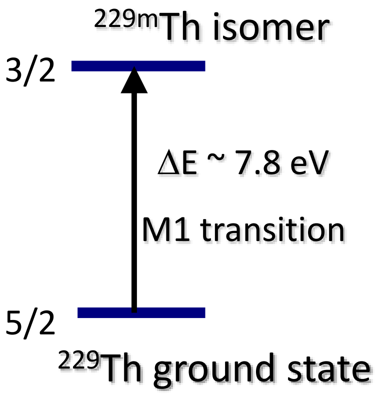
Search for the low-energy optical transition in ^{229}Th.

M. Okhapkin, D.-M. Meier, J. Thielking,
P. Glowacki, E. Peik

Th 229: the nucleus with the lowest-lying excited state



The only known isomer with an excitation energy in the optical range and in the range of outer shell electronic transitions.

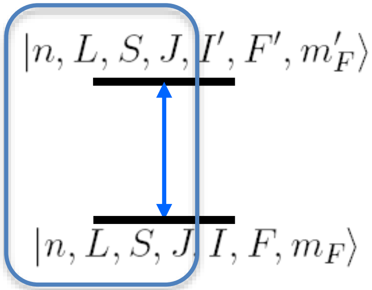
✓ γ - spectroscopy of two decay cascades from the 71.82-keV-level.
Isomer energy: VUV – range – 7.8 ±0.5 eV
B. R. Beck et al. (LLNL), PRL 98,142501 (2007).

✓ Deexcitation of the isomer is observed in the recoil experiment (unfortunately the energy of the isomer is not derived). LMU: Direct detection of the 229Th nuclear clock transition. L. von der Wense et. al. Nature17669 (2016).

✓ Proposal for nuclear optical clocks E. Peik and Chr. Tamm, Europhys. Lett. **61**, 181 (2003)

- The nuclear transition frequency is independent of the shifts depending only on the electronic quantum numbers.
- More stable against external perturbations due to small dimensions of nucleus in comparision with atoms.

Th 229: proposal for nuclear optical clocks

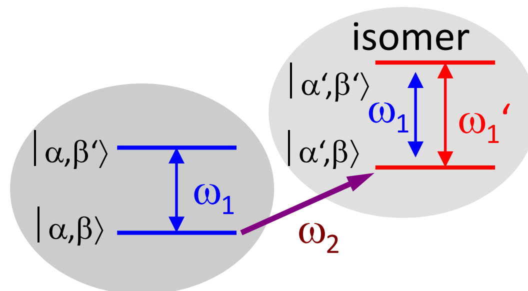


Nuclear and total-angular-momentum quantum numbers (I, F, m_F) can change, purely electronic quantum numbers (n, L, S, J) remain constant.

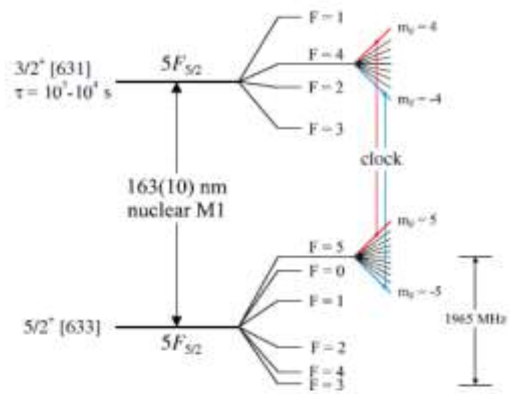
E. Peik and Chr. Tamm, Europhys. Lett. **61**, 181 (2003)

Influence of the electron shell to the nuclear transition: Frequency shifts that depend of (n, L, S, J) are common for both levels. The nuclear transition frequency is independent of the shifts depending only on the electronic quantum numbers.

Holds for: Scalar quadratic Stark shift, including the effects of static electric fields, collisions, blackbody AC Stark shift
Tensor quadratic Stark and electric quadrupole shift: vanish for J<1 or F<1
Hyperfine Stark shift: expected: $\approx 10^{-19}$
Linear Zeeman shift: use component $m_F=0 - 0$ or a pair of stretched states (diff. shift of 4 kHz/mT)
Doppler shift: use ion trapping and laser cooling



- Cryogenic ion trap (Th^{3+} is very reactive).
- Sympathetic cooling of Th^{3+}

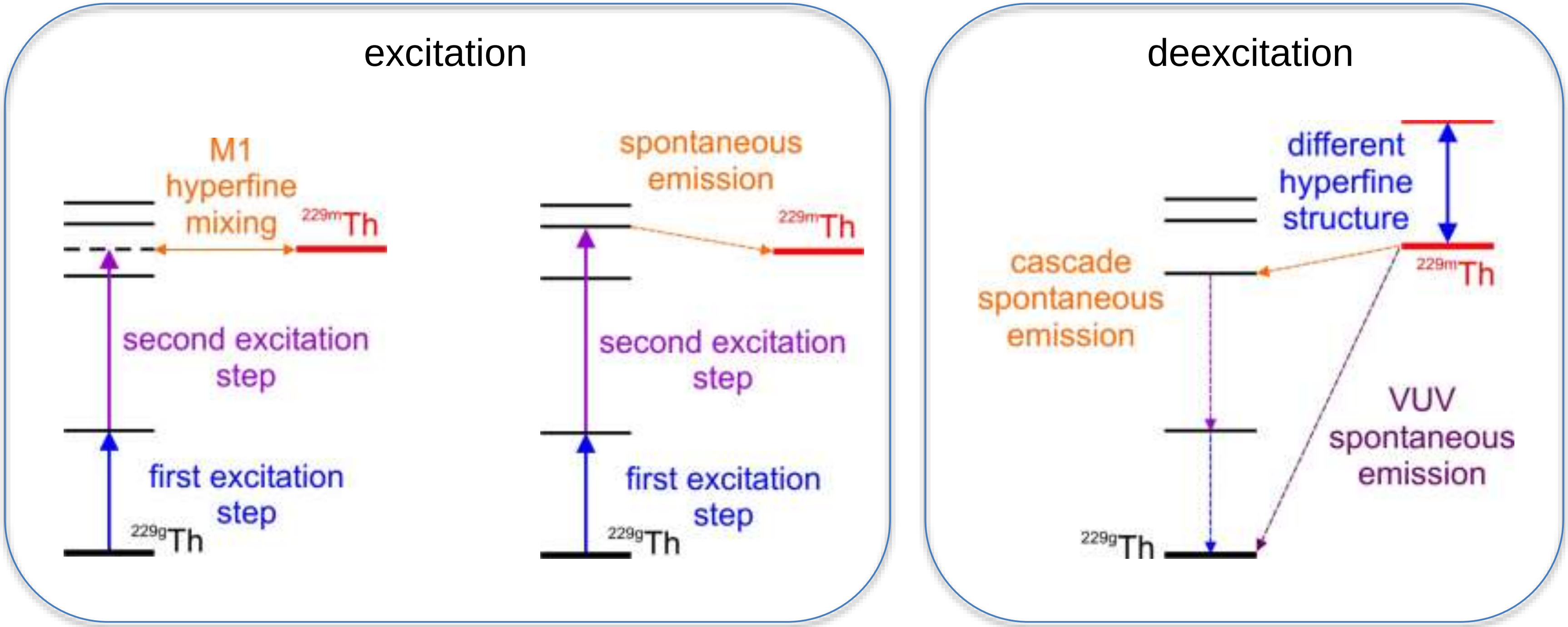


Frequency standard based on the pair of stretched hyperfine states: $5F_{5/2}$, $I_g=5/2$, $F=5$, $m_F=\pm 5\rangle \leftrightarrow |5F_{5/2}$, $I_m=3/2$, $F=4$, $m_F=\pm 4\rangle$.
Systematic shift suppression allows clock performance with a total fractional inaccuracy approaching 1×10^{-19}.
C.J. Campbell et al. PRL 108, 120802 (2012).

Excitation of nuclear transition

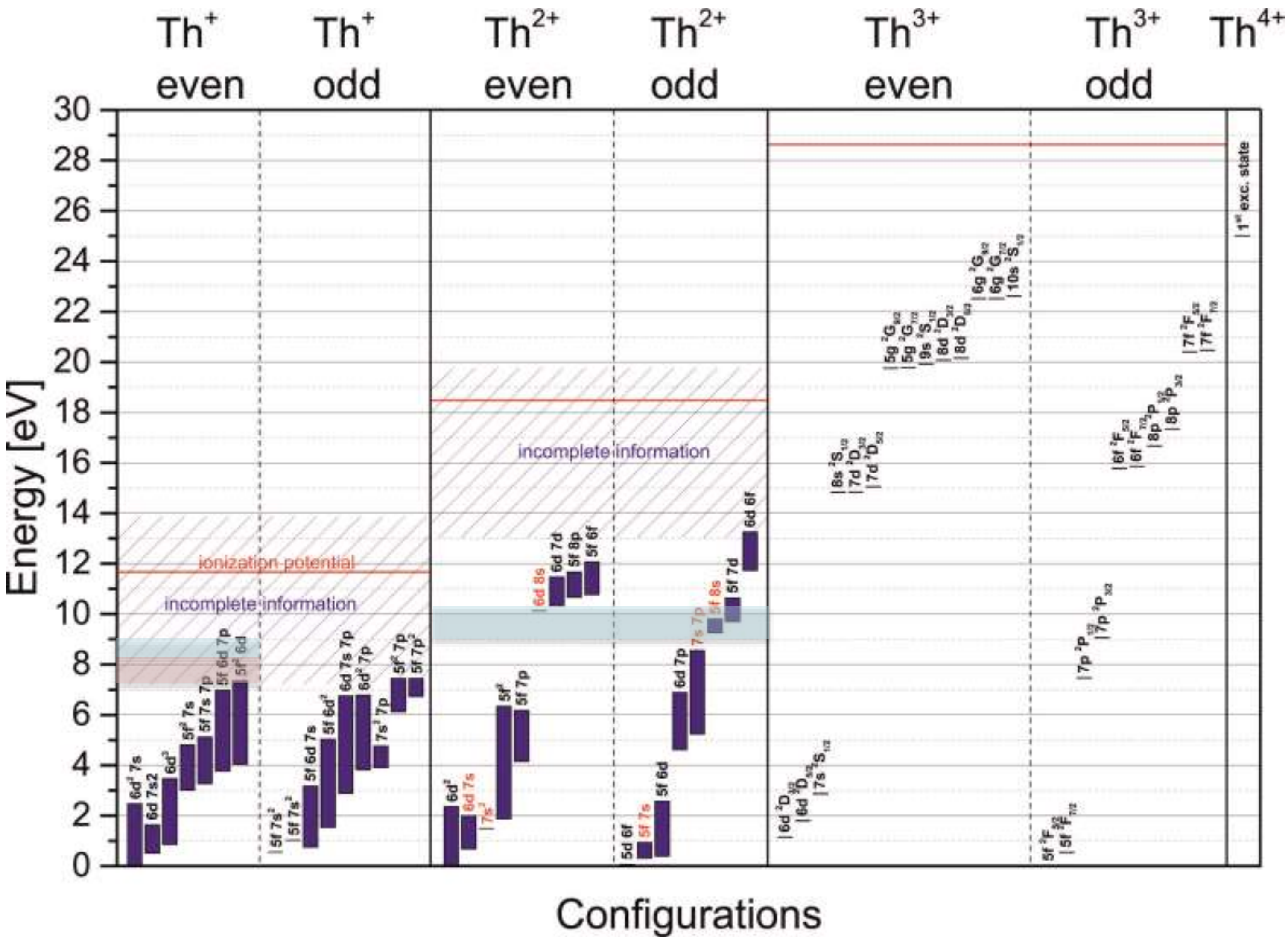
Our search method: Two-photon electronic bridge (or NEET) excitation

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



E.V. Tkalya, Usp. Fiz. Nauk 46, p. 315 (2003);
S.G. Porsev, V.V. Flambaum, PRA, 042516 (2010);
S.G. Porsev, V.V. Flambaum, E. Peik, Chr. Tamm, PRL, 105, 182501 (2010).

Electronic levels of Th carged states



Outline

Electronic bridge enhancement:

$K \approx (E_{M1}^2 \, \Delta\nu_{el}) / (\Delta\nu_{ne}^2 \, \Delta\nu_{nu}) \sim 10^3 \ldots 10^4$
(if the isomer energy is located between electronic levels of Th^+, or higher for small detunings)

Assumption: $\Delta\nu_{ne} >> \Delta\nu_{el} >> \Delta\nu_{nu}$
$\Delta\nu_{el} \sim 10^7$ Hz – electronic transition width,
$\Delta\nu_{nu} \sim 10^{-3}$ Hz – width of the isolated nuclear transition,
$\Delta\nu_{ne} \sim 3\times10^{12}$ Hz– frequency difference between nuclear and electronic transitions,
$E_{M1} \sim 10^9$ Hz – magnetic dipole coupling energy between electron and nucleus (in Hz)

E.V. Tkalya, Phys. Uspekhi 46, 315 (2003)

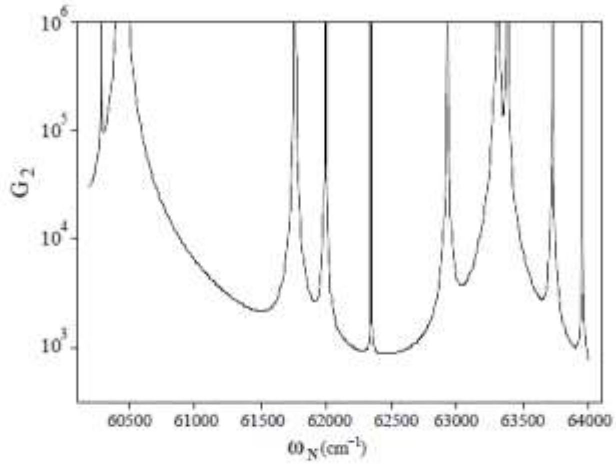
Excitation probability:

Laser parameters: f = 1 kHz; $P_p \sim 500$ W, $\tau_p \sim 15$ ns, $\Delta\nu \sim 1$ GHz;
Beam dia. 0.5 – 0.8 mm $\rightarrow I_p \geq 10^9$ W/m^2 $\rightarrow I_p(\nu) \sim 1$ W/(m^2·Hz);
$\gamma \sim 10^{-3} \sim \Delta\nu_{nu}$

$P \approx 2\pi^3 c^3 \gamma / (h\omega^3) \times \tau_p I_p / (c\Delta\nu) \sim 5\times10^{-7}$ [1/(ion×pulse)]

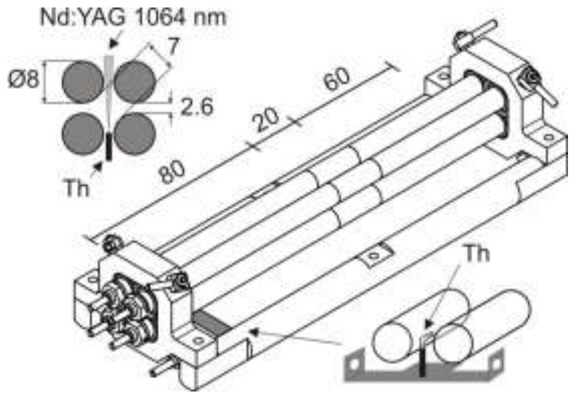
Ions in the beam ~ 2×10^4 (^{229}Th)
Enhancement factor (min) K ~ $10^3 \rightarrow (\gamma^* \sim \gamma\times10^3)$;
Detection efficiency (PMT solid angle and quantum efficiency) $\geq 3\times10^{-4}$;

P ~ 5×10^{-3} photons/pulse ≥ 1000 pulses average is required



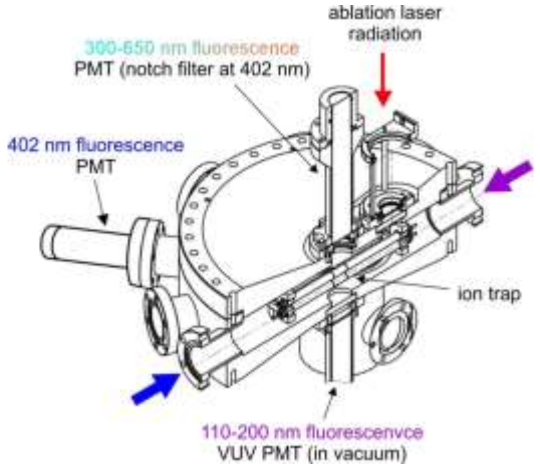
S. G. Porsev, V.V. Flambaum, E. Peik, Chr. Tamm. PRL 105, 182501 (2010) based on *ab initio* calculations

Linear rf Paul trap



* Trap parameters

* RF voltage 500...900 V at frequency of ~ 2 MHz;
* Transverse secular frequency of ~ 155...280 kHz;
* Pseudopotential depth of 15...44 eV;
* Capacity to store up to 10^6 ions;
* Buffer gas cooling and quenching with Ar at 0.1 Pa pressure.

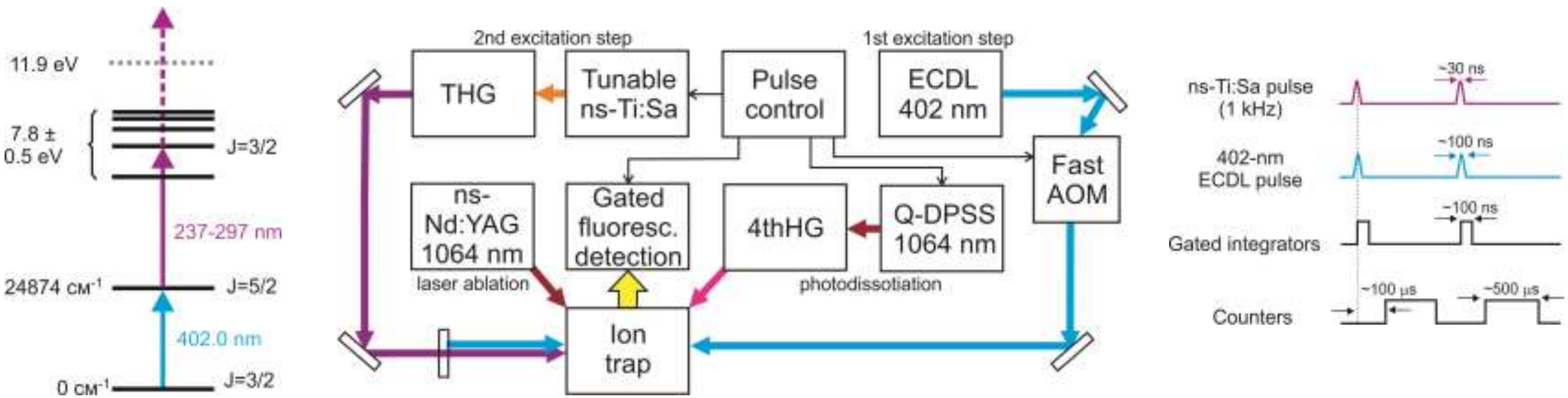


*** Ablation:** Nd:YAG laser, single pulse mode, 10 ns, 1 mJ pulse energy;
Loading efficiency for multiple loadings from $Th(NO_3)_4$ solution is ~ 10^{-6} i.e. the ratio of the number of stored ions over multiple loadings to the number of Th atoms deposited on the substrate (~ 10^{14} Th atoms on W substrate).

*** Photodissociation:** 4th harmonics of Nd:YAG (266 nm), 1 ns pulse, pulse energy of 10 mJ, 1 kHz repetition rate.
The storage time observed for Th+ is ~ 1000 s, limited by the formation of $ThCH_2^+$ molecules.

*** Detection:** PMTs in visible and VUV ranges

Excitation and detection

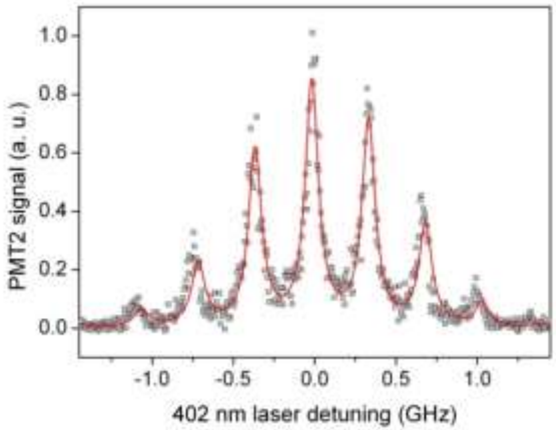


✓ Pulse mode:

- rep. rate 1 kHz
- pulse duration of ECDLs: ~ 70-100 ns.
- pulse duration of ns-TiSa laser: ~ 20-30 ns; THG pulse power: ~ 500 W (~ 10 mW CW).
- efficient population transfer during short pulse.

✓ Detection:

Gated fluorescence detection. The counters gates are shifted according to expected isomer lifetime to avoid signal of long-lived electronic decay channels and LIF of optical windows. Comparison of the detected signals for both ^{229}Th and ^{232}Th isotopes.



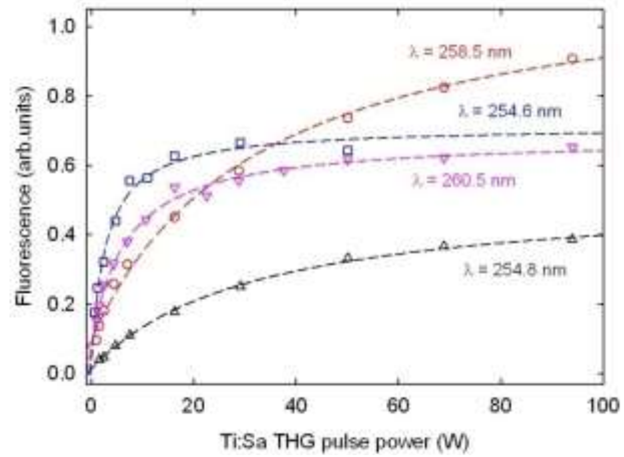
GI fluorescence signal from high-lying state

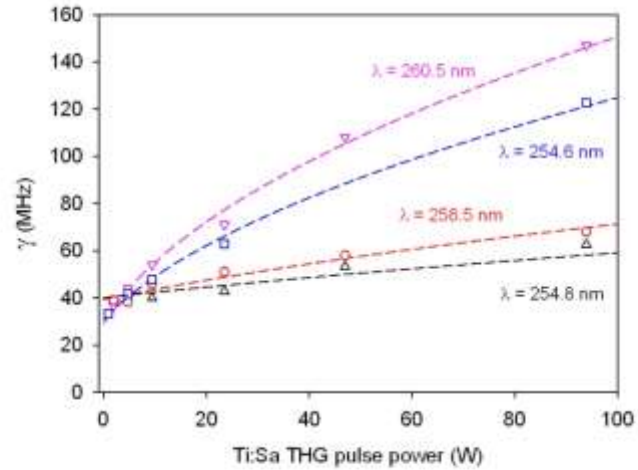
Th^+ electronic levels in the isomer energy range

Levels of Th^+ for the isomer NEET excitation are observed with the ^{232}Th isotope.

Level (cm^{-1})	J	Sf_{pulse} (kW/cm^2)
58875.5		197.9
59387.1*		148.0
59477.4	3/2	0.62
59803.0		0.28
60380.1	3/2	2.2
60618.6	3/2	10.7
60721.3		2.0
61032.4	3/2	0.34
61388.0		0.1
61428.6		0.54
61726.3	3/2	4.0
61963.6	3/2	0.36
62307.2		5.6
62373.8	3/2	63
62477.0		8.9
62560.1		2.7
62562.2	3/2	5.6
62753.1		7.7
63257.5		0.66
63298.4		26.9
63557.7		19.1
64122.0		9.96

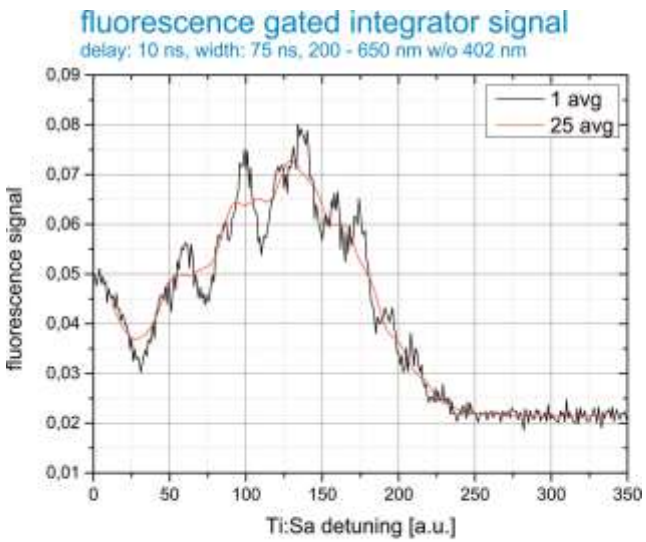
Level (cm^{-1})	J	Sf_{pulse} (kW/cm^2)
64150.3	3/2	2.8
64560.4	3/2	6.95
64813.7		0.32
64860.4		> 460
64920.1		20.8
65037.7	3/2	6.5
65144.4		1.1
65191.1		>334
65730.4	3/2	0.55
65738.1		44.4
65799.6	3/2	2.85
65910.0		9.8
65946.3		1.3
66052.0		19.5
66141.2		>113
66333.7	3/2	15.9
66558.0		0.3
66609.0		4.2
66702.9	3/2	64.1
66831.1	3/2	0.28
66855.6		14.9
67066.2		>22





* - observed by R. Zalubas, C.H. Corliss. J. Res. Nat. Bur. St. A78, 163 (1974)

Search of the nuclear transition in Th^+



Scan in progress

Problems:

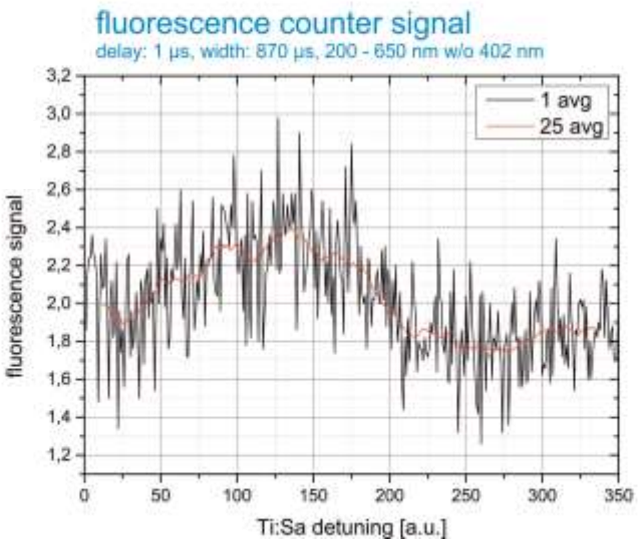
- LIF due to high power UV pulse limits detection sensitivity;
- Th^+ - second ionization potential lies in the 11.9…12.3 eV range.

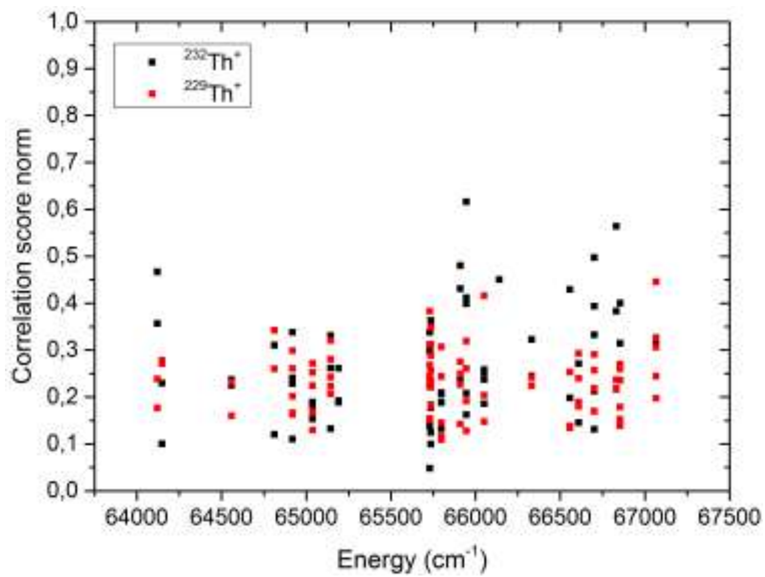
Resonant 3-photon ionization interferes with 2-photon excitation of the electronic levels.

- Long average time (~ 10^2 s for one data point)

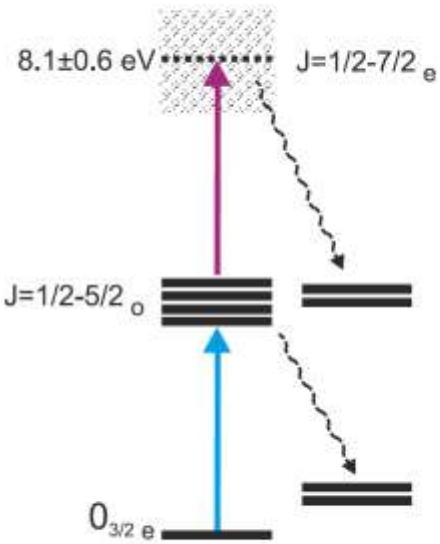
Data analysis:

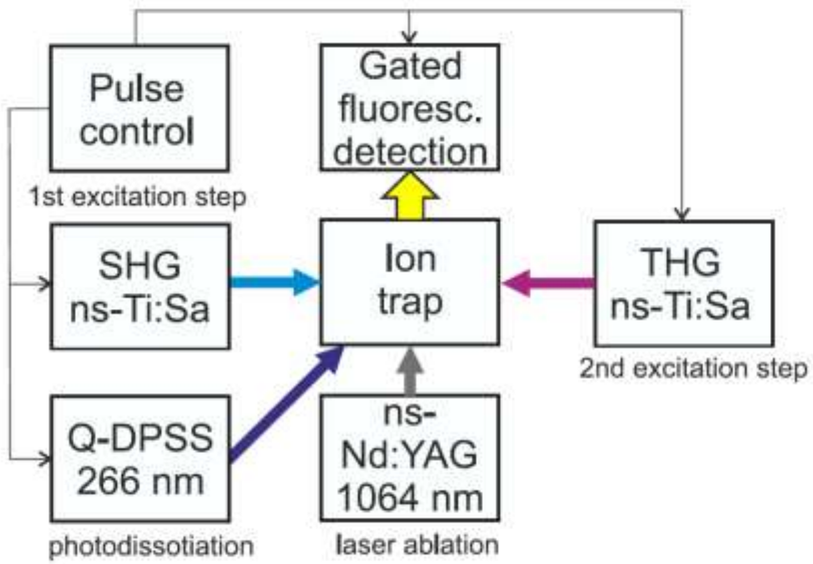
- Correlation analysis between the electronic decay signal of the gated integrator and counters signals from PMTs.
- The counters gates are delayed by 100 µs (to avoid LIF and decays from electronic states, the isomer lifetime estimated to be ≥ 1 ms).
- Comparison of the signals for $^{229}Th^+$ and $^{232}Th^+$.





Extension of the isomer energy searching range





IS	J	Config.
25027	1/2	$7s7p$+$6d7s7p$
26626	1/2	$6d7s(^3\mathrm{D})7p$ $^4\mathrm{D}$, $^2\mathrm{P}$
26965	3/2	$5f(^3\mathrm{F})6d^2$ $^4\mathrm{S}$, $^2\mathrm{P}$
27403	3/2	$5f(^1\mathrm{D})6d^2$ $^2\mathrm{D}$+$5f(^3\mathrm{P})6d^2$ $^4\mathrm{D}$
26424	5/2	$5f(^3\mathrm{P})6d^2$ $^4\mathrm{F}$, $^4\mathrm{D}$
28244	5/2	$6d7s(^3\mathrm{D})7p$ $^4\mathrm{F}$+ $6d^2(^3\mathrm{F})7p$ $^4\mathrm{G}$

New Th^+ electronic levels in the -σ…+2σ range of the isomer energy

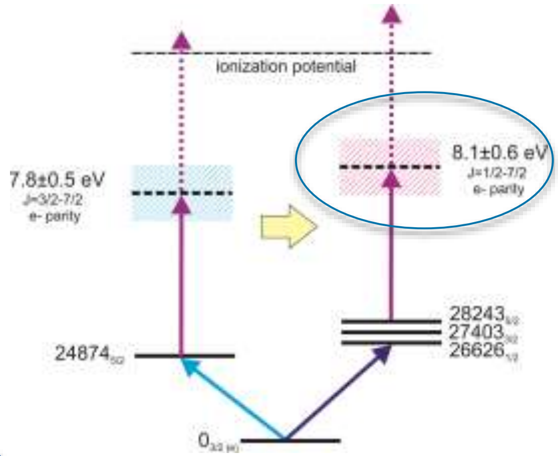
Levels of Th^+ for the isomer NEET excitation are observed with the ^{232}Th isotope.

	Observed from intermediate state [cm-1]							
	25027,038	26626,485	26586,273	26965,205	27403,18	24873,982	26424,481	28243,812
	1	2		3	4		5	6
Energy [cm-1]	1/2	1/2	3/2	3/2	3/2	5/2	5/2	5/2
62873,110		X		X	X			
63268,900	X	X		X	X			
63680,285	X	X		X	X		X	X
64107,508				X	X		X	X
64368,240				X	X		X	X
64442,103	X	X		X	X			
64887,795	X	X		X	X			
65753,450	X	X		X	X			
66324,519	X	X		X	X			
66388,814	X	X		X	X			
66429,640				X	X			X
66666,961	X	X			X			
67154,047	X			X	X		X	X
67177,763							X	X
67378,611							X	X
67509,637		X		X	X		X	X
67577,711				X				X
67657,301		X		X	X			
67737,621				X	X		X	X
67803,247				X				X
67843,316			X	X	X			X
67866,095					X		X	X
68033,328							X	X
68088,027		X		X	X			X
68278,648								X
68497,879					X			X
68564,189				X	X			X
68598,833				X	X			X
68752,065		X		X	X			X
68812,644				X	X			X
68898,666				X	X			X
68913,767					X			
68921,301					X			X
69381,631								X
69523,570								X
69582,982								X
69588,677								X
70036,553								X

Level	J	IS	Level	J	IS
62873.1(2)	1/2	2-4	67803.2(2)	5/2 (3/2)	3;6
63268.9(2)	1/2	1-4	67843.3(2)	5/2 (3/2)	3;4;6
63680.3(2)	3/2	1-6	67866.1(2)	5/2 (3/2)	4-6
64107.5(2)	5/2	3-6	68033.3(3)	7/2	5;6
64368.2(2)	5/2	3-6	68088.0(2)	3/2	2-4;6
64442.1(2)	1/2	1-4	68278.6(3)	7/2	6
64887.8(2)	1/2	1-4	68497.9(2)	5/2 (3/2)	4;6
65753.5(2)	1/2	1-4	68564.2(2)	5/2 (3/2)	3;4;6
66324.5(2)	1/2	1-4	68598.8(2)	5/2 (3/2)	3;4;6
66388.8(2)	1/2	1-4	68752.1(2)	3/2	2-4;6
66429.6(2)	5/2	3;4;6	68812.6(2)	5/2 (3/2)	3;4;6
66667.0(2)	1/2	1;2;4	68898.7(2)	3/2-5/2	3;4;6
67154.0(2)	3/2	1;3-6	68913.8(3)	1/2-5/2	4
67177.8(2)	7/2	5;6	68921.3(2)	3/2-5/2	4;6
67378.6(3)	7/2	5;6	69381.6(3)	3/2-7/2	6
67509.6(2)	3/2	2-6	69523.6(3)	3/2-7/2	6
67577.7(3)	5/2 (3/2)	3;6	69583.0(3)	3/2-7/2	6
67657.3(2)	1/2	2-4	69588.7(3)	3/2-7/2	6
67737.6(2)	5/2 (3/2)	3-6	70036.6(3)	3/2-7/2	6

Extended search above + σ range

Th^{+}



✓ Excitation:

The first step is provided by SHG radiation of Ti:Sa;
the second excitation step: THG of Ti:Sa.

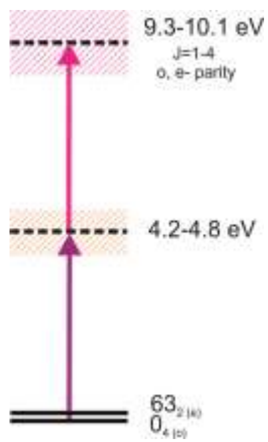
✓ Advantages:

High density of the levels.

✓ Disadvantages:

High ionization rate due to the resonant 3-photon ionization (limits the excitation power).

Th^{2+}



✓ Excitation:

THG radiation of 2 Ti:Sa lasers.

✓ Advantages:

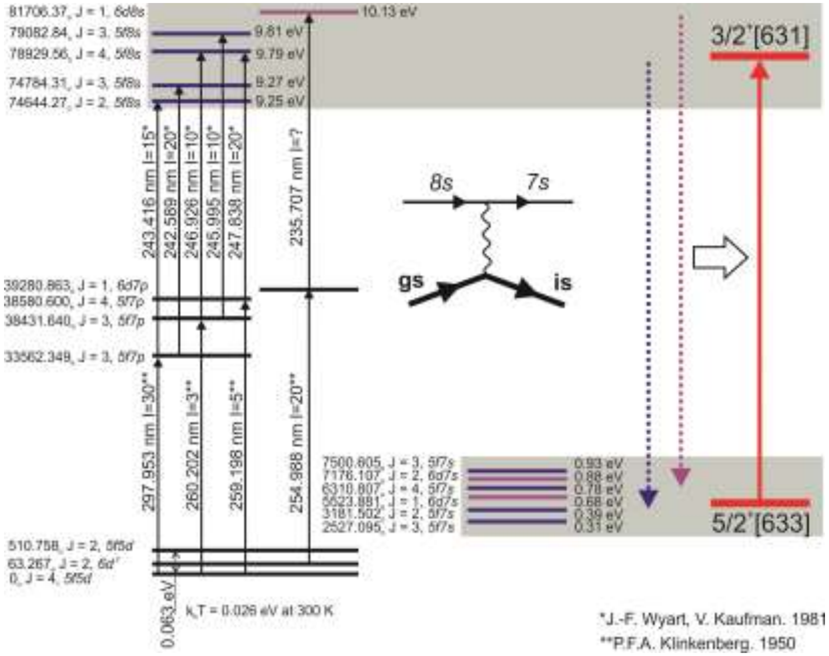
Th^{2+} ionization potential is ≥18.3 eV (avoids 3-photon ionization).

8s-electron configurations available for the NEET excitation.

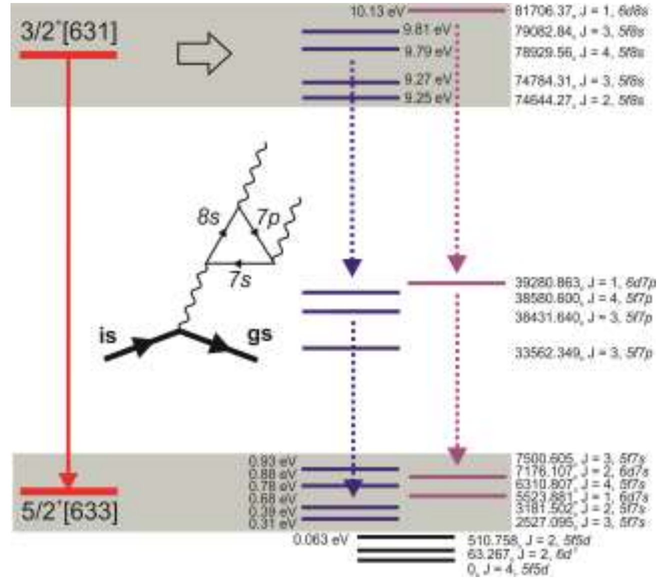
✓ Disadvantages:

Relatively lower density of the electronic states in the range of search.

NEET excitation in Th^{2+}



*J.-F. Wyart, V. Kaufman. 1981
**P.F.A. Klinkenberg. 1950

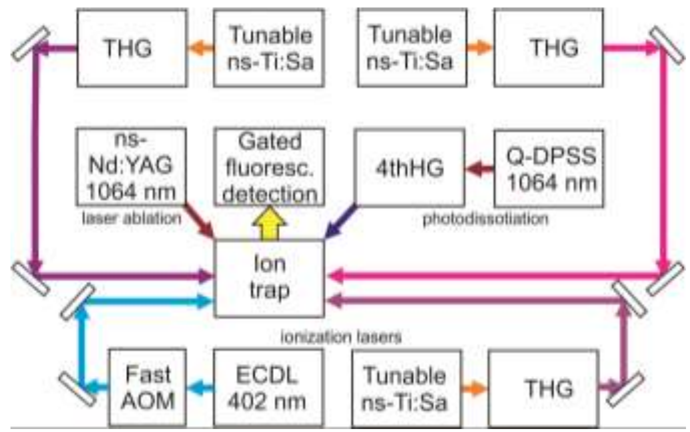


Excitation:

THG of ns- Ti:Sa lasers;
rep. rate 1 kHz;
pulse duration 15 -20 ns;
pulse power ~ 10^2 - 10^3 W.

Trap loading:

Resonant 3-photon ionization of Th^+.



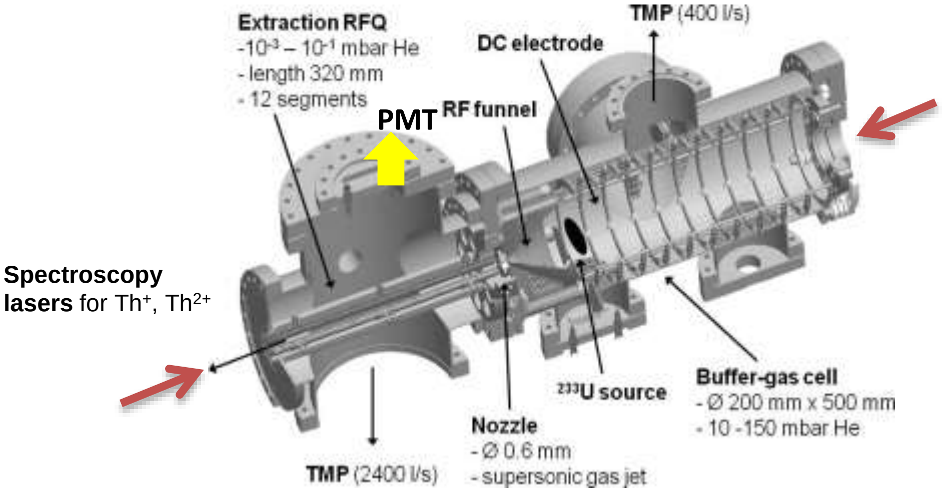
Search of HFS of 229mTh isomer

nuClock

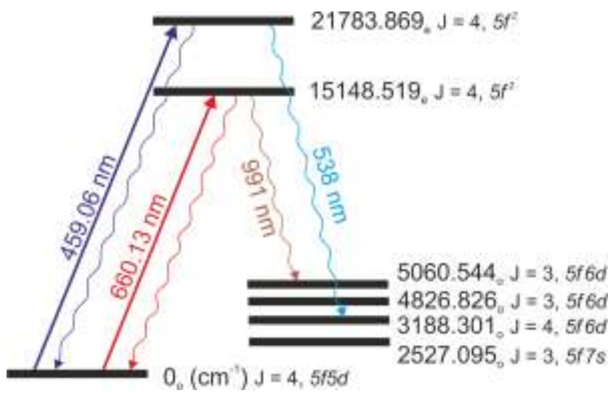
- Searching of the isomer energy
- Optical excitation of the isomer
- Developement of lasers for the nuclear optical clock
- Developement of optical clocks based on the ion trap technique and Th doped crystals

PTB/LMU experiment:

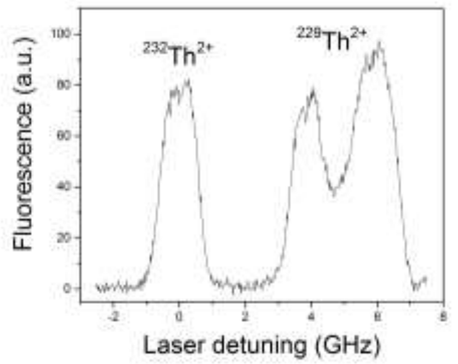
Searching of the hyperfine structure of the isomer in different charge states of Th.

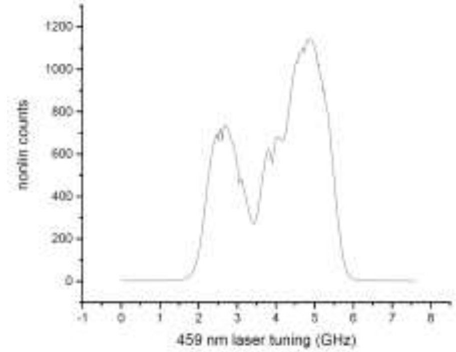


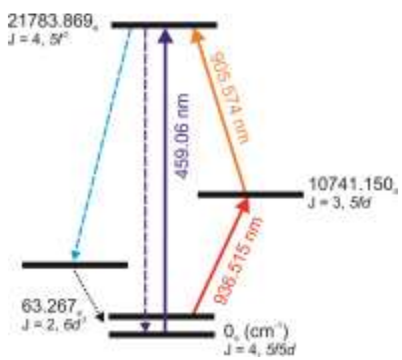
Search of HFS of ^{229m} Th^{2+} isomer in LMU

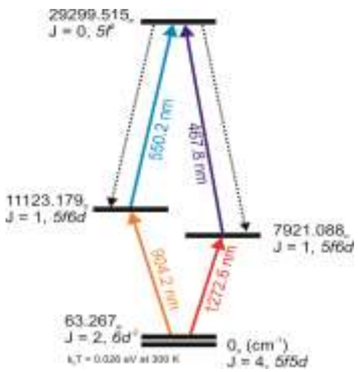


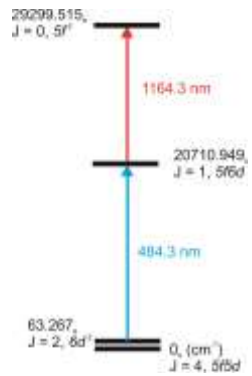
Palmer Engleman 1983 Atlas of the thorium spectrum











✓ Expected FWHM of the resonances is about 70 MHz;

✓ Background-free detection;

Requires signal selection in the case when the splitting of the intermediate state HFS components is ~ *kv*

Coming soon

- Tests of the NEET excitation in Th^{2+};
- Extension of the scanning range in Th^{+}.

Thank you for your attention!

Group leader: E. Peik

Ion trap experiment / nuClock

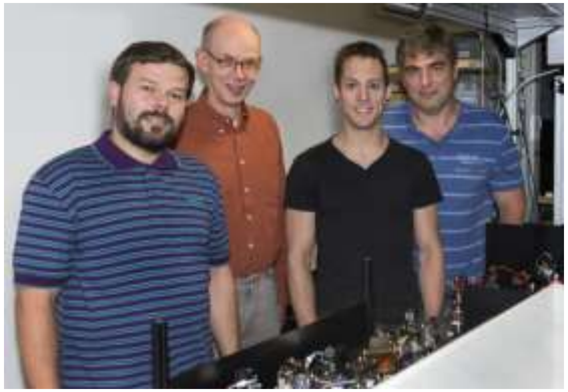
Scientist: M. Okhapkin

Ph.d. students: D. Meier

J. Thielking

Experiment with crystals / nuClock

Scientist: P. Glowacky



Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Maxim Okhapkin
E-Mail: maksim.okhapkin@ptb.de

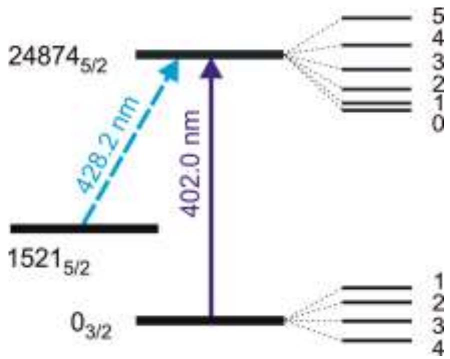
www.ptb.de

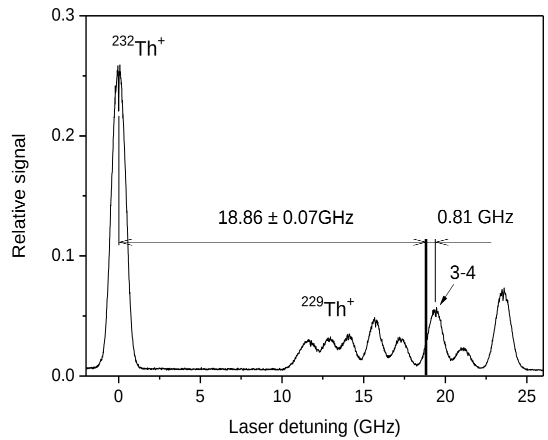
Selection of the charge states

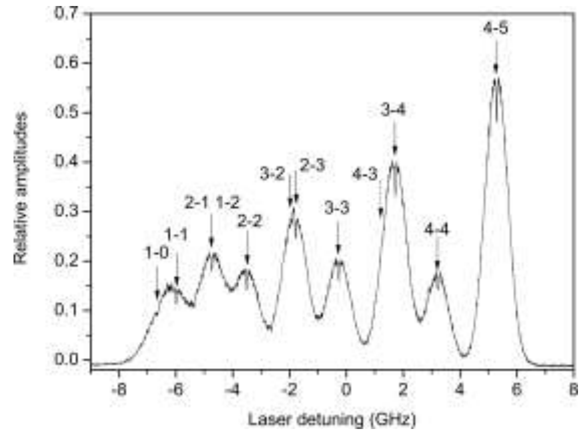
- **Th^{+}:**
  - − Small extraction efficiency from ^{233}U source, hence unknown isomer lifetime*.
  - + Laser system is already existing including Doppler-free two photon excitation.
  - + HFS has been investigated and splitting factors are known.
- **Th^{2+}:**
  - + Extraction efficiency factor from ^{233}U source is 20 times higher compared to Th^{+}.
  - + Isomer lifetime > 60 s**.
  - + Suitable transitions in the visible range are available. Single photon excitation is developed.
- **Th^{3+}:**
  - + Highest initial amount from ^{233}U source.
  - − Transitions in the IR and UV range.
  - − Production and storage in PTB experiments are not tested.

* L. v. d. Wense et al., *Eur. Phys. J. A* **51**, 28 (2015).
** L. v. d. Wense et al., *Nature* 533.7601 (2016): 47-51.

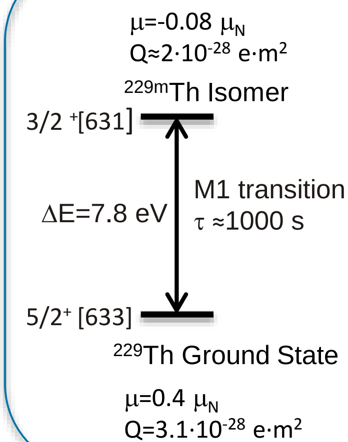
Hyperfine structure of 402 nm $^{229}Th^{+}$ line





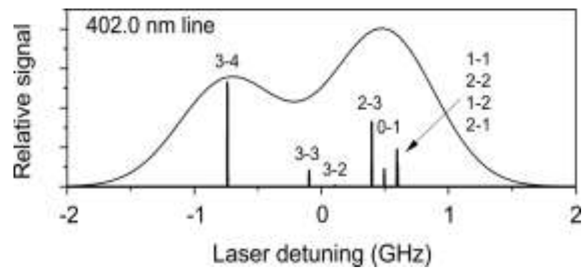


Level [cm^{-1}]	A factor [MHz]	B factor [MHz]	Ref.
0	-444.2(1.9) -444.2(3.4)	303(6) 308.4(12.7)	* **
24874	488.9(3.7) 489.2(3.7)	-412.8(15.5) -408.8(17.9)	**/* **



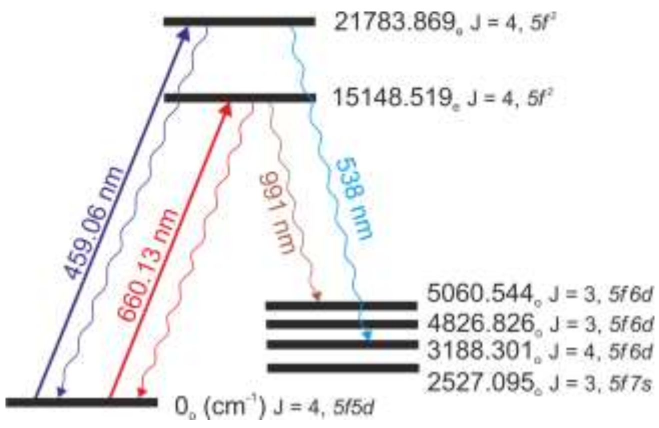
Expected HFS of the isomer

$A_{is}/A_{gs} \sim \mu_{is}/\mu_{gs}$, $B_{is}/B_{gs} \sim Q_{is}/Q_{gs}$



* W. Kälber et al., Z. Phys. A - Atomic Nuclei **334**, 103 (1989).
** M.V. Okhapkin et al., Phys. Rev. A **92**, 020503 (2015)

Excitation in Th^{2+}

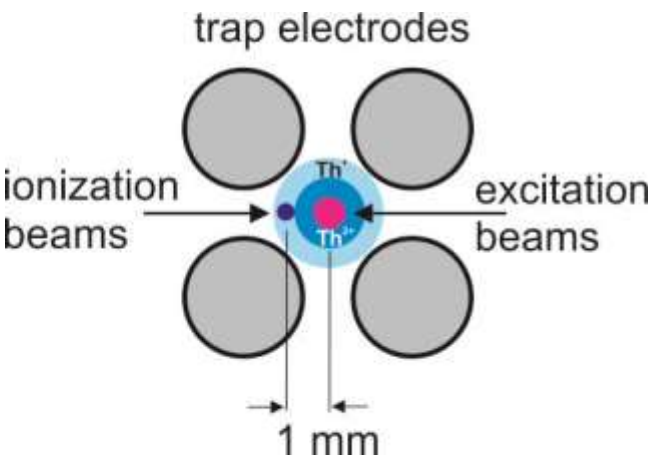


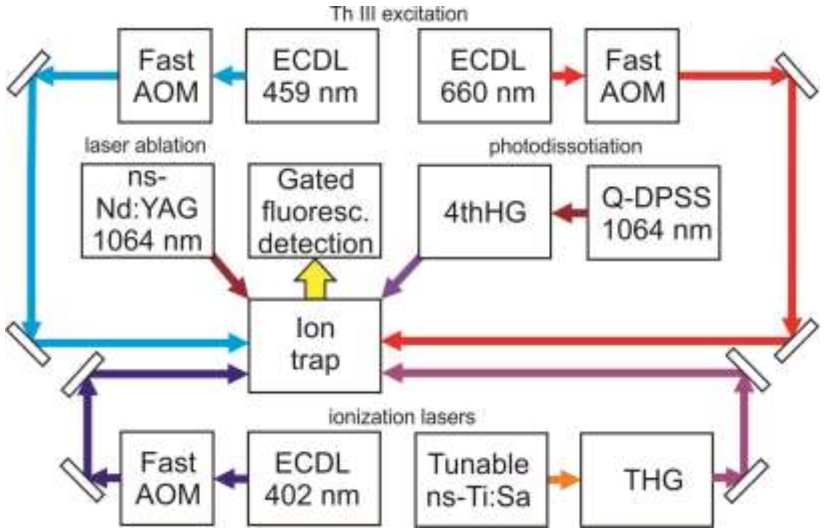
Palmer Engleman 1983 Atlas of the thorium spectrum

Th^{2+} storage time is $\tau \sim 10^3$ s (loss rate of $\sim$1 ion/s due to chemical reactions).

Steady state amount of Th^{2+} ions in the trap is ~ 10^3 (ionization rate = ion loss rate).

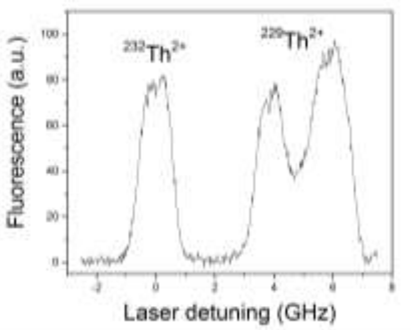
The trap operation time with one loading of $^{229}Th^{+}$ is > 10^5 s.

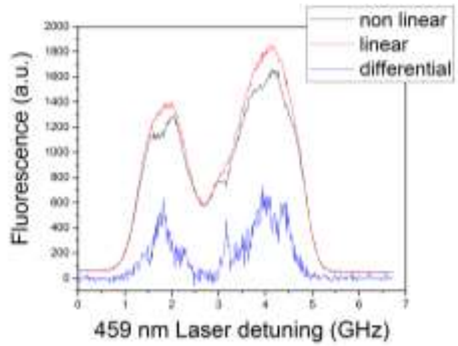


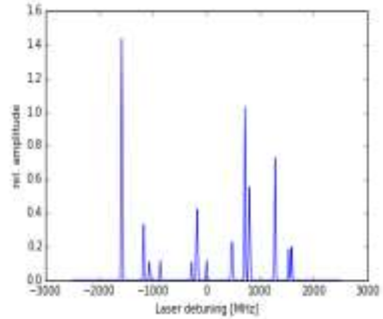


HFS of Th^{2+} resonant lines

Th^{2+} 459 nm line. Detection at 538 nm.





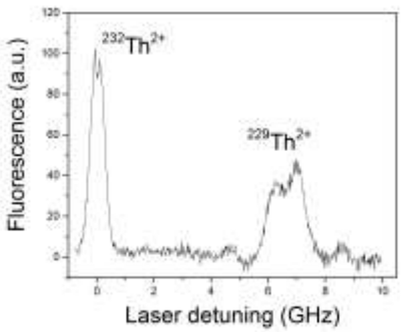


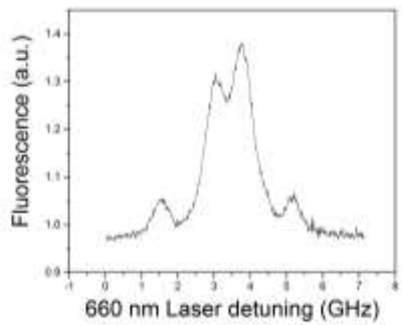
Positive isotope shift of $^{229}Th^{2+}$ relatively to $^{232}Th^{2+}$ is 5.3±0.2 GHz.

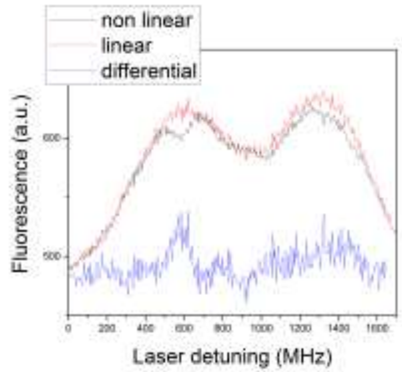
High signal-to-noise ratio due to background-free detection at 538 nm.

Hyperfine structures of ^{229m}Th and ^{229}Th expected to be superimposed.

Th^{2+} 660 nm line. Detection at 660 nm.







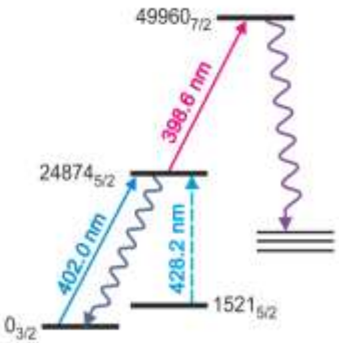
Positive isotope shift of $^{229}Th^{2+}$ relatively to $^{232}Th^{2+}$ is 6.7±0.3 GHz.

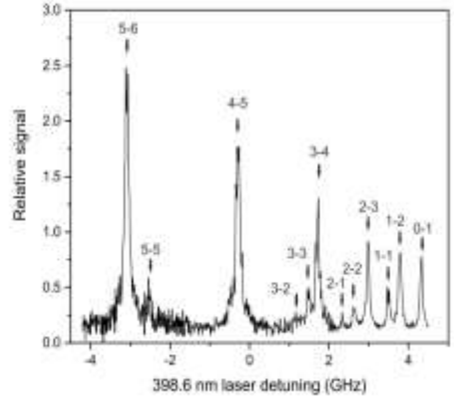
Disadvantage: Background-free detection is in the IR range. Detection at 660 nm is influenced by laser stray light.

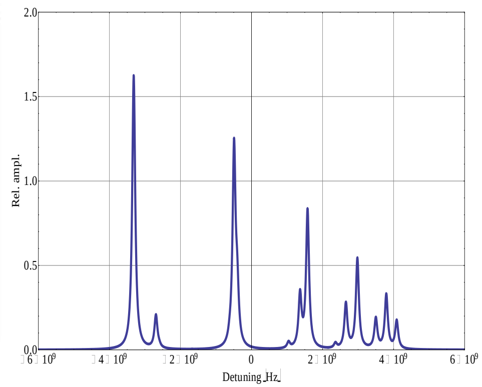
Doppler-free two-photon spectroscopy of the HFS in Th^+ and Th^{2+}

Th^+

- ✓ FWHM of the resonances is about 40 MHz;
- ✓ Background-free detection in the range of 300 nm;







Estimated HFS factors:

A_{24873}=489×10^6 *;

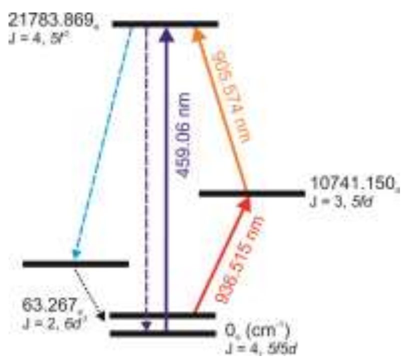
B_{24873}=-409×10^6 *;

A_{49960}=-10×10^6;

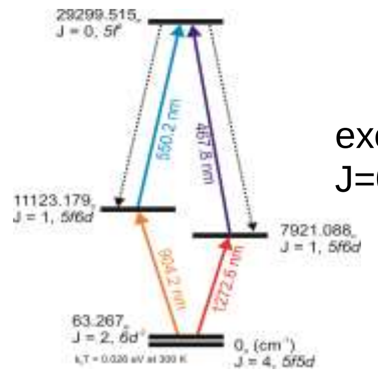
B_{49960}=-1100×10^6

* - fixed according to the measurements of the 402 nm line

Th^{2+}



- ✓ Expected FWHM of the resonances is about 100 MHz;
- ✓ Background-free detection at 459 or 540 nm;
- ✓ The common upper level for the single photone excitation at 459 nm and for the two photon excitation.



excitation of J=0 sate

Requires signal selection in the case when the splitting of the intermediate state HFS components is ~ *kv*

Coming soon

- First tests with the LMU system;
- Tests of the NEET excitation in Th^{2+};
- Extension of the scanning range in Th^{+}.

Thank you for your attention!

Group leader: E. Peik

Ion trap experiment / nuClock

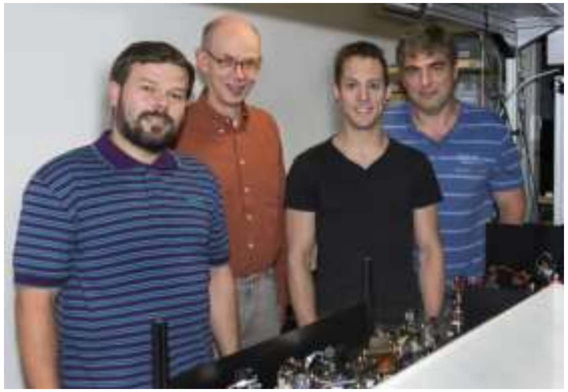
Scientist: M. Okhapkin

Ph.d. students: D. Meier

J. Thielking

Experiment with crystals / nuClock

Scientist: P. Glowacky



Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

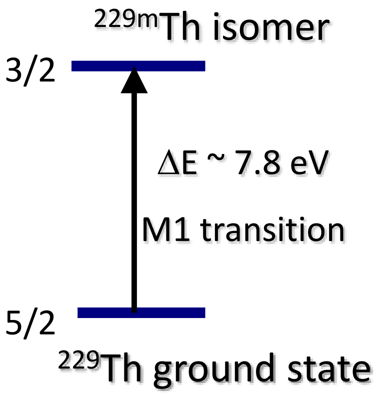
Maxim Okhapkin
E-Mail: maksim.okhapkin@ptb.de

www.ptb.de

Outline

- ✓ Nuclear optical clocks and optical excitation of the isomer.
- ✓ Experiments for the optical excitation of the isomer in PTB:
  - Experimental setup for the excitation of the isomer in thorium.
  - Search of the isomer energy with trapped Th^{+} ions.
  - Extended range search of the isomer excitation with Th^{2+} ions.
- ✓ NuClock project: investigation of the hyperfine structure of thorium and search of the isomeric state HFS in the experiment with recoil nuclei (in collaboration with LMU).
  - Investigation of the HFS in Th^{+} and Th^{2+}.
  - Experimental setup for the observation of the isomer HFS.

Th 229: the nucleus with the lowest-lying excited state

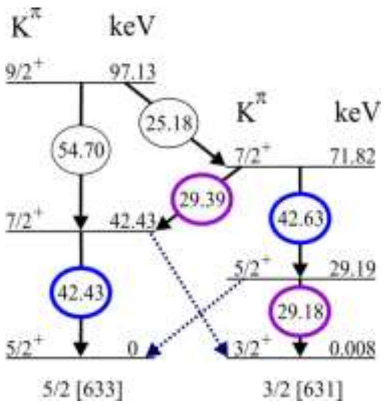


The only known isomer with an excitation energy in the optical range and in the range of outer shell electronic transitions.

- C.W. Reich, R.G. Helmer. PRL, 64, p.271 (1990) – 3.5 ± 1,0 eV
- B. R. Beck et al. (LLNL), PRL 98,142501 (2007).

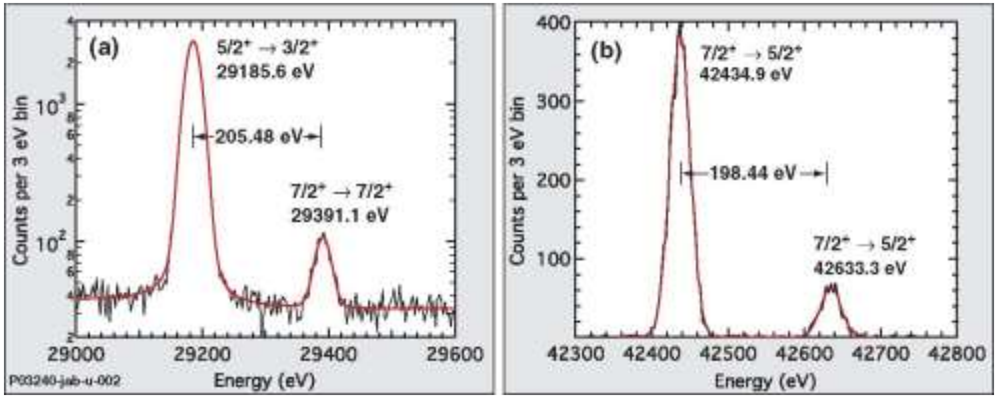
γ - spectroscopy of two decay cascades from the 71.82-keV-level

VUV – range – 7.8 ±0.5 eV



29 KeV lines

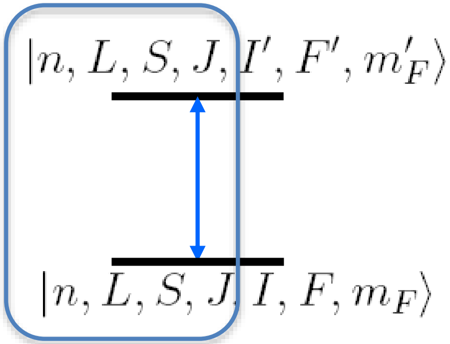
42 KeV lines



✓ Deexcitation of the isomer is observed in the recoil experiment (unfortunately the energy of the isomer is not derived).

Direct detection of the 229Th nuclear clock transition. L. von der Wense et. al. Nature17669 (2016).

Th 229: proposal for nuclear optical clocks



Nuclear and total-angular-momentum quantum numbers (I,F,m_F) can change, purely electronic quantum numbers (n,L,S,J) remain constant.

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

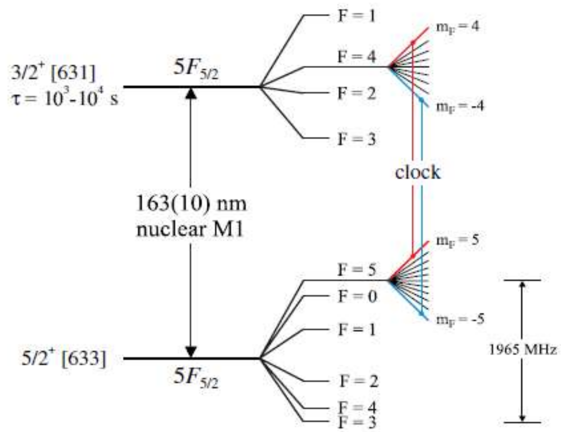
Influence of the electron shell to the nuclear transition: Frequency shifts that depend of (n,L,S,J) are common for both levels. The nuclear transition frequency is independent of the shifts depending only on the electronic quantum numbers.

Holds for: Scalar quadratic Stark shift, including the effects of static electric fields, collisions, blackbody AC Stark shift

Tensor quadratic Stark and electric quadrupole shift: vanish for J<1 or F<1
Hyperfine Stark shift: expected: ≈10^{-19} blackbody shift at room temperature
Linear Zeeman shift: use component m_F=0 – 0 or a pair of stretched states (diff. shift of 4 kHz/mT)
Doppler shift: use ion trapping and laser cooling

Frequency standard based on the pair of stretched hyperfine states:
$5F_{5/2}, I_g=5/2, F=5, m_F=\pm 5\rangle \leftrightarrow |5F_{5/2}, I_m=3/2, F=4, m_F=\pm 4\rangle$.
Systematic shift suppression allows clock performance with a total fractional inaccuracy approaching 1×10^{-19}.

C.J. Campbell et al. PRL 108, 120802 (2012).



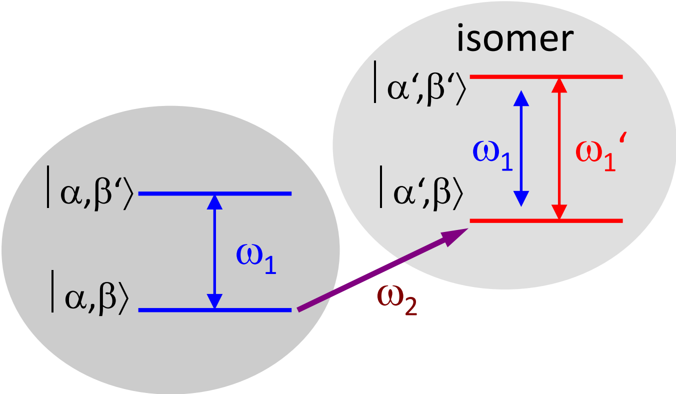
Th 229: proposal for nuclear optical clocks

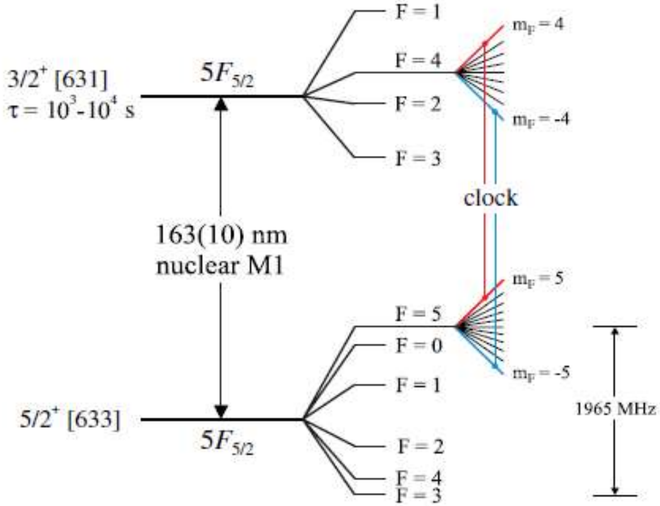
• The nuclear transition frequency is independent of the shifts depending only on the electronic quantum numbers.
E. Peik and Chr. Tamm, Europhys. Lett. **61**, 181 (2003)

More stable against external preturbations due to small dimensions of nuclear in comparision with atom.

Nuclear and total-angular-momentum quantum numbers (I,F,m_F) can change, purely electronic quantum numbers (n,L,S,J) remain constant. Frequency shifts that depend of (n,L,S,J) are common for both levels.

• Systematic shift suppression allows clock performance with a total fractional inaccuracy approaching 1×10^{-19}. C.J. Campbell et al. PRL 108, 120802 (2012).
Frequency standard based on the pair of stretched hyperfine states: $5F_{5/2}, I_g=5/2, F=5, m_F=\pm5\rangle \leftrightarrow |5F_{5/2}, I_m=3/2, F=4, m_F=\pm4\rangle$.





Test of fundamental constants

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 two ~1.4 MeV contributions to the nuclear level energies.

>10 theory papers
2006-2009

See for example:

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

E. Litvinova et al., Phys. Rev. C **79**, 064303 (2009) (|A|○$4x10^4$)

Test of fundamental constants

V.V. Flambaum. PRL 97, 092502 (2006).

Ground state 5/2+[633]

(deformed oscillator quantum numbers $N = 6$, $n_Z = 3$, projection of valence neutron orbital angular momentum $\Lambda = 3$, spin projection $\Sigma = -1/2$, total angular momentum $J = \Lambda + \Sigma = 5/2$.

Excited state 3/2+[631]

$\Lambda = 1$, $\Sigma = -1/2$, $J = 3/2$.

Energy of states: $E_{e,g} = E0 + C\,\Lambda\,\Sigma + D\,\Lambda 2$, $\omega = E_e - E_g = 2C\text{-}8D$, $2C \approx 8D \approx -1.4$ MeV, $\omega \approx 3.5$ eV ,

$$\frac{\delta\omega}{\omega} = \frac{\delta(2C) - \delta(8D)}{\omega} \approx 4\times 10^5 \left(\frac{\delta D}{D} - \frac{\delta C}{C}\right) \approx 10^5 \left(4\frac{\delta\alpha}{\alpha} + \frac{\delta X_q}{X_q} - 10\frac{\delta X_s}{X_s}\right)$$

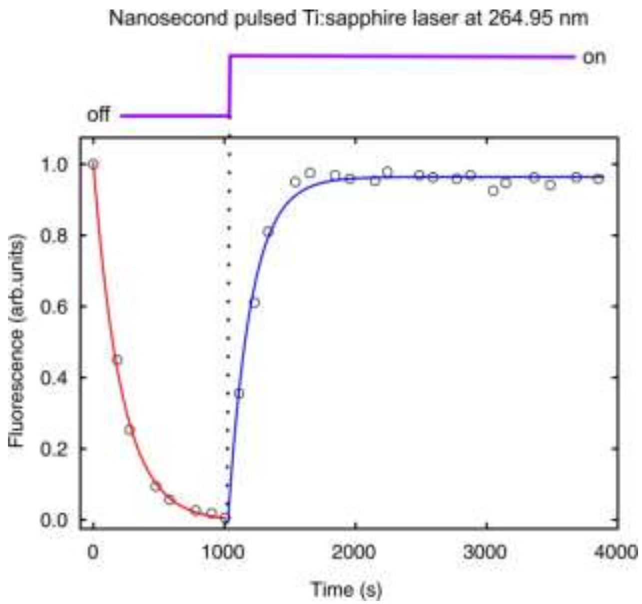
$X_q = m_q/\Lambda_{QCD}$, $X_s = m_s/\Lambda_{QCD}$.

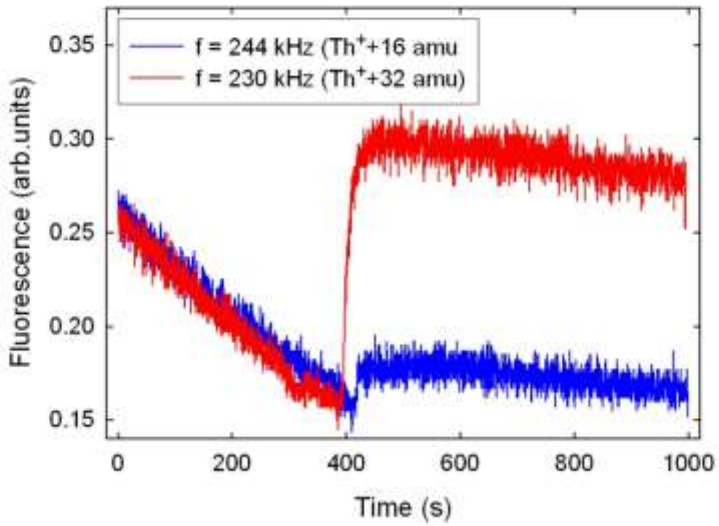
Comparing the Th nuclear frequency to present atomic clocks will allow to look for temporal variations at the level 10^{-21} per year

Photodissotiation of Th^+-containing molecular ions

Th^+ ions are highly reactive with O_2, H_2O, NO, CO_2, CH_4…
ThO^+ (double bond of 9.1 eV dissotiation energy)
$ThOH^+$, ThO_2^+
$ThCH_2^+$ (dissociation energy of 4.8 eV)

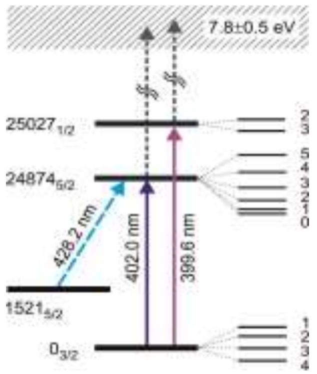
Typical storage time in the trap with buffer gas:
a few hundred sec.
With THG radiation of Ti:Sa ($I_{pulse} \geq 50$ kW/cm^2,
wavelength range 237 – 289 nm) $\tau \geq 30000$ s
<u>At low laser intensity observed resonant structure</u>



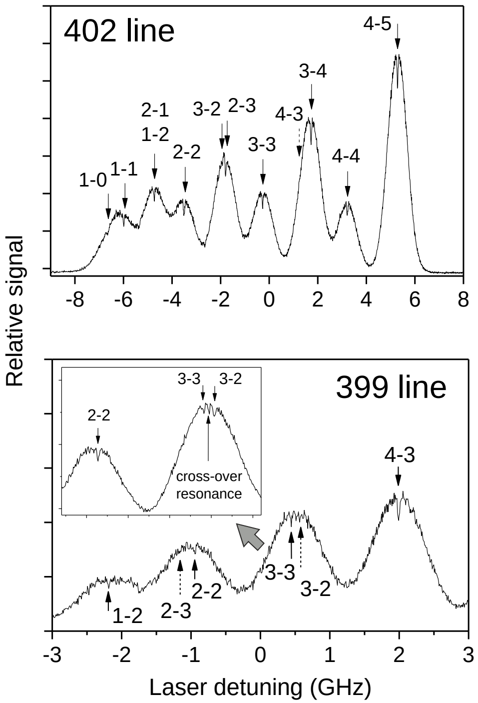


Ejection of ions with secular frequency, applied to DC electrodes of middle secton.
f = 244±2 kHz – ejection of Th^+X with 246-259 amu
f = 230±2 kHz – ejection of Th^+X with ≈265 amu

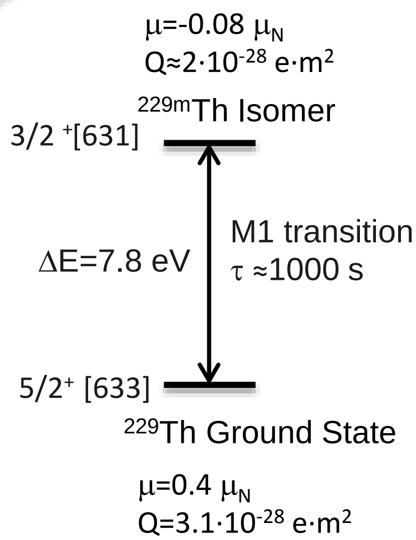
Hyperfine structure of $^{229}Th^{+}$ lines

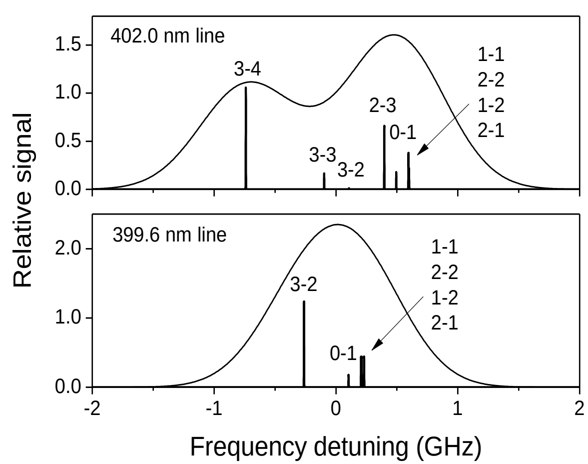


Level [cm^{-1}]	A factor [MHz]	B factor [MHz]	ref
0	-444.2(3.4) -444.2(1.9)	308.4(12.7) 303(6)	* Kälber et al.
24874	489.2(3.7) 488.9(3.7)	-408.8(17.9) -412.8(15.5)	Based on *
25027	-45(19) -42(16)		Based on *



Expected HFS of the isomer





Assuming $A_{is}/A_{gs} \sim \mu_{is}/\mu_{gs}$, $B_{is}/B_{gs} \sim Q_{is}/Q_{gs}$

Isotope shift of $^{229}Th^{+}$ lines

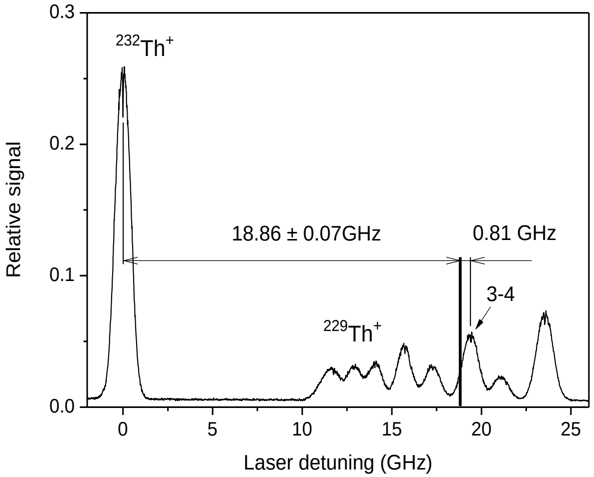
402 nm line:

Positive isotopic effect (blue shift of $^{229}Th^{+}$ line) 0.61 cm^{-1} (18.3 GHz).
E.A. Vernyi, V.N. Egorov, Opt. Spectr. 9 (1960).

Ground state: leading components: *6d²7s* and *6d7s²*;
24874 state: leading components: *6s7s7p* and *5f6d²*
R. Zalubas, C.H. Corliss. J. Res. Nat. Bur. St. A78, 163 (1974)

Very small probability to observe negative isotopic effect in Th (since the s- electrons of the ground state (volume effect) make the gratest contribution to the isotopic effect).

A few hundred $^{229}Th^{+}$ and $^{230}Th^{+}$ lines were investigated - positive isotopic effect observed. G.L. Stukenbroeker, J.R. McNally, Jr. J. Opt. Soc. Am. 43, 1 (1953)



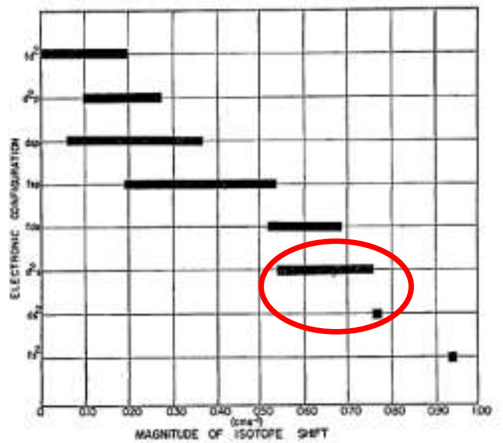


FIG. 3. Approximate range of isotope shifts as a function of electronic configurations.

399 nm line:

24874 state: leading component: *5f6d²*
R. Zalubas, C.H. Corliss. J. Res. Nat. Bur. St. A78, 163 (1974)

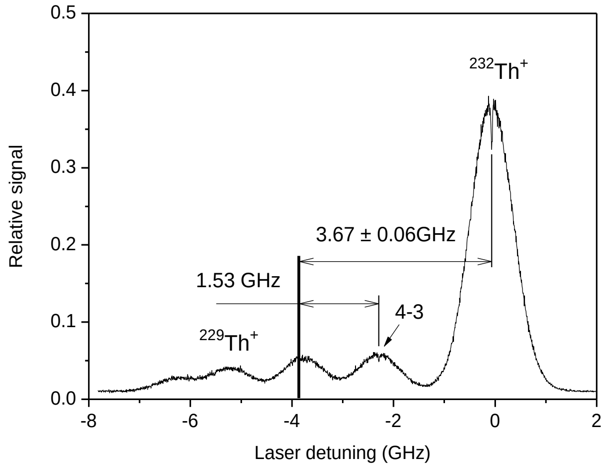
We observe negative isotopic effect

fs² configurations only appear at low energies

s²p configuration? Missed on the graph.

A few levels with *s²p* configurations were identified in this energy range.

Ab initio calculations: S. Porsev, M. Safronova – leading configuration 7s²7p!



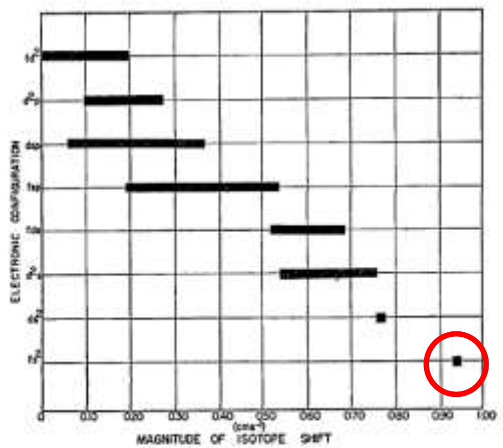
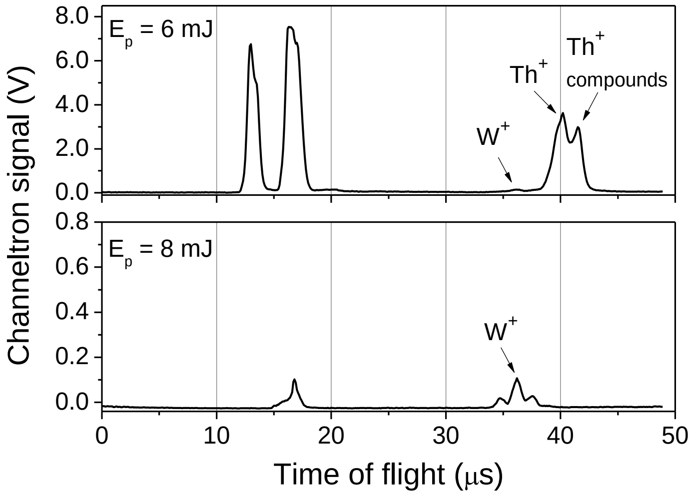


FIG. 3. Approximate range of isotope shifts as a function of electronic configurations.

Trap loading with $^{229}Th^+$

Tests with TOF spectrometer

Different targets with $^{232}Th(NO_3)_4$
Ablation laser: pulsed Nd:YAG (1064, 532, 355 nm); pulse duration ~ 10 ns, pulse energy < 10 mJ
Ablation of Th from Al and W substrates at 1064 nm demonstrates the most promising result.

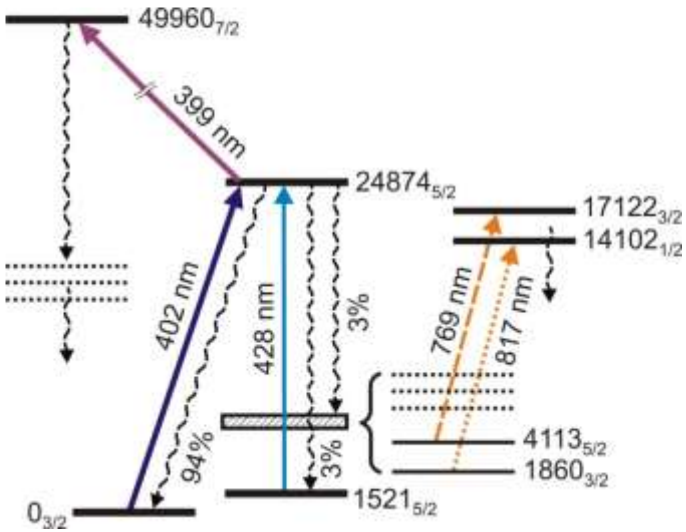


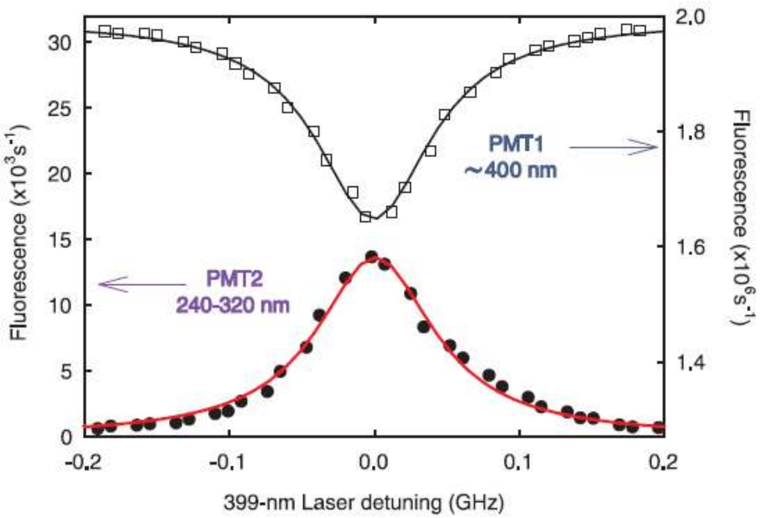
Trap loading tests

Amount of ^{232}Th on substrate: ~ 4×10^{14} atoms, 140 ng $\rightarrow$ 1 kBq activity of ^{229}Th
Loading from W substrate:
Executed > 500 loadings with the ion number > 30% of the maximum trap capacity
Loading efficiency $\geq 10^{-6}$ (one order of magnitude higher than acheived with evaporated method*.
Loading from Al substrate: not efficient. Influence of a big number of Al ions in ablation plume which affect Th trajectories.
Loading of ^{229}Th: ~ 50 loadings are executed…

* W Kälber et al. J. Mod. Opt. 39 335 (1992)

Population trapping and two photon excitation in CW mode



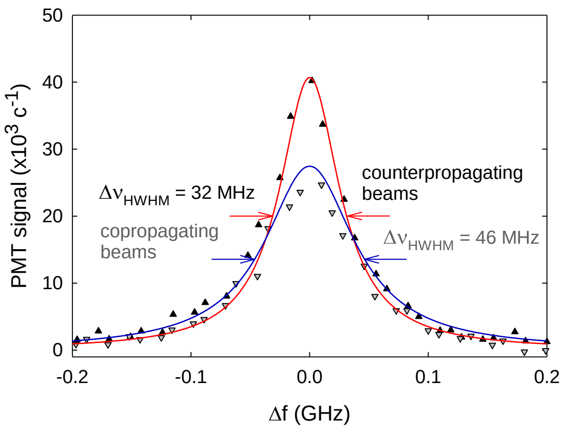


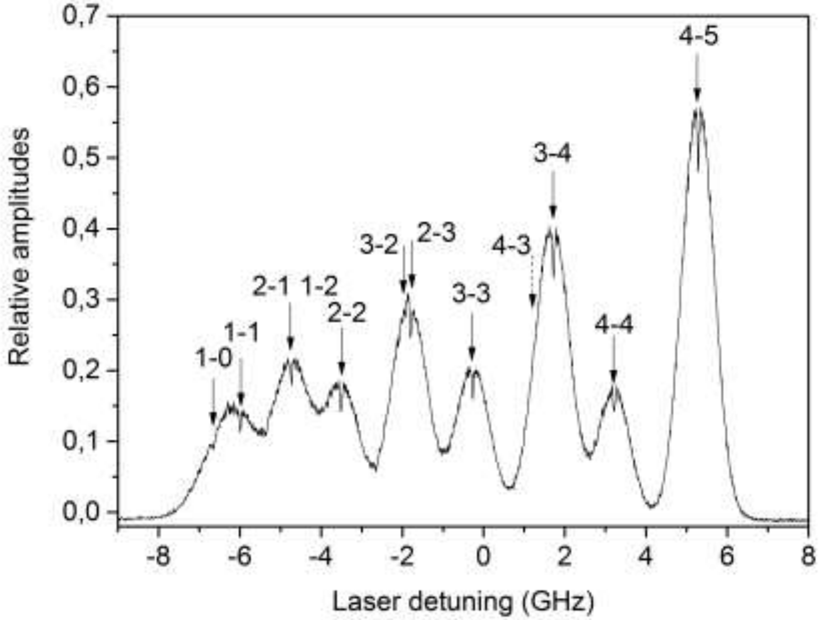
deplition of 24874 cm^{-1} state and fluorescence from 49960 cm^{-1} state

- CW mode – population trapping
- Collisional quenching (He, Ar, N_2)
- Repumper at 428 nm.

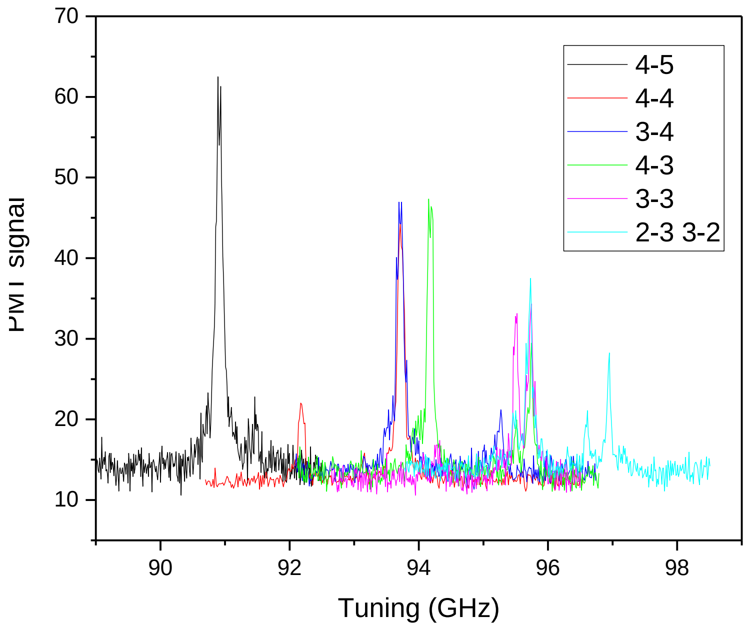
✓ Two photon excitation with 2 ECDLs: low fraction ~ 0.1% is transfered to the 24874 state.

O.A. Herrera-Sancho, M.V. Okhapkin, K. Zimmermann, Chr. Tamm, E. Peik, A.V. Taichenachev,
V.I. Yudin, P. Glowacki Phys.Rev. A 85, 033402 (2012).



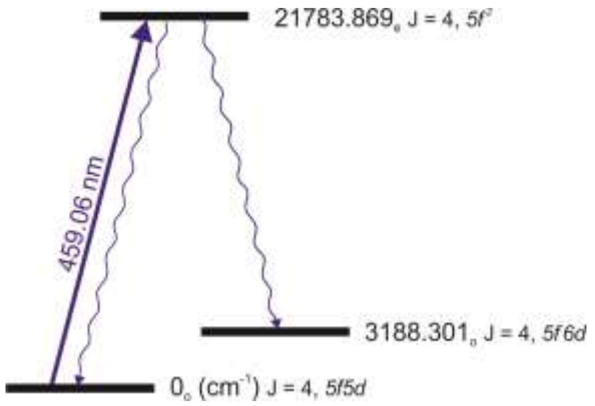


Relative amplitudes
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
4-5
3-4
3-2
2-3
4-3
2-1 1-2
3-3
2-2
4-4
1-1
1-0
-8
-6
-4
-2
0
2
4
6
8
Laser detuning (GHz)



70
60
50
40
30
20
10
4-5
4-4
3-4
4-3
3-3
2-3 3-2
90
92
94
96
98
Tuning (GHz)

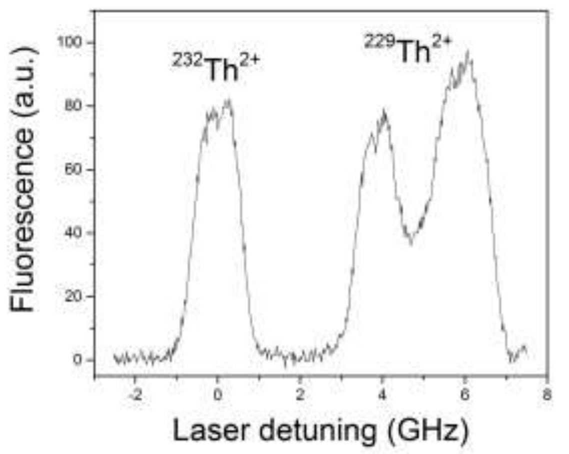
Th^{2+} 459 nm line

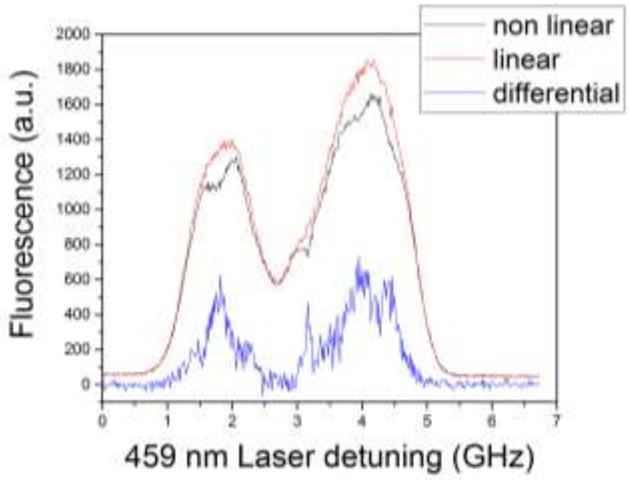


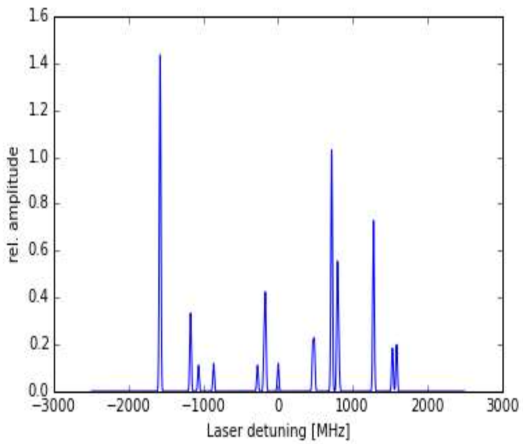
Positive isotope shift of $^{229}Th^{2+}$ relatively to $^{232}Th^{2+}$ is 5.3±0.2 GHz.

High signal-to-noise ratio due to background-free detection at 538 nm.

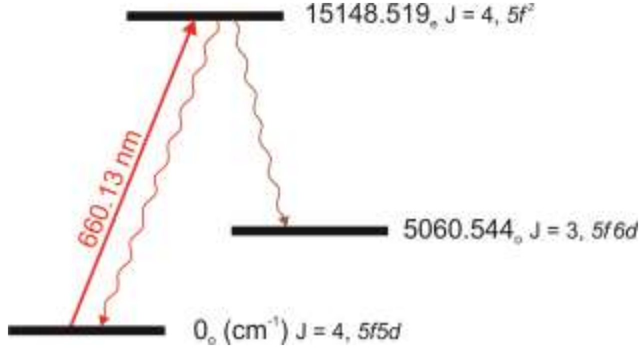
Hyperfine structures of ^{229m}Th and ^{229}Th expected to be superimposed.







Th^{2+} 660 nm line

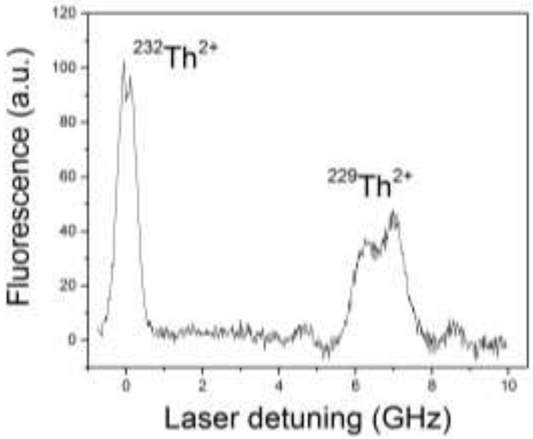


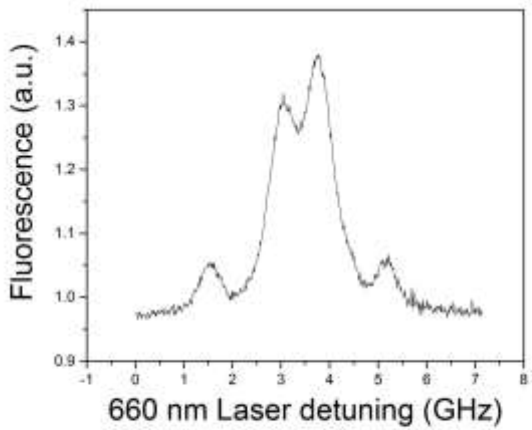
Positive isotope shift of $^{229}Th^{2+}$ relatively to $^{232}Th^{2+}$ is 6.7±0.3 GHz.

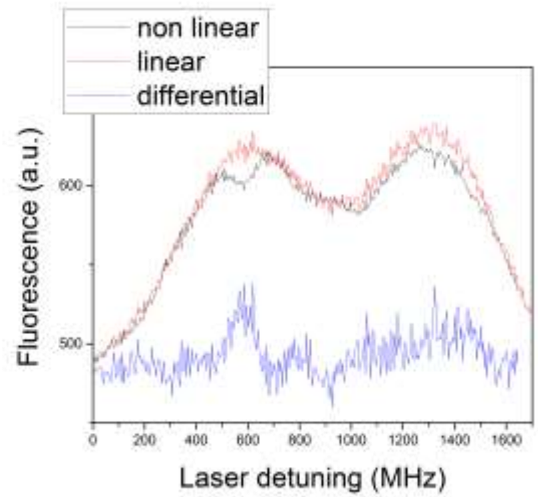
Disadvantage:

- Background-free detection is in the IR range.
- Detection at 660 nm is influenced by laser stray light.

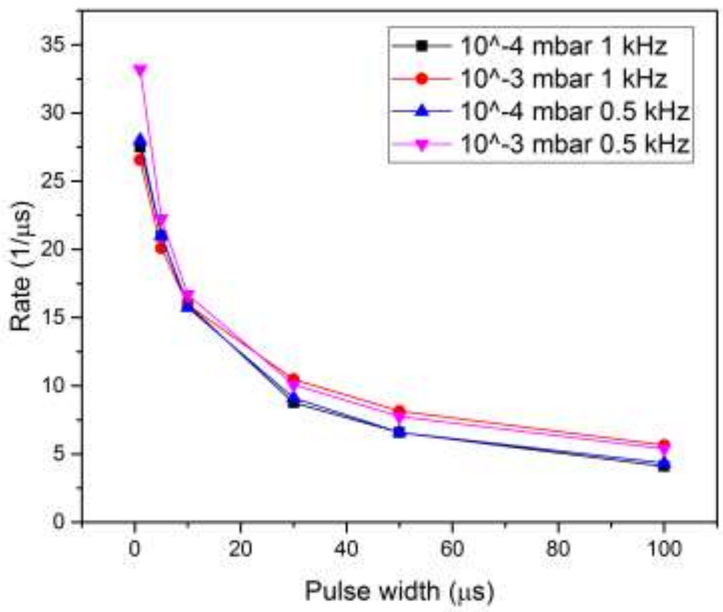
Detection at 991 nm is in preparation.

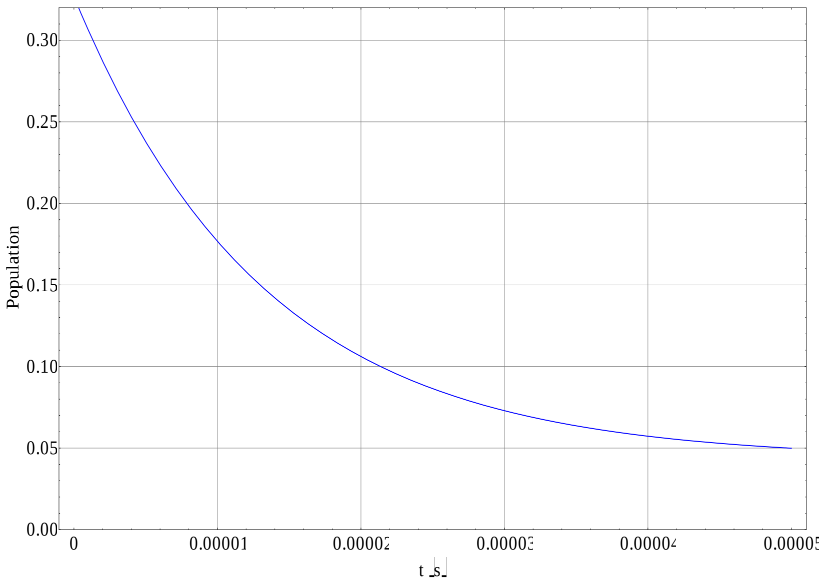






Th^{2+} 459 nm line





γ_{21}=1*10^8;
γ_{31}=1*10^8;
γ_{23}=1*10^8;
γ_{41}=1*10^4;
γ_{24}=2*10^5;

Outline

Outline