Prospects of direct Th229m energy measurement and search for its γ decay

CSN3/TORIO_229

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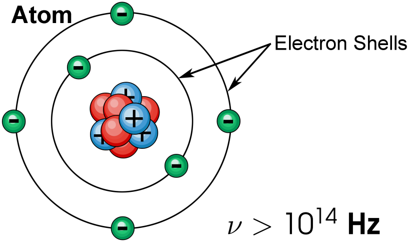
Seminar, LNL, 15 April 2021

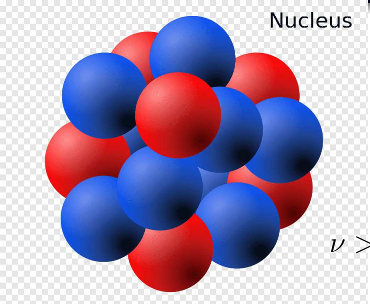
Atomic and nuclear scales



$\nu > 10^{14}$ **Hz**

Radius: 0.5-2 Å
Excitations: eV - keV

- 1 s≡9.192.631.770 RF oscillations in Cs clock,
- *highly monochromatic coherent* lasers (eV),
- visible-microwave comb ($\frac{\Delta\nu}{\nu} \sim 10^{-18}$),
- optical ion clocks: Yb^+, Al^+, Ca^+, Sr^+, Hg^+ etc.



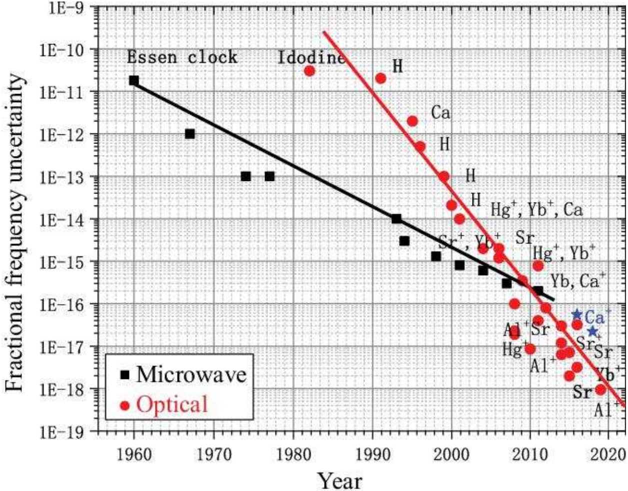
$\nu > 10^{17}$ **Hz**

Radius: 1.3-8 fm
Excitations: keV - MeV

- incoherent γ-sources,
- Mössbauer spectroscopy ($\frac{\Delta\nu}{\nu} > 10^{-22}$),
- broad linewidth FELs ($\frac{\Delta\nu}{\nu} \sim 10^{-3} \div 10^{-5}$),
- no link to RF electronics.

Atomic clock evolution

1. Cs atomic fountain - J. Zacharias 1956,
2. GPS application -1978/1993,
3. optical ion clock - H.G. Dehmelt and W. Paul (Nobel Prize 1989),
4. laser cooling - S. Chu, C. Cohen and W.D. Phillips (Nobel Prize 1997),
5. visible-microwave comb - Th. Hänsch and J. Hall 1999 (Nobel Prize 2005).

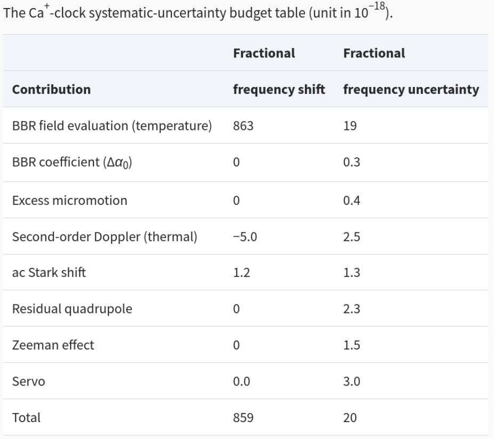


[1] *K.Gao ,Nat.Sci.Rev.7, 1799 (2020).*

‣ K.Gao ,Nat.Sci.Rev.7, 1799 (2020).

Atomic clock precision

1. Black Body Radiation (BBR),
2. servo frequency steering,
3. 2d order Doppler shift,
4. electric quadruple shift,
5. Zeeman shift,
6. Stark shift.



The Ca^+-clock systematic-uncertainty budget table (unit in 10^{-18}).

Contribution	Fractional frequency shift	Fractional frequency uncertainty
BBR field evaluation (temperature)	863	19
BBR coefficient ($\Delta\alpha_0$)	0	0.3
Excess micromotion	0	0.4
Second-order Doppler (thermal)	−5.0	2.5
ac Stark shift	1.2	1.3
Residual quadrupole	0	2.3
Zeeman effect	0	1.5
Servo	0.0	3.0
Total	859	20

[1] *K.Gao ,Nat.Sci.Rev.7, 1799 (2020).*

▸ K.Gao ,Nat.Sci.Rev.7, 1799 (2020).

Nuclear clock precision

1. first idea from E. Peik and C. Tamm, Eur.Phys.Lett.61, 181 (2003),
2. small coupling of external fields to nucleus,
3. atomic shell screening,
4. small black-body radiation.

Type of shift	Shift ($\times 10^{-20}$)	Uncertainty ($\times 10^{-20}$)
Excess micromotion	10	10
Gravitational	0	10
Cooling laser stark	0	5
Electric quadrupole	3	3
Secular motion	5	1
Linear Doppler	0	1
Linear Zeeman	0	1
Collisions	0	1
Blackbody radiation	0.013	0.013
Clock laser stark	0	$\ll 0.01$
Trapping field stark	0	$\ll 0.01$
Quadratic Zeeman	0	0
Total	18	15

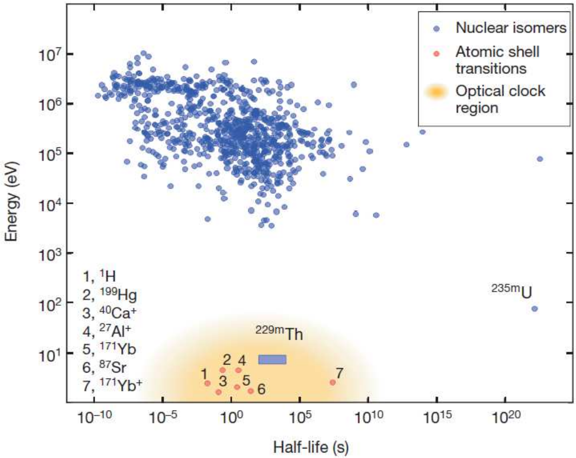
[1] *C.J. Campbell et al.,Phys.Rev.Lett.108,120802 (2012)*

▸ C.J. Campbell et al.,Phys.Rev.Lett.108,120802 (2012)

Known nuclear isomers

1. ^{235m}U at 76.8 eV with half life 25 min. (IC) or 10^{14} years (γ),
2. ^{229m}Th at 8 eV with half life 7 μs (IC) or 1 hour (γ),

All other known nuclear isomers have energy $>$1 keV.



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[1] *L. von der Wense et al.,Nature 533, 47 (2016)*

▸ L. von der Wense et al.,Nature 533, 47 (2016)

^{229m}Th isomer

- 43 years from the first indication to the final confirmation,
- γ decay has not been observed so far,
- induced excitation of ^{229m}Th not yet demonstrated.

Year	Energy (eV)	Ref.
1976	<100	L.A. Kroger, C.W. Reich, Nucl.Phys.**A259**, 29
1990	1±4	C.W. Reich, R. Helmer, Phys.Rev.Lett.**64**, 271
1994	3.5±1	R. Helmer, C.W. Reich, Phys.Rev.**C49**, 1845
2007	7.6±0.5	B.R. Beck *et al.*, Phys.Rev.Lett.**109**, 142501
2019	8.3±0.2	B. Seiferle *et al.*, Nature **573**, 243

Non-spherical ^{229}Th rotational splitting

1. ^{229}Th deformed nucleus (axial),
2. Nilsson model[1] level scheme[2]:

$$E(\Omega^{\pi}[N, n_z, \Lambda]) \ ,$$

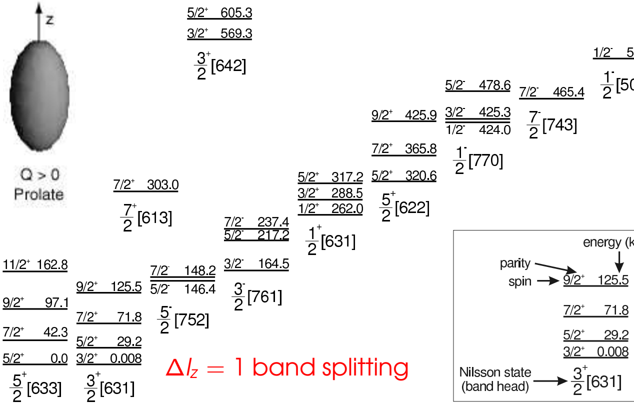
$$\Omega = j_z, \ [2j+1]$$
$$N = n_z + n_{\perp}$$
$$\Lambda = l_z, \ [2n_{\perp}+1]$$

3. deformation parameter:

$$\delta = 1 - \left(\frac{L_{\perp}}{L_z}\right)^2$$

4. ^{229}Th prolate[3,4,5]

$$\delta \sim 0.1, L_z \sim 1.05 L_{\perp}$$
$$M1\left(\tfrac{3}{2}^{+} \to \tfrac{5}{2}^{+}\right)$$



$\Delta l_z = 1$ band splitting

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[1] S.Nilsson,Matematisk-fysiske Med-delelser,29(16)(1955).

[2] G.Musiol et al.,Kern und El.physik.,Weinheim(1988).

[3] E.Ruchowska et al.,Phys.Rev.C73,044326(2006).

[4] A.Hayes et al.,Phys.Rev.C78,024311(2008).

[5] E.Litvinova et al.,Phys.Rev.C79,064303(2009).

^{229m}Th isomer decay

1. magnetic dipole transition M1: $\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$,
2. lifetime[1,2,3] (γ only):
$$\tau_\gamma \sim \frac{10.95h}{E_\gamma^3 B(M1)} \sim 1h, \quad B(M1) \sim 0.025\mu_N^2$$
3. ionization energy of 6.5 eV shortens the lifetime (IC) to 10^{-4} s in metal[4] (overestimates ^{235m}U lifetime by 3 orders of magnitude),
4. energy scaling from the same transition $\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$ of ^{233}U(312 keV) level yields lifetime of 4 h[1],
5. scaling from another M1 $\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$ transition yields lifetime of 0.3 h[5],
6. electronic bridge (EB) process may be important in presence of resonant atomic levels.

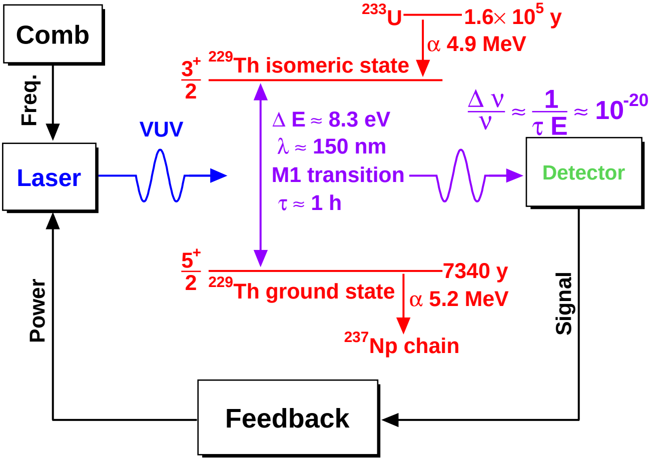
[1] *R.Helmer and C.Reich. Phys.Rev.C49,1845(1994).*
[2] *V.Strizhov and E.Tkalya.Sov.Phys.JETP,72,387(1991).*
[3] *E.Ruchowska et al.,Phys.Rev.C73,044326(2006).*
[4] *E.Tkalya.JETP Lett.70,371(1999).*
[5] *J.Jeet et.al.Phys.Rev.Lett.114,253001(2015).*

^{229}Th-based Nuclear Clock

1. Lowest nuclear exited state[1],
2. dominant IC decay[2] can be suppressed,
3. VUV-laser excitation,
4. very narrow γ-linewidth[3],
5. $N=10^5 \div 10^{12}$ oscillators[4,5],

$$FoM = \frac{\nu\sqrt{N}}{\Delta\nu},$$

6. $>10^1 \div 10^2$ FoM improvement wrt atomic clock.



Comb

Freq.

Laser

VUV

^{233}U — 1.6×10^5 y

α 4.9 MeV

$\frac{3}{2}^+$ ^{229}Th isomeric state

$\Delta E \approx 8.3$ eV

$\lambda \approx 150$ nm

M1 transition

$\tau \approx 1$ h

$\frac{\Delta\nu}{\nu} \approx \frac{1}{\tau E} \approx 10^{-20}$

Detector

$\frac{5}{2}^+$ ^{229}Th ground state — 7340 y

α 5.2 MeV

^{237}Np chain

Signal

Power

Feedback

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[1] *L.Kroger and C.Reich, Nucl.Phys.A259, 29(1976).*

[2] *B.Seiferle et al., Nature 573, 243 (2019).*

[3] *V.Strizhov and E.Tkalya, Sov.Phys.JETP 72, 387 (1991).*

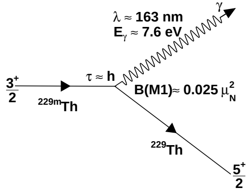
[4] *C.Campbell et al., Phys.Rev.Lett. 102, 233004 (2009).*

[5] *R.Jackson et al.,J.Phys.Cond.Mat.21, 325403 (2009).*

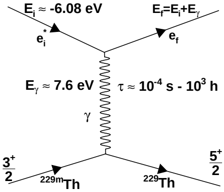
TORIO-229 proposal (CSN3 meeting 22/06/2016)

1. Direct measurement of ^{229}Th lowest level energy and lifetime in the region 5-50 eV and 1 ms-1 h,
2. sum of all possible decay channels: γ, IC and EB,
3. cryogenic μcalorimeter with $<$ 3 eV threshold and $<$0.5 eV resolution,
4. ^{233}U, ^{229}Th and ^{228}Th deposits,
5. background studies with ^{238}U and ^{232}Th samples,
6. signal studies with ^{235m}U (77 eV, 26 m, E3), ^{239}Pu deposit.

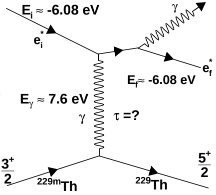
γ



IC



EB



μcalorimeter with embedded source (2016)

Cryogenic μcalorimeter heat capacity budget:

1. 3.8 ng ^{233}U target 17.3 fJ/K,
2. Ir TES 8 fJ/K,
3. Au absorber 0 fJ/K,
4. Si membrane 0.013 fJ/K.

Energy resolution:

$$\sigma_E \sim \sqrt{kT^2C} \sim 0.42eV\ .$$

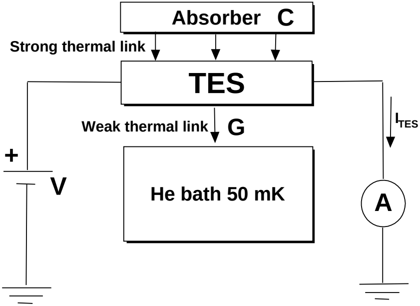
Energy dynamic range 160 eV:

$$\Delta T \sim \frac{E_{dep}}{C} < 1mK\ .$$

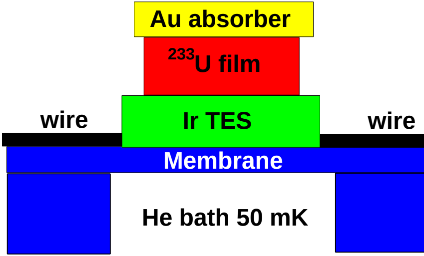
Target activity: 3.8 ng ^{233}U, 1.3 Bq α activity (A=0.35$\times M_U[ng]$), or 100 ^{229m}Th/h.

Signal decay time:

$$\tau_D \sim \frac{C}{G} \sim 2.5ms\ .$$

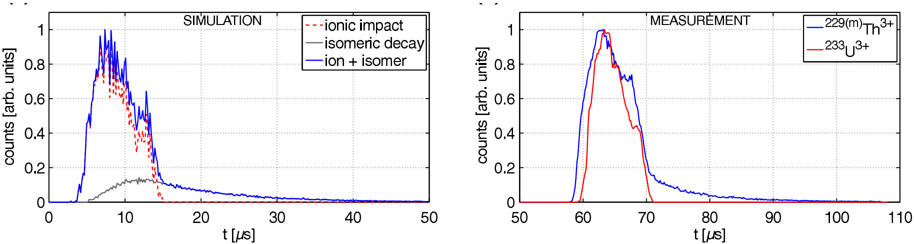


[1] F.Ponce, PhD thesis, LLNL (2017).



LMU ^{229m}Th lifetime measurement (2017)

1. Extension of direct observation experiment[1],
2. long $^{229m}\text{Th}^{3+}$ ion transport (90 ms),
3. fast decay after impact onto MCP (neutralization),
4. neutral ^{229m}Th lifetime (IC)[2]: $7 \pm 1\ \mu s$,
5. 9 orders of magnitude lower than expected (γ): 1 h,
6. relative linewidth (IC): $\sim 10^{-11}$ (atomic clock $< 10^{-13}$),
7. neutral ^{229m}Th γ-decay branching: $\sim 10^{-9}$ (theor.).



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[1] *L.von der Wense et.al.Nature 533,47(2016),*

[2] *B.Seiferle et.al.Phys.Rev.Lett.118,042501(2017).*

▸ B.Seiferle et.al.Phys.Rev.Lett.118,042501(2017)

μcalorimeter pile-up

Updated decay rate estimate:

1. 3.8 ng ^{233}U target (10^{13} atoms)
2. 1.3 Bq α activity ($A = 0.35 \times M_U[ng]$),
3. 100 ^{229m}Th/h,
4. 10^{-3} ^{229m}Th γ decay/y.

Signal decay time:

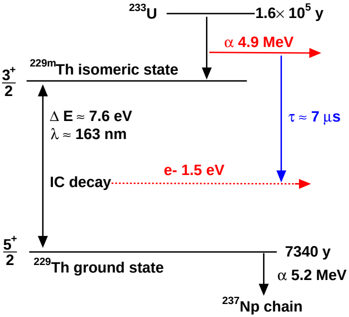
$$\tau_D \sim \frac{C}{G} \sim 2.5ms \ .$$

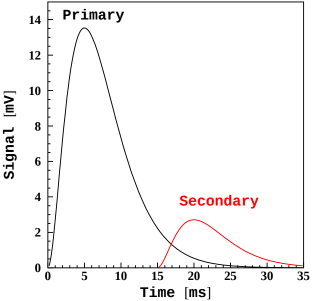
Separation of two decays:

$$\Delta t > \tau_D ln \frac{E_{primary}}{E_{secondary}} \ .$$

Probability of separated decay:

$$P \sim \exp\left[-\frac{2.5ms}{7\mu s}\right] \sim 10^{-155} \ .$$



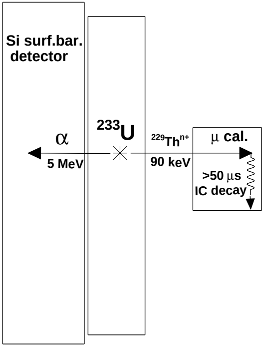


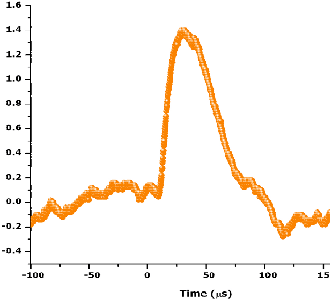
TORIO-229 setup (CSN3 meeting 22/06/2017)

- Fast cryogenic μcalorimeter with signal full decay time $\Delta t < 50\ \mu s^1$,
- α-^{229}Th$^+$ coincidence,
- ^{233}U deposited on Si detector,
- long. range of 90 keV ^{229}Th$^+$ in U is 6.7 nm (path 10.7 nm), in UO$_2$ is 8.3 nm (path 16.1 nm),
- 10 nm thick ^{233}U film with 1 nm Mg layer or 20 nm thick ^{233}UO$_2$ film, activity A_U<5 kBq,
- expected rate of time-separated events (assumes $t_{IC} = 7\ \mu s$):

$$R_{IC}^{\mu cal} \sim A_U B_{229m} A_{\mu cal}^{geom} e^{-\Delta t / t_{IC}} \ ,$$

$$R_{IC}^{\mu cal} \sim 10^4 * 0.02 * 10^{-4} * 10^{-3} \sim \frac{1}{day} \ .$$





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[1] D.Bagliani et al.,J.Low.Temp.Phys.151,234(2008).

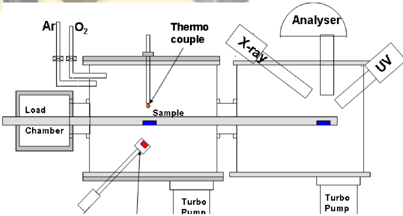
Primary sources (R. Caciuffo, JRC, Karlsruhe)

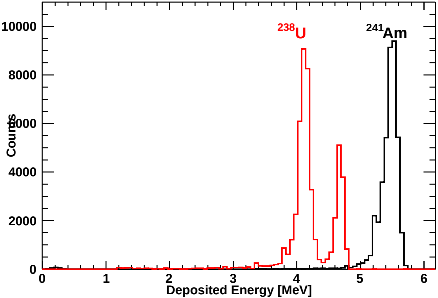
First source was deposited by sputtering on active surface of Si detector (300 mm^2), in form of UO_2 dielectric film with diameter 10mm and thickness 10 nm:

1. ^{238}U $<$0.2 Bq (+0.1 Bq ^{234}U), delivered for background measurements,
2. ^{233}U $<$5 kBq, authorization received, waiting for working TES prototype.

Source requirements:

- E-loss limits thickness $\leq$20 nm,
- Si-rate limits activity $<$40 kHz.





μcalorimeter principles

μcalorimeter operation:

① constant current flows through TES without resistance,

② deposited energy is transformed in heat,

③ heat increases TES resistance,

④ Resistance reduces flowing current,

⑤ current read by SQUID.

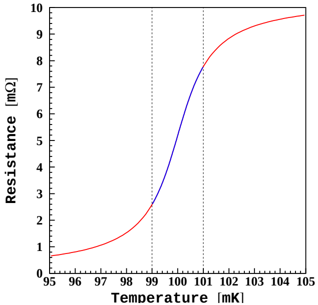
Signal:

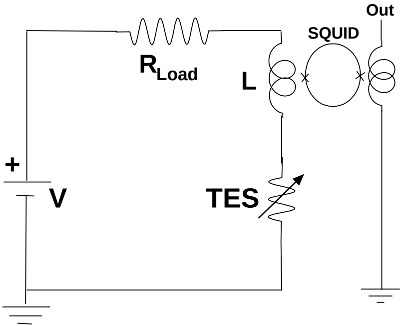
$$\Delta T = E_{dep}/C \sim 2fJ/K\ .$$

Energy resolution:

$$\sigma_E \sim \sqrt{kT^2C}\ .$$

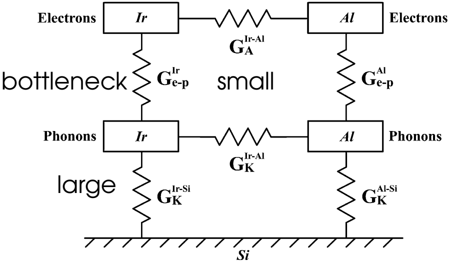
SQUID noise: 1 pA/$\sqrt{Hz}$.

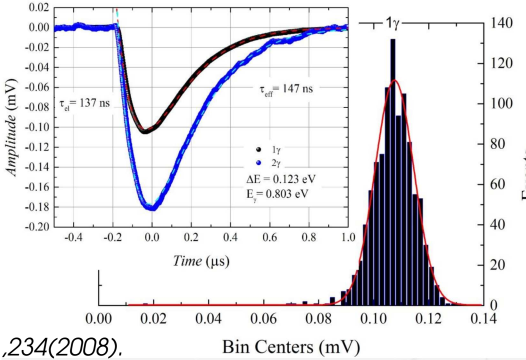




μcalorimeter optimization

- Signal decay time at $T = 100$ mK:
$$\tau \sim \frac{C \sim 1 fJ/K}{G \sim 10^5 fW/K} \sim 10\mu s\,.$$
- T-dependence:
$$\frac{C \simeq \gamma V T}{G \sim G_{ep} \simeq 5\Sigma V T^4} = \frac{\gamma}{5\Sigma T^3}$$
- T=100mK→300mK:
$$\tau(300mK) \sim \frac{\tau(100mK)}{30}$$
- noise power:
$$NEP \sim \sqrt{4k_b T^2 G}\,,$$
$$V_{noise} \sim [20 k_b \Sigma V]^{1/4} T^{3/2}$$





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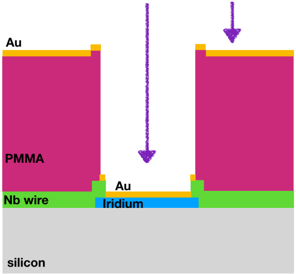
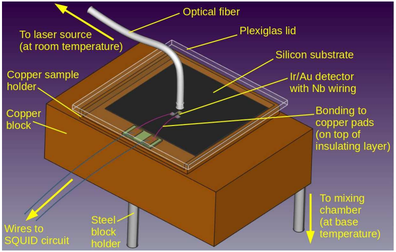
[1] D.Bagliani et al.,J.Low.Temp.Phys.151,234(2008).

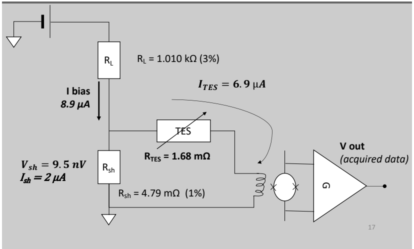
[2] C.Portesi et al.,IEEE Trans.App.Supercond.25,3(2015).

TES development details

① design lithographic mask,
② tested Ti-Au and Ir TESs,
③ tested Nb and Al wiring,
④ PLD of Ir, sputtering of Nb,
⑤ PMMA+Au shadow mask[1],
⑥ wire bonding to SQUID,
⑦ alignment of fiber,
⑧ SQUID calibrations.







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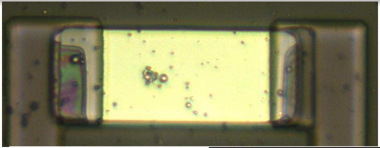
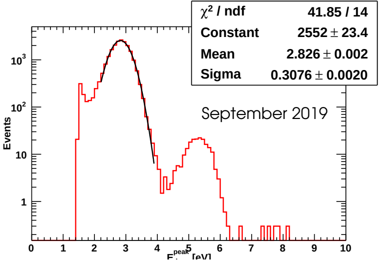
[1] M.Fedkevych et al., 10.1109/TASC.2021.3063328

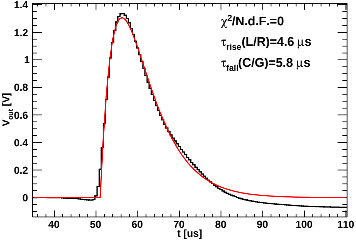
▸ M.Fedkevych et al.,IEEE TASC (2021)

Detector development and characterization

1. developed Ir TES satisfying experimental requirements[1]: signal fall time $\tau < 10\ \mu s$, resolution $\Delta E < 1$ eV,
2. $15 \times 26\ \mu m^2$, 150 nm thick Ir,
3. few μm PMMA + 50 nm Au shadow mask,
4. transition $T_C = 110.5$ mK,
5. laser calibrations and Poissonian fit,
6. analysis of data and extraction of TES parameters.







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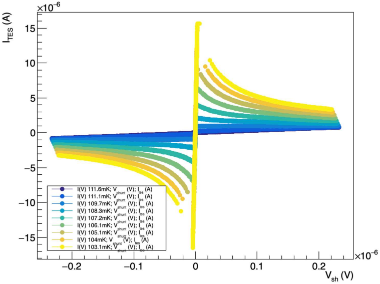
[1] *M.Fedkevych et al,10.1109/TASC.2021.3063328*

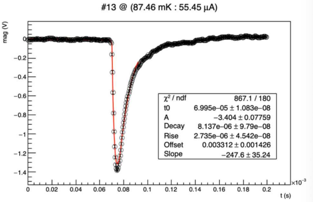
▸ M.Fedkevych et al.,IEEE TASC (2021)

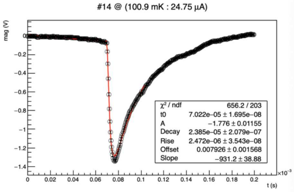
TES characterization details

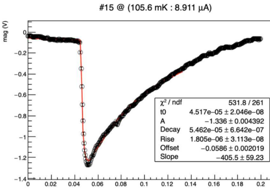
1. high bias current 60μA,
2. operation at 90 mK$<T_C$,
3. large negative electrothermal feedback[1]:

$$\tau_{eff} \simeq \frac{\tau_{th}}{1+\alpha P/GT} \,.$$









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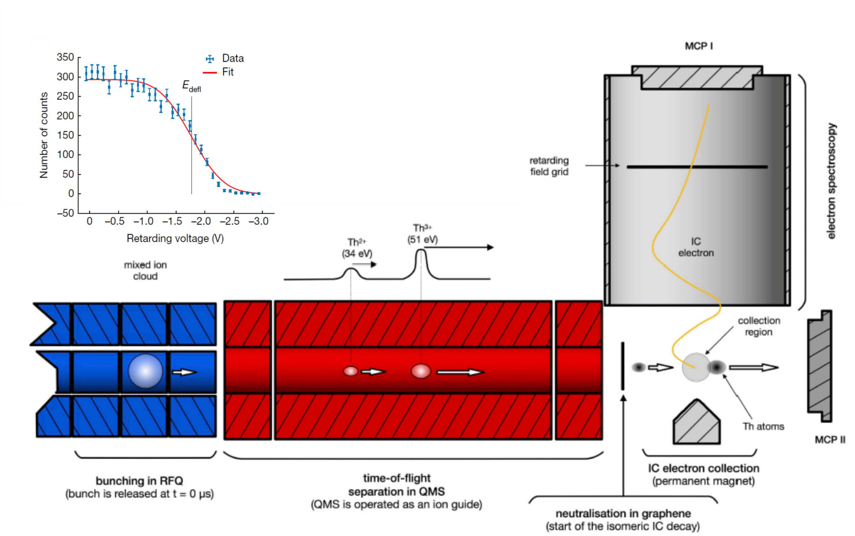
[1] *M.Biasotti, internal report (2020),*

LMU ^{229m}Th energy measurement (2019)

measured 1.77 eV + 6.51 eV (binding) = 8.28 $\pm$ 0.17 eV



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[1] *B. Seiferle et al., Nature 573, 243 (2019).*

‣ B. Seiferle et al., Nature 573, 243 (2019)

^{229m}Th γ-decay search

- IC decay has broad linewidth:

$$\frac{\Delta\nu}{\nu} \simeq \frac{1.4 \times 10^5 Hz}{2 \times 10^{15} Hz} \simeq 10^{-10} ,$$

- γ-decay in neutral atom:

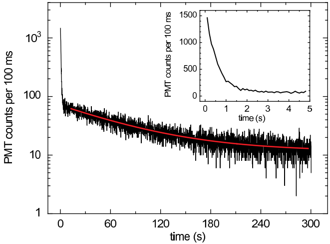
$$\frac{\Gamma_\gamma}{\Gamma_{IC}} \simeq \frac{1/1h}{1/7\mu s} \simeq 2 \times 10^{-9} ,$$

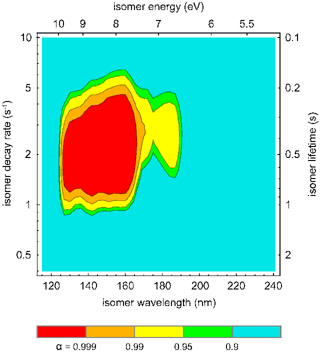
1. Th^{n+} ion traps (10^6 Th/cm^3):

$$\sigma_{\gamma_{abs}} \sim 10^{-11} cm^2 \frac{3 \times 10^{-19} eV}{\Delta\nu_{source}}$$

$$R_{\gamma_{dec}} \sim \rho x \sigma_\gamma \frac{n_\gamma}{\tau_\gamma \sim 1h} \sim \frac{10^2}{s} \frac{\Gamma_\gamma}{\Delta\nu_{source}}$$

2. wide bandgap crystals with ^{229}Th: CaF$_2$[1], MgF$_2$, LiSrAlF$_6$, LiCaAlF$_6$





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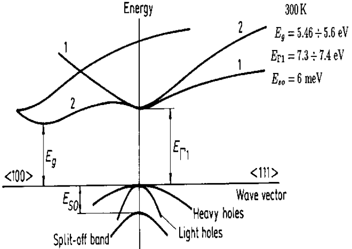
[1] S.Stellmer et.al.Phys.Rev.A97 (2018) 062506.

▸ S.Stellmer et.al.Phys.Rev.A97 (2018) 062506

Chemical binding IC suppression

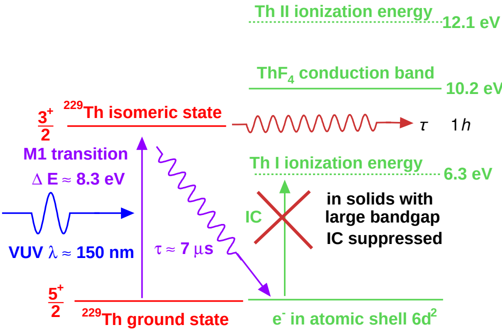
1. IC decay requires: $E_{decay} > E_{gap}$,
2. find Th-compound with $E_{gap} > 8.3$ eV,
3. theoretical calculations[1] suggested Na_2ThF_6 and ThF_4 would have $E_{gap} > 8.9$ eV, while ThX4 (X=Cl, Br, I) $E_{gap} < 6.5$ eV.

Comp.	Bandgap (eV)
CaF_2	12
UO_2	1.3
UC,UN,UCl,UF	2-3
Other	?



[1] J.K.Ellis et al.,Inorg.Chem.53 (2014) 6769.

▸ J.K.Ellis et al.,Inorg.Chem.53 (2014) 6769



Th II ionization energy 12.1 eV

ThF_4 conduction band 10.2 eV

$\frac{3}{2}^+$ ^{229}Th isomeric state

τ 1 h

M1 transition

Δ E ≈ 8.3 eV

Th I ionization energy 6.3 eV

IC

in solids with large bandgap IC suppressed

VUV $\lambda \approx$ 150 nm

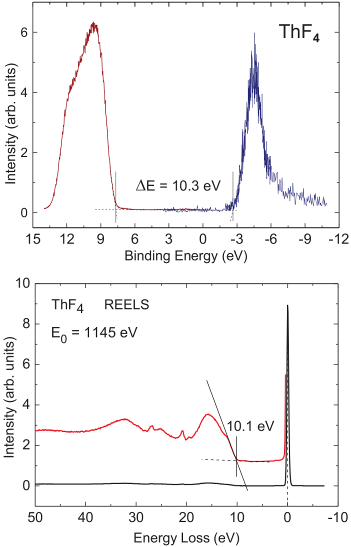
$\tau \approx 7\ \mu s$

$\frac{5}{2}^+$ ^{229}Th ground state

e^- in atomic shell $6d^2$

ThF_4 bandgap measurements (JRC, Karlsrue)

1. 25 nm film of ThF_4 grown on Au substrate,
2. XPS measured valence band,
3. BIS measured conduction band,
4. REELS confirmed XPS-BIS results,
5. $E_g = 10.2 \pm 0.2$ eV,
6. > 8.3 eV, suitable for nuclear clock matrix.



T.Gouder et al.,Phys.Rev.Research 1 (2019) 033005

▸ T.Gouder et al.,Phys.Rev.Research 1 (2019) 033005

ThF$_4$ γ-decay search

1. H2D2-lamp yields:
   $\sim 10\ \mu W/nm$ at 150 nm,
2. it will excite ^{229m}Th:

$$N_{Th229m} = n_{Th229}\frac{1}{3}\frac{\Gamma_\gamma}{2}\lambda_0^2\frac{dN_\gamma}{dE}\ ,$$

3. 1 kBq in 1 cm^2 gives:

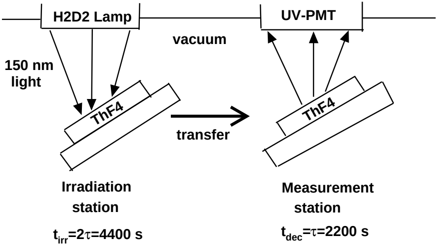
$$N_{Th229m} \simeq 6.7\times 10^{-14}\ nm\,\frac{dN_\gamma}{d\lambda}$$

$$\frac{dN_{Th229m}}{dt} \simeq 0.5\ Hz\ ,$$

$$S = \frac{dN_{Th229m}}{dt}\tau(1-e^{-\frac{t_{irr}}{\tau}})(1-e^{-\frac{t_{dec}}{\tau}})$$

$$S\times Acc\times Eff/N \sim \frac{610\times 0.1\times 0.3}{R_{bkg}2200\ s}\ .$$

$>4\sigma$ deviation in 10-100 measurements.


H2D2 Lamp

UV-PMT

vacuum

150 nm light

ThF4

transfer

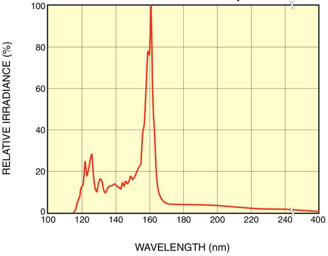
ThF4

Irradiation station

$t_{irr}=2\tau=4400$ s

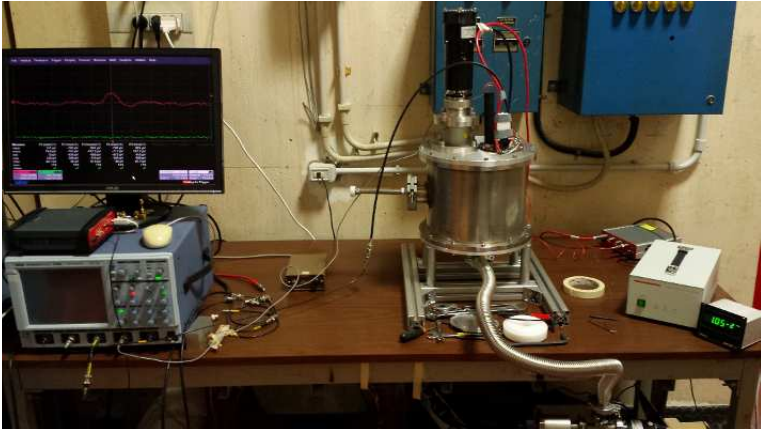
Measurement station

$t_{dec}=\tau=2200$ s


H2D2 emission spectrum

ThF_4 setup in Genova

1. Hamamatsu VUV-lamp L11798 and solar blind PMT R10454, visible veto PMT R1450,
2. vacuum chamber for 10^{-2} mbar,
3. commercial ThF_4 samples from II-VI Inc.,
4. parallel setup in glove box at JRC (Karlsruhe).



Variations of α_{EM} (with respect to α_S)

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

$$\frac{\delta\nu}{\nu} \simeq k = 10^5 \times \left[4\frac{\delta\alpha}{\alpha} + \frac{\delta X_q}{X_q} - 10\frac{\delta X_s}{X_s}\right], \; X_{q,s} = \frac{m_{q,s}}{\Lambda_{QCD}}, \; k = \frac{\Delta E_C}{E_{iso}}$$

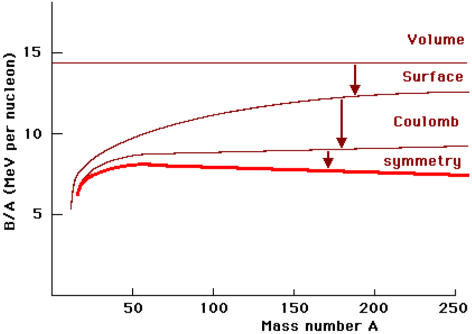
leading to sensitivity:

▸ V. Flambaum Phys.Rev.Lett.97 (2006) 092502

$$\frac{1}{\alpha}\frac{d\alpha}{dt} \simeq 10^{-20}/year << 10^{-17}/year(current) \, ,$$

- in PRA102 052833 (2020) $k \simeq -10^4$ was obtained, leading to $\delta\nu \sim$ 200 Hz/year.

▸ P.Fadeev et al.,Phys.Rev.A102 (2020) 052833



Other applications

1. topological and axionic dark matter detection:
   α_{EM} and Schiff moment;
2. ^{229m}Th-based nuclear laser:
   Zeeman splitting in 100 T magnetic field;
3. GPS (precision 3-5 m):
   atmospheric disturbance, clock synchronization and stability, satellite position;
4. Chronometric geodesy:
   10^{-19} clock geodesy at 1 mm, earthquake prediction, search for natural resources, tests of general relativity, clock-based gravitational wave detection.

For review see: ▸ L. von der Wense and B. Seiferle, Eur. Phys. J. A56 (2020) 277.

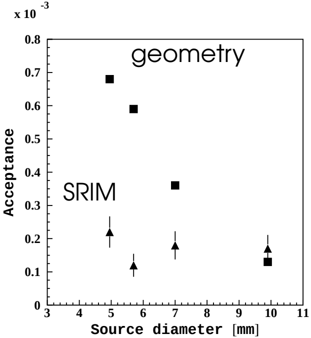
Summary

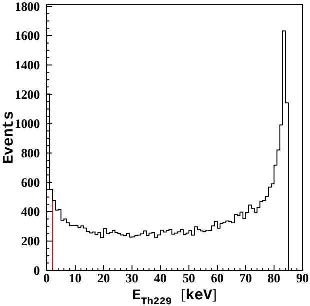
- ^{229m}Th is the lowest known nuclear isomer,
- latest measurements give its energy around 8.3 eV, corresponding to 150 nm wavelength,
- neutral ^{229m}Th atom decays through IC in 7 μs,
- if IC decay is suppressed (by ionization of chemical binding) γ-decay is expected to occur in 1 hour,
- γ-decay-only linewidth is suitable for very precise nuclear clock (10^{-19} precision on a single atom in cooled trap, 10^{-16} precision on a single atom in crystal),
- γ-decay is not yet observed and our experiment is aiming to search for it in ThF$_4$ crystal.

Backup slides

Acceptance Simulations

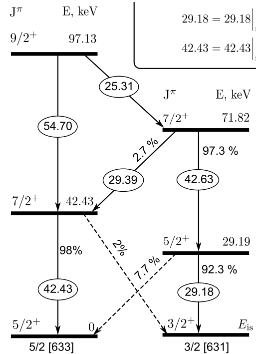
1. μCal. is small $200\times200\ \mu\mathrm{m}^2$,
2. it can be installed at 1 mm from U-source,
3. source activity fixed $<$5 kBq,
4. geometrical acceptance falls with source diameter,
5. SRIM acceptance is flat,
6. if $\tau_D > 7\ \mu$s and noise $\simeq$ signal only recoils with $<$100 eV have to be selected,
7. further reduction of rate by a factor of 10.

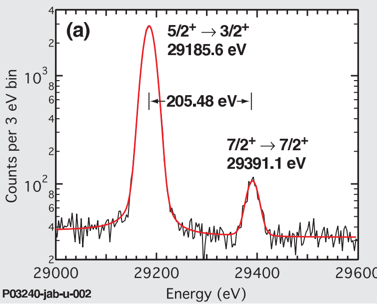




Energy level of ^{229m}Th isomer

1. indirect measurement[1] by comparison of 43+29 keV γs with 26 eV resolution (HgTe μcalorimeter with 3 ms decay time),
2. 100 μCi ^{233}U source covered by 50 μm Ti foil at 3.5 cm distance,
3. direct search at ALS[2] with ^{229}Th-doped LiSrAlF$_6$ crystal excluded γ-decay in the region: $1-2<\tau<2000-5600$ s for $7.3<E_\gamma<8.8$ eV at 90 CL,
4. MCP counting observation[3], obtained upper limit $<$18.3 eV.





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[1] *B.Beck et.al.Phys.Rev.Lett.98,142501(2007).*

[2] *J.Jeet et.al.Phys.Rev.Lett.114,253001(2015).*

[3] *L.von der Wense et.al.Nature 533,47(2016).*

Primary sources (Roberto Caciuffo, JRC, Karlsruhe)

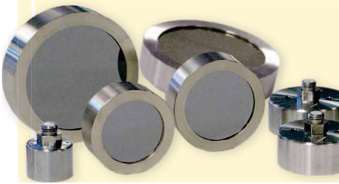
Sources being to be deposited on active surface of Si detector (300 mm^2), with film diameter 10mm:

1. ^{238}U metal (10 nm): 0.2 Bq,
2. ^{233}U metal (10 nm): $<$5 kBq,
3. ^{239}Pu metal (10 nm): $<$5 kBq,

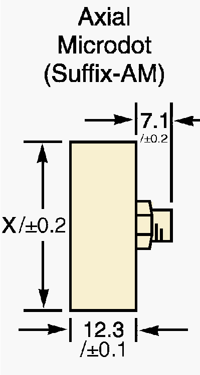
+1 nm Mg capping layer, or

1. $^{238}UO_2$ dielectric (20 nm),
2. $^{233}UO_2$ dielectric (20 nm),
3. $^{239}PuO_2$ dielectric (20 nm),

- E-loss limits thickness $\leq$20 nm,
- Si-rate limits activity $<$40 kHz,
- ^{239}Pu smaller size: $<$2 mm,
- ^{238}U rate too low (use ^{234}U?).

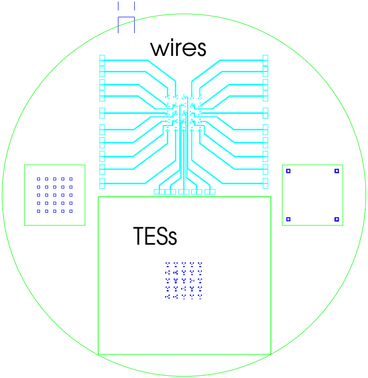


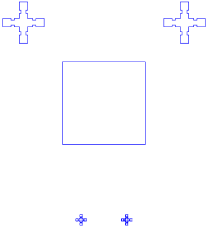
X=28.6 mm



Lithographic mask design

1. 5×5 TESs of different size,
2. maximum size 300 μm,
3. minimum size 10 μm,
4. 30 μm arrays read in parallel,
5. Be mask to reduce α heating.

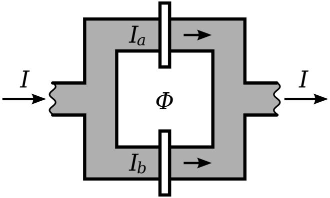




DC SQUID principles

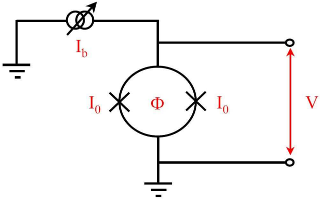
SQuID current:

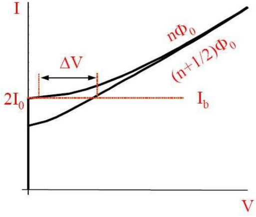
$$I = I_0 \left\{ \sin\left(\delta_0 + \frac{e}{\hbar}\Phi\right) + \sin\left(\delta_0 - \frac{e}{\hbar}\Phi\right) \right\}$$

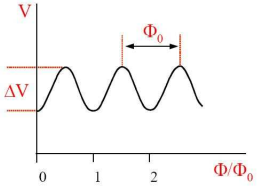


which can be rewritten as following:

$$I = 2I_0 \sin\delta_0 \cos\frac{\pi\Phi}{\Phi_0}$$







SQUID calibrations

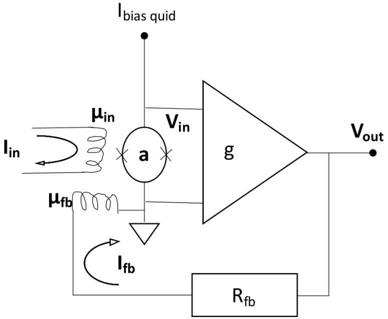
SQuID gain defined as $V_{out} = G I_{in}$ is given by:

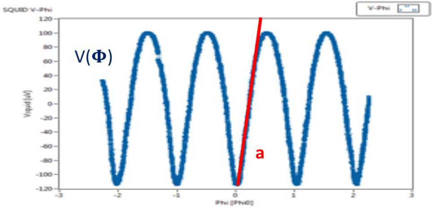
$$G = \frac{ga\mu_{in}}{1 + ga\mu_{fb}/R_{fb}} \rightarrow \lim_{ga\rightarrow\infty} G = R_{fb}\frac{\mu_{in}}{\mu_{fb}} ,$$

where g is the op-amp open loop gain,

$$V_{in} = a\left\{\Phi_{in} - \Phi_{fb}\right\} , \quad \Phi_{in,fb} = \mu_{in,fb} I_{in,fb} ,$$

$$I_{fb} = \frac{V_{out}}{R_{fb}} , \quad V_{out} = gV_{in} .$$





μcalorimeter calibrations

Laser based energy calibration[1]:

① 439 nm (2.824 eV) blue laser,

② quartz optical fiber in cryostat,

③ 1-7 photons on TES/pulse,

④ $<$10 kHz pulse rate,

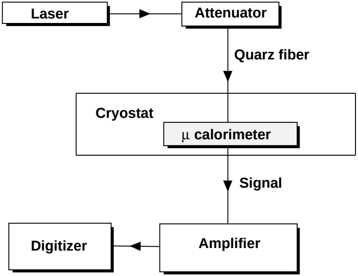
⑤ timing calibration,

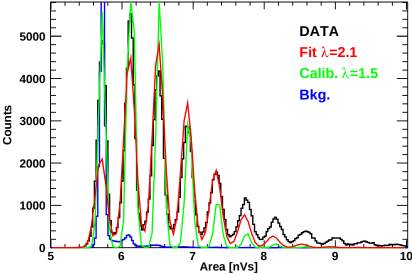
⑥ pile-up test.

Convoluted Poissonian deposited energy spectrum:

$$\sum_n e^{-\frac{(E_{dep}/3eV-n)^2}{\sigma_E^2}} \frac{\mu^n}{n!} e^{-\mu} .$$

Test on known energy peaks: ^{235m}U and first atomic levels of U.





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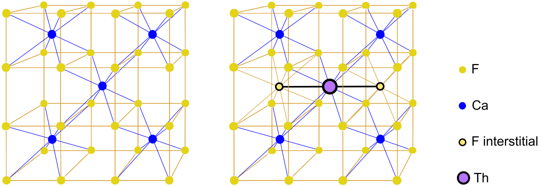
[1] A.Miller et al.,Appl.Phys.Lett.83,791(2003).

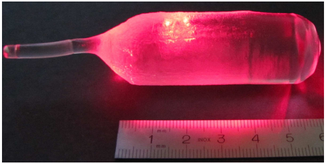
TU Vienna/UCLA

1. UV-transparent crystals (bandgaps 12 and 8 eV): CaF_2 (Vienna)[1] and $LiCaAlF_6$ (UCLA)[2],
2. $^{229}Th^{4+}$ ion replaces Ca,
3. high number of oscillators ($> 10^{15}$),
4. $<$ 10 photons/s spontaneous emission,
5. easy to handle solid state target.

[1] *G.Kazakov et al.,New J.Phys.14,083019(2012).*
[2] *W.Rellergert et al.,Phys.Rev.Lett.104,200802(2010).*

T.Schumm, www.thorium.at
E.Hudson, hudsongroup.physics.ucla.edu/229th-nuclear-clock





University of Michigan/PTB

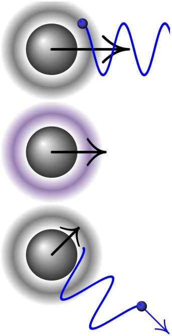
1. ion trap for $^{229}\mathrm{Th}^{3+}$,
2. laser cooling,
3. laser ablation source,
4. low number of oscillators ($< 10^5$),
5. 100 s trapping lifetime,
6. measurement of hyperfine structure of $^{229}\mathrm{Th}^{3+}$ atom.

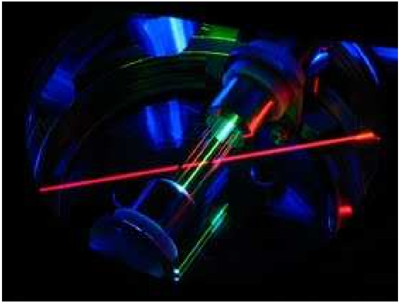
[1] *A.Radnaev et al.,Phys.Rev.A86,060501(R)(2012).*

[2] *N.Huntemann et al.,Phys.Rev.Lett.116,063001(2016).*

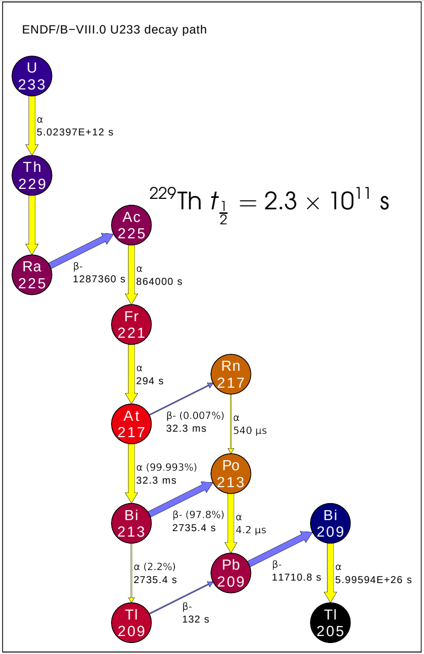
A.Kuzmich, sites.lsa.umich.edu/kuzmich-lab/

E.Peik, www.ptb.de/cms/en/ptb/fachabteilungen/abt4/fb-44/ag-443.html

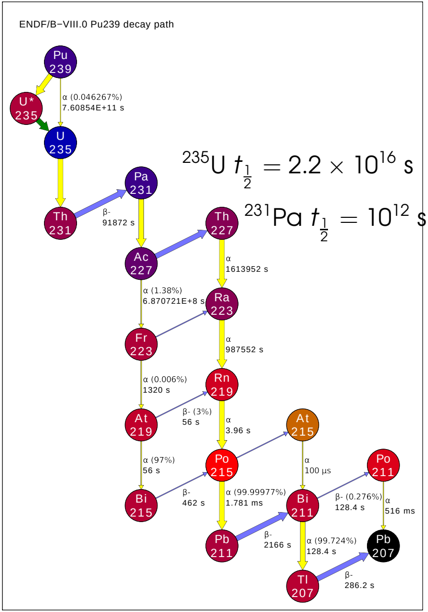




U233 and Pu239 Decay Chains



$$^{229}\mathrm{Th}\ t_{\frac{1}{2}} = 2.3 \times 10^{11}\ \mathrm{s}$$



$$^{235}\mathrm{U}\ t_{\frac{1}{2}} = 2.2 \times 10^{16}\ \mathrm{s}$$

$$^{231}\mathrm{Pa}\ t_{\frac{1}{2}} = 10^{12}\ \mathrm{s}$$

Thorium Decay Chain