Prospects for Nuclear Optical Clocks

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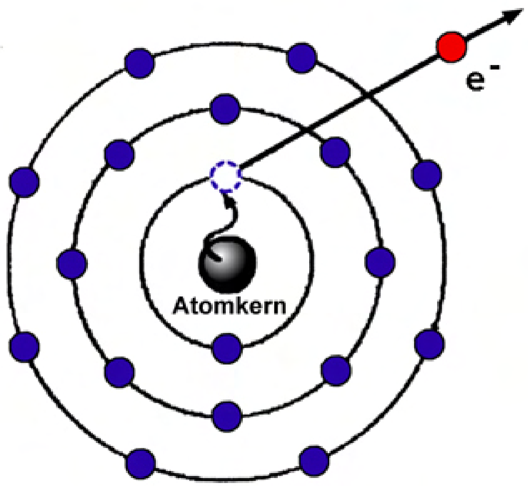
Nuclei with low-energy isomers

Tc-99	2150 eV
Hg-201	1561 eV
W-183	544 eV
U-235	73 eV
Th-229	3.5 eV

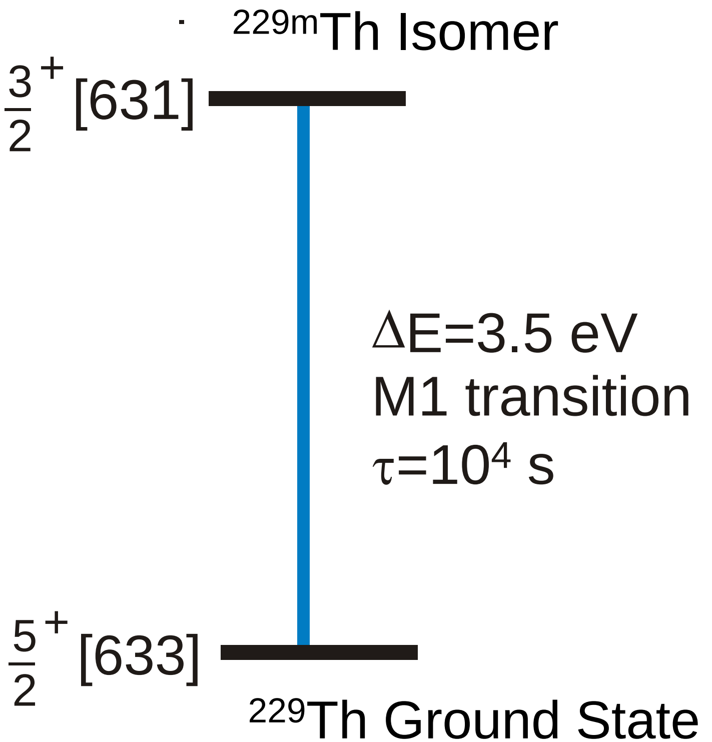
Energies comparable to those of electrons in the shell

Decay via internal conversion



The Thorium Isomer at 3.5 eV: An Optical Mössbauer Transition

The lowest-lying known excited state of a nucleus is an isomer of Th-229 at about 3.5 eV. This nucleus can be excited by the absorption of ultraviolet light.



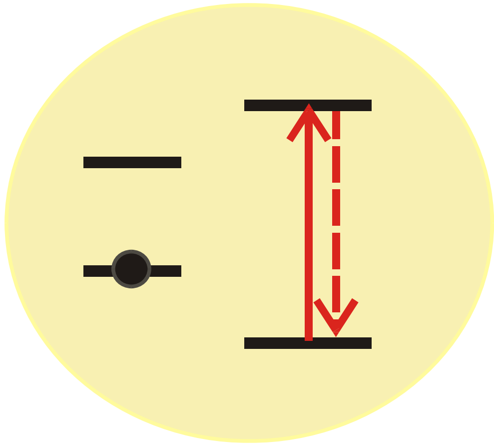
Measurements of ΔE

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	" #

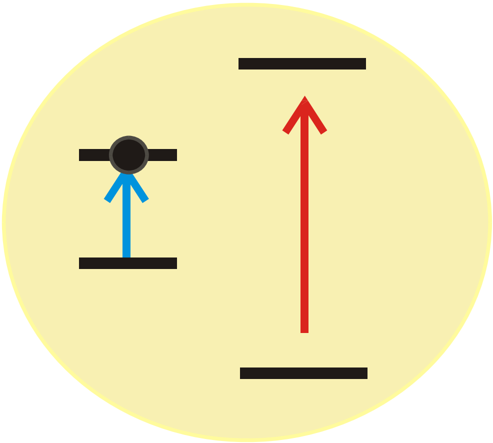
*R. Helmer and C. Reich, Idaho
#V. Barci et al., Nice

§Reanalysis 2005: 5.5(1.0) eV
Guimaraes-Filho and Helene

Detection of the Nuclear Excitation in Nuclear-Electronic Double-Resonance with a Single Ion: Observation of Quantum Jumps



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.

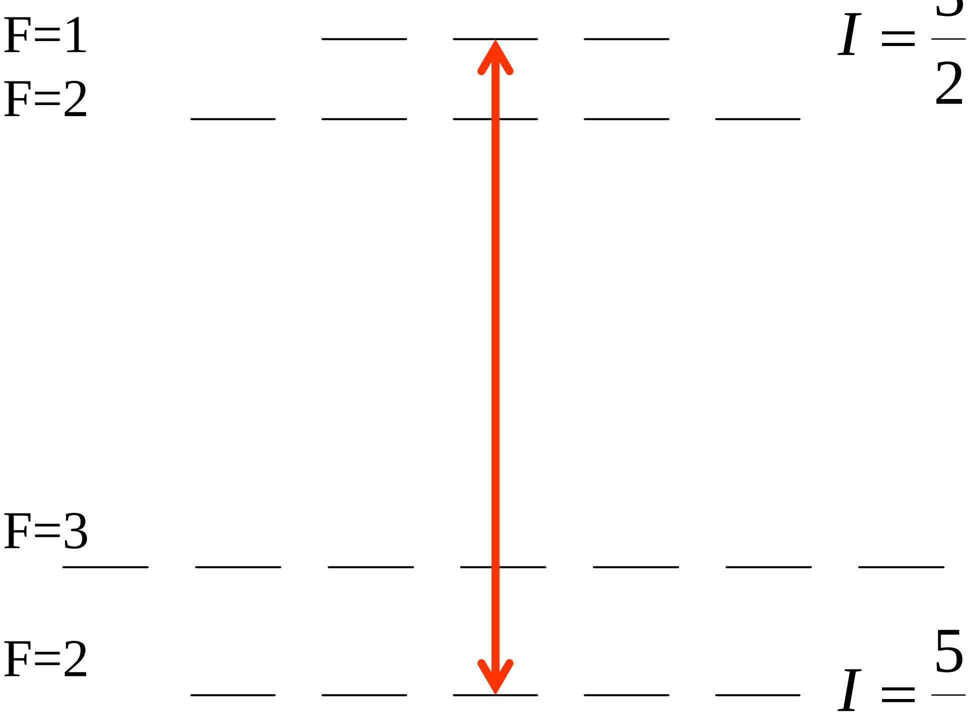
Possibility for a single-ion frequency standard with a nuclear excitation as the reference transition.

- 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)

Hyperfine and Zeeman Structure of the Nuclear Resonance:

electronic state: $^2S_{1/2}$



$$I = \frac{3}{2},\ {}^2S_{1/2}\ , F = 1, m_F = 0$$

Isomeric state with hyperfine coupl.

Ground state with hyperfine coupl.

$$I = \frac{5}{2},\ {}^2S_{1/2}\ , F = 2, m_F = 0$$

Absolute shifts of the transition frequency due to electromagnetic fields, collisions, etc., should be comparable to those in the Cs ground state HFS, but for a 10^5 times higher reference frequency !

Solid-state Th-229-Clock

- 10^{10} nuclei of Th-229 doped into 1 mm^3 of a transparent crystal like $^{232}ThO_2$ or $^{232}ThF_4$

- main systematic frequency shifts:
  temperature dependent isotope shift ($\delta\nu/\nu\delta T=10^{-10}$/K, worst case)
  second-order Doppler shift ($\delta\nu/\nu\delta T=10^{-15}$/K)

- inhomogeneous linewidth: kHz-range (?)

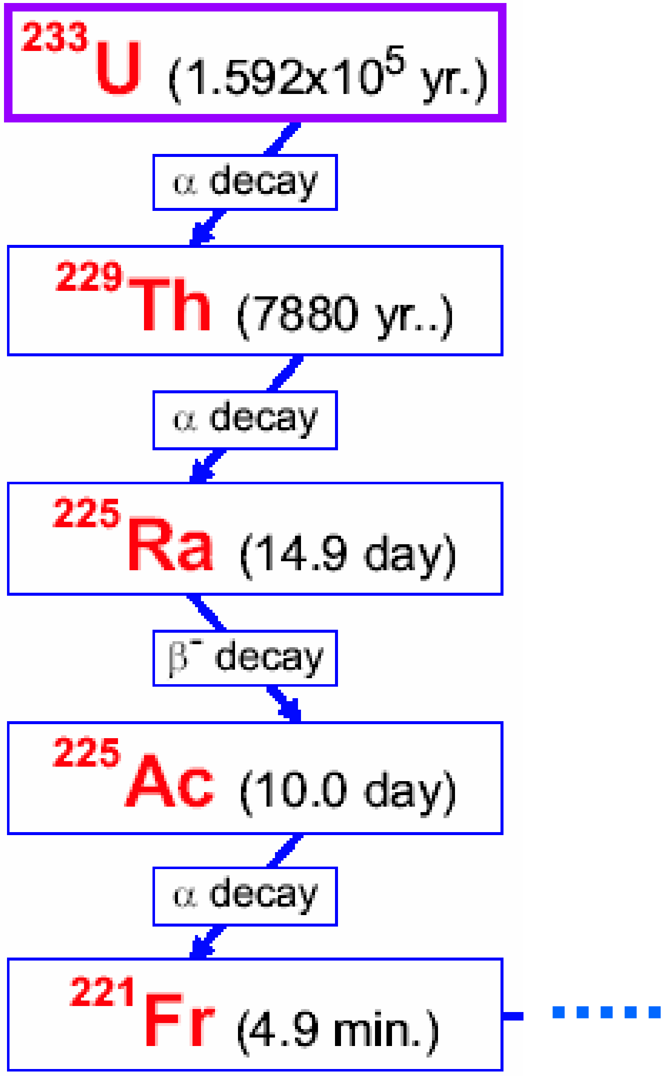
- 10^6 fluorescence photons per s, SNR 10^3 in 1 s (?)

⇒ Instability: 10^{-15} $(t/s)^{-1/2}$

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

Production of ^{229}Th

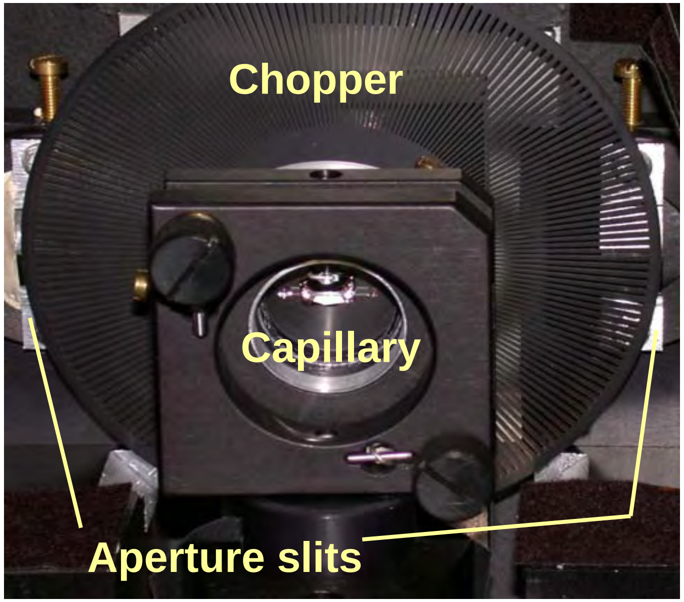
^{229}Th is radioactive
and is produced in the decay chain of ^{233}U.
In 2% of the decays of ^{233}U the
isomer ^{229m}Th is produced and the decay
chain should proceed with the emission
of a UV photon.

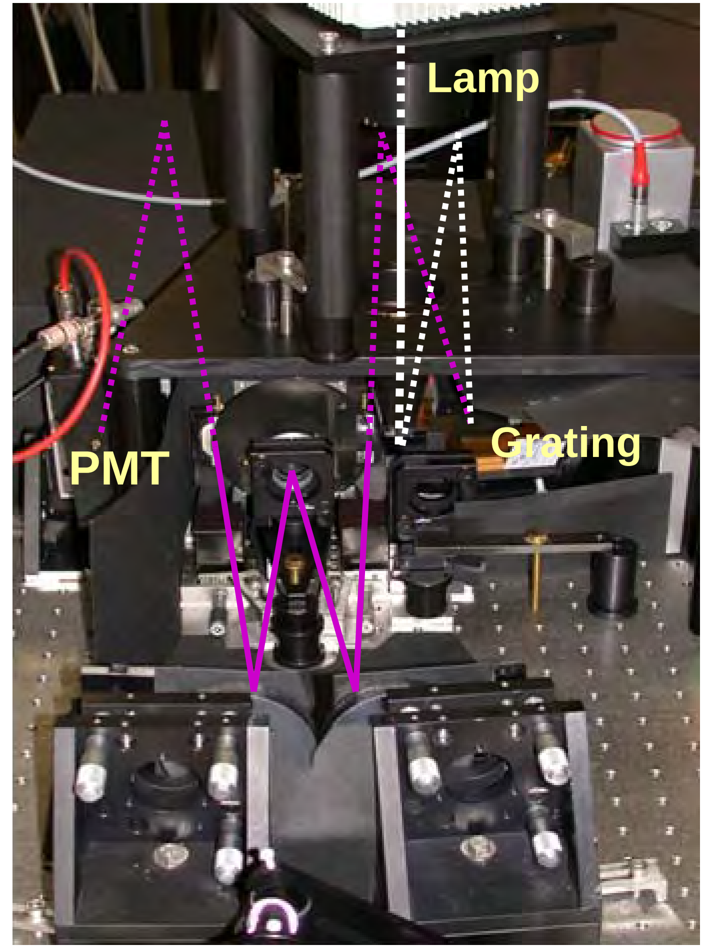


But:
Nobody has unambiguously
detected this light.

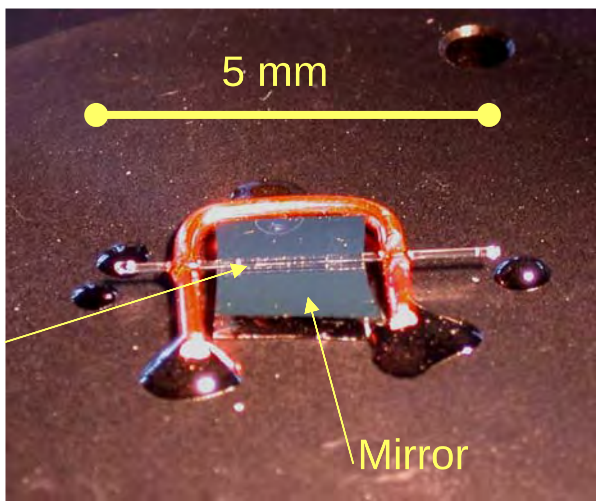
The experimental challenge:
precise measurement of the wavelength.

Details of the setup





quartz capillary
with Th solution



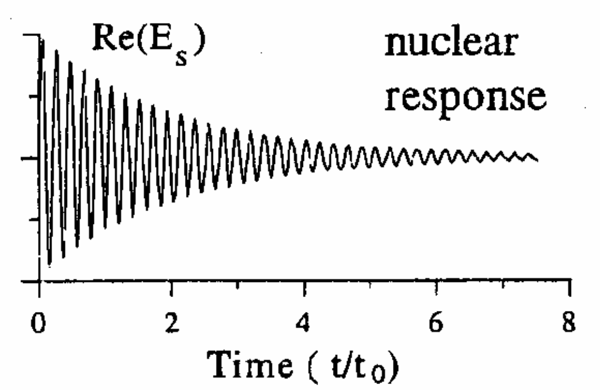
Detection of the optical transition in ^{229}Th in delayed forward scattering

Principle: Detection of the induced nuclear polarisation after pulsed excitation

Related experiments:

Synchrotron radiation + Mössbauer transitions

ps-/fs-laser + electronic transitions



-- emission is coherent with exciting beam

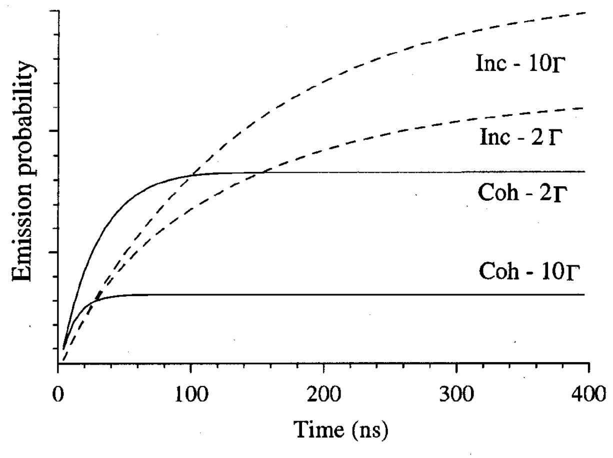
-> geometry like for a transmission experiment

-- time constant ≈1 / inhomogeneous linewidth

-> Th in H_2O(fl): 1...10 μs

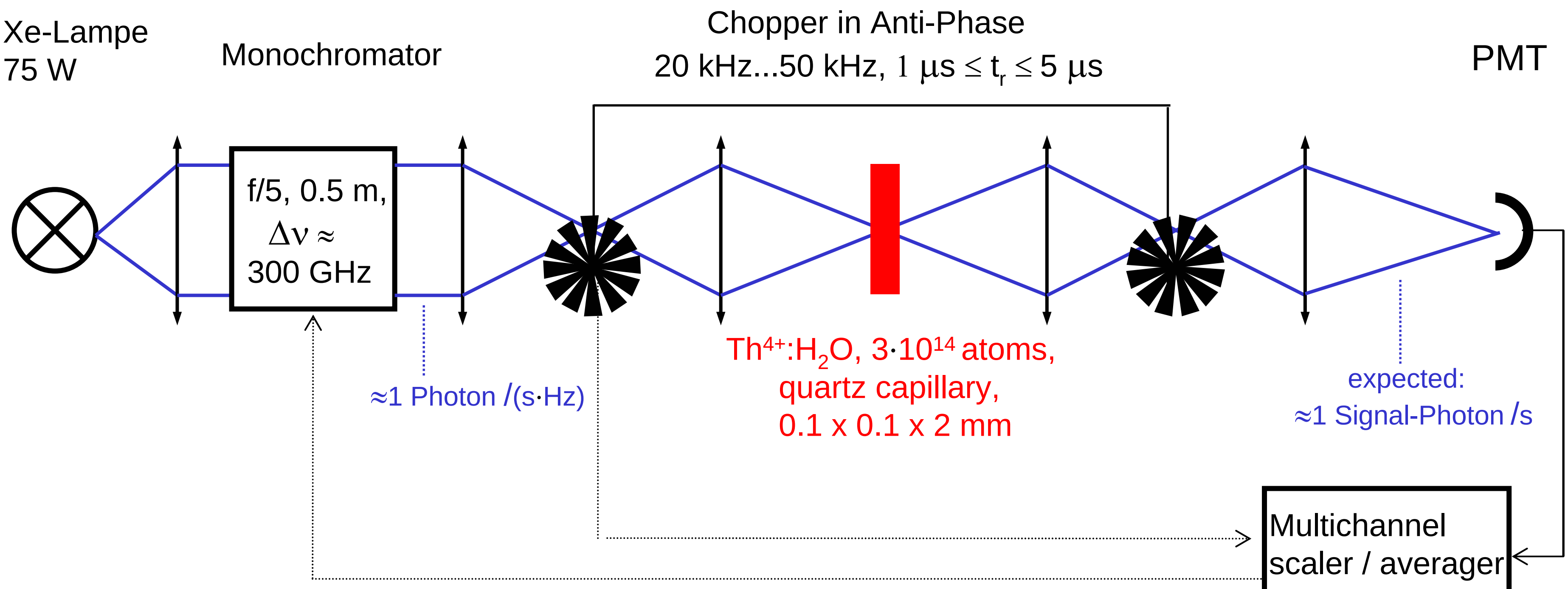
-- excitation and detection are separated in time

-> reduction of background



G.V. Smirnov, "General properties of nuclear resonant scattering", Hyperfine Interactions 123/124 (1999), 31

Experimental setup:



- Achromatic setup with mirrors
- Shortest wavelength in search range: 190 nm

Search for variations of fundamental 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 $X_q = m_q/\Lambda_{\rm QCD}$ and $X_s = m_s/\Lambda_{\rm QCD}$

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 of the fine structure constant at the level 10^{-20} per year.