Improvement of single-ion spectroscopy of quadrupole transitions in ytterbium ions towards search for temporal variation of the fine structure constant

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### Coworkers

<table>
<thead>
<tr>
<th>Role</th>
<th>Name</th>
<th>Task</th>
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<tr>
<td>Yb⁺:</td>
<td>Yasutaka Imai</td>
<td>S-D clock transition</td>
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<td></td>
<td>Ren Irie</td>
<td>S-D clock transition</td>
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<td>Ba⁺:</td>
<td>Hiroto Fujisaki</td>
<td>S-D clock transition</td>
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<td>Sinya Kawada</td>
<td>Clock laser</td>
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<td>Comb:</td>
<td>Masaya Hatake</td>
<td>Mode-locked laser</td>
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<td>Project leader:</td>
<td>Kazuhiko Sugiyama</td>
<td></td>
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<td>Supervisor:</td>
<td>Masao Kitano</td>
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Optical clock (frequency standard)

- Frequency stability
  \[ \sigma^{-1} \propto \frac{1}{Q} = \frac{\omega_0}{\Delta \omega} \]
  \( \omega_0 \) : center frequency
  \( \Delta \omega \) : resonance width

\[ \omega_0 = \begin{cases} 
10^{10} \text{ Hz (microwave)} \\
10^{15} \text{ Hz (optical)} 
\end{cases} \]

Higher stability

Microwave: \( 10^{-16} \)
Optical: \( 10^{-18} \)  C.-W. Chou et al., PRL 104, 070802 (2010)

- Optical frequency measurement: frequency comb

Possible precise frequency ratio measurement between optical clocks.
Search for temporal variation of fine structure constant $\alpha$

- Fine structure constant $\alpha$
  - Dimensionless: no dependence on units
  - Depending on by frequency of electric transition: affect each reference frequency of optical clocks

Repeatable measurement by frequency comparison between two optical clocks with optical frequency comb

- Current limit
  - Hg$^+/\text{Al}^+$ (NIST) $(1.6 \pm 2.3) \times 10^{-17}/\text{yr}$ Rosenband et al., Science 319, 1808 (2008).
  - Yb$^+$ (PTB, NPL) $(-2.0 \pm 2.0) \times 10^{-17}/\text{yr}$ N. Huntemann et al., Phys. Rev. Lett. 113, 210802 (2014).
  $(-0.7 \pm 2.1) \times 10^{-17}/\text{yr}$ R. M. Godun et al., Phys. Rev. Lett. 113, 210801 (2014).
Characteristic of Yb$^+$

- Isotope $^{171}$($I=1/2$)
  - $m_F = 0$ - $m_F = 0$ clock transition: no 1st-order Zeeman shift
  - Simple hyperfine structure: small system with simple light source

- Clock transition
  - $^2S_{1/2} - ^2D_{5/2}$ $\lambda=411$ nm $\gamma = 22$ Hz Roberts et al., PRA 60, 2867 (1999)
  - $^2S_{1/2} - ^2D_{3/2}$ $\lambda=435$ nm $\gamma = 3$ Hz Tamm et al., PRA 80, 043403 (2009)
  - $^2S_{1/2} - ^2F_{7/2}$ $\lambda=467$ nm $\gamma < 10^{-9}$ Hz Huntemann et al., PRL 108, 090801 (2012)
Advantage of Yb\(^+\) on search for temporal variation of \(\alpha\)

- Frequency ratio measurement on three transitions in Yb\(^+\)
  - Measurement in a single same ion: exact evaluation of uncertainties
  - Ratio measurement among three
    - \(^2S_{1/2} - ^2F_{7/2}\)
      - Large sensitivity
    - \(^2S_{1/2} - ^2D_{3/2}, ^2S_{1/2} - ^2D_{5/2}\)
      - Similar sensitivities

<table>
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<tr>
<th>Ion</th>
<th>Transition</th>
<th>sensitivity A</th>
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<tbody>
<tr>
<td>Hg</td>
<td>(^2S_{1/2} - ^2D_{5/2})</td>
<td>-3.19</td>
</tr>
<tr>
<td>Al</td>
<td>(^1S_0 - ^3P_0)</td>
<td>0.008</td>
</tr>
<tr>
<td>Yb</td>
<td>(^2S_{1/2} - ^2F_{7/2})</td>
<td>-5.20</td>
</tr>
<tr>
<td></td>
<td>(^2S_{1/2} - ^2D_{3/2})</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>(^2S_{1/2} - ^2D_{5/2})</td>
<td>0.88</td>
</tr>
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- \(^2S_{1/2} - ^2F_{7/2}\) vs \(^2S_{1/2} - ^2D_{3/2}\) or \(^2S_{1/2} - ^2D_{5/2}\): Detect temporal variation of \(\alpha\)
- \(^2S_{1/2} - ^2D_{3/2}\) vs \(^2S_{1/2} - ^2D_{5/2}\): Investigate other variations

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Progress

• $^2S_{1/2} - ^2D_{5/2}$ transition (411 nm)
  - Single-ion spectroscopy in $^{174}$Yb$^+$

• $^2S_{1/2} - ^2D_{3/2}$ transition (435 nm)
  - Single-ion spectroscopy in $^{171}$Yb$^+$

• $^2S_{1/2} - ^2F_{7/2}$ transition (467 nm)
  - Developing clock laser
Detection of the $^2S_{1/2} - ^2D_{5/2}$ clock transition

The $^2S_{1/2} - ^2D_{5/2}$ clock transition is detected by shelving

<table>
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<tr>
<th>State</th>
<th>Lifetime</th>
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<tbody>
<tr>
<td>$^2P_{1/2}$</td>
<td>8.1 ns</td>
</tr>
<tr>
<td>$^2D_{5/2}$</td>
<td>7.2 ms</td>
</tr>
<tr>
<td>$^2F_{7/2}$</td>
<td>&lt; 10 yr</td>
</tr>
<tr>
<td>$^1D[5/2]_{5/2}$</td>
<td>&lt; 160 ms</td>
</tr>
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- Lifetime of each state
- Partial term scheme of Yb$^+$
- Quantum-jump signal

Decay $^2D_{5/2}$ to $^2F_{7/2}$ state → Fluorescence disappears

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Procedure for spectroscopy of the $^2S_{1/2} - ^2D_{5/2}$ transition

1: Laser cool a single $^{174}$Yb$^+$
2: Irradiate ion with probe laser
3: Detect shelving
   - Not shelved: repeat this cycle
   - Shelved: depopulation from the $^2F_{7/2}$ state

Clock laser
- Linewidth: ~ 500 Hz
- Frequency drift: ~ 20 kHz/h
- Power: 1 ~ 100 µW
Spectrum of the $^2S_{1/2} - ^2D_{5/2}$ transition in a single $^{174}$Yb$^+$

- Spectrum of the $^2S_{1/2}(m_j = -1/2) - ^2D_{5/2}(m_j = -5/2)$ transition

Many sidebands are observed

Identification of sidebands

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Measurement of secular frequency

Sweep RF frequency applied to endcap by changing trap potential

RF frequency corresponds to secular frequency

\[ V = V_{DC} + V_{AC} \cos \Omega t \]

Fluorescence disappears

- Dependence of secular frequency on trap RF potential \((V_{DC}=0 \text{ V})\)
- Dependence of secular frequency on trap DC potential \((V_{AC}=130 \text{ V})\)

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Excess micromotion and nonlinear motion

Nonlinear motion: larger as an ion deviates from trap center

\[ \Delta V = \frac{1}{2} V_0 C_4 \left( \frac{1}{z_0^4} \right) \left[ z^4 + 3z^2r^2 + \frac{3}{8} r^4 \right] \]

Excess micromotion: larger as an ion deviates from trap center by stray electric field

Nonlinear motion is suppressed by compensation of excess micromotion
Compensation of excess micromotion

- RF-photon correlation method

1. Compensate excess micromotion with a cooling laser
2. Compensate excess micromotion with two cooling lasers irradiated from different directions each other
3. Observe displacement of a trapped ion caused by amplitude modulation of trap RF

Detect only a component of excess micromotion parallel to a cooling laser


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Compensation by amplitude modulation of trap RF

Measure fluorescence variation caused by amplitude modulation of trap RF
Modulation index: 0.5, Modulation frequency: 200 mHz

- Fluorescence variation caused by amplitude modulation of trap RF
- Maximum fluorescence variation

Adjust so that fluorescence variation is minimum

Spectrum of the $^{2}S_{1/2} - ^{2}D_{5/2}$ transition in a single $^{174}$Yb$^{+}$

- Spectrum of the $^{2}S_{1/2} - ^{2}D_{5/2}$ transition (compensate micromotion with a cooling laser)

- Spectrum of the $^{2}S_{1/2} - ^{2}D_{5/2}$ transition (compensate micromotion with two cooling lasers)

- Spectrum of the $^{2}S_{1/2} - ^{2}D_{5/2}$ transition (all compensation methods are applied)

Nonlinear motion is suppressed
Single–ion spectroscopy of the $^2S_{1/2}(F=0)-^2D_{3/2}(F=2)$ transition

- Zeeman components of $^2S_{1/2}(F=0)-^2D_{3/2}(F=2)$ transition in single $^{171}\text{Yb}^+$

- Carrier spectrum of the $^2S_{1/2}(F=0, m_F=0)-^2D_{3/2}(F=2, m_F=0)$ clock transition

The clock frequency is feed-forward compensated by 32 Hz in 1 s intervals during measurement.

Yasutaka Imai et al., Radio Sci. 51, 1385–1395 (2016)
Summary

• Current status
  - Nonlinear motion is suppressed by optimization of micromotion

• Next tasks
  - Narrowing linewidth and improving stability of the clock lasers
  - Construction of $^{171}\text{Yb}^+$ ion clocks and evaluation of their uncertainties