Zero-dead-time Differential Spectroscopy Beyond the Laser Coherence Limit

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Image credit: Nate Phillips
Outline

I - Clocks and tests of fundamental physics

II - Differential spectroscopy

III - Zero-dead-time differential spectroscopy
Part I – Clocks and tests of fundamental physics
# Clocks

<table>
<thead>
<tr>
<th></th>
<th>Ticking rate (Hz)</th>
<th>Instability (s/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old pendulum clock</td>
<td>$10^0$</td>
<td>$10^0$</td>
</tr>
<tr>
<td>Mechanical clock</td>
<td>$10^7$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Electronic clock</td>
<td>$10^{10}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Cesium atomic clock</td>
<td>$10^{15}$</td>
<td>$10^{-13}$</td>
</tr>
</tbody>
</table>

- **Ticking rate (Hz)**: The frequency at which a clock ticks. Higher frequencies indicate more accurate clocks.
- **Instability (s/day)**: The instability of a clock, measured in seconds per day. Lower values indicate more stable clocks.
Do we need better?
Tests of ultralight dark matter

DM matter wave

DM object perturbs the clock, but to measure this we need to compare against another clock

Tests of ultralight dark matter

DM matter wave

DM wave perturbs the frequency ratio between the clocks

https://doi.org/10.1103/PhysRevD.91.015015
Tests of ultralight dark matter

DM matter wave

DM wave perturbs the frequency ratio between the clocks

Highly local

Extraordinary precision (better than $10^{-16}$ in fractional frequency)

Bandwidth of $\sim$Hz and below ($\sim10^{-15}$ eV and below)

Constraints on ultralight dark matter

Clock instability

Dick effect: technical biasing phenomenon related to the OLO noise properties

Other sources of noise:

$$\sigma_y(\tau) = \left(\frac{S}{N}\right)^{-1} n_{\text{meas}}^{-1/2}$$

Contributions: technical detection noise, photon shot noise, quantum projection noise (QPN)

QPN is fundamental (for uncorrelated quantum systems). Other sources are subject to technical reduction.
Quantum projection noise

$(\phi, \psi) \in \Re \times \Re$

$p \in \mathcal{B}$

$$\left(\frac{S}{N}\right)^{-1} = \frac{\Delta f}{f_0} = \frac{(df/dp)\Delta p}{f_0}$$

but due to projection noise, $\Delta p \approx \frac{1}{2}$. For Ramsey spectroscopy, $\frac{df}{dp} \approx \frac{1}{\pi T_i}$

$$\left(\frac{S}{N}\right)^{-1} = \frac{1}{2\pi T_i f_0}$$

for a single quantum oscillator. For $N$ oscillators, $\left(\frac{S}{N}\right)^{-1} = \frac{1}{2\pi T_i f_0 \sqrt{N}}$. 
Quantum projection noise

\[ \sigma_y(\tau) = \left( \frac{S}{N} \right)^{-1} n_{meas} \]

The number of measurements we have is \( n_{meas} = \frac{\tau}{T_c} \), where \( \tau \) is the measurement time and \( T_c \) is the cycle time.

\[ \sigma_y(\tau) = \frac{1}{2\pi T_i f_0} \sqrt{\frac{T_c}{N\tau}} \approx \frac{1}{2\pi f_0 \sqrt{NT_i \tau}} \]
How to decrease QPN?

\[ \sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{NT_i \tau}} \]

Increase \( \tau \)
Increase \( f_0 \)
Increase \( N \)
Increase \( T_i \)
How to decrease QPN?

\[ \sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{NT_i \tau}} \]

- Increase \( \tau \)
- Increase \( f_0 \)
- Increase \( N \)
- Increase \( T_i \)

Pity the grad student!

PhD length (lower bound)

Target instability

\[ \tau \approx \frac{1}{(2\pi f_0 \sigma_y)^2 NT_i} \]
How to decrease QPN?

$$\sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{NT_i \tau}}$$

Increase $\tau$
Increase $f_0$
Increase $N$
Increase $T_i$

Image credit: May Kim
How to decrease QPN?

\[ \sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{N T_i \tau}} \]

Increase \( \tau \)

Increase \( f_0 \)

**Increase** \( N \)

Increase \( T_i \)
Can we increase $N$?

Two major types of optical clocks: ion clocks and neutral atom clocks

- Lattice clocks can operate with $N \approx 10^4$
- Coupling between ions have so far constrained ion clocks to $N = 1$

However, exemplary systematic uncertainties have been attained by ion clocks

Also, some ion clocks have high sensitivity for tests of fundamental physics

<table>
<thead>
<tr>
<th>Effect</th>
<th>Shift ($10^{-19}$)</th>
<th>Uncertainty ($10^{-19}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess micromotion</td>
<td>$-45.8$</td>
<td>$5.9$</td>
</tr>
<tr>
<td>Blackbody radiation</td>
<td>$-30.5$</td>
<td>$4.2$</td>
</tr>
<tr>
<td>Quadratic Zeeman</td>
<td>$-9241.8$</td>
<td>$3.7$</td>
</tr>
<tr>
<td>Secular motion</td>
<td>$-17.3$</td>
<td>$2.9$</td>
</tr>
<tr>
<td>Background gas collisions</td>
<td>$-0.6$</td>
<td>$2.4$</td>
</tr>
<tr>
<td>First-order Doppler</td>
<td>$0$</td>
<td>$2.2$</td>
</tr>
<tr>
<td>Clock laser Stark</td>
<td>$0$</td>
<td>$2.0$</td>
</tr>
<tr>
<td>AOM phase chirp</td>
<td>$0$</td>
<td>$&lt;1$</td>
</tr>
<tr>
<td>Electric quadrupole</td>
<td>$0$</td>
<td>$&lt;1$</td>
</tr>
<tr>
<td>Total</td>
<td>$-9336.0$</td>
<td>$9.4$</td>
</tr>
</tbody>
</table>

Our previous comparisons

Sr lattice clock at JILA

$\text{Al}^+ \text{ ion clock and Yb lattice clock at NIST}$

20 days of continuous comparison to reach $1 \times 10^{-18}$ instability for $\text{Al}^+/\text{Yb}$ or $\text{Al}^+/\text{Sr}$

Interspecies comparisons

Comparisons between different optical clocks

- NIST Yb/Sr
- NIST Al+/Yb
- RIKEN Sr/Yb
- RIKEN Sr/Hg
- RIKEN Sr/Yb
- NIST Al+/Hg+
- PTB E3/E2
- NIST Al+/Sr

One-second Instability

Date

2007 2010 2013 2016 2019

$10^{-15}$

$10^{-14}$

Lattice-lattice
Ion-ion
Lattice-ion
How to decrease QPN?

$$\sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{N T_i \tau}}$$

Increase $\tau$

Increase $f_0$

Increase $N$

Increase $T_i$
The coherence limit to interrogation

Clock measurements

Clock laser drift during measurement

Clock measurement is wrong!

Image credit: Nick Nardelli
Increase the stability of the OLO?

Part II – Differential spectroscopy
Novel interrogation schemes

Use one or several systems to prestabilize another


Dynamical decoupling

Novel interrogation schemes

**Nondestructive measurements to achieve a phase lock**


**Correlation spectroscopy**


Differential spectroscopy – a proposal

Phase lock OLOs to each other

Interrogate synchronously

Phase corrections from Yb

Differential spectroscopy – implementation

Provide phase corrections from a high-(S/n), lower-frequency clock

The high frequency clock can operate outside of its inversion regime

Increase interrogation time by the frequency ratio (2.16 for Al\(^+\)/Yb)

Measure $\Delta \phi_{Yb}$
Correct Al\(^+\) by $2.16 \times \Delta \phi_{Yb}$

$\text{OLO phase (} \pi \text{ radians)}$

$\text{Time}$

$\text{Clock laser intensity}$

$\text{Ramsey free evolution time}$
Differential spectroscopy – results with 500 ms spectroscopy

\[ 4.4 \times 10^{-16} / \sqrt{\tau} \]
Part III – ZDT differential spectroscopy
Zero-dead-time spectroscopy

Originally demonstrated to suppress the Dick effect

Can be naturally paired with differential spectroscopy

Combining differential spectroscopy with zero-dead-time spectroscopy

\[ \phi_{est} = \sum_{i=1}^{n} \phi_i \]
Differential spectroscopy results

- No phase corrections from Yb
- Single-clock differential spectroscopy
- ZDT differential spectroscopy
Four cycles, 1.7 s spectroscopy time

Lifetime limit for QPN:

$$6 \times 10^{-17}/\sqrt{\tau}$$

Previously, 20 days to reach

$$1 \times 10^{-18}$$

Now, 7 hours

Image credit: Nick Nardelli
What continues to limit the instability?

Magnetic field fluctuations on both clocks

Phase-noise-cancellation instability

Frequency transfer uncertainty through the comb

All these are technical and subject to reduction
Interspecies clock comparisons

Comparisons between different optical clocks

- Lattice-lattice
- Ion-ion
- Lattice-ion

One-second Instability

Date

2007 2010 2013 2016 2019

10^{-16} 10^{-15} 10^{-14}

NIST Al/Yb
RIKEN Sr/Yb
RIKEN Sr/Hg
RIKEN Sr/Yb
NIST Al+/Hg
PTB E3/E2
NIST/JILA Al+/Sr
NIST/JILA Yb/Sr
this work
Perspectives: improvement to DM constraints

Improved interspecies instability affords improved constraint of DM coupling

ZDT differential spectroscopy can improve any interspecies comparison

\[
K_{Yb} = 0.31
\]
\[
K_{Al^+} = 0.008
\]

\[
K_{Yb+} = -5.95 \text{ (Ekkehard Peik’s talk)}
\]

HCIs, Th nuclear clock, etc. offer even better improvements (Marianna Safronova’s and Steven King’s talks)

Acknowledgments

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David Hume
David Leibrandt