Development of second Yb^+ ion trap for frequency comparison

Kazuhiko Sugiyama, Takayuki Morimoto, Keisuke Yoshida, and Takahiro Enomoto

Graduate School of Electronic Science and Engineering, Kyoto University

Yasutaka Imai

Research Institute for Interdisciplinary Science, Okayama University

Fundamental Physics Using Atoms 2024 (FPUA2024)

March 14-15, 2024, in Okayama, Japan

Kyoto University, Katsura Campus, since 2003.9.

Purpose

- Two setups of Yb^+ ion trap
  - Evaluation of uncertainties of optical clocks
  - Search for temporal variation of α [1,2,3]
  - Measurement of isotope shifts
    - Search for nonlinearity in King's plot [4,5] caused by
      - Higher-order volume shifts
      - Interaction with unknown particles?

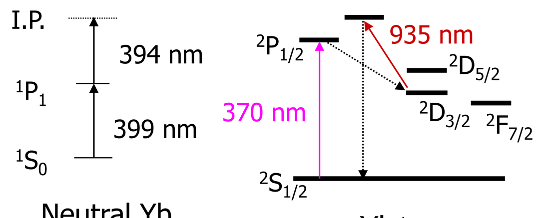
      Yb: five stable even isotopes w/o hyperfine structures
    - $^2S_{1/2}-{}^2D_{5/2}$ transition
      - Uncertainty in isotope shifts <10 Hz [6]

Natural abundance

Isotope	Abundance / %
168	0.13
170	3.1
171	14.4
172	16.2
174	31.6
176	12.6

[1] R. M. Godun et al., Phys. Rev. Lett., 113, 210801 (2014)
[2] N. Huntemann et al., Phys. Rev. Lett., 113, 210802 (2014)
[3] M. Filzinger et al., Phys. Rev. Lett., 130, 253001 (2023)
[4] C. Delaunay et al., Phys. Rev. D 96, 093001 (2017).
[5] K. Mikami et al., Eur. Phys. J. C, 77, 896 (2017).
[6] C. Yeh et al., IFCS-EFTF2023, 7279 (2023).

Yb^+



Neutral Yb for photoionization | Yb^+

Clock transitions:
- 411 nm: $^2S_{1/2}-{}^2D_{5/2}$ τ = 7 ms
- 435 nm: $^2S_{1/2}-{}^2D_{3/2}$ τ = 52 ms
- 467 nm: $^2S_{1/2}-{}^2F_{7/2}$ τ ~ 4000 d

H. A. Fürst *et al.*, PRL 125, 163001 (2020)
J. Stuhler *et al*, Measurement: Sensors, 18, 100264 (2021)
N. Huntemann *et al.*, PRL 116, 063001 (2016)

- Isotope 171 (I=1/2)
  - $m_F=0 \rightarrow m_F'=0$, no 1st-order Zeeman shift
  - simplest hyperfine structure because of I=1/2
  - (only $^{199}Hg^+$ has I=1/2)
- Small system with simple light sources

- Optical frequency standard: PTB, NPL
- Quantum information processing: IonQ

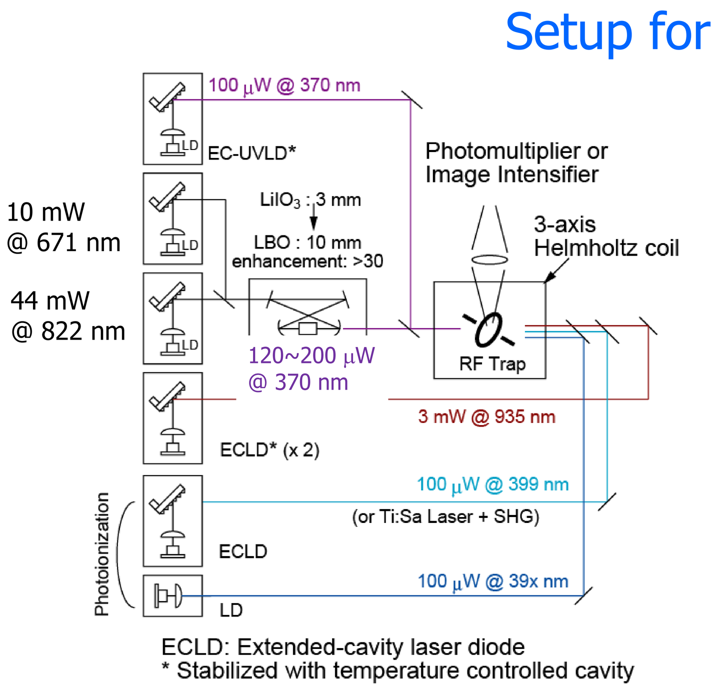
Two setups of RF trap

- Trap #1
  - Oven #1: Natural mixture, 171 enriched
  - Previous status
    - Isotope-selective single-ion loading
    - Single-ion spectroscopy of $^2S_{1/2}-{}^2D_{3/2}$ transition in $^{171}Yb^+$
    - 1 cooling beam, 2D micromotion minimization
- Trap #2
  - Oven #1: 174 enriched, 171 enriched
  - Previous status
    - Single-ion spectroscopy of $^2S_{1/2}-{}^2D_{5/2}$ transition in $^{174}Yb^+$
    - 2 cooling beams, 3D micromotion minimization
    - (Almost) Lamb-Dicke confinement achieved

This work

- 2 cooling beams, 3D micromotion minimization
- Single-ion spectroscopy of $^2S_{1/2}-{}^2D_{5/2}$ transition in $^{174}Yb^+$
- Single-ion spectroscopy of $^2S_{1/2}-{}^2D_{3/2}$ transition in $^{171}Yb^+$

Setup for laser cooling of Yb^+



$2r_0$ = 0.8 mm
$\Omega/2\pi$ ~ 14 MHz
V ~ 100 V

Replacing a LBO crystal more transparent
⇒ Increase of SF radiation
⇒ Simultaneous trap and cooling using two setups achieved

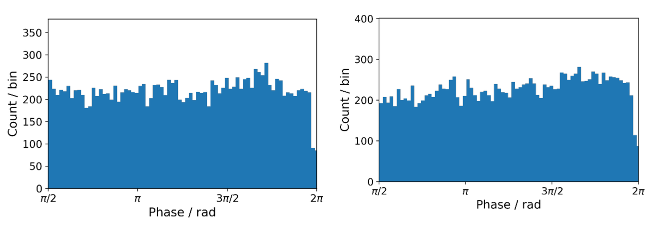
UV SF radiation is frequency stabilized by offset locking of one of the fundamental laser to the clock laser at 822 nm.
Δf < ±200 kHz @ 370 nm

We acknowledge Prof. Kawakami and Nichia Ltd. for providing us UV-LDs.

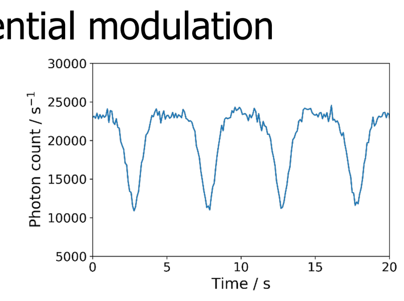
SFM: K. Sugiyama *et al*, Applied Optics, 49, 5510 (2010)
Photoionization: Y. Onoda *et al*, Applied Physics B (2011)

Cooling

- 3D cooling of secular motion using two cooling beams
  - For degeneration of radial direction ($\omega_x = \omega_y$)
- Micromotion minimization
  - 2D: RF-photon correlation measurement using two cooling beams
  - 3rd direction: (Almost) No space for 3rd cooling beam
  - ▶Fluorescence intensity change with slow potential modulation

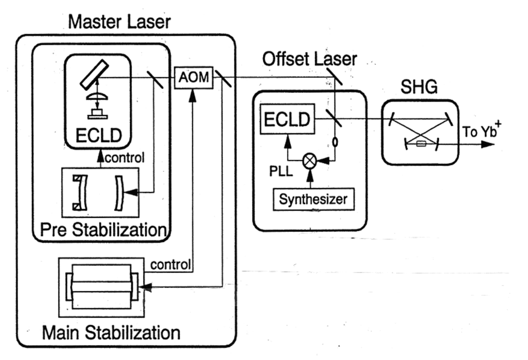


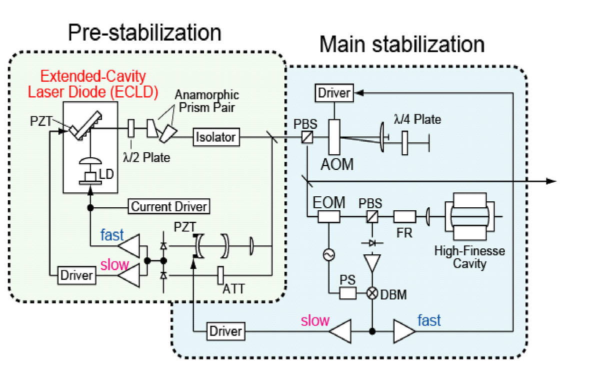
Resolution
compensation electrode: 1 V / 200 V
endcap: 0.01 V / 0.3 V

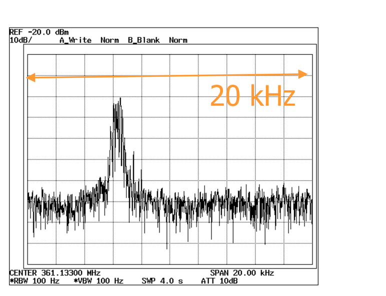


Resolution
compensation electrode: 5 V / 200 V

Clock laser for $^2S_{1/2}-{}^2D_{5/2}$ transition at 411 nm (similar but no prestabilizer for $^2S_{1/2}-{}^2D_{3/2}$ transition at 435 nm)





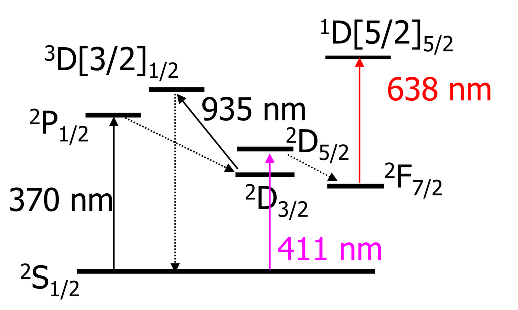


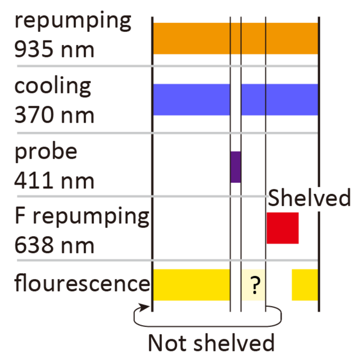
Beatnote of two independent system
Linewidth<500 Hz
Drift ~50 Hz/s

Pre: Δ_{cavity} = 15 MHz (super inver)
Transparent fringe side, fast: current, slow: PZT

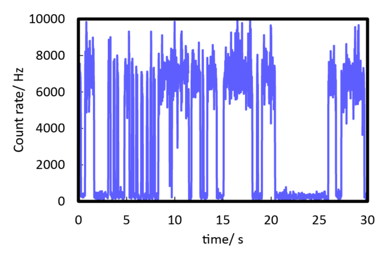
Main: Δ_{cavity} = ~50 kHz (ULE)
FM sideband, fast: AOM, slow: PZT @pre stab. cavity

Trap #1: Single-ion spectroscopy of $^2S_{1/2}-{}^2D_{5/2}$ transition in $^{174}Yb^+$ with three-dimensional cooling

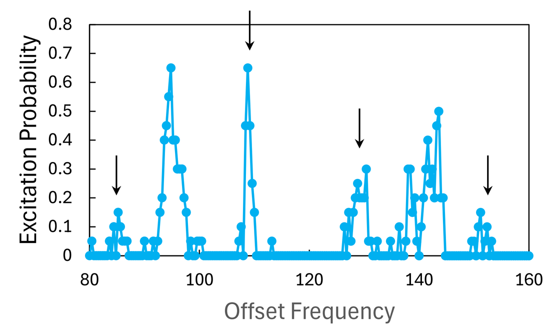




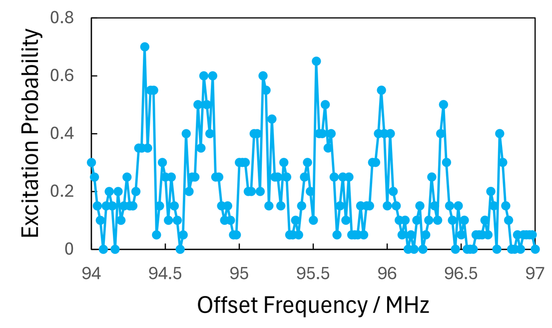
Timetable of spectroscopy



Quantum-jump signal

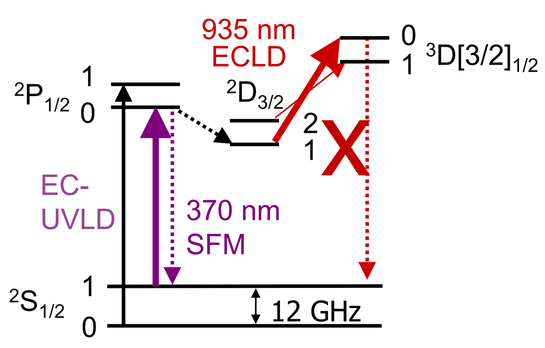


Zeeman component of $\Delta m_j = \pm 2$
(↓: micromotion sideband)



$^2S_{1/2}(m_j=-1/2)-{}^2D_{5/2}(m_j=-5/2)$ component

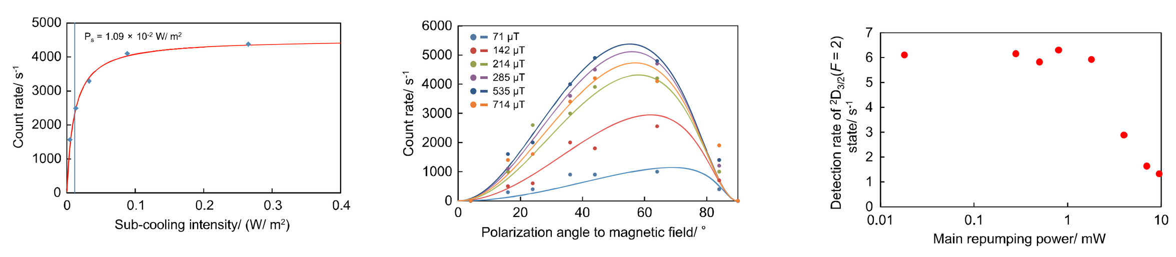
Trap #2: Single-ion spectroscopy of $^2S_{1/2}(S=0) - {}^2D_{3/2}(F=2)$ transition in $^{171}Yb^+$



- Previous results in Trap #1
  - 7 mK with one cooling beam
    - cf. Doppler cooling limit ~0.5 mK

    Y. Imai *et al*, Radio Science, 51, 1385 (2016)
- Transfer 3D cooling technique developed using $^{174}Yb^+$ in trap #2

Previous knowledge from Trap #1

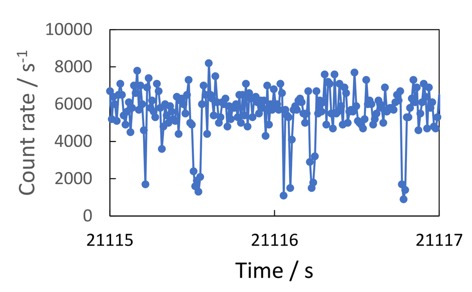


- Power requirement for sub cooling laser
  - A few nW
- Polarization angle of main cooling laser
  - ~45° (max 55°)
- Decoupling $^2D_{3/2}$ (F=2)
  - Main repumping power should be adjusted

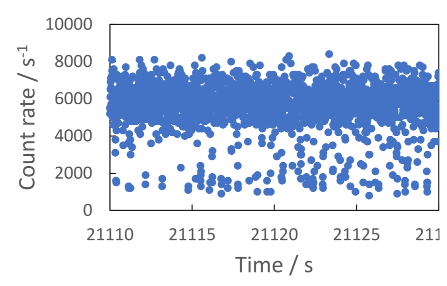
Y. Imai *et al*, Radio Science, 51, 1385 (2016)

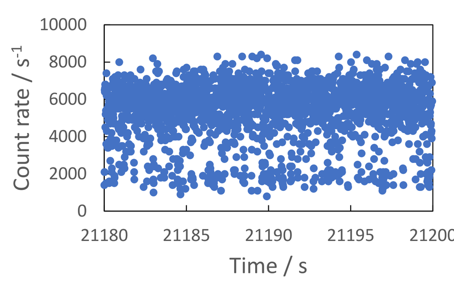
D. Engelke and C. Tamm, Europhys. Lett. 33, 347 (1996)
V. Buehner and C. Tamm, Phys. Rev A61, 061801(R)(2000)

New results with Trap #2 with 3D cooling

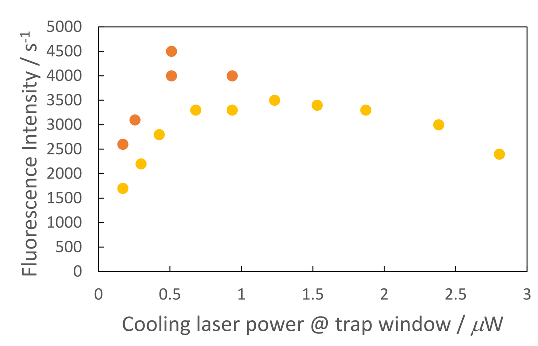


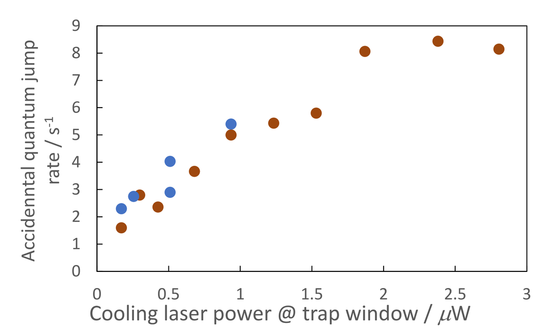
"Accidental" quantum jumps by pumping to the $^2D_{3/2}$ (F=2)





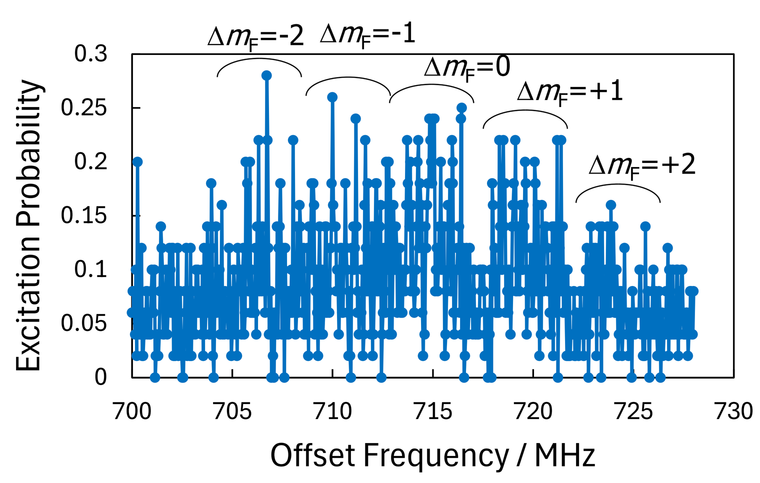
Low cooling power (not measured but ~1 μW?) | Power at ~fluorescence saturated



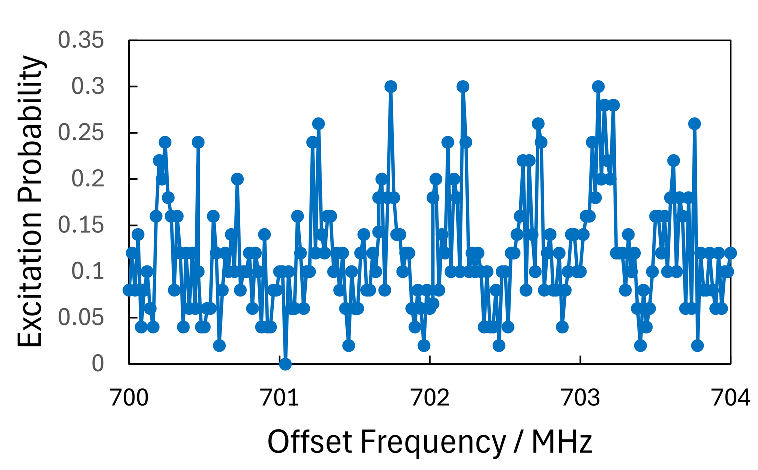


Preliminary results (remeasurement required after magnetic field optimized)

Single-ion spectroscopy of $^2S_{1/2}(S=0) - {}^2D_{3/2}(F=2)$ transition in $^{171}Yb^+$



Zeeman components (maybe)



Sideband structure by secular motions (Zeeman component not assigned)

Conclusions

- Two setups are being developed
  - Three-dimensional cooling
  - Single-ion spectroscopy
    - Trap #1: $^2S_{1/2}(F=0) - {}^2D_{3/2}(F=2)$ transition in $^{171}Yb^+$
    - Trap #2: $^2S_{1/2} - {}^2D_{5/2}$ transition in $^{174}Yb^+$
- Next step
  - Lamb-Dicke confinement
  - Simultaneous single-ion spectroscopy using two setups, then...
    - Measurement: uncertainty, isotope shifts
  - Improvement required for long continuous operation