Towards the Lifetime Measurement of the $^{229m}Th^{3+}$ Nuclear Clock Isomer

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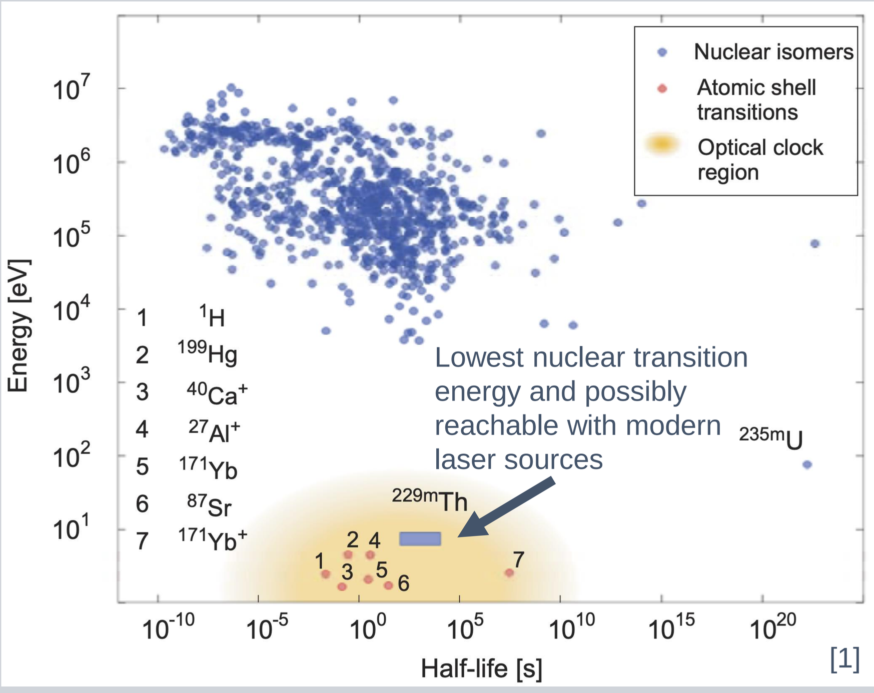
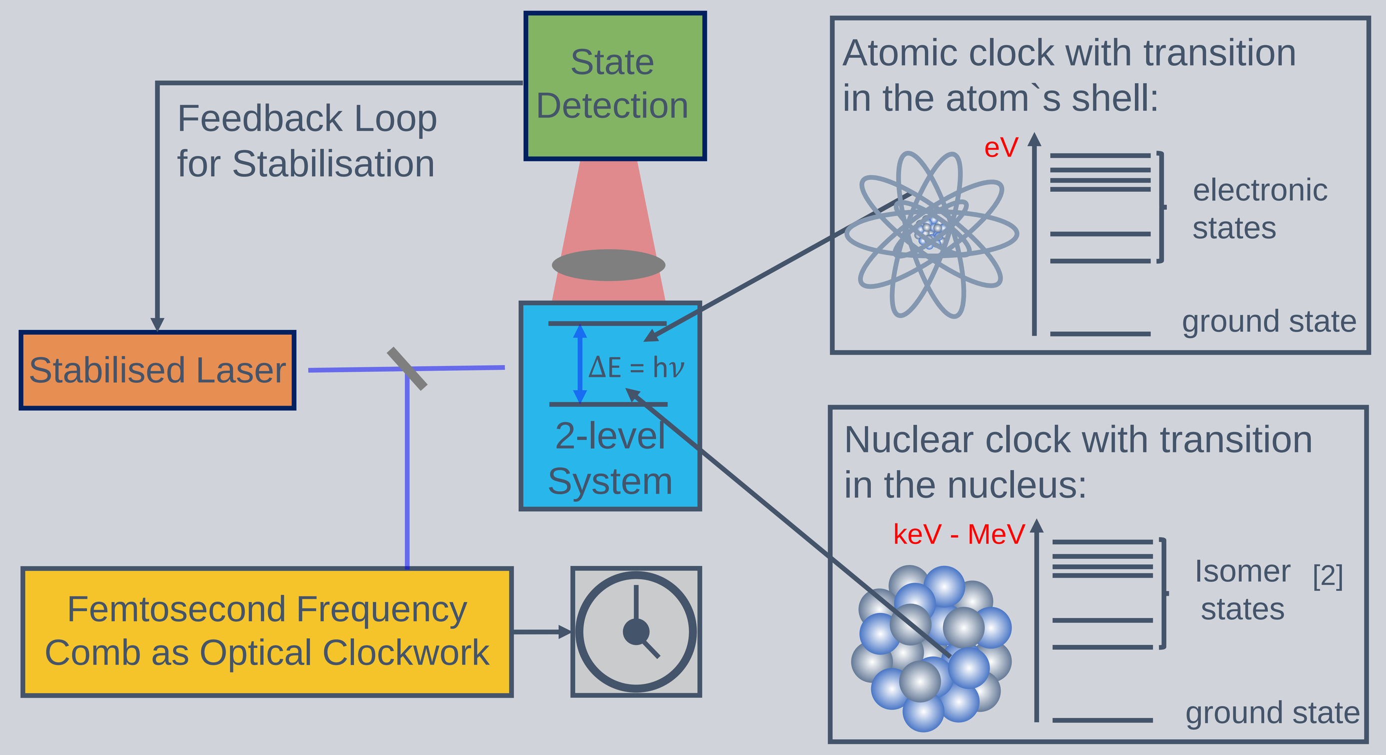
Why ^{229m}Th?



Nuclear vs. Atomic optical clock



^{229}Th Nuclear Clock Applications

- Expected systematic frequency uncertainty of 1.5 x 10^{-19} [3]
- fundamentally different operation principle compared to atomic clocks => **complementary to atomic: unique quantum sensor beyond timekeeping capability** [4, 5]
- theoretical expectation of time variation of fundamental constants -> ^{229}Th provides largely enhanced sensitivity to variations [4,6,7]
- Search for Dark Matter [4,8]
- Gravity sensor -> clock height shifts in gravitational potential of 1 cm correspond to frequency shifts at 10^{-18} precision level [8]

What do we know so far?

- Identification via direct decay in internal conversion (IC) decay branch [1]
- Lifetime of the neutral isomer: $\tau_{IC} = 7 \pm 1\ \mu s$ [9]
- Hyperfine structure measured via collinear laser spectroscopy of $^{229m}Th^{2+}$ [10]
- First direct and precise measurement of the excitation energy:
  -> via IC: $E_{ex} = 8.28 \pm 0.17$ eV [11]
  -> via magnetic microcalorimetry: $E_{ex} = 8.10 \pm 0.17$ eV [12]

What is still missing?

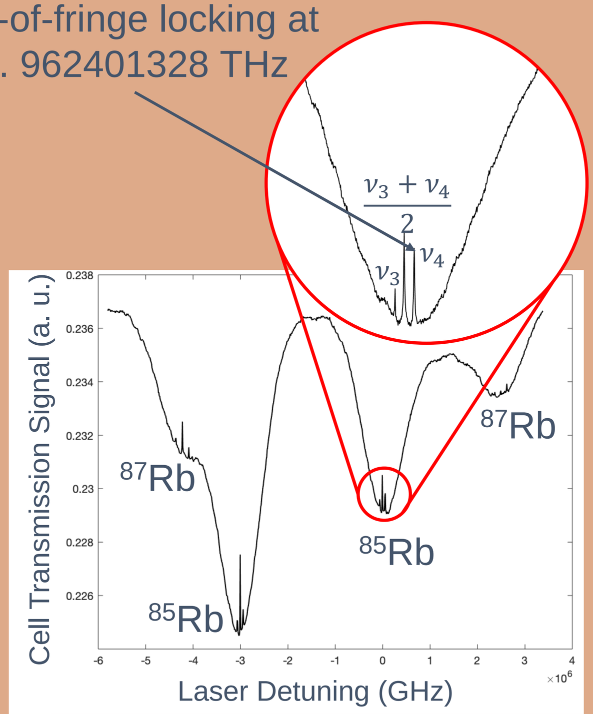
- Ionic lifetime τ_γ
- Theoretical prediction: $\tau_\gamma = 10^3 - 10^4$ s
  => Natural linewidth $\Gamma = \frac{1}{2\pi\,\tau} < 0.16$ mHz

Confine $^{229m}Th^{3+}$ ions in a cryogenic Paul trap with long storage times!
(Storage time at 273 K is only 1 min)

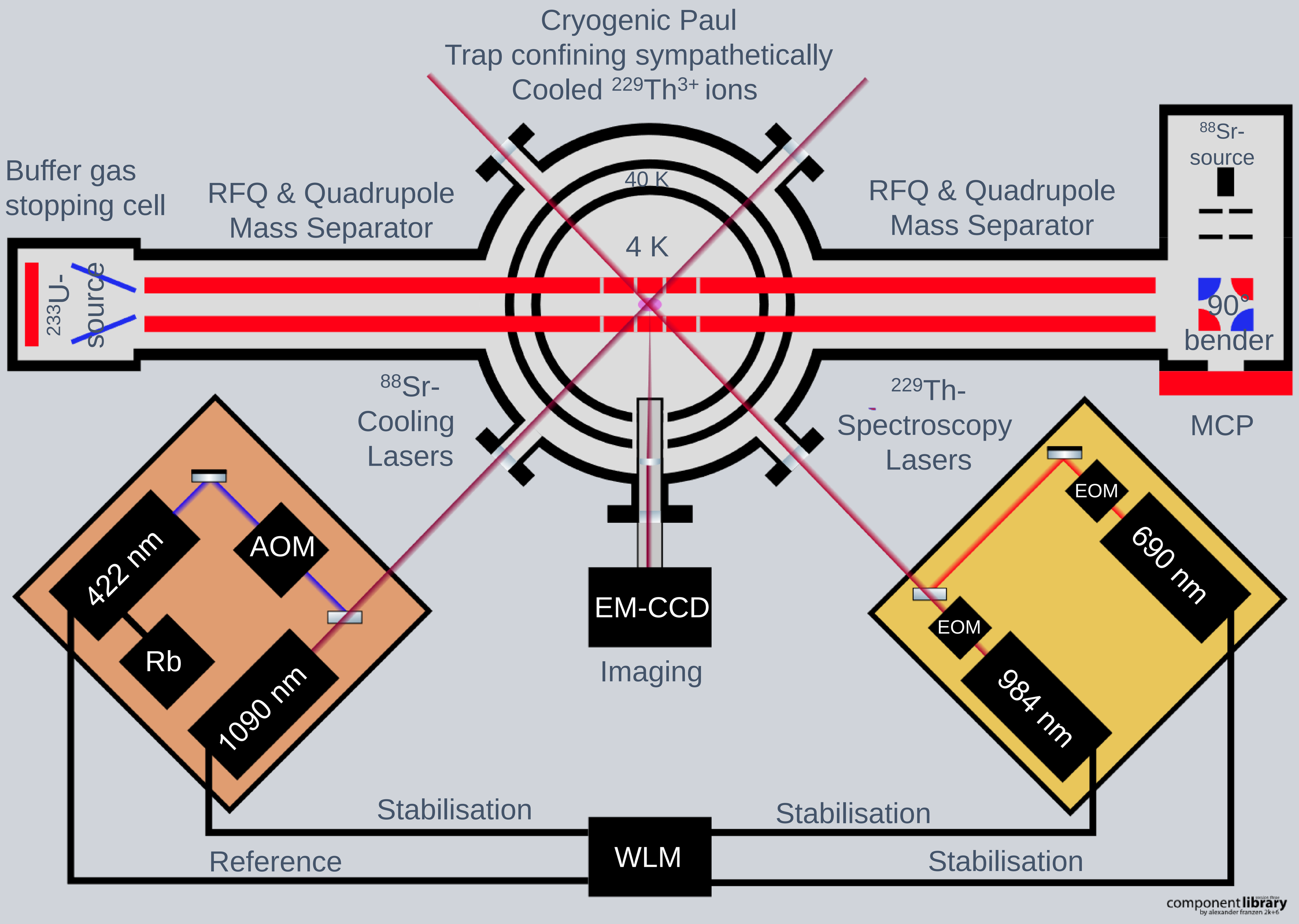
Experimental Setup

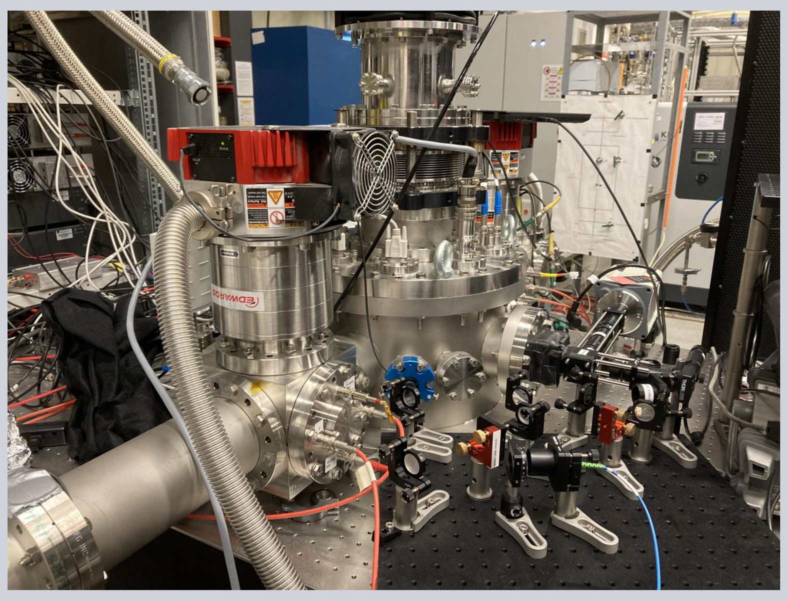
Lock the 422 nm laser to Rb-transition via saturation spectroscopy:

Top-of-fringe locking at 710. 962401328 THz

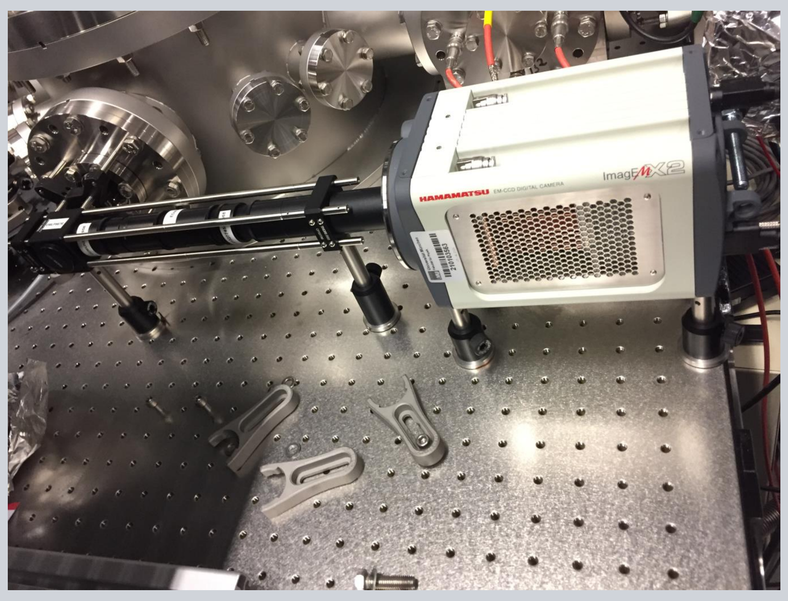


Use 422 nm laser as reference for the wavemeter to stabilise the other three lasers



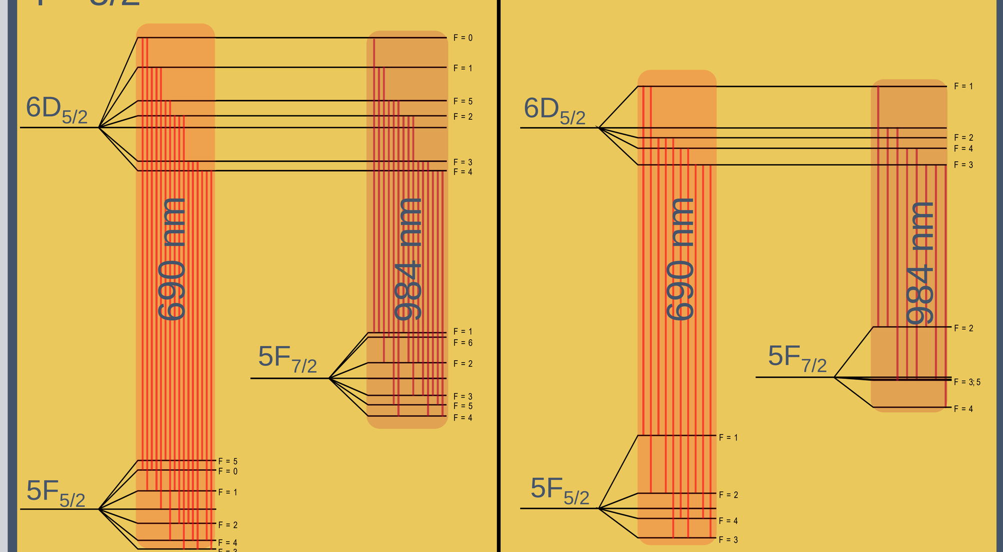


Cryogenic Paul trap in vacuum chamber with optical access ports



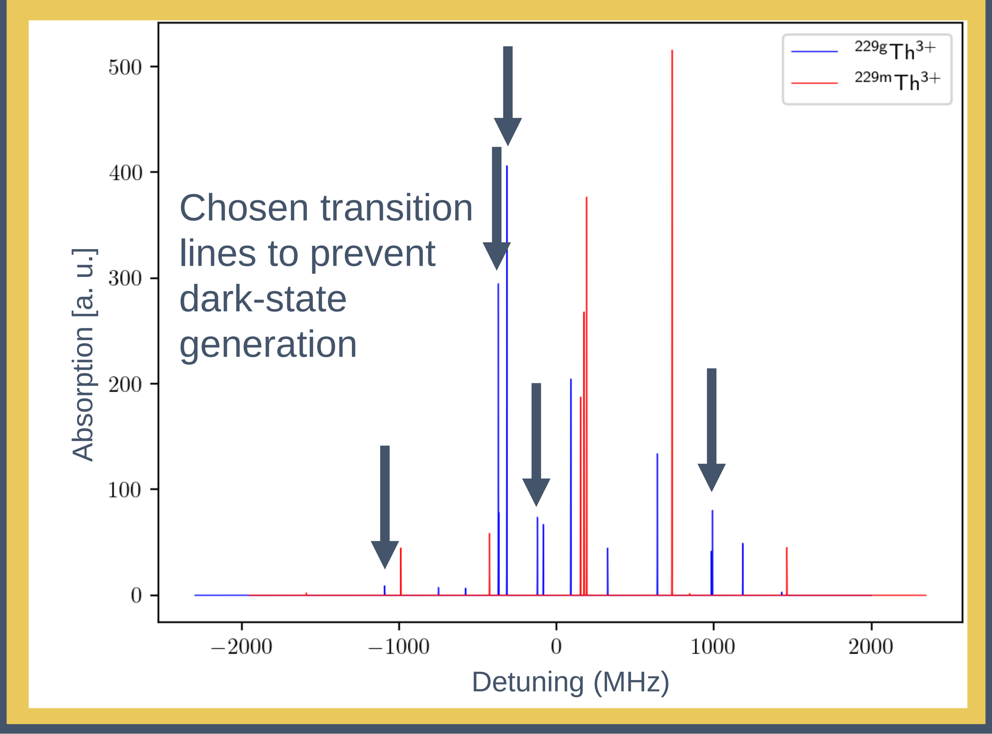
Imaging/fluorescence detection setup

Hyperfinstructure spectroscopy of $^{229}Th^{3+}$



Laser spectra are modified with EOMs to fit for the chosen HFS spectrum of $^{229}Th^{3+}$ -> e. g. sideband generation of 984 nm laser for $^{229g}Th^{3+}$ with

f_{cen} = -0.685 GHz
f_{mod1} = 0.049 GHz
f_{mod2} = 0.6275 GHz



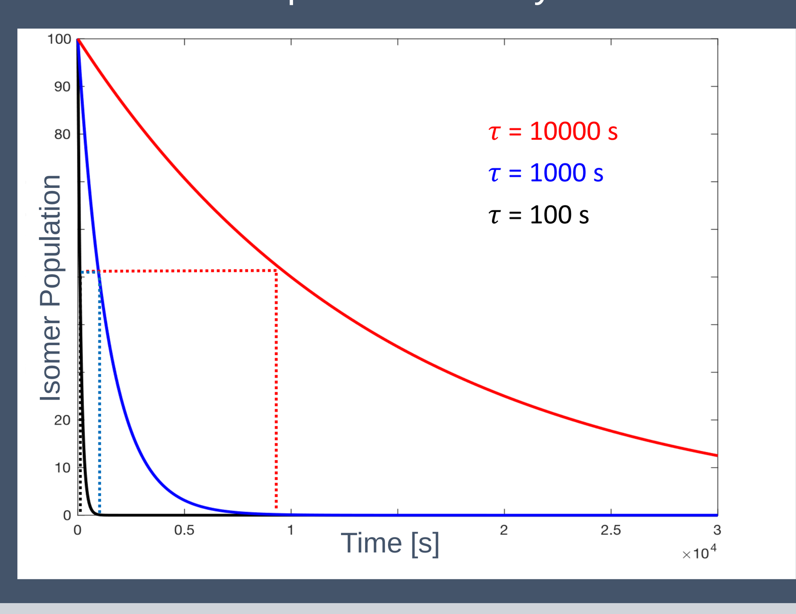
Measurement Strategy

690 nm and 984 nm lasers are modulated to drive isomer HFS transitions → Detect isomer fluorescence with EM-CCD Camera → Stop measurement when fluorescence vanishes → 690 nm and 984 nm lasers modulated to drive nuclear ground state HFS transitions

Tricky: resolve single isomers in sympathetically cooled crystalline structure!

Fluorescence visible → $^{229}Th^{3+}$ ions still in trap → **Successful measurement** → After N meaurement cycles extract the lifetime from an accumulated exponential decay curve

No fluorescence -> $^{229}Th^{3+}$ ions not in trap → **Discard data and restart.**



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