Precision Time Measurement and a Novel Two-Photon Clock Scheme

An E1-M1 Clock

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Overview

E1-M1 Clock
A Hot Hg Clock
Experimental Progress
The Clock Transition

\[ \sigma_\nu = \frac{\Delta \nu}{\nu} \sqrt{\frac{T}{\tau N}} \]

\(\Delta \nu\) is the linewidth of the system
\(\nu\) is the frequency of the sampling probe
\(T\) is the duty cycle of the experiment
\(\tau\) is the total experiment time
\(N\) is the sample size per duty cycle
The Clock Transition

\[ \sigma_\nu = \frac{\Delta \nu}{\nu} \sqrt{\frac{T}{\tau N}} \]

Clock Wisdom:
If you can’t relax, you can’t get excited.
You need to reduce the forbiddenness.

\( \Delta \nu \) is the linewidth of the system
\( \nu \) is the frequency of the sampling probe
\( T \) is the duty cycle of the experiment
\( \tau \) is the total experiment time
\( N \) is the sample size per duty cycle
The Work-Around

Just Add:
- Levels
- Nuclear Spin
- or-
- Magnetic Field

\[ ^1S_0 \quad \text{weakly ALLOWED FORBIDDEN} \]

\[ ^1P_1 \]

\[ ^3P_2 \]

\[ ^3P_0 \]

\[ ^3P^1_0 \]

E1
\[ \sigma_\nu = \frac{\Delta \nu}{\nu} \sqrt{\frac{T}{\tau N}} \]

\(^1P_1 \quad \text{\textbf{ALLOWED}} \quad ^3P_2 \]

\(^1S_0 \quad \text{E1} \quad \text{M1} \]

\[ \Delta \]
$\Omega_{2\gamma} = \frac{2I}{\hbar^2 c^2 \epsilon_0} \frac{\langle 3P_0 | \mu | 3P_1 \rangle_{M1} \langle 3P_1 | d^1 S_0 \rangle_{E1}}{\Delta} \approx 2I \cdot 10^{-5} \text{[Hz]}$

$I$ is the excitation laser intensity
$\langle 3P_0 | \mu | 3P_1 \rangle_{M1}$ is the magnetic dipole matrix element
$\langle 3P_1 | d^1 S_0 \rangle_{E1}$ is the electric dipole matrix element
$\Delta$ is the detuning of an excitation photon’s energy from the intermediate $3P_1$ level

It is experimentally feasible to achieve $I > 10^{10}[\frac{W}{m^2}]$
Hot Hg Clock

Frequency Standard Proposal

5d^{10}6s7s \ ^3S_1
5d^{10}6s6p \ ^1P_1
5d^{10}6s6p \ ^3P_2
5d^{10}6s6p \ ^3P_1
5d^{10}6s^2 \ ^1S_0

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http://www.umich.edu/aehardt
• $10^{13}$ Hg atoms/cm$^3$ @ 293 K
• First-order Doppler Broadening
Clock Stability vs. Size

Rb\text{CHIP} $10^{-11}$

Hg$_2\gamma$ $10^{-13}$

Hg$_{1\gamma}$

Sr $10^{-15}$

Al\textsuperscript{+} $10^{-16}$

Rb\text{CHIP} Knappe et al OL 2005

Hg$_{1\gamma}$ McFerran et al IEEE 2012

Sr Ludlow et al Science 2008

Al\textsuperscript{+} Chou et al PRL 2011

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# Hot Hg Clock Broadening Mechanisms

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<td><strong>Total</strong></td>
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**Stability** $\sigma_{\nu} \left[ \frac{1}{\sqrt{T}} \right] = 3.3 \times 10^{-13}$

Vapor Cell @ 250° K  
531nm beam:  
D = 2mm  
P = 10 W

$\Delta \nu_{STARK} = 5.5$kHz

$\sigma = 56$ Hz / $100mW$

Special Thanks to Guangfu Wang for furnishing the exact values at 531nm
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1μ Radian

**Experimental Challenge:** Precise Retro-Alignment
# Hot Hg Clock

## Collision Broadening

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**Stability**  

$$\sigma_\nu \left[ \frac{1}{\sqrt{T}} \right] = 3.3 \times 10^{-13}$$
Experimental Progress
Laser System

Seed
40mW  
1062nm  
< 1kHz  
Orbits Lightwave

Amplifier
50 W  
1062nm  
< 2kHz

SHG
6 W  
531nm

IPG
HCP

Hg
Mercury
200.59
\([\text{Xe}^+5d^06s^2]^{10.4375}\)
Experimental Progress

$I^2$ Reference

$I^2$ Gerstenkorn 1980
Hg Peterson PRL 2008
Next Steps

Novel Observation

E1-M1 Optical Access to a Clock Level

Bosonic Spectroscopy of Clock Level

Optimal Clock

Collision Effects

Stark Shift

Atom Number Temperature
Thank You

Leanhardt Lab

- Funding:
  - DARPA/ARO
  - AFOSR

Slides available at: http://www-personal.umich.edu/~ealden/
Fourier Limited
Seed & Amplifier Homodyne

Seed with Seed

Seed with Amplifier

Linewidth:
12.1 ± 6.1 Hz

Linewidth:
7.2 ± 3.6 Hz

1062 nm
14.2 W

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Laser Characterization

- Increasing amplifier power:

\[ \Delta \text{Linewidth} [\text{Hz}] \]

\[ \text{IR Power} [\text{W}] \]

- After replacing the amplifier in the system, measurements show no systematic change in the linewidth of the beat note.
Cold Hg Clock

Advantages
• Dense MOT
3S1 - Detection

- QE 435: OD 2.64 0.2%
- SNR: 7 counts/sec

Life Time and Branching Data:
- a) A.P. Mishra and T.K. Balasubramamian. JQSRT 69, 769 - 780 (2001)
Sample Scan

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2012/06/04-08:51-17.mat - 2012/06/04-10:48:33.mat
Normalized
mean # = 6.999
SNR/sec = 7.729
median # / sqrt(n) = 0.30912#
median # = 4.3005#

Duty time = 58 min
Exp Time = 16 min
Size = 1 MHz
medMHz = 0.1

Freq [THz]

Abs. Gain [# V]

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