Measurement of ^{229m}Th decay energy for nuclear clock application

CSN3/TORIO-229

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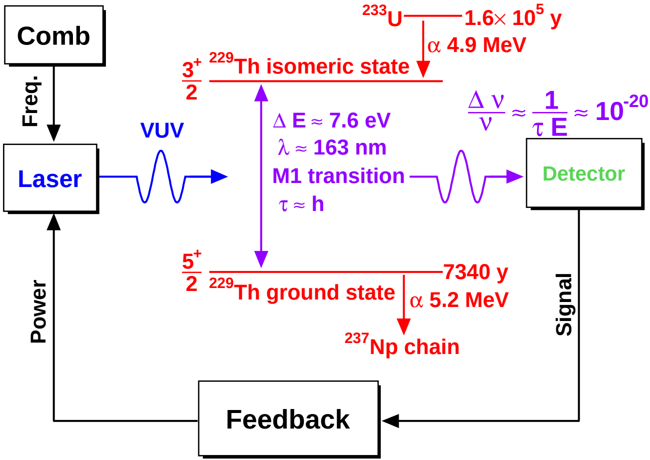
^{229m}Th-based Nuclear Clock

1. Lowest nuclear exited state[1],
2. energy from indirect observation[2],
3. VUV-laser excitation,
4. very narrow linewidth[3],
5. $N = 10^5 \div 10^{12}$ oscillators[4,5],

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

6. $>10^3$ FoM improvement wrt atomic clock.



[1] L.Kroger and C.Reich, Nucl.Phys.A259, 29(1976).
[2] R.Beck et al., Phys.Rev.Lett.98, 142501 (2007).
[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).

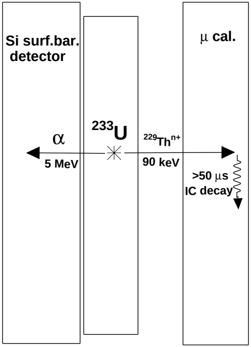
Fast μcalorimeter measurement

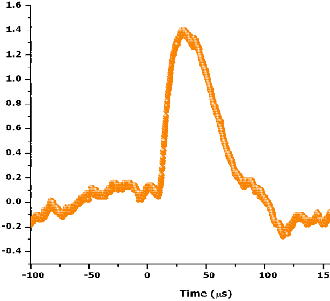
- μcalorimeter signal $< 50\ \mu s$[1],
- α-$^{229}Th^{+}$ coincidence,
- ^{233}U deposited on Si detector,
- long. range of 90 keV $^{229}Th^{+}$ in UO_2 is 8.3 nm (path 16.1 nm),
- 20 nm thick $^{233}UO_2$ film, activity A_U<5 kBq,
- expected rate of time-separated events:

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

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

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



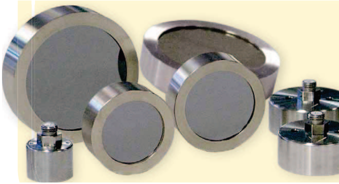


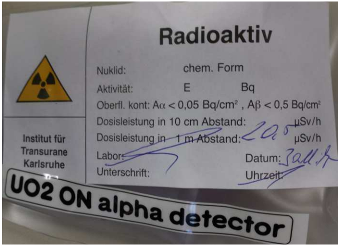
[1] D.Bagliani et al.,J.Low.Temp.Phys.151,234(2008).

Primary sources (Roberto 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, delivered for background measurements,
2. ^{233}U <5 kBq, authorization received, waiting for working TES prototype.



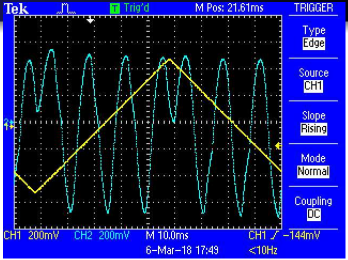


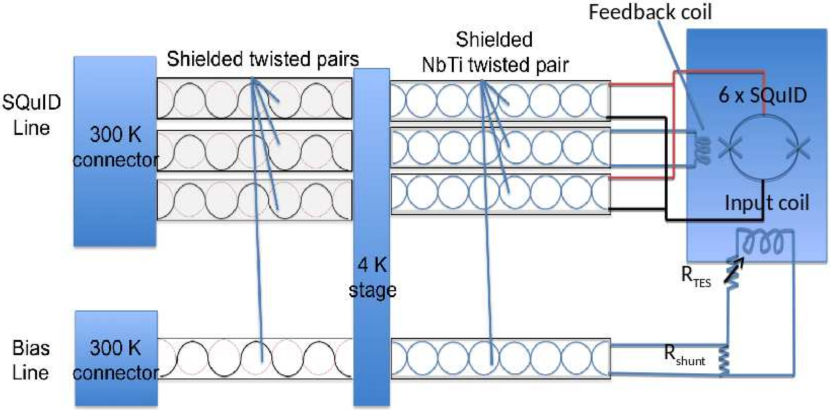
Source requirements:

- E-loss limits thickness ≤20 nm,
- Si-rate limits activity <40 kHz,
- ^{238}U rate too low (use ^{234}U?).

SQUID setup (V. Ceriale)

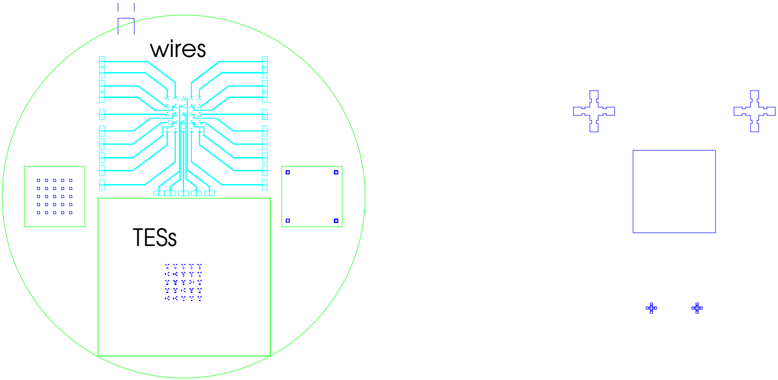
1. J3 VTT 6 loop DC SQUID,
2. bandwidth 0.81 MHz,
3. gain G$\sim$15.8 mV/μA,
4. $I_c \sim$60 μA,
5. $I_{noise} \sim$1 pA/$\sqrt{Hz}$.





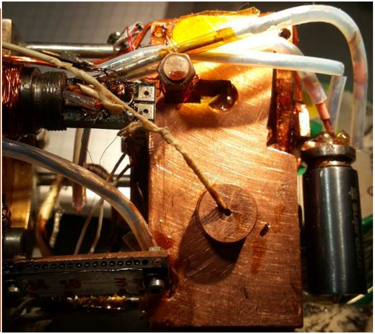
Lithographic mask design (V. Ceriale)

1. large 37×33 mm^2 wafer ($>$28.6 mm of PIPS),
2. 5×5 TESs/ of different size,
3. maximum size 500 μm,
4. minimum size 10 μm,
5. 30 μm 4×4 array read in parallel,
6. mask to reduce α heating (in progress).



Fast TES prototype (F. Gatti)

1. total area $25\times25\ \mu m^2$ (need $>100\times100\ \mu m^2$),
2. Au-Ti bilayer with high T_c (fast),
3. proximization approx. ($T_c(Ti)$=390 mK):
$$T_c(Ti-Au) = T_c(Ti)\left[1-0.54t_{Au}/t_{Ti}\right],$$
4. t_{Au} ~40 nm, t_{Ti} ~56 nm.

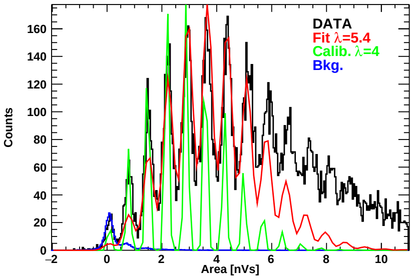


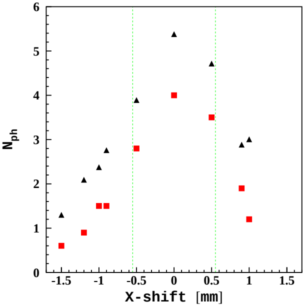
μcalorimeter calibrations

1. 439 nm (2.824 eV) blue laser,
2. 101 ps pulse, rate $<$100 MHz,
3. p.p. 63 mW, $<1.4\times10^7$ γ/pulse,
4. FC/PC-SMA 440 μm fiber,
5. SMA feedthrough,
6. quartz optical fiber in cryostat,
7. transmission 2.6×10^{-5},
8. NA=0.22 at 2.3 mm,
9. 0.035 photons on TES/pulse,

Convoluted Poissonian spectrum:

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





μcalorimeter calibrations cont.

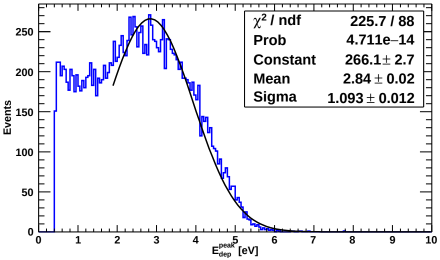
1. $25\times25\ \mu m^2$ TES at 2.3 mm: $\lambda \sim 0.035\ \gamma$,
2. relative second peak height: $2\gamma/1\gamma \sim 0.02$,
3. expected resolution (C=2 fJ/K) (RMS 1.1 eV):

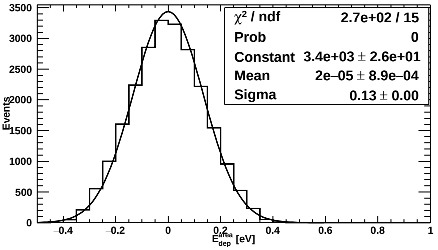
$$\sigma_E \sim \sqrt{4kT^2C} \sim 0.4eV\ ,$$

4. expected noise (G=2 nW/K) (RMS 0.13 eV, S/N∼22):

$$\sigma_{ph} \sim \sqrt{4kT^2G\Gamma\tau} \sim 1.8eV\ ,\ \ \sigma_J \sim \sqrt{4kT\xi/\tau R}G_{SQUID} \sim 1.3meV$$

5. Need to increase number of γ by $\times 100$ ($\lambda \sim 3\ \gamma$).





μcalorimeter timing

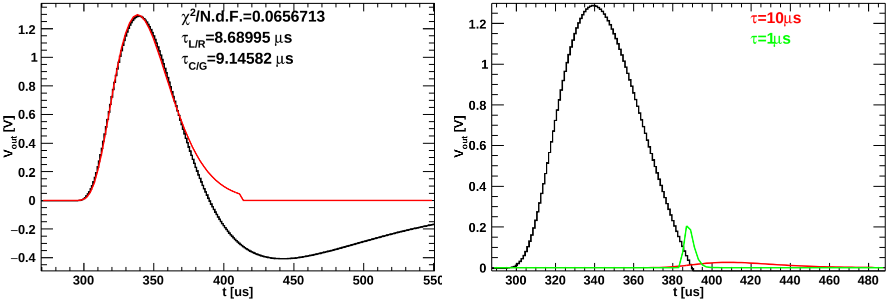
1. expected rise-time (observed 20 μs):

$$\tau_R \sim \frac{L_{SQUID} = 2nH + L_{wires} \sim 10nH}{R_{TES} \sim 0.01\Omega} \sim 1.2\mu s\ ,$$

2. expected fall-time (observed 40 μs):

$$\tau_D \sim \frac{C \sim 2fJ/K}{G \sim 2nW/K} \sim 1\mu s\ ,$$

3. need rise-time <1 μs and fall-time <20 μs.



Results/Future Developments

- first prototype of fast μ-calorimeter was developed,
- laser calibrations showed low number of γ/pulse,
- new fiber setup is under study,
- rise-time has to be improved by factor of 20,
- different TES materials and shapes will be tested,
- fall-time has to be improved by factor of 2,
- resolution has to be improved by factor of 2.

Manpower 2019

Preliminary estimates:

Person	Participation (%)
Mikhail Osipenko	70
Mauro Taiuti†	40
Mauro Giovannini†	20
Marco Ripani	20
Flavio Gatti†	10
Michele Biasotti†	0
Giovanni Gallucci	0
Total	160

† associato INFN.

Richieste Servizi 2019

Servizio	Richieste (m.u.)	Obiettivi
Progettazione	1	Supporto Si/Fibra
Officina	1	Supporto Si/Fibra
Supporto tecnico	1	montaggio, cavi, test
Utilizzo criostato piccolo		test Si e TES, misure

Schedule of experiment