New Approaches To An Indium Ion Optical Frequency Standard

Kazuhiro HAYASAKA

National Institute of Information and Communications Technology (NICT)

e-mail: hayasaka@nict.go.jp
Outline

1. Introduction

2. New approaches

3. Status of the project
   (0)\textit{In}^+\textit{-Ca}^+ \text{ chain synthesis}
   (1)\textit{quantum logic spectroscopy}
   (2)\textit{VUV excitation}
   (3)\textit{$^1S_0$-\textit{$^3P_1$ excitation}}

4. Summary
Motivation: smaller frequency uncertainty

$^{40}$Ca$^+$ optical clock at NICT

1st system: no magnetic shield

2nd system: with magnetic shield

However, fractional uncertainty is limited to in the order of $10^{-15}$ due to quadrupole shift, black body radiation (BBR) shift.

need of IIIA ions ($B^+$, $Al^+$, $Ga^+$, $In^+$, $Th^+$) for smaller fractional uncertainty
Energy structure of IIIA ions

Common feature of III A ions
• good clock transition (\(^1S_0 - ^3P_0\))
  • high Q value
  • no quadrupole shift
  • small BBR shift
• cooling/detection transition (\(^1S_0 - ^1P_1\)) in VUV hard to access

\( ^{27}\text{Al}^+ \) (NIST)

\( ^1S_0 \rightarrow ^3P_2 \rightarrow ^3P_1 \rightarrow ^1P_1 \)
\( \lambda = 167 \text{ nm} \)
\( \Gamma = 1.5 \text{ GHz} \)

\( ^{115}\text{In}^+ \) (MPQ, Erlangen)

\( ^1S_0 \rightarrow ^3P_2 \rightarrow ^3P_1 \rightarrow ^1P_1 \)
\( \lambda = 159 \text{ nm} \)
\( \Gamma = 1.1 \text{ GHz} \)

Quantum logic spectroscopy (QLS) recorded the smallest uncertainty of \( 8.6 \times 10^{-18} \)

Traditional In$^+$ optical clock (MPQ, Erlangen)

Single In$^+$ in a Paul-Straubel trap
- bicromatic sideband cooling at 230nm
clock transition ($^1S_0$-$^3P_0$)
- linewidth 0.8Hz
- no quadrupole shift
- small BBR shift estimated at 300K
  $< 7 \times 10^{-17}$ Becker et al. PRA 63,051802(2001)
  $4.7 \times 10^{-17}$ Peik (2002)
  $3.8 \times 10^{-17}$ Wang et al. (2006)
  $2.0 \times 10^{-17}$ Kajita (2010)

Fractional uncertainty in the order of $10^{-18}$ is expected

However, reported numbers remain in the order of $10^{-13}$

1 267 402 452 899.92 (0.23) kHz  (1.8 $\times 10^{-13}$)

1 267 402 452 901.265 (0.256) kHz  (2.35 $\times 10^{-13}$)
New approaches

• Basic configuration: In\textsuperscript{+} in a linear trap with other ions
  • Cooling is provided by sympathetic cooling (currently by \(^{40}\text{Ca}^+\), in future by \(^{115}\text{Cd}^+\))
  • Detection is provided by three methods
    1. Quantum logic spectroscopy (QLS)
    2. Vacuum ultraviolet (VUV) excitation at 159nm
       multimode pulses generated by high harmonic generation (HHG) of Ti:S laser (795nm) might be used.
    3. \(^1\text{S}_0^\text{I}-^3\text{P}_1\) excitation at 230nm
       slow detection is compensated by clock laser locked to Sr optical lattice clock.
Procedure of building Ca\(^+\)- In\(^+\) chains

Target example: \(\text{Ca}^+ \text{In}^+ \text{Ca}^+\)

1. prepare a Ca\(^+\) chain

2. load In\(^+\) by resonant photo-ionization

3. reduce number of In\(^+\) by rf-kick

4. adjust position of In\(^+\) by axial potential adjustment
Experimental setup

linear trap
$r_0 = 1.83\text{mm}$
$2z_0 = 8\text{mm}$
$\Omega/2\pi = 12.6\text{MHz}$, $\omega/2\pi = 0.82\text{MHz}$
DC 1-100V

In oven
image-intensified CCD camera
magnification ~20

In oven

Doppler cooling beam
397nm
repump beam
866nm
DC control
rf control
Ca oven
Ca ionization beams
423nm+390nm
In ionization beam
411nm
Ca$^+$
fluorescence
at 397nm

300ms integration

In$^+$ is NOT visible

ECTI2010
Snapshot of Ca\(^+\)-In\(^+\) chain synthesis

**Ca\(^+\) number adjustment by rf control**

- rf voltage: 430V->60V for 1s

**Loading of In\(^+\) by resonant photo-ionization**

- 411nm: auto-ionizing

**In\(^+\) number adjustment by rf control**

\[
\omega_r = \sqrt{\frac{eV_0}{2mr^2\Omega_0}} \propto \frac{1}{m}
\]

\[
\frac{\omega_r(\text{In}^+)}{\omega_r(\text{Ca}^+)} = 0.35
\]

- \(V_0=98\text{V}\) for 1sec
- \(\omega_r(\text{Ca}^+)/2\pi=177\text{kHz}\)
- \(\omega_r(\text{In}^+)/2\pi=62\text{kHz}\)

**Configuration control by DC control**

- DC electrode voltage: 10->22V

ECTI 2010
Identification of $\text{In}^+$

Vibrational frequencies depend on mass ⇒ identification of the mass possible

- Configuration $\omega_z (\text{mixed}) / \omega_z (\text{Ca}^+)$ (of the lowest mode)
  - $\text{Ca}^{40}^+$: 1.00
  - $\text{Ca}^{115}^+$: 0.59
  - 0.689
  - 0.703
  - 0.702
  - 0.702

Quantum logic spectroscopy

Collaboration with Prof. Urabe group at Osaka univ.

$^{115}\text{In}^+$

$^{40}\text{Ca}^+$

$^1S_0$  $^1P_1$  $^3P_1$  $^3P_2$  $^3P_0$

$\lambda=159\text{nm}$  $\Gamma=1.1\ \text{GHz}$

clock  $237\text{nm}$  $0.8\text{Hz}$

detection  $397\text{nm}$  $20\text{MHz}$

$qubit$  $729\text{nm}$  $0.2\text{Hz}$

 mj=$1/2$  mj=$5/2$

$^2S_{1/2}$  $^2P_{1/2}$  $^2D_{5/2}$

sideband cooling  (729nm)

to the ground state  is in progress

$\text{In}^+ + \text{Ca}^+$ chain is generated with high reproducibility
Coherent VUV source for optical clocks

Common level structure of atomic clocks

<table>
<thead>
<tr>
<th></th>
<th>Sr</th>
<th>Al⁺</th>
<th>In⁺</th>
<th>Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock scheme</td>
<td>Lattice clock</td>
<td>Quantum logic spectroscopy</td>
<td>Single ion</td>
<td>??</td>
</tr>
<tr>
<td>Clock transition</td>
<td>¹S₀⁻³P₀</td>
<td>¹S₀⁻³P₀</td>
<td>¹S₀⁻³P₀</td>
<td>Nuclear transition</td>
</tr>
<tr>
<td>λ of clock transition (nm)</td>
<td>698</td>
<td>267</td>
<td>237</td>
<td>164 ± 11</td>
</tr>
<tr>
<td>λ of ¹S₀⁻¹P₁ transition (nm)</td>
<td>461</td>
<td>167</td>
<td>159</td>
<td></td>
</tr>
</tbody>
</table>

All within 5ᵗʰ harmonic of Ti:S!

Our target
VUV generation Setup

- DPSS laser (7W, 532nm, CW)
- Mode-locked Ti:S oscillator (~700mW, 795nm, 65fs)
- Pulse compressor (SF10 prism pair)
- Feedback to PZT to lock freq (112MHz)

Vacuum Chamber

- 99.68% Input coupler
- Roundtrip length: 2.7m
- Vacuum: <1e-5 torr
- Curvature mirror: 100mm
- average intracavity power: 250W
- peak intensity: $10^{13}$W/cm$^2$

- Xe gas jet
- Grating mirror
- Fluorescent plate

Hänsch-Couillaud locking
Observation of the VUV output

first measurement of 5\textsuperscript{th} high harmonic (159nm) with a phototube:
1.5\mu W
(4.2 \times 10^5\text{ modes total})

stable output is maintained over 1 minute even with manual adjustment of $f_{\text{ceo}}$
Estimation of photon counting rate

In$^+$

$^1P_1$
- F=9/2
- F=11/2

$^1S_0$

159nm

Three HFS levels are simultaneously excited by $5^{th}$ HH of the 110MHz comb


<table>
<thead>
<tr>
<th>items</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>high harmonic average power</td>
<td>100µW*</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>110MHz</td>
</tr>
<tr>
<td>Number of comb teeth</td>
<td>$4.2 \times 10^5$</td>
</tr>
<tr>
<td>$^1S_0-^1P_1$ linewidth</td>
<td>177MHz</td>
</tr>
<tr>
<td>Focus diameter</td>
<td>1µm</td>
</tr>
<tr>
<td>Detection solid angle</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Detector efficiency</td>
<td>40%</td>
</tr>
</tbody>
</table>

single In$^+$ photon counting rate: 12,000 cps

*Fiber laser based system at JILA: 50uW at 153nm (7th)!!
Stabilization of $\text{In}^+-\text{Ca}^+$ configuration

$\text{(Ca}^+,\text{In}^+,\text{Ca}^+)\quad \nu_0=100.5\text{kHz}$

$\text{(In}^+,\text{Ca}^+,\text{Ca}^+)\quad \nu_0=98.5\text{kHz}$

$\text{(Ca}^+,\text{Ca}^+,\text{In}^+)\quad \nu_0=98.5\text{kHz}$

AM applied to $\text{Ca}^+$ laser (397nm)

configuration-selective destabilization is possible

simple way to keep $\text{In}^+-\text{Ca}^+$ configuration
diode-laser based 230nm source

$^{115}$In$^+$

$1^S_0$ \rightarrow $3P_1$ \rightarrow $230nm$ 360kHz

$\lambda = 159nm$
$\Gamma = 1.1$ GHz

$1^S_0$ \rightarrow $3P_0$ \rightarrow $237nm$ 0.8Hz

$230nm$ \rightarrow optical feedback

ECTI2010

15mW is expected for 300mW input from MOPA at 922nm

115mW is expected for 300mW input from MOPA at 922nm

ECDL (922nm) \rightarrow PPKTP cavity

Critical phase matching
$(\theta = 60^\circ, \phi = 0^\circ)$

922nm 80mW

461nm 40mW

BBO cavity

230nm 2.0mW

optical feedback

QPM
$(40.6 \pm 0.1^\circ C)$

15mW is expected for 300mW input from MOPA at 922nm

ECTI2010
Clock laser under construction

Vacuum Chamber

Isolator

PD

λ/4

M

M

PBS

Master

ECDL

Servo

DBM

15MHz

Single Mode Fiber (2m)

EOM

To optical comb

Toptica

LD-0935-0100-AR

25 mW

Isolator

~900mW

After fiber

~300mW

M2K

Tapered Amp.

25 mW ~900mW ~300mW

To optical comb

PPKTP

Ricol

1 x 1 x 10mm³

AR coating at 946nm+473nm

Super BBO

Casix

3 x 3 x 10mm³

AR coating at 473nm+237nm

>>1mW

To ion trap chamber

Vibration-insensitive

Cubic ULE cavity

designed finesse 250,000

Relative stability of 10^{-15} at 1s is expected

Vibration-insensitive

Cubic ULE cavity

designed finesse 250,000
Hybrid optical clock

A clock with stability of optical lattice clock and accuracy of single ion clock
Summary

• New approaches to In$^+$ an optical frequency standard
  – Sympathetically cooled In$^+$ in a linear trap
  – Detection by three methods
    • Quantum logic spectroscopy
      – Initialization of In$^+$-Ca$^+$ is in progress
    • VUV excitation
      – 1.5$\mu$W at 159 nm was generated
      – 12,000cps expected when 100$\mu$W is available
    • $^1S_0-^3P_1$ excitation assisted by Sr optical clock
      – all components are almost ready
• Clock operation will be reported in the 2$^{nd}$ ECTI conference