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

Yasutaka Imai

Graduate School of Electronic Science and Engineering, Kyoto University

FPUA2018@Nagoya University

Coworkers

• Yb^+:	Yasutaka Imai	S-D clock transition
	Ren Irie	S-D clock transition
• Ba^+:	Hiroto Fujisaki	S-D clock transition
	Sinya Kawada	Clock laser
• Comb:	Masaya Hatake	Mode-locked laser

- Project leader: Kazuhiko Sugiyama
- Supervisor: Masao Kitano

Optical clock (frequency standard)

- Frequency stability $\sigma^{-1} \propto \frac{1}{Q} = \frac{\omega_0}{\Delta\omega}$ ω_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)

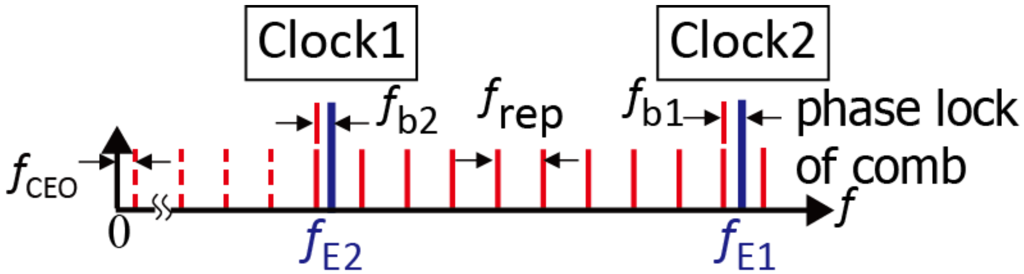
- Optical frequency measurement: frequency comb

Possible precise frequency ratio measurement between optical clocks.

Search for temporal variation of fine structure constant α

- Fine structure constant α
  - Dimensionless: no dependence on units
  - Depended on by frequency of electric transition: affect each reference frequency of optical clocks

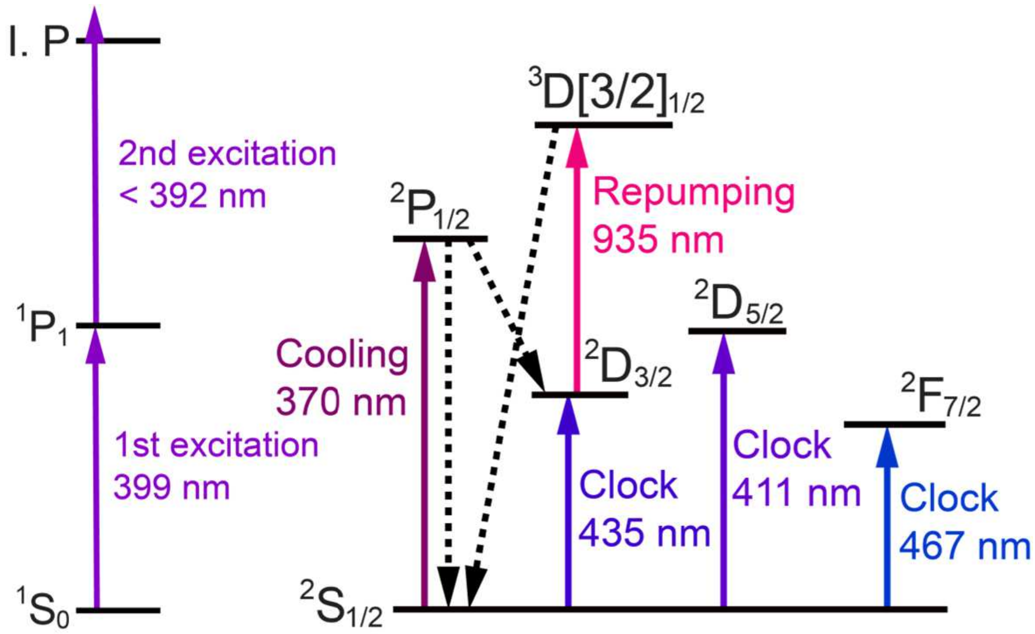
Repeatable measurement by frequency comparison between two optical clocks with optical frequency comb



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



- Partial term scheme of Yb and Yb^+

- Clock transition
  - $^2S_{1/2} - {}^2D_{5/2}$ λ=411 nm γ = 22 Hz — Roberts *et al*., PRA 60, 2867 (1999)
  - $^2S_{1/2} - {}^2D_{3/2}$ λ=435 nm γ = 3 Hz — Tamm *et al*., PRA 80, 043403 (2009)
  - $^2S_{1/2} - {}^2F_{7/2}$ λ=467 nm $\gamma < 10^{-9}$ Hz — Huntemann *et al*., PRL 108, 090801 (2012)

Advantage of Yb^+ on search for temporal variation of α

- 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

Ion	Transition	sensitivity A
Hg	$^2S_{1/2}$-$^2D_{5/2}$	-3.19
Al	$^1S_0$-$^3P_0$	0.008
Yb	$^2S_{1/2}$-$^2F_{7/2}$	−5.20
	$^2S_{1/2}$-$^2D_{3/2}$	0.88
	$^2S_{1/2}$-$^2D_{5/2}$	0.88

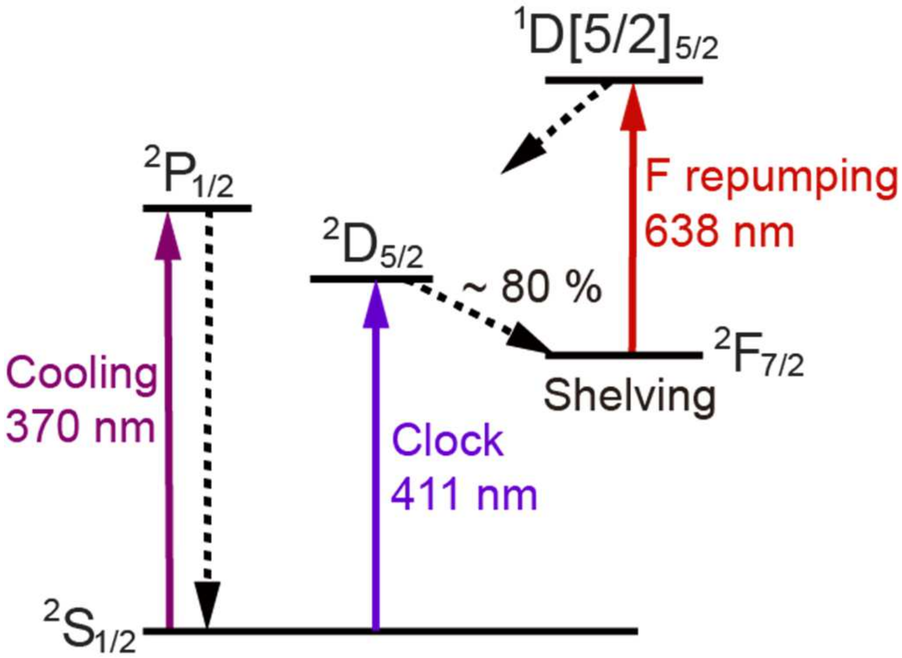
- $^2S_{1/2}$-$^2F_{7/2}$ vs $^2S_{1/2}$-$^2D_{3/2}$ or $^2S_{1/2}$-$^2D_{5/2}$: Detect temporal variation of α
- $^2S_{1/2}$-$^2D_{3/2}$ vs $^2S_{1/2}$-$^2D_{5/2}$: Investigate other variations

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

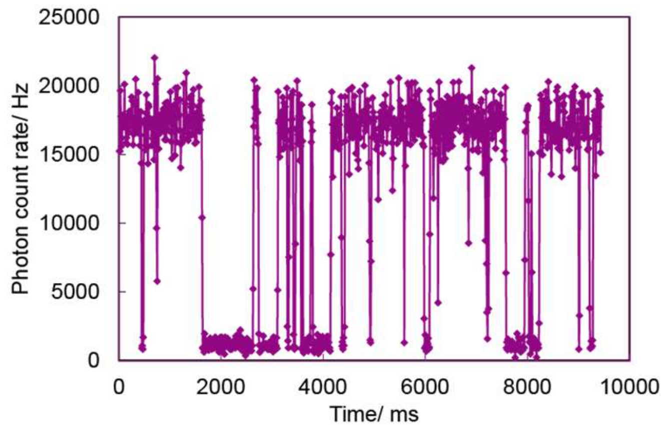
The $^2S_{1/2}$ - $^2D_{5/2}$ clock transition is detected by shelving



- Partial term scheme of Yb^+

$^2P_{1/2}$	8.1 ns
$^2D_{5/2}$	7.2 ms
$^2F_{7/2}$	< 10 yr
$^1D[5/2]_{5/2}$	< 160 ms

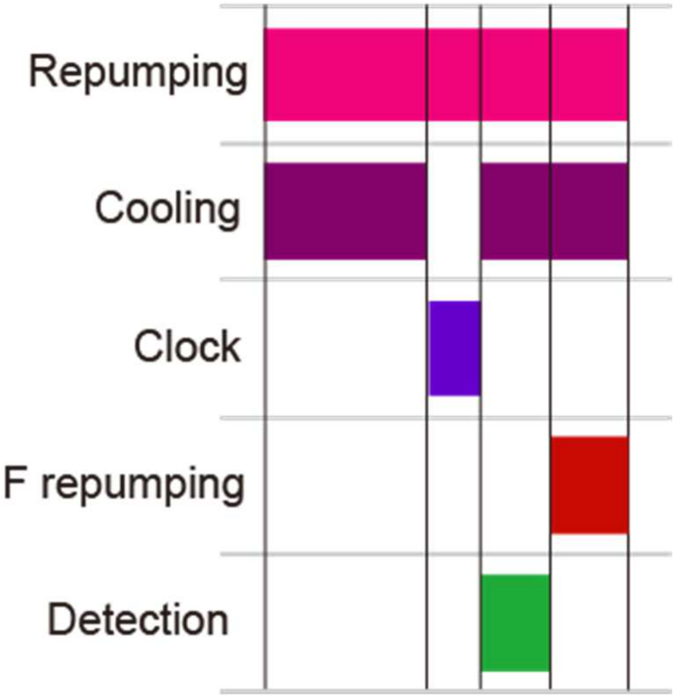
- Lifetime of each state



- Quantum-jump signal

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

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



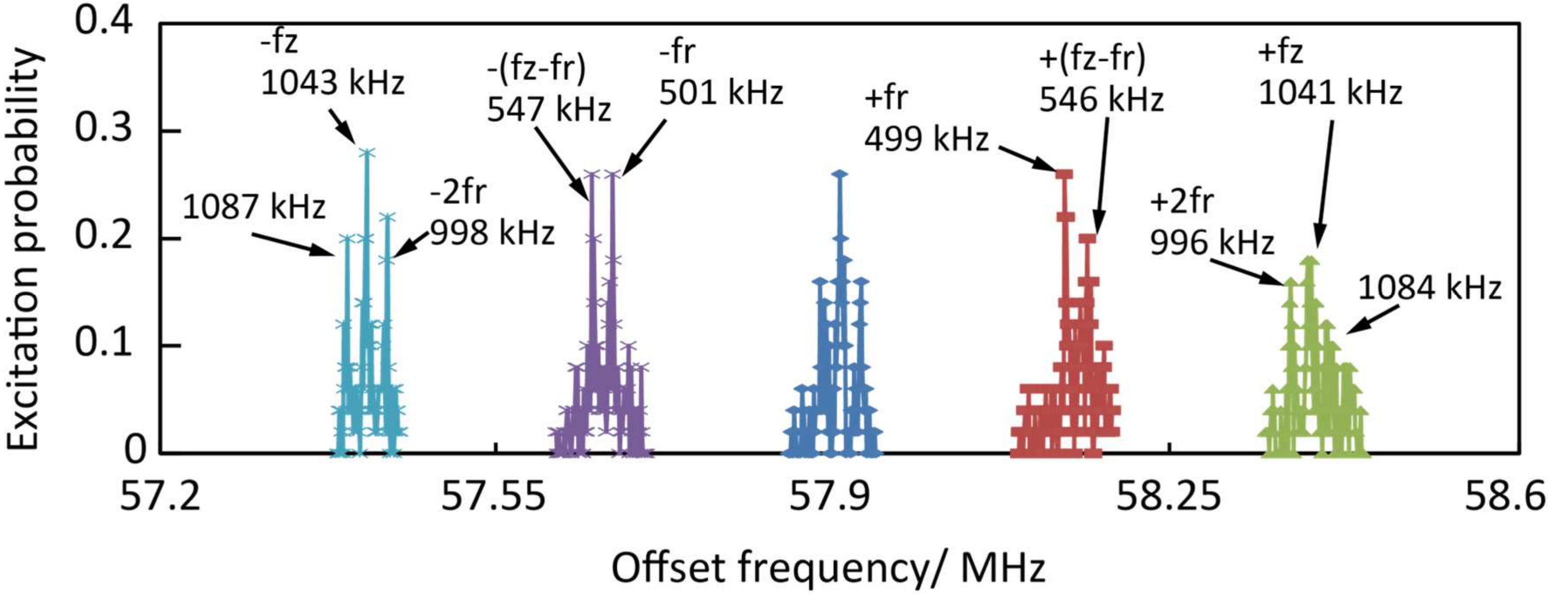
- Time table of spectroscopy

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

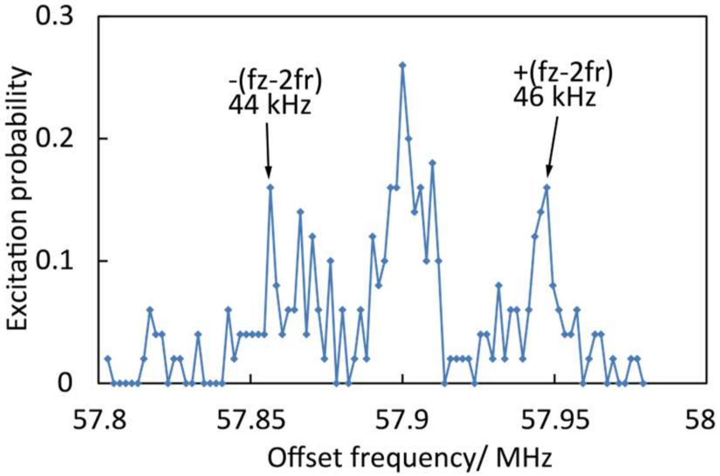
Clock laser

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



- Carrier spectrum

Many sidebands are observed

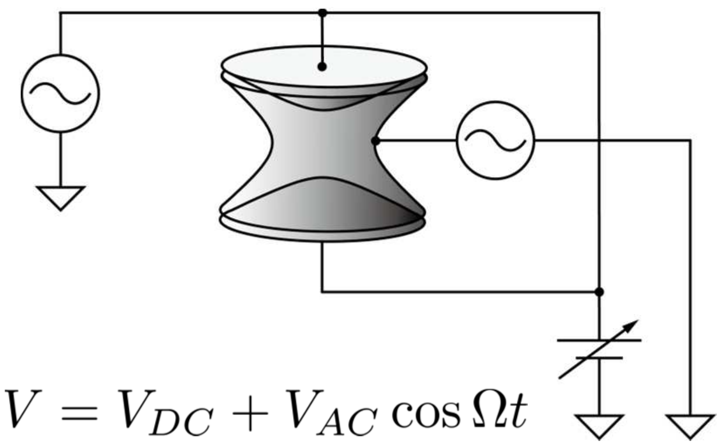
Identification of sidebands

Measurement of secular frequency

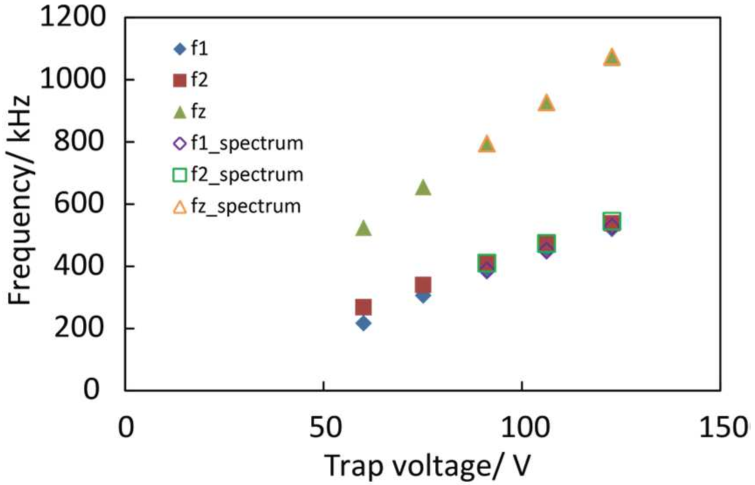
Sweep RF frequency applied to endcap
by changing trap potential

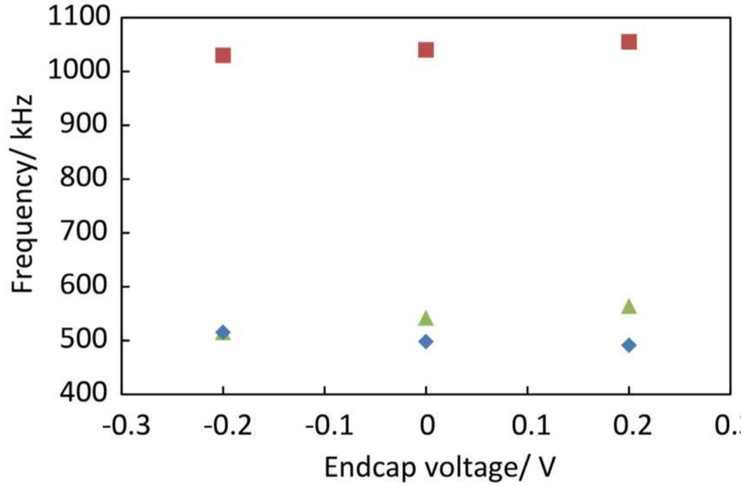
RF frequency corresponds to secular frequency

⇨ Fluorescence disappears



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



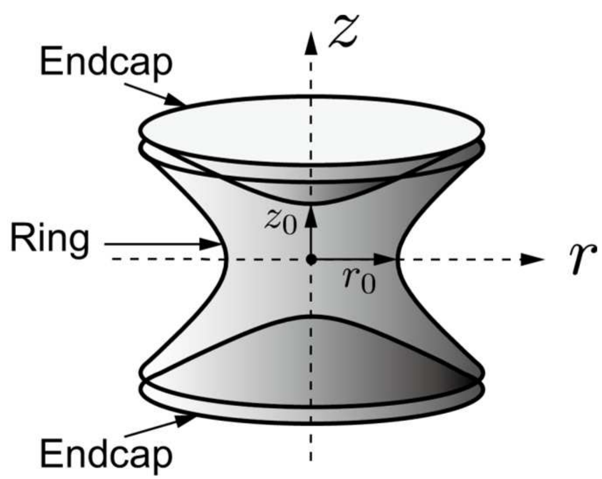


- Dependence of secular frequency on trap RF potential (V_{DC}=0 V)
- Dependence of secular frequency on trap DC potential (V_{AC}=130 V)

Excess micromotion and nonlinear motion

Nonlinear motion: larger as an ion deviates from trap center

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

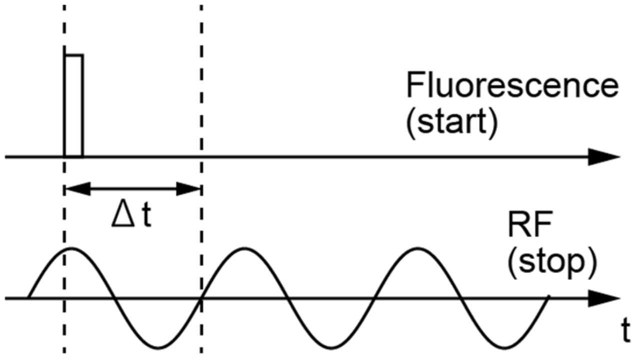


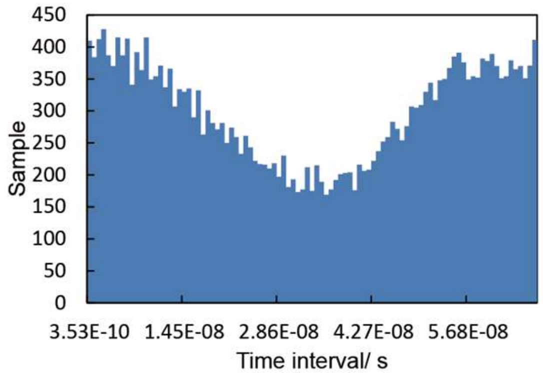
Excess micromotion: larger as an ion deviates from trap center by stray electric field

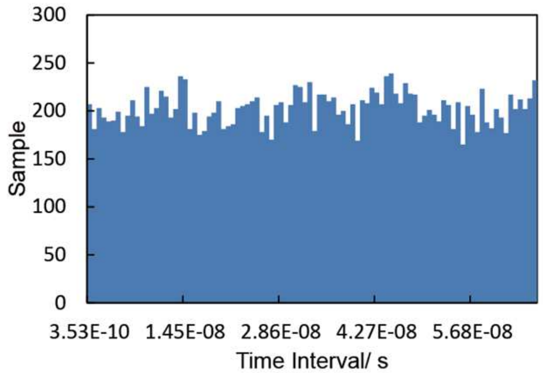
Nonlinear motion is suppressed by compensation of excess micromotion

Compensation of excess micromotion

- RF-photon correlation method







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

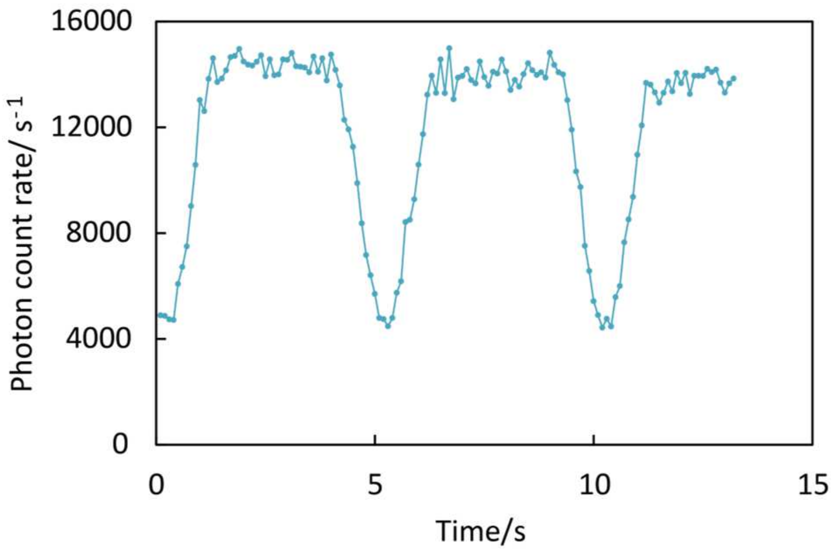
1. Compensate excess micromotion with a cooling laser
2. Compensate excess micromotion with two cooling lasers irradiated from different directions each other
3. Observe displacement of a trapped ion caused by amplitude modulation of trap RF

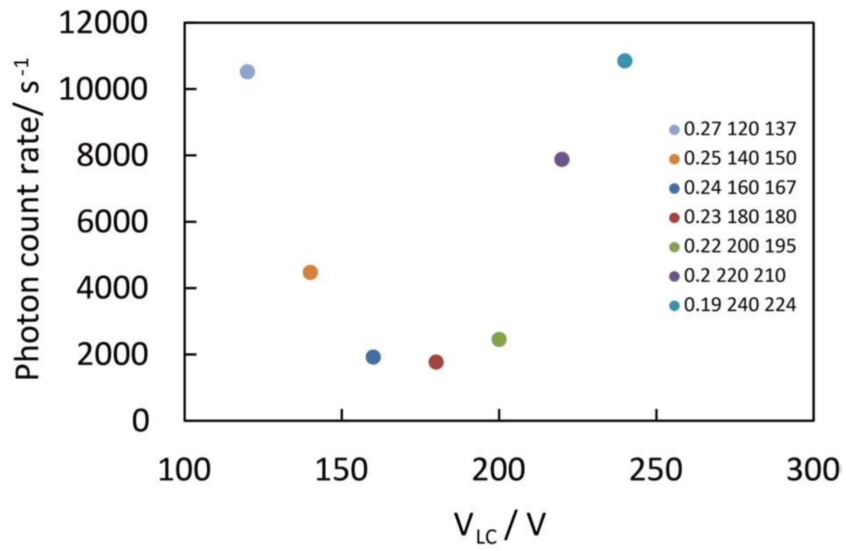
D. J. Berkeland *et al*., J. Appl. Phys **83**, 5025 (1998)

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



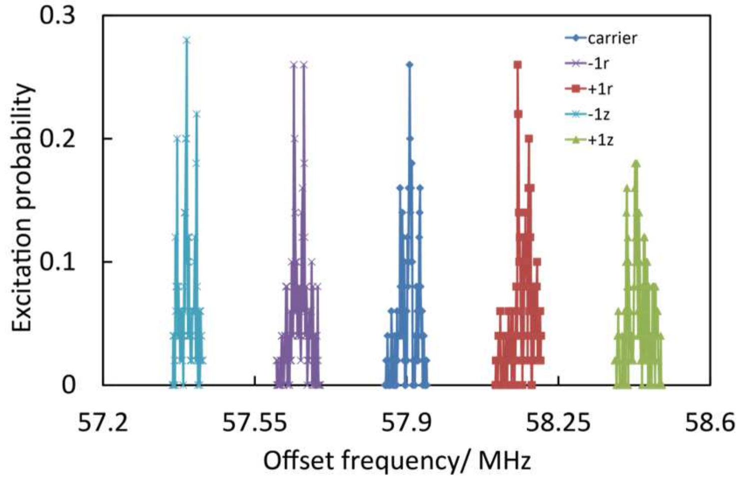


- Fluorescence variation caused by amplitude modulation of trap RF
- Maximum fluorescence variation

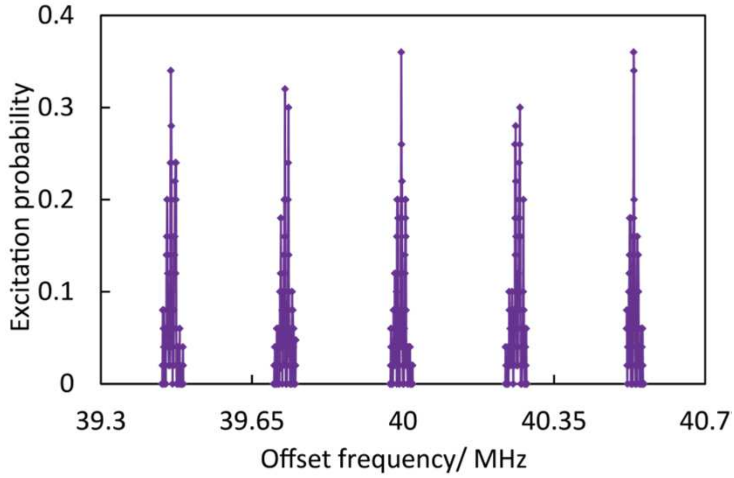
Adjust so that fluorescence variation is minimum

More sensitive method: Y. Ibaraki *et al*., Appl. Phys B **105**, 219 (2011)

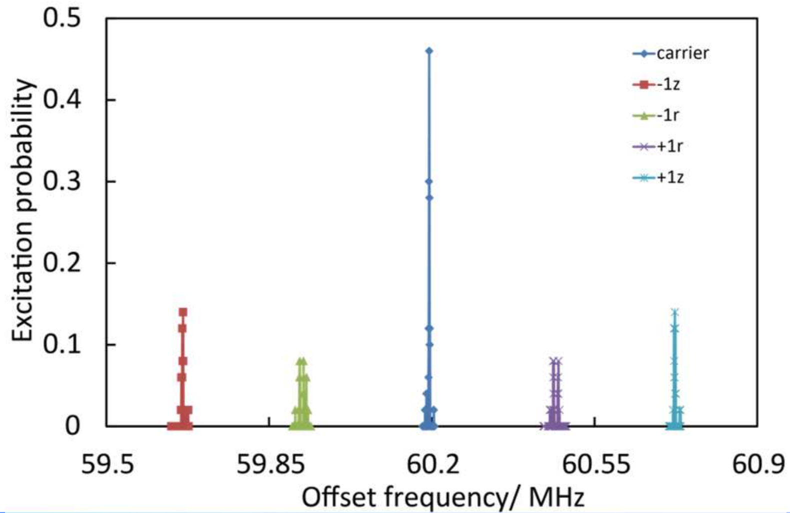
Spectrum of the $^2S_{1/2}$-$^2D_{5/2}$ transition in a single $^{174}Yb^+$



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



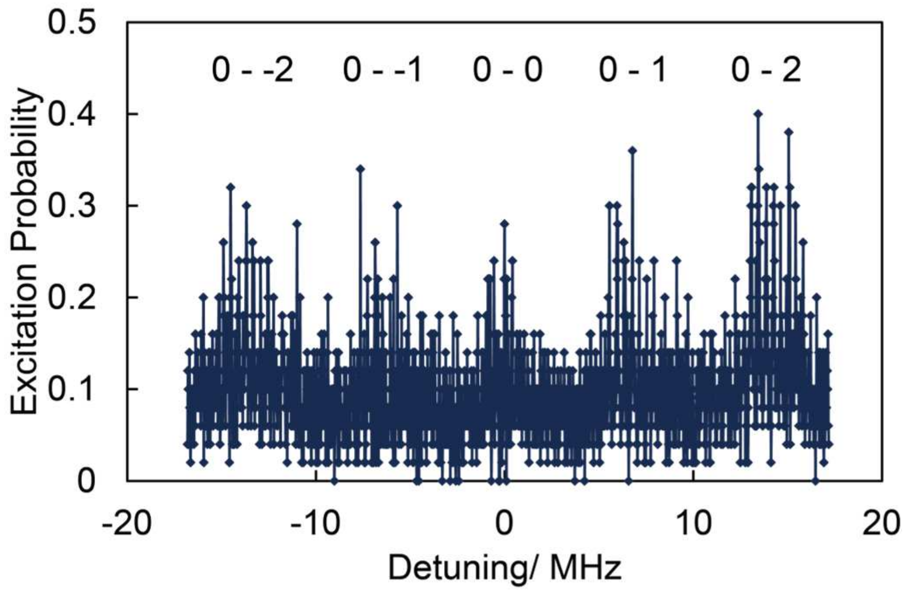
- Spectrum of the $^2S_{1/2}$ - $^2D_{5/2}$ transition (compensate micromotion with two cooling lasers)



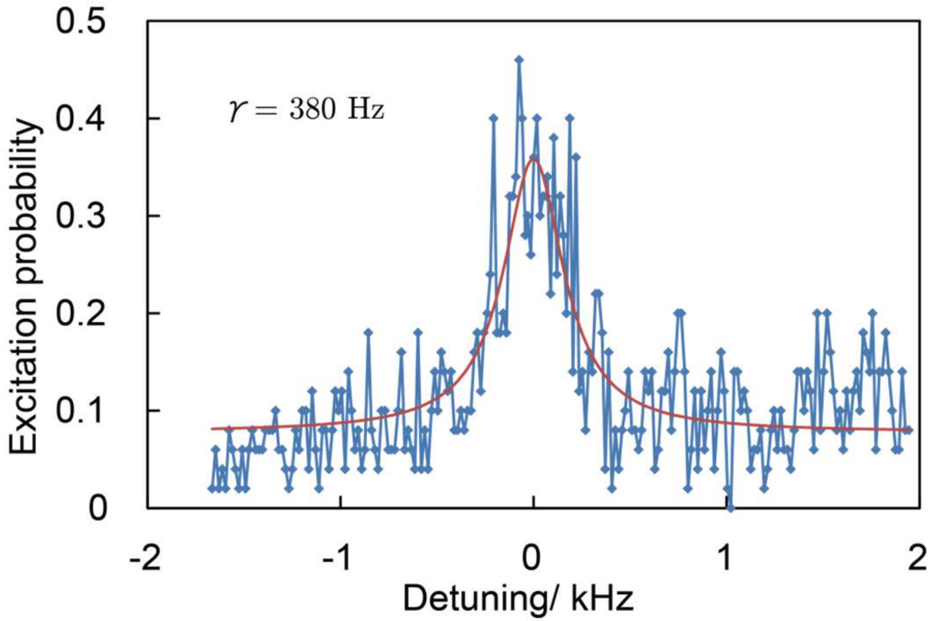
- Spectrum of the $^2S_{1/2}$ - $^2D_{5/2}$ transition (all compensation methods are applied)

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 $^{171}Yb^+$



- 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 $^{171}Yb^{+}$ ion clocks and evaluation of their uncertainties