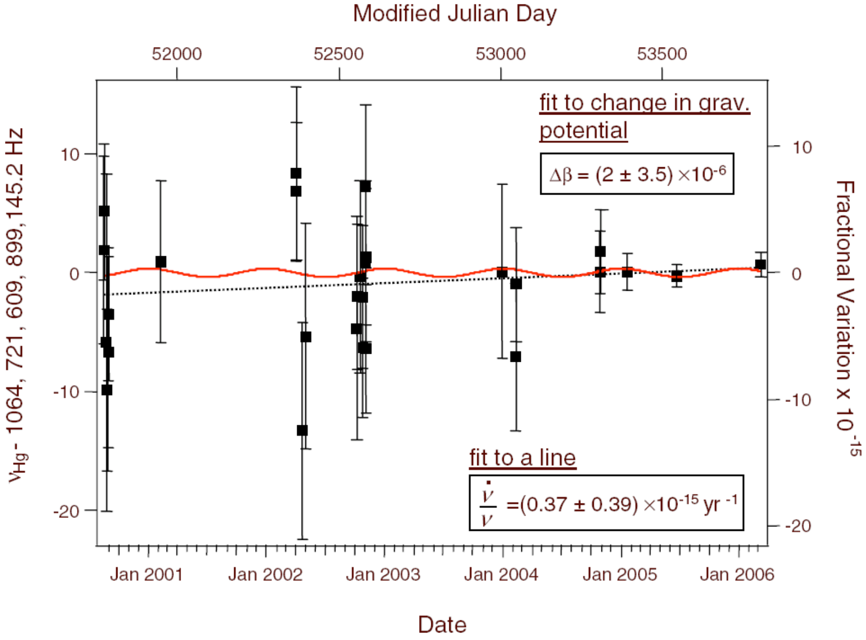
Remote comparison of single-ion clocks NIST-PTB, 2000-2008

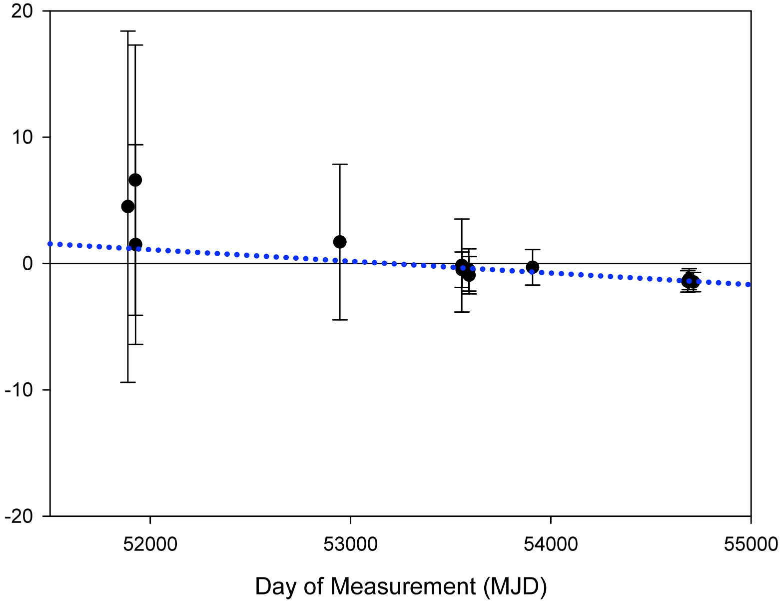


$^{199}Hg^{+}$, S - D at 1064 THz
(NIST Boulder)

A(Yb)= 1.00
A(Hg)=−3.19

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

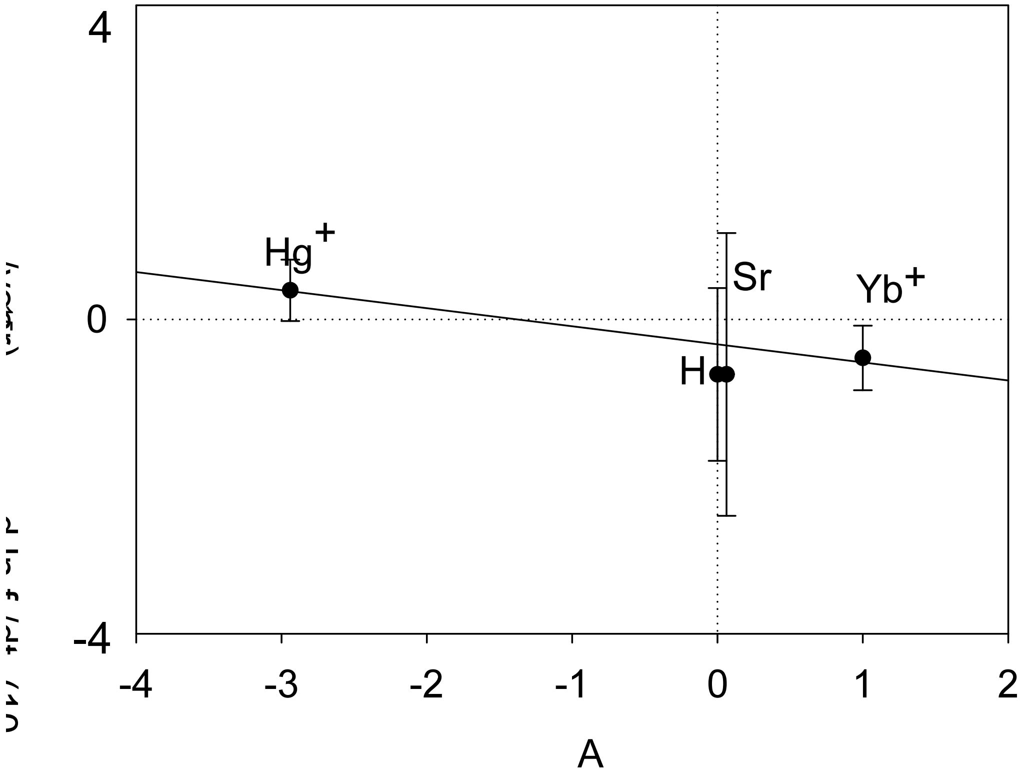




T. Fortier et al., Phys. Rev. Lett. **98**, 070801 (2007)

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



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

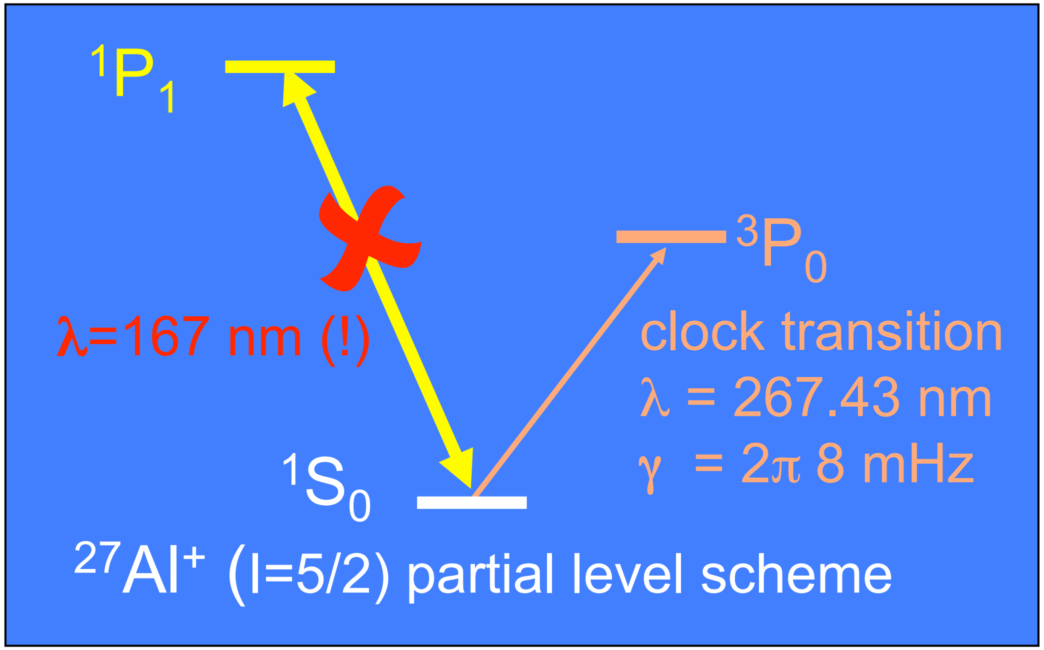
Hg+: NIST
Yb+: PTB
Sr: Boulder, Paris, Tokyo, PRL 100, 140801 (2008)
H: MPQ (ICAP 2010)

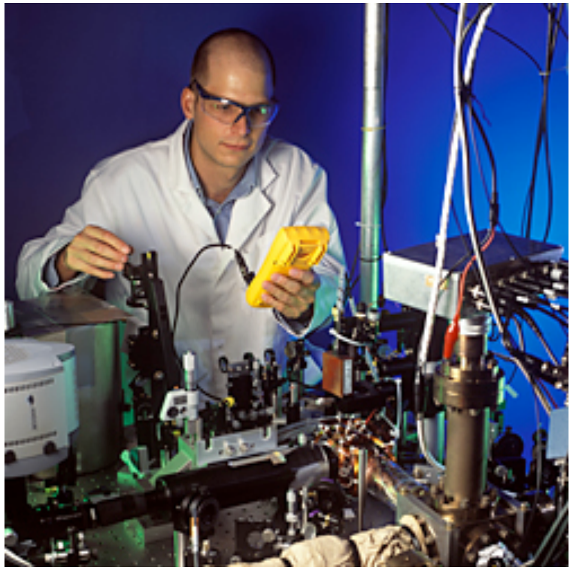
From the slope of a weighted linear regression:

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

The Al^+ clock (NIST, Boulder)

- $J=0\rightarrow 0$ transition with small systematic shifts
- Sympathetic laser cooling via Be^+ or Mg^+
- Quantum logic for state readout
- „Anchor“ transition with $A\approx 0$



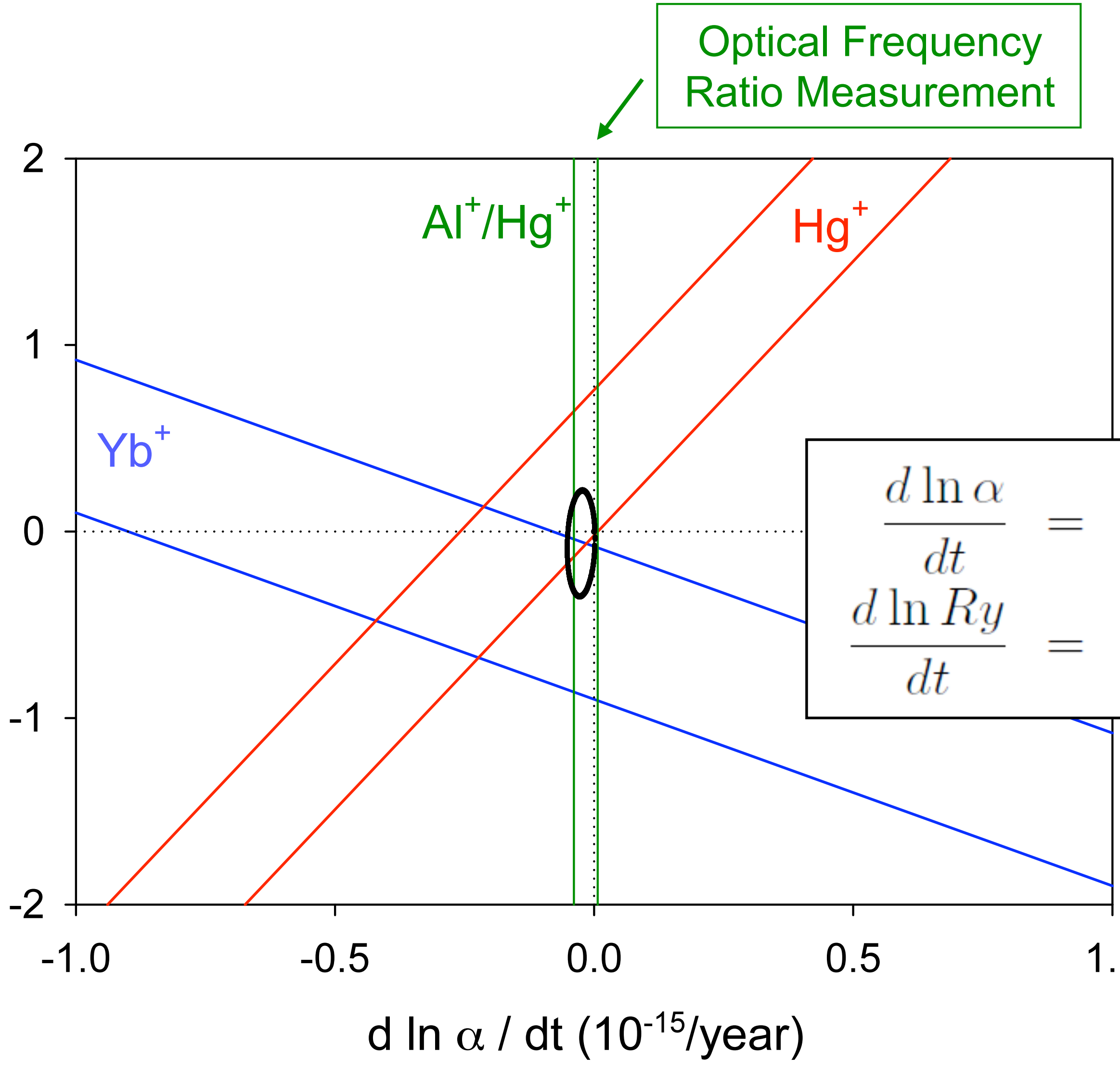


T. Rosenband, NIST

Proposed by D. Wineland in 2001
P.O. Schmidt *et al.*, *Science*, **309**, 749 (2005)
T. Rosenband *et al.*, Science **319**, 1808 (2008)

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

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

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

Limits for Temporal Variations of the proton-electron mass ratio

From a rovibrational transition in SF_6 relative to Cs:

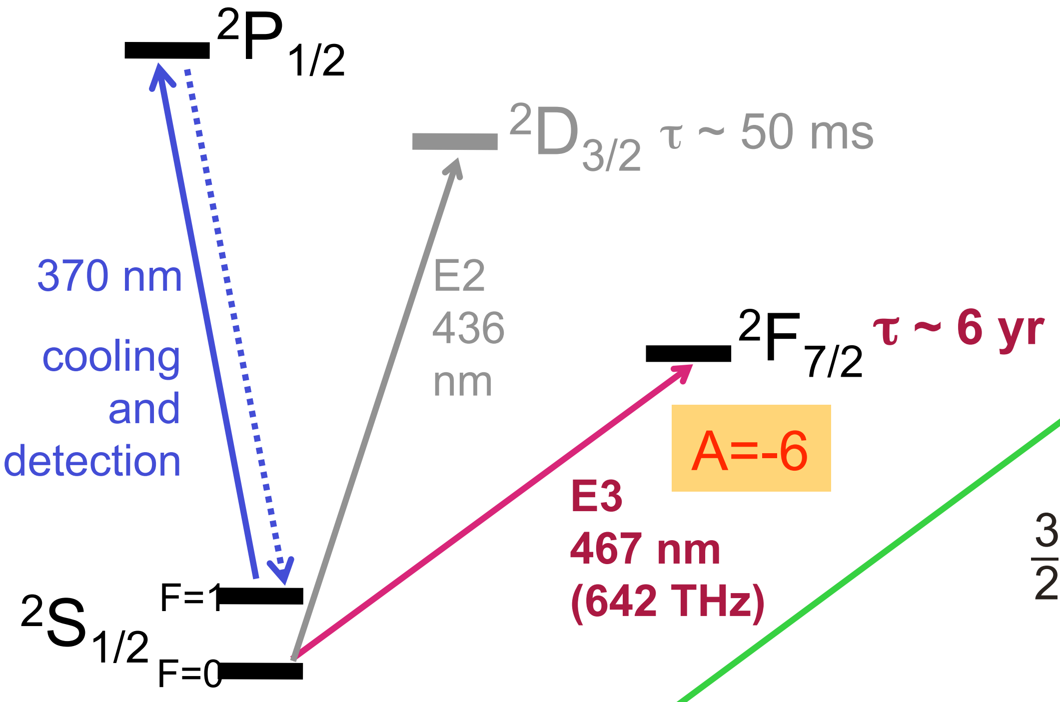
$d \ln \mu / dt = (-3.8 \pm 5.6)\times10^{-14}$ /yr LPL Paris

From the combination of atomic optical and HFS measurements:

$d \ln \mu / dt = (1.5 \pm 3.0)\times10^{-16}$ /yr Paris, arXiv 1205:4235

Further prospects for $d\alpha/dt$ measurements: Transitions with high sensitivity

Yb^+ electric octupole transition



$^2P_{1/2}$

$^2D_{3/2}$ $\tau \sim 50$ ms

$^2F_{7/2}$ **$\tau \sim 6$ yr**

$^2S_{1/2}$ F=1 F=0

370 nm

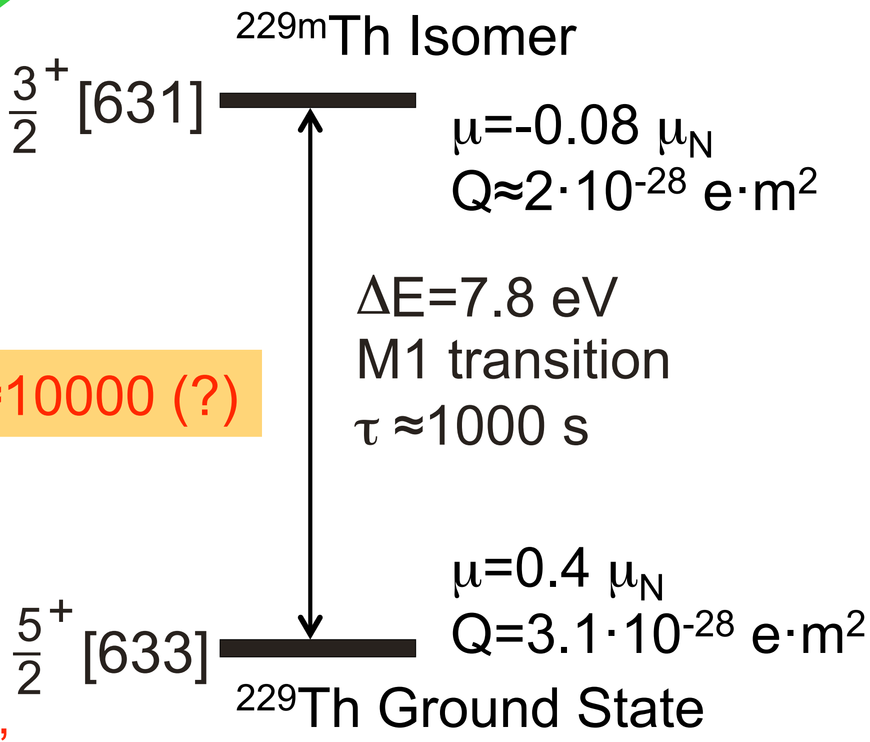
cooling and detection

E2 436 nm

E3 467 nm (642 THz)

A=-6

Thorium-229 nuclear transition



$^{229m}\mathrm{Th}$ Isomer

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

$\mu=-0.08\ \mu_N$

$Q \approx 2 \cdot 10^{-28}\ e \cdot m^2$

$\Delta E = 7.8$ eV

M1 transition

$\tau \approx 1000$ s

A≈10000 (?)

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

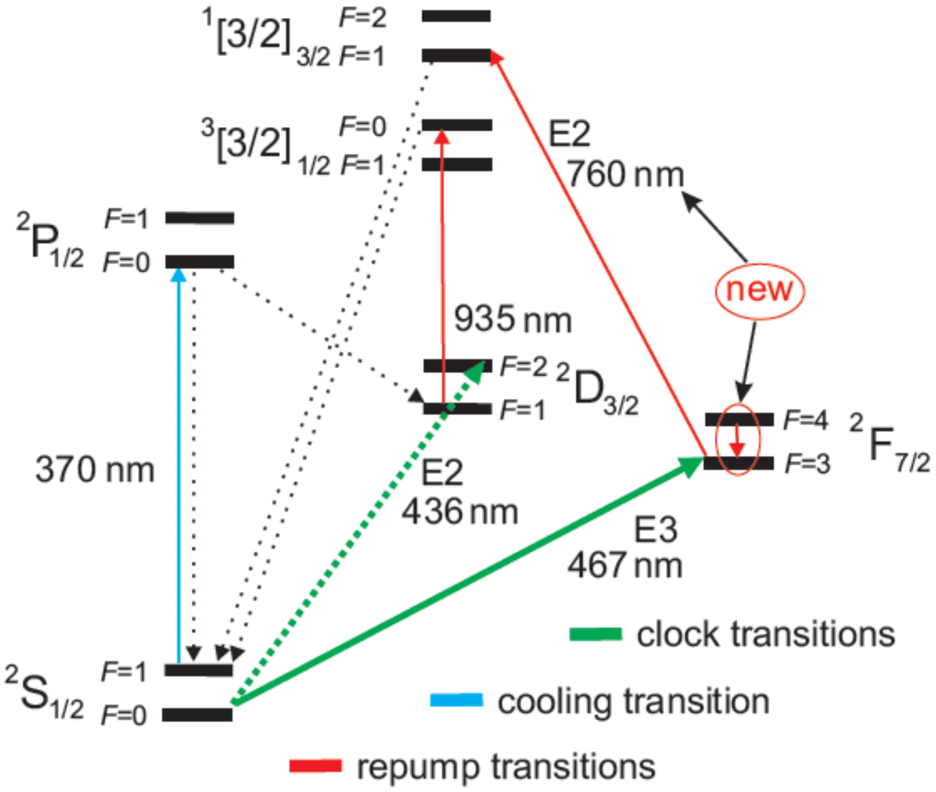
$\mu=0.4\ \mu_N$

$Q=3.1 \cdot 10^{-28}\ e \cdot m^2$

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

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

Two Clock Transitions in ^{171}Yb^{+}



Advantages of ^{171}Yb^{+}

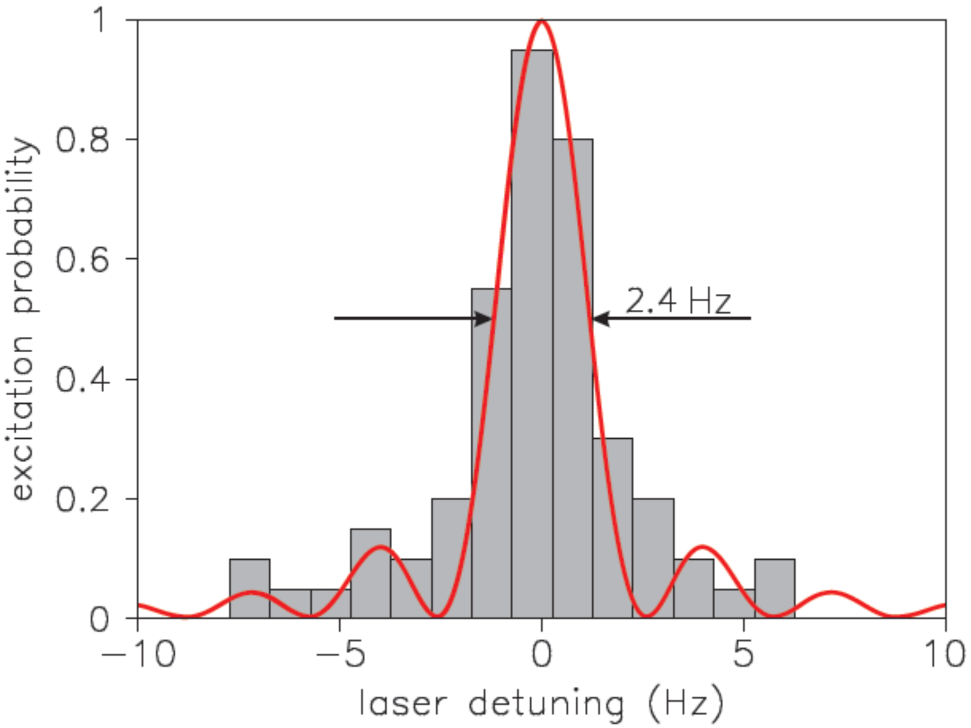
- All transitions driven by diode lasers
- permits long storage times
- two *clock*-transitions with high sensitivity to $\dot{\alpha}$

Octupole (E3) vs. Quadrupole (E2)

- Lower sensitivity to magnetic and electric fields
- Narrow line-width in the nHz-range $\Rightarrow$ very high stability
- Huge AC-stark shift by the clock laser ($0.65(3)\Delta f^{2}$ Hz^{-1})

Huntemann *et al.*, PRL **108**, 090801 (2012)

Precision frequency measurement of the Yb$^+$ octupole transition



Excitation spectrum

- 335 ms pulse duration
- 50 μW laser power
- Fourier-limited linewidth
- $Q = 2.7 \times 10^{14}$
- Light shift $\approx$ 4 Hz

$$\nu\left[{}^2\mathrm{S}_{1/2}(\mathrm{F}=0) - {}^2\mathrm{F}_{7/2}(\mathrm{F}'=3)\right] = 642\,121\,469\,772\,645.15\ (52)\ \mathrm{Hz}$$

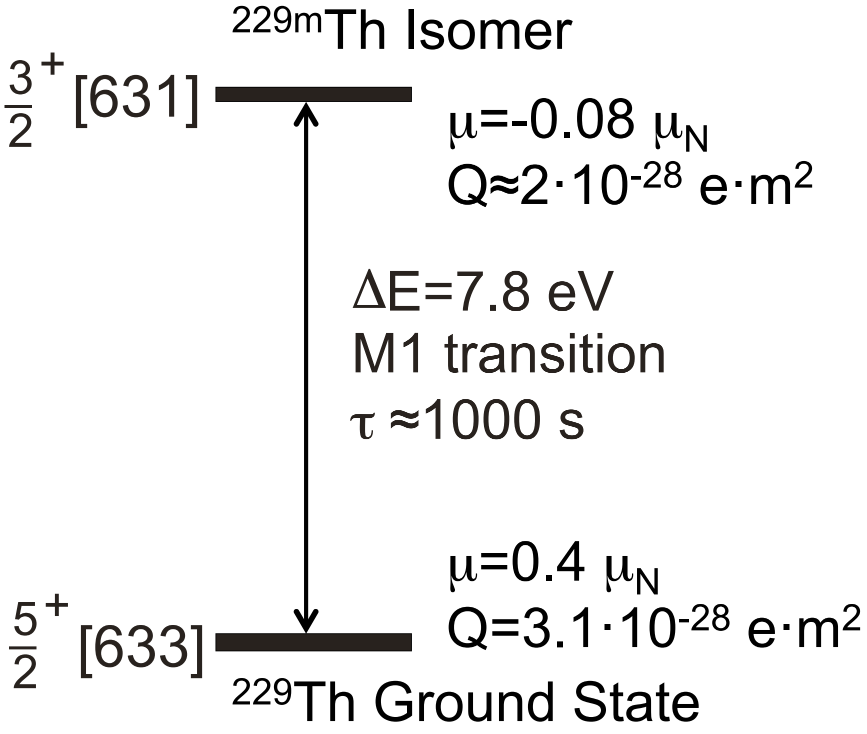
Absolute frequency measurement with uncertainty 8 × 10^{-16}
(Cs-limited)
Yb$^+$ systematic uncertainty contribution: 8 × 10^{-17}

Th-229: A high-precision optical nuclear clock

The lowest-energy isomeric state known in nuclear physics.

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.



^{229m}Th Isomer

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

$\mu = -0.08\ \mu_N$

$Q \approx 2 \cdot 10^{-28}\ e \cdot m^2$

$\Delta E = 7.8$ eV

M1 transition

$\tau \approx 1000$ s

$\mu = 0.4\ \mu_N$

$Q = 3.1 \cdot 10^{-28}\ e \cdot m^2$

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

^{229}Th Ground State

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 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 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) ($|A| <\approx 10^3$)

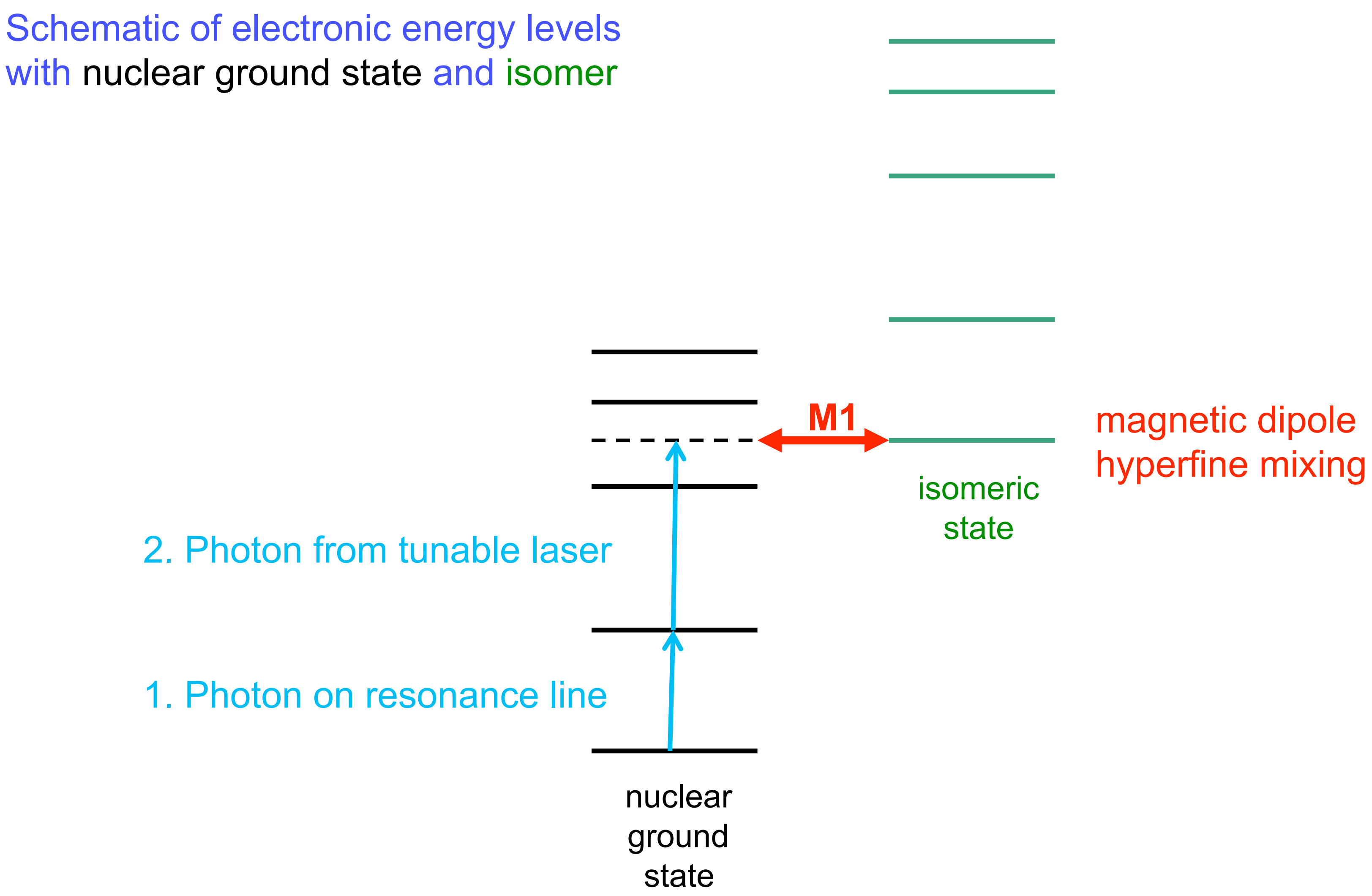
E. Litvinova et al., Phys. Rev. C **79**, 064303 (2009) ($|A| <\approx 4\times10^4$)

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)

Search for the optical transition: Two-photon electronic bridge excitation

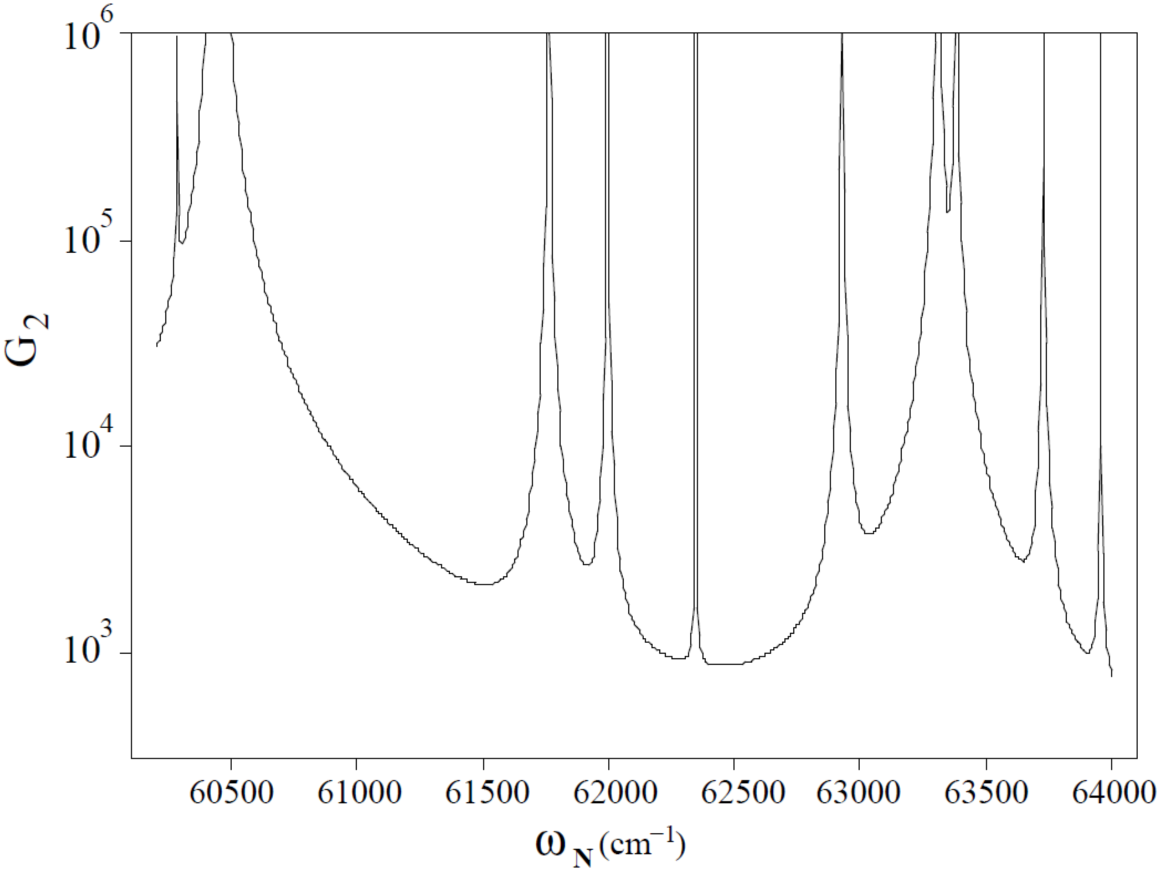
- uses the electron shell as an „antenna“ to enhance the nuclear excitation rate
- does not require the use of a widely tunable VUV laser



Two-photon electronic bridge excitation rate

S. G. Porsev, V. V. Flambaum, E. Peik, Chr. Tamm, Phys. Rev. Lett. **105**, 182501 (2010)

Based on an ab-initio calculation of the relevant electronic level structure

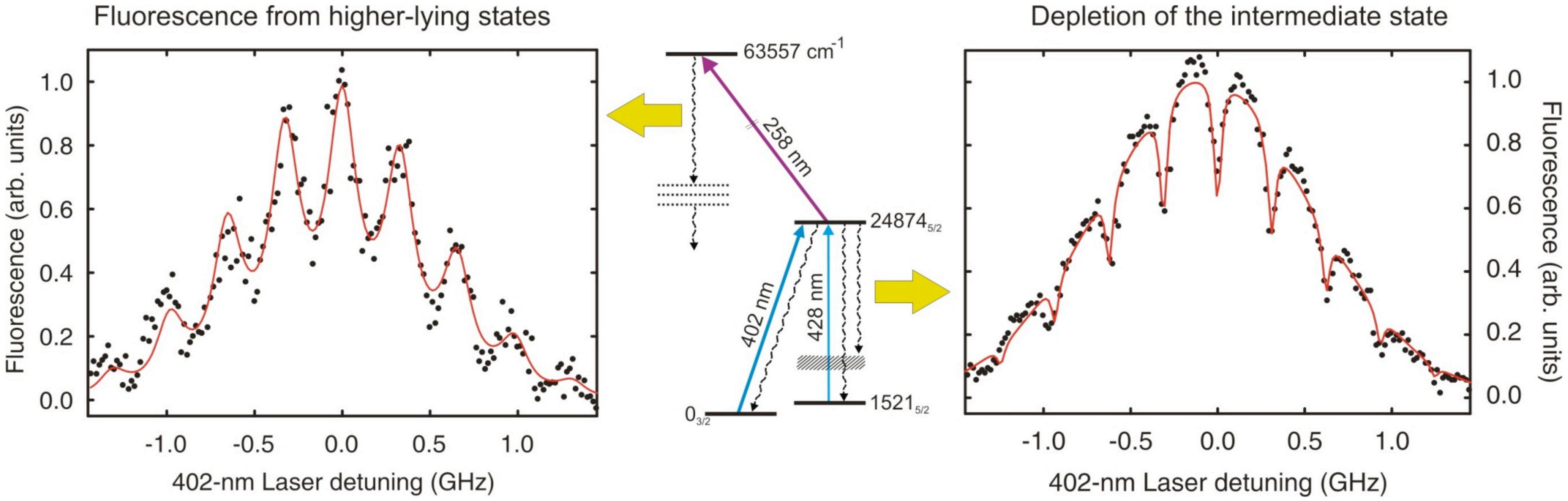


Prop. excitation rate

nuclear resonance frequency

Two-photon laser excitation of Th⁺

Resonances induced by the pulsed Ti:Sa; 402-nm laser scanned over the Doppler-broadened profile of the ion cloud.



Five new electronic levels detected so far, search ongoing.

Next steps: experiments with Th-229 and search for the nuclear resonance

Conclusion and Outlook

- Development of high precision optical clocks enables 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

- A variety of sensitive systems is under development. Measurements on several transitions will be required to interpret and verify a signal $dX/dt \neq 0$

- 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

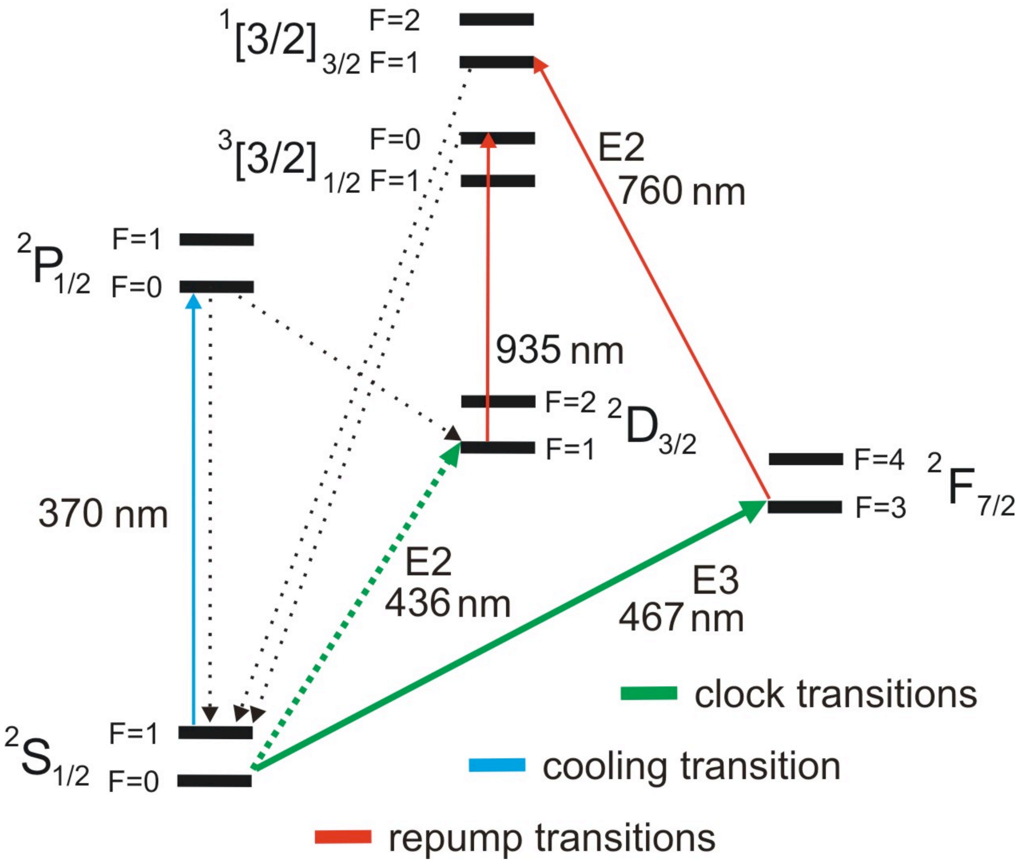
Chr. Tamm
M. Okhapkin
B. Lipphardt
S. Weyers

N. Huntemann Yb+ octupole
O. A. Herrera Sancho Th+ nuclear spectroscopy

Funding:
DFG
FQXi
QUEST
DAAD
TEC

Theory:
S. Karshenboim, Pulkovo Obs. and MPQ
S. G. Porsev, St. Petersburg
V. V. Flambaum, UNSW

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



Advantages of Yb^{+}

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

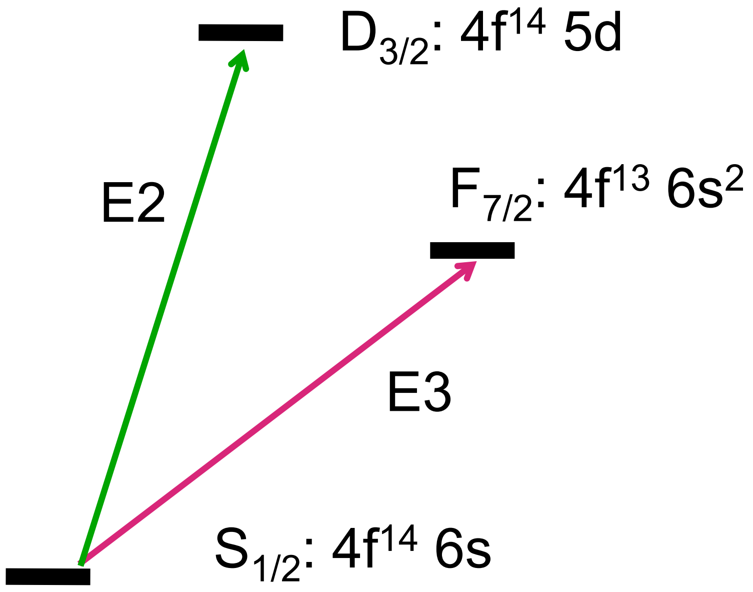
Quadrupole Transition S-D

- secondary representation of the second
- syst. uncertainty ≈ 5×10^{-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.

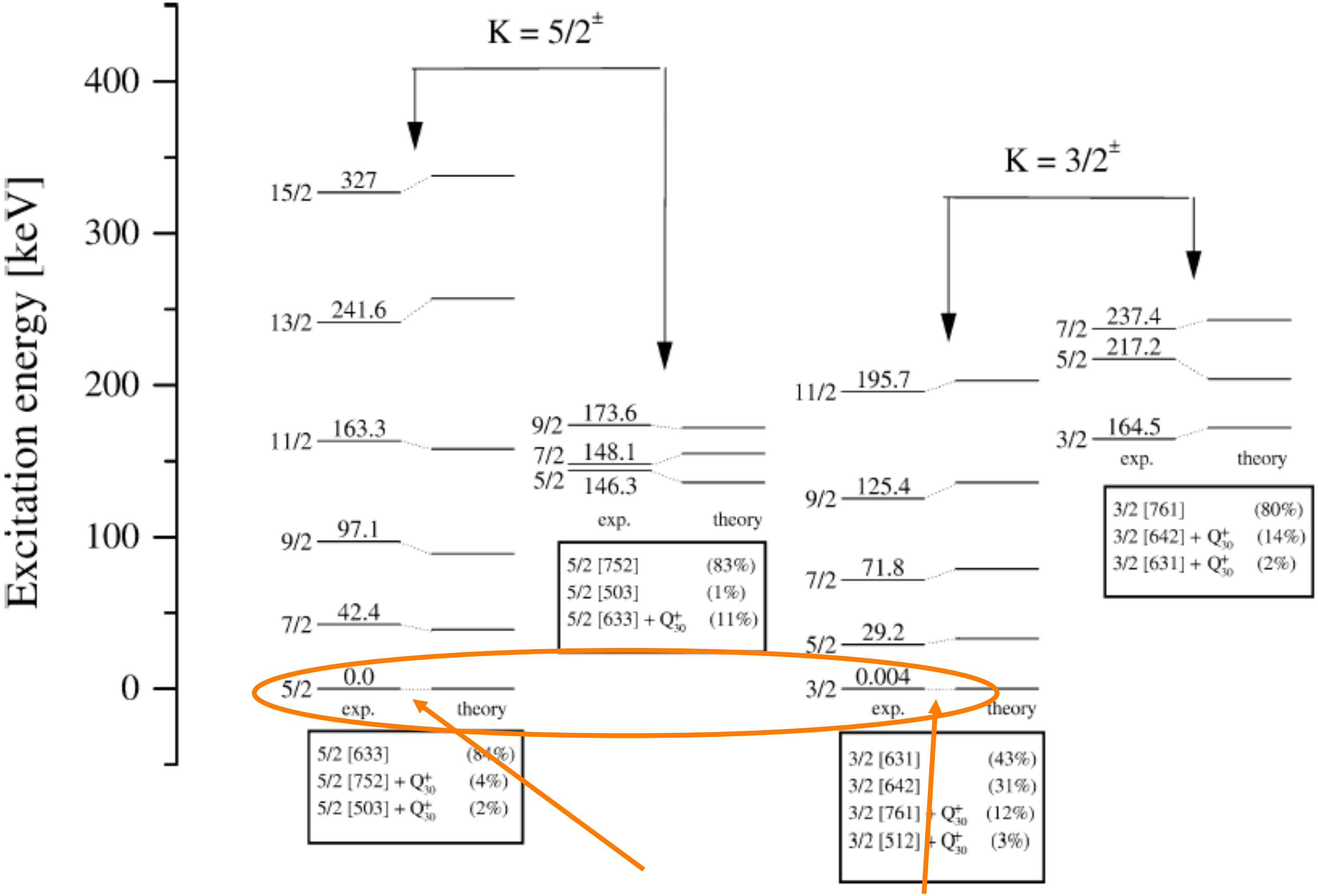
E2/E3 frequency ratio has high sensitivity to value of the fine structure constant.

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

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

K. Gulda et al. / Nuclear Physics A 703 (2002) 45–69

The nuclear structure of ^{229}Th



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