A nuclear clock with $^{229}\text{Th}$

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Thorium Energy Conference 2018

Brussels
Outline

1. Motivation

2. Experiments towards a nuclear clock

3. Conclusion
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How to build a Clock

- recurring event
  → oscillations of a pendulum
- counter
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How to build a good Clock

Pendulum clock problems:
- frequency depends on
  - length
  - gravitational field
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How to build a **good** Clock

- reproducible
- universal
- accurate & precise
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**Optical Atomic Clock:**
- drive an atomic transition with a laser
- measure its frequency
Optical Atomic Clocks

- **best atomic clocks:** Strontium lattice clock at NIST
  - frequency uncertainty [1]: $2.1 \times 10^{-18}$
  - distance earth-moon: 1 nm

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  - precision is only limited by external electric and magnetic fields

Can one do better? - A nuclear optical clock

**Idea:** Use nuclear transition for time measurement [2]
- expected frequency uncertainty: \(1.5 \times 10^{-19}\) [3]

**Expected advantages:**
- nucleus is 5 orders of magnitudes smaller than the atom
  \(\rightarrow\) highly resistant to external influences
- solid state clock feasible? [4]
  \(\rightarrow\) \(10^{19}\) nuclei in crystal lattice vs. \(10^4 - 10^6\) in an optical lattice

Potential applications of a nuclear optical clock

- satellite navigation
- geodesy
  \[ \text{relative frequency shifts are proportional to gravitational potential differences} \]
- clock networks for dark matter search
- are fundamental constants really constant?
  \[ \dot{\alpha} \propto \Delta V_C \]
  \[ \text{differences in the coulomb potential can be huge in nuclei} \]
Requirements for a nuclear clock transition

- laser access
  - transition energy in the eV range
- small linewidth
  - lifetime in the range of at least some seconds
$^{229}$Th - What is known so far

- lowest excitation energy of all known nuclear states
  \[ E_I = 7.8 \pm 0.5 \text{ eV} \ (\approx 159 \text{ nm}) \] [5]

Motivation

229\textsuperscript{Th} - What is known so far

- lowest excitation energy of all known nuclear states
  \[ E_I = 7.8 \pm 0.5 \text{ eV} \ (\approx 159 \text{ nm}) \] [5]

\[ \begin{array}{c}
\text{229m\textsuperscript{Th}} \\
\uparrow \Delta E = 7.8 \pm 0.5 \text{ eV} \\
\text{M1 transition} \\
\downarrow \\
\text{229g\textsuperscript{Th}}
\end{array} \]

\[ \begin{array}{c}
\text{3/2}^+ \\
\text{[631]} \\
\text{5/2}^+ \\
\text{[633]}
\end{array} \]

\gamma-decay

- \( \tau \approx 10^4 \text{ s} \)
  \[ \Delta E/E \approx 10^{-20} \]

internal conversion decay

- \( \tau \approx 10 \mu\text{s} \) [6]
  - only possible in neutral 229\textsuperscript{m}Th
    \[ \rightarrow 1\text{st IP} < E_I < 2\text{nd IP} \]

Why don’t you simply build a nuclear clock?

- direct nuclear laser excitation has not been achieved so far
- transition energy is not known precisely

**Experimental Objectives:**

- determine the lifetime
  - internal conversion ✓
  - γ-decay
- improved energy measurement
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Experiments towards a nuclear clock

Indirect Measurements

\[ {\text{233U}} \rightarrow {\text{229Th}} \rightarrow {\text{229mTh}} \]
Experiments towards a nuclear clock

Indirect Measurements

Direct Measurements

233\text{U} \xrightarrow{\alpha} 229\text{Th} \xrightarrow{} 229_{\text{m}}\text{Th}

233\text{U} \xrightarrow{\alpha} 229\text{Th} \xrightarrow{2\%} 229_{\text{m}}\text{Th}

233\text{U} \xrightarrow{\alpha} 229\text{Th} \xrightarrow{98\%} 229\text{Th}
Experiments towards a nuclear clock

**Indirect Measurements**

\[ ^{233}\text{U} \rightarrow ^{229}\text{Th} \rightarrow ^{229m}\text{Th} \]

**Direct Measurements**

\[ ^{233}\text{U} \rightarrow ^{229}\text{Th} \rightarrow ^{229m}\text{Th}, 2\% \]

\[ ^{229}\text{Th} \rightarrow ^{229m}\text{Th}, 98\% \]

**Direct Excitation**

\[ ^{229}\text{Th} \rightarrow ^{229m}\text{Th} \]
Indirect Measurements

- $\gamma$ spectrum following the $\alpha$-decay of $^{233}$U
  - first evidence already in 1976
- compare lines that populate the isomer with lines populating the ground-state
  - currently best energy value

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- populate $^{229\text{m}}\text{Th}$ via the 2\% decay branch of the $^{233}\text{U}$ $\alpha$-decay
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- populate $^{229m}$Th via the 2% decay branch of the $^{233}$U $\alpha$-decay
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- neutralize the $^{229m}$Th ions
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- populate $^{229m}\text{Th}$ via the 2% decay branch of the $^{233}\text{U}$ $\alpha$-decay
- create a pure $^{229m}\text{Th}$ ion beam
- neutralize the $^{229m}\text{Th}$ ions
- detect the electron emitted during the internal conversion decay
Direct Measurements

- exploit the long lifetime of the isomer in $^{229}\text{Th}$ ions
- trigger internal conversion by neutralization
  - first direct detection [7]
  - first lifetime measurement [6]
  - energy determination via IC electrons

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Direct Excitation

- $^{229}$Th surface + tunable pulsed laser [8]
- use internal conversion electrons as a signature
  - first nuclear laser excitation
  - giant step towards a nuclear clock
  - work is ongoing

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Conclusion

- $^{229}$Th
  - lowest excited state of all known nuclear levels
  - laser excitation feasible
  - nuclear optical clock feasible

- experimental efforts are ongoing
  - precise energy measurement needed

- nuclear clock
  - complementary technology
  - (probably) highly sensitive to temporal variation of fundamental constants
Thank you for your attention!

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