Search for new physics with clocks

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PTB Braunschweig and Leibniz Universität Hannover

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The measurement with the most significant digits ever performed:

$$2.162887127516663703(13)$$
(Quantum) Metrology with optical clocks

The measurement with the most significant digits ever performed:

$$\frac{f_{\text{Al}^+}}{f_{\text{Yb}}} = 2.162887127516663703(13)$$

[BACON collaboration, Nature 591, 564 (2021)]

optical clock comparison with 18 digits

...no fundamental limit for improvement in sight
What does $10^{-18}$ mean?

- $1 : 1,000,000,000,000,000,000$
- 300x better than Cs fountain clocks
- 1 s deviation in 30 billion years
- $1^{st}$ order Doppler shift: 0.3 nm/s or 30 mm/Jahr
- Distance measurement earth-sun to 1/1000 of the diameter of a hair

Who needs clocks this good?
Who Needs Better Clocks?

- Clocks have many applications:
  - Tests of fundamental physics
  - Geodesy
  - Synchronization of large networks
  - Navigation
  - ...
Overview

• Introduction to clocks
• New physics with clocks
  – variation of fundamental constants
  – searches for dark matter
  – tests of relativity: LPI, LLI tests
  – searches for 5th forces
• Summary & future

Many more examples!

\[ |e\rangle \]
\[ \begin{array}{c}
|g\rangle \\
\hbar \omega(\alpha) \\
\alpha
\end{array} \]

Lorentz invariance

\[ \eta \omega \]

Dark matter

normal matter

Changing constants

[Safronova et al. Rev. Mod. Phys. 90, 025008 (2018)]
INTRODUCTION TO CLOCKS
Principle of microwave atomic clocks

Since 1967:
The second is defined as being equal to the time duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental unperturbed ground-state of the caesium-133 atom.
Why optical clocks?

- **microwave vs. optical clocks**
  - Low frequency (mw) 
  - High frequency (optical) 
  - $\times 10^5$

- **line width $\Delta \nu$**

- **small frequency shift $\delta \nu$ (species dependent)** 
  - Even smaller relative shift $\delta \nu/\nu_0$

- **relevant quantity**: $\frac{\Delta \nu}{\nu_0}$

- **collisions**
- **Doppler shift**
- **electric and magnetic fields**

- **Doppler shift**
Principle of Optical Clocks

- Laser Oscillator
- Reference (Atom(s))
- fs-comb
- Internal State Detection
- Frequency Feedback
- 500 THz
- Laser
- Electron Shelving

11:15am

Compare to other clock(s)
Ion clocks and neutral atom lattice clocks

• We want:
  – good statistical uncertainty $\rightarrow$ long probe times
  – good systematic uncertainty $\rightarrow$ small systematic shifts

need to trap & laser cool the atoms $\rightarrow$ full quantum control

• Trapping: 3d harmonic confinement
• Cooling: localisation and quantum control over motional degrees
NEW PHYSICS WITH CLOCKS
General considerations

- **transition energy of clocks can not be calculated with 18 digits accuracy**
  - no direct comparison with theory
  - search for changes in frequency ratio measurements
  - isotope shift measurements (many digits common mode)
- **no predictions what to search for**
  - null measurements
  - exclusion plots of phenomenological models
  - often “dual use” of data

need models to motivate searches
Variation of fundamental constants

• Motivated by theories beyond the SM:
  – string theory & other theories with extra dimensions: dilaton field
  – Discrete & loop quantum gravity
  – Dark energy theories: chameleon & quintessence model
  – ...

• typically: cosmological evolution towards a minimum of the field
• spatial as well as temporal variation possible
• if one constant varies, all of them do (equivalence principle)

• dark matter candidate: e.g. ultralight scalar field $\phi$
  – oscillating field: $\phi(t) = \phi_0 \cos(m_\phi t)$
  – topological field (forming “clumps“)
  – ...

• weak (non-gravitational) linear coupling to matter:

$$\mathcal{L}_\phi = \frac{4\pi\phi}{M_{Pl}} \left[ \frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} - d_{m_e} m_e \bar{e} e - \frac{d_g \beta_3}{2 g_3} G^A_{\mu\nu} G^{A\mu\nu} - \sum_{i=u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right]$$

$\Rightarrow$ apparent variation of fundamental constants ($\alpha$, fermionic masses, ...)

[Arvanitaki et al., Phys. Rev. D 91, 015015 (2015); review: Safronova et al., RMP 90, 025008 (2018)]
Variation of Fundamental Constants

fine-structure constant $\alpha$

$$\Delta \omega \over \omega = K \frac{\Delta \alpha}{\alpha}$$

<table>
<thead>
<tr>
<th>System</th>
<th>$K$</th>
<th>$\lambda$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sr</td>
<td>0.06</td>
<td>699</td>
</tr>
<tr>
<td>Yb$^+$ E2</td>
<td>0.91</td>
<td>436</td>
</tr>
<tr>
<td>Yb$^+$ E3</td>
<td>-6</td>
<td>467</td>
</tr>
<tr>
<td>Hg$^+$</td>
<td>-2.9</td>
<td>281.5</td>
</tr>
<tr>
<td>Al$^+$</td>
<td>0.01</td>
<td>267</td>
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</tbody>
</table>
Drifting constants: Combined data from clocks

\[ \frac{\Delta \omega}{\omega} = K \frac{\Delta \alpha}{\alpha} \]

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<td>0.01</td>
<td>267</td>
</tr>
<tr>
<td>Ir(^{17+}) T1</td>
<td>-22</td>
<td>ca. 280</td>
</tr>
<tr>
<td>Ir(^{17+}) T2</td>
<td>145</td>
<td>ca. 1980</td>
</tr>
<tr>
<td>Cf(^{16+}) T1</td>
<td>59</td>
<td>ca. 775</td>
</tr>
<tr>
<td>Cf(^{17+}) *</td>
<td>-48</td>
<td>ca. 535</td>
</tr>
<tr>
<td>Th(^{\ast}) nuclear</td>
<td>8000</td>
<td>ca. 150</td>
</tr>
</tbody>
</table>

\(\dot{\alpha}/\alpha = 1.0(1.1) \times 10^{-18}/\text{year}\)

[courtesy: E. Peik]

highest sensitivity of all known atomic systems

\(\rightarrow\) level-crossing transitions

[Lange et al. PRL 126, 011102 (2021)]
Transient variations: network of clocks

- comparison of clock frequency ratios via fibre network
- transient duration: $\tau_{int}$
- time between consecutive transitions: $\mathcal{T}$
Oscillating constants: clock/clock/cavity comparisons

Rb/Cs: A. Hees et al., PRL 117, 061301 (2016)
UW: Schlamminger et al., PRL 100, 041101 (2008)
MICROSCOPE: Bergé et al., PRL 120, 141101 (2018)

[Kennedy et al., PRL 125, 201302 (2020)]
Coupling of fundamental constants to gravity

• motivation: local position invariance test
• fundamental constant $\eta$ couples to solar gravity potential $\Delta U(t)$:

$$\frac{\delta \eta}{\eta} = k_\eta \frac{\Delta U(t)}{c^2}$$

• combine measurements of several years:

$\rightarrow k_\alpha = (-5.5 \pm 5.2) \times 10^{-7}$ (fine-structure constant)
$\rightarrow k_\mu = (-2.5 \pm 5.4) \times 10^{-6}$ ($m_e/m_p$)
$\rightarrow k_q = (3.8 \pm 4.9) \times 10^{-6}$ (light quark mass)

[Leefer et al., PRL 111, 060801 (2013); Peil et al., PRA 87, 010102 (2013)]

[S. Blatt et al., PRL 100 140801 (2008)]
Testing local Lorentz invariance with clocks

- probe for LLI violation in electron-photon sector
- idea: electron orbitals have directionality → measure sidereal energy oscillations
- Yb$^+\ ^2F_{7/2}$ state is very sensitive

![Lomb-Scargil periodogram](image1)

[Dreissen et al., arXiv:2206.00570]

[Pruttivarasin et al., Nature 517, 592 (2015)]
Search for 5th forces

Isotope shift spectroscopy: King’s plot

\[ \delta \nu_i^{A,A'} = F_i \delta \langle r^2 \rangle_{A,A'} + k_i \frac{A-A'}{AA'} \]

- field shift
- recoil shift
- use 2 transitions \( i, j \rightarrow \) eliminate \( \delta \langle r^2 \rangle_{A,A'} \)

Additional hypothetical 5th force (relaxion, DM, ...)

- new force mediated through scalar field with mass \( m_\phi \rightarrow X_i \)
- coupling constant: \( \alpha_{NP} \)

\[ \rightarrow \text{nonlinearity in King’s plot:} \]

\[ \delta \nu_i^{A,A'} = F_i \delta \langle r^2 \rangle_{A,A'} + k_i \frac{A-A'}{AA'} + \alpha_{NP} X_i (A - A') \]

Isotope shift spectroscopy of $^{40,42,44,46,48}\text{Ca}^{+}/^{14+/15+}$

- need transitions of different character

→ **promising approach:**

isotope shifts of clock transitions in $\text{Ca}^+ \& \text{Ca}^{14+/15+}$

(with Surzhykov, Berengut, Fuchs & Crespo)

[Rehbehn, *et al.*, PRA 103, L040801 (2021)]

[adapted from: Solaro *et al.*, PRL 125, 123003 (2020)]
Approach to precision HCl spectroscopy: CryPTEx-PTB

### Specifications Vacuum System:
- Vacuum: $< 10^{-14}$ mbar
  - HCl lifetime: $\sim$ 100 min
- Temperature: $< 5$ K
- Vibrations: $< 20$ nm
- Magnetic field: $< 200$ pT

### Specifications EBIT:
- Magnetic field: 0.86 T (72 permanent magnets)
- Acceleration voltage: 10 kV
- Current: $> 80$ mA

### Specifications Ion Trap:
- 5 segments, Au-coated $\text{Al}_2\text{O}_3$, 0.7 mm ion-electrode distance
- Trapping frequencies: $> 1$ MHz
- Heating rates: $\sim 1$ 1/s
- $f/\# \sim 1$ imaging with bi-aspheric lens

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**Machine room**

**Laser Laboratory**

- cryogenic linear Paul trap
- compact EBIT
- 30 cm
- 1 m

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[Micke *et al.*, RSI 89, 063109 (2018)]

with J. Crespo @ MPIK Heidelberg
## Systematic shifts for Ar$^{13+}$

<table>
<thead>
<tr>
<th>Shift source</th>
<th>Mitigation</th>
<th>Shift ($10^{-18}$)</th>
<th>Uncertainty ($10^{-18}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micromotion</td>
<td>Real-time measurement</td>
<td>-443</td>
<td>22</td>
</tr>
<tr>
<td>AC Zeeman shift</td>
<td>Calibration at much higher powers and extrapolation</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>First-order Doppler</td>
<td>Counter-propagating beams</td>
<td>0</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Electric quadrupole</td>
<td>Small coefficient, averaging over multiple Zeeman components</td>
<td>0</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Linear Zeeman</td>
<td>Averaging over multiple Zeeman components</td>
<td>0</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Quadratic Zeeman</td>
<td>Small coefficient, small field</td>
<td>&lt; 1</td>
<td>&lt;&lt; 1</td>
</tr>
<tr>
<td>2nd order Doppler</td>
<td>Algorithmic cooling</td>
<td>-1</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

### Notes:
- **no fundamental limitations**
- **$^{40}$Ar$^{13+}$ clock with $2.2 \times 10^{-17}$ systematic uncertainty**
- **$^{40/36}$Ar$^{13+}$ isotope shift: confirm QED nuclear recoil effect**

atomic data from: [Y-M. Yu and B.K. Sahoo, PRA 99, 022513 (2019)]

Summary

• optical clocks offer 18 significant digits in frequency comparisons
• searches for new physics at the high-precision, low-energy frontier
  – variation of fundamental constants
  – searches for dark matter
  – tests of relativity: LPI, LLI tests
  – searches for 5th forces
• need theory input for interpretation & models

Future

• optical clocks will further improve
• new types of clocks: Th, HCI
• quantum clock interferometry?
• entangled states in gravity?
• improved redshift tests?
Quantum Logic Spectroscopy Group

Collaborators:
• J. Crespo López-Urrutia (MPIK, Heidelberg)
• N. Huntemann, R. Lange, E. Benkler (PTB)
• A. Surzhykov (PTB & TU Braunschweig)
• K. Hammerer (LUH, Hannover)
• J. Berengut (U. of New South Wales)
• M. Safronova (U. of Delaware)

PhD/PostDoc openings

www.quantummetrology.de
THE END