FUNDAMENTAL PHYSICS RESEARCH WITH CLOCKS

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LNE-SYRTE, Observatoire de Paris

Rencontres de Moriond, 2007
I. The LNE-SYRTE clock ensemble
II. Testing Lorentz invariance using a Cs fountain clock
III. Variation of fundamental constants
IV. Pushing further….
LNE-SYRTE CLOCK ENSEMBLE

- **H-glow**
- **opt Sr**, **opt Cs**, **µwave**
- **H, µwave**
- **FO1 fountain**
- **Cs, µwave**
- **Cryogenic sapphire Osc.**
- **Macroscopic osc., 12 GHz**
- **Phaselock loop**, \( \tau \sim 1000 \text{ s} \)
- **FO2 fountain**
- **Rb, Cs, µwave**
- **FOM transportable fountain**
- **Cs, µwave**
- **Optical lattice clock**
- **Hg, opt**
- **Sr, opt**
- **Optical lattice clock (ongoing)**
Lorentz Invariance test using a Cs fountain

- Hughes-Drever type test, looking for dependence of transition frequencies as a function of orientation of spin.
- Analyse within Lorentz violating Standard Model Extension (SME) matter sector [Kostelecky et al.].
- Photon sector covered in M. Tobar’s talk (Wed. afternoon).

- Frequency shift of the Cs hyperfine transition in the SME
- Experimental strategy
- Data and analysis
- Systematic effects
- Results

P. Wolf, F. Chapelet, S. Bize, A. Clairon, 
SME APPLIED TO CESIUM HFS

- SME shift of atomic energy levels in the local frame

\[ \delta E(m_F, F) = \frac{m_F}{F} \sum_{e^-, p^+, n} \left( \beta_w \tilde{b}_3^w + \delta_w \tilde{d}_3^w + \kappa_w \tilde{g}_d^w \right) + \frac{3m_F^2 - F(F+1)}{3F^2 - F(F+1)} \sum_{e^-, p^+, n} \left( \gamma_w \tilde{c}_q^w + \lambda_w \tilde{g}_q^w \right) \]

- \( \beta_w, \delta_w, \kappa_w, \gamma_w, \lambda_w \) are specific to the atom and the particular state
- The tilde coefficients are combinations of SME parameters
- They are in general time dependent due to atom motion wrt supposedly preferred frame

- Cs hyperfine transition in the SME

\[ \hbar \delta \omega = B_p \tilde{b}_3^p + D_p \tilde{d}_3^p + G_p \tilde{g}_d^p + C_p \tilde{c}_q^p + B_e \tilde{b}_3^e + D_e \tilde{d}_3^e + G_e \tilde{g}_d^e \]

\[ + Z^{(1)} B + Z^{(2)} B^2 \]

SME part: \( Z^{(1)} B \approx m_F \cdot 1400 \text{Hz}, Z^{(2)} B^2 \approx -2 \text{ mHz} \)

Classical part: \( Z^{(1)} B \approx m_F \cdot 1400 \text{Hz}, Z^{(2)} B^2 \approx -2 \text{ mHz} \)

- An observable which is free of 1st order Zeeman effect

\[ v_{+3} + v_{-3} - 2v_0 = \frac{1}{\hbar} K_p \tilde{c}_q^p - \frac{9}{8} K_{z}^{(2)} B^2 \quad K_p \approx 10^{-2} \]
EXPERIMENTAL STRATEGY

- Alternate $m_F = 3$ and $m_F = -3$ measurement every second (interleaved servo-loops).
- Measure $m_F = 0$ clock transition every 400 s (reference).
- Limited by stability of magnetic field at $\tau < 4$ s.
- Reduce launching height to optimize stability of observable.

\[
\tilde{c}_q^p = A + C_{\omega_{\odot}} \cos(\omega_{\odot} t) + S_{\omega_{\odot}} \sin(\omega_{\odot} t) + C_{2\omega_{\odot}} \cos(2\omega_{\odot} t) + S_{2\omega_{\odot}} \sin(2\omega_{\odot} t)
\]

- $A$, $C_i$, $S_i$, are functions of the 8 proton components: $\tilde{c}_Q$, $\tilde{c}_X$, $\tilde{c}_Y$, $\tilde{c}_Z$, $\tilde{c}_-$, $\tilde{c}_{TX}$, $\tilde{c}_{TY}$, $\tilde{c}_{TZ}$
- 3 proton components ($\tilde{c}_{TX}$, $\tilde{c}_{TY}$, $\tilde{c}_{TZ}$) are suppressed by $v_{\odot}/c \approx 10^{-4}$
- Search for offset, sidereal and semi-sidereal signatures in the observable
21 days of data in April 2005, 14 days in September 2005. Least squares fit:

\[ A = -5.3(0.04); \quad C_{\omega} = 0.1(0.06); \quad S_{\omega} = -0.03(0.06) \]

\[ C_{2\omega} = 0.04(0.06); \quad S_{2\omega} = 0.03(0.06) \]

in mHz
SYSTEMATICS: Residual 1st order Zeeman Shift

- Magnetic field gradients and non-identical trajectories of \( m_F = +3 \) and \( m_F = -3 \) atoms can lead to incomplete cancellation of \( Z^{(1)} \).
- Confirmed by TOF difference \( \approx 158 \, \mu s \) (\( \rightarrow 623 \, \mu m \)).
- Variation of \( B \) with launching height \( \approx 0.02 \, \text{pT/mm} \) (at apogee).
  \( \Rightarrow \) MC simulation gives offset of only \( \approx 6 \, \mu \text{Hz} \).

- Contrast as function of \( m_F \): 0.94, 0.93, 0.87, 0.75
- MC simulation with only vertical \( B \) gradient cannot reproduce the contrast
  \( \Rightarrow \) horizontal \( B \) gradient of \( \approx 6 \, \text{pT/mm} \) (\( \approx 2 \, \text{pT/mm} \) from tilt measurements).
- Complete MC simulation, assuming horizontal asymmetry between trajectories is same as vertical (worst case) gives offset \( \approx 25 \, \text{mHz} \).

- Fitting sidereal and semi-sidereal variations to the TOF difference and using the above gradients we obtain no significant effect within the statistical uncertainties (\( \approx 0.03 \, \text{mHz at both frequencies} \)). We take this as our upper limit of the time varying part of the residual first order Zeeman.
RESULTS

8 proton parameters

\[
\begin{align*}
\tilde{c}_Q &= -0.3(2.2) \times 10^{-22} \\
\tilde{c}_- &= -1.8(2.8) \times 10^{-25} \\
\tilde{c}_X &= 0.6(1.2) \times 10^{-25} \\
\tilde{c}_Y &= -1.9(1.2) \times 10^{-25} \\
\tilde{c}_Z &= -1.4(2.8) \times 10^{-25}
\end{align*}
\]

- Sensitivity to \(c_{TJ}\) reduced by a factor \(v_{\odot}/c \approx 10^{-4}\).
- Assuming no cancellation between \(c_{TJ}\) and others.
- First measurements of four components.
- Improvement by 11 and 13 orders of magnitude on previous limits (re-analysis of IS experiment, [Lane C., PRD 2005]).
- Dominated by statistical uncertainty (factor 2) except for \(c_Q\).

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Parameter} & p^+ & n & e^- \\
\hline
\tilde{b}_X, \tilde{b}_Y & 10^{-27} & 10^{-31} & 10^{-29} \\
\tilde{b}_Z & \ldots & \ldots & 10^{-28} \\
\tilde{b}_T, \tilde{g}_T, \tilde{H}_{JT}, \tilde{d}_\pm & \ldots & 10^{-27} & \ldots \\
\tilde{d}_Q, \tilde{d}_{XY}, \tilde{d}_{YZ} & \ldots & 10^{-27} & \ldots \\
\tilde{d}_X, \tilde{d}_Y & 10^{-25} & 10^{-29} & 10^{-22} \\
\tilde{d}_{XZ}, \tilde{d}_Z & \ldots & \ldots & \ldots \\
\tilde{g}_{DX}, \tilde{g}_{DY} & 10^{-25} & 10^{-29} & 10^{-22} \\
\tilde{g}_{DZ}, \tilde{g}_{JK} & \ldots & \ldots & \ldots \\
\tilde{g}, \tilde{c} & \ldots & 10^{-27} & \ldots \\
\tilde{g}^-, \tilde{g}_Q, \tilde{g}_{TJ} & \ldots & \ldots & \ldots \\
\tilde{c}_Q & 10^{-22}(-11) & \ldots & 10^{-9} \\
\tilde{c}_X, \tilde{c}_Y & 10^{-25} & 10^{-25} & 10^{-19} \\
\tilde{c}_Z, \tilde{c}_- & 10^{-25} & 10^{-27} & 10^{-19} \\
\tilde{c}_{TJ} & 10^{-21}(-8) & \ldots & 10^{-6} \\
\hline
\end{array}
\]
Variation of Fundamental Constants


• Atomic transition frequencies and their dependence on fundamental constants
• Which constants vary?
• How do they vary?
• Recent results
Atomic transition frequencies and fundamental constants

### Hyperfine transitions: (microwave)

- Numerical constant
- \( R_y \sim 3.3 \times 10^{15} \text{ Hz} \)
- \( \mu_B \)

\[
\nu^{(i)}_{hf} = \text{const}^{(i)} \times R_y \times \frac{\mu^{(i)}}{\mu_B} \alpha^2 F^{(i)}_{rel}(\alpha)
\]

### Gross structure transitions: (optical)

- \( \nu^{(i)} = \text{const}^{(i)} \times R_y \times F^{(i)}_{rel}(\alpha) \)

### Variation:

\[
\frac{\delta (\nu^{(i)}_{hf} / R_y)}{(\nu^{(i)}_{hf} / R_y)} = (2 + K^{(i)}) \frac{\delta \alpha}{\alpha} + \frac{\delta (\mu^{(i)} / \mu_B)}{\mu^{(i)} / \mu_B}
\]

\[
\frac{\delta (\nu^{(i)} / R_y)}{(\nu^{(i)} / R_y)} = K^{(i)} \frac{\delta \alpha}{\alpha}
\]

Comparison of hf - hf or hf - opt. limits variation of combination of constants

Direct comparison of two optical transitions with \( K^{(1)} \neq K^{(2)} \) limits variation of \( \alpha \) independently

Nuclear magnetic moment

Direct comparison of two optical transitions with \( K^{(1)} \neq K^{(2)} \) limits variation of \( \alpha \) independently
Which constants vary?

V. V. Flambaum and A. F. Tedesco, PR C73, 055501 (2006)

• Can constrain variation of transition independent constants ($\alpha$) and transition dependent ones ($\mu^{(i)}$).
• Alternatively, reduce transition dependent ones to more fundamental independent ones (quark masses, electron mass, $\Lambda_{\text{QCD}}$).
• Cosmology and unification theories in general consider variations of fundamental (transition independent) constants.

$\frac{\delta\left(\frac{\mu^{(i)}}{\mu_B}\right)}{\left(\frac{\mu^{(i)}}{\mu_B}\right)} = \kappa_q^{(i)} \frac{\delta\left(\frac{m_q}{\Lambda_{\text{QCD}}}ight)}{\left(\frac{m_q}{\Lambda_{\text{QCD}}}ight)} + \kappa_e^{(i)} \frac{\delta\left(\frac{m_e}{\Lambda_{\text{QCD}}}ight)}{\left(\frac{m_e}{\Lambda_{\text{QCD}}}ight)}$

with $m_q = (m_u + m_d)/2$ and assuming $\frac{\delta(m_s/\Lambda_{\text{QCD}})}{(m_s/\Lambda_{\text{QCD}})} = \frac{\delta(m_q/\Lambda_{\text{QCD}})}{(m_q/\Lambda_{\text{QCD}})}$

• The coefficients $\kappa$ can be calculated from nuclear models.
• Schmidt model provides first approximation, but can be wrong by more than an order of magnitude.
Which constants vary?

V. V. Flambaum and A. F. Tedesco, PR C73, 055501 (2006)

- Recent accurate calculations of sensitivities for many commonly used transitions can be found

\[
\frac{\delta (\nu^{(i)} / \text{Ry})}{(\nu^{(i)} / \text{Ry})} = \kappa_\alpha \frac{\delta \alpha}{\alpha} + \kappa_q \frac{\delta (m_q / \Lambda_{\text{QCD}})}{(m_q / \Lambda_{\text{QCD}})} + \kappa_e \frac{\delta (m_e / \Lambda_{\text{QCD}})}{(m_e / \Lambda_{\text{QCD}})}
\]

<table>
<thead>
<tr>
<th></th>
<th>( \kappa_\alpha )</th>
<th>( \kappa_q )</th>
<th>( \kappa_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rb hf</td>
<td>2.34</td>
<td>-0.064</td>
<td>1</td>
</tr>
<tr>
<td>Cs hf</td>
<td>2.83</td>
<td>-0.039</td>
<td>1</td>
</tr>
<tr>
<td>H opt</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Yb(^+) opt</td>
<td>0.88</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hg(^+) opt</td>
<td>-3.2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
How do fundamental constants vary?

- String theory inspired cosmological models suggest existence of additional massless (very light) scalar fields $\phi$, eg. Dilaton [Damour 1994,...].
- Assuming that they couple differently to different low energy Lagrangian fields, they will lead to variation of fundamental constants in time and space.

Assuming further that they are given by a field equation whose source is proportional to $T = T^{\mu}_{\mu}$ (the trace of the energy-momentum tensor)

\[
\phi = \phi_C + \frac{Q}{r}
\]

where it is reasonable to assume:

\[
Q \propto \frac{GM}{c^2}
\]  
[Flammbaum & Shuryak physics/0701220, (2007)]

- The “local” part ($Q/r$) will lead to a variation of fundamental constants as a function of the Newtonian potential, and can be parameterized:

\[
\frac{\delta \alpha}{\alpha} = k_\alpha \delta \left( \frac{GM}{rc^2} \right); \quad \frac{\delta (m_q / \Lambda_{QCD})}{(m_q / \Lambda_{QCD})} = k_q \delta \left( \frac{GM}{rc^2} \right); \quad \frac{\delta (m_e / \Lambda_{QCD})}{(m_e / \Lambda_{QCD})} = k_e \delta \left( \frac{GM}{rc^2} \right)
\]

- This leads to two types of variation: long term drift ($\phi_C$) and local (periodic) terms $\delta (GM/r)$. Can be distinguished in laboratory or space-borne experiments !!

- In the remainder of this talk we will consider only the long term drift, but laboratory measurements and constraints on the latter are starting to become available.
Recent measurements at LNE-SYRTE


\[ \frac{d}{dt} \left( \frac{\nu_{hfs}^{(Rb)}}{\nu_{hfs}^{(Cs)}} \right) = \left( \frac{-0.5 \pm 5.3}{yr} \right) \times 10^{-16} \]

\[ \frac{d}{dt} \left( \frac{\nu_{hfs}^{(Rb)}}{\nu_{hfs}^{(Cs)}} \right) = -0.49 \frac{d}{dt} \alpha + \frac{d}{dt} \left( \frac{\mu_{hfs}^{(Rb)}}{\mu_{hfs}^{(Cs)}} \right) = -0.49 \frac{d}{dt} \alpha - 0.025 \frac{d}{dt} \left( \frac{m_q}{\Lambda_{QCD}} \right) \]
Combined with other results:

\[
\frac{\delta(v^{(Rh)}_{\|}/v^{(Cs)}_{\|})}{(v^{(Rh)}_{\|}/v^{(Cs)}_{\|})} = (-0.5 \pm 5.3) \times 10^{-16} \text{ yr}^{-1} = -0.49 \frac{\frac{d}{dt} \alpha}{\alpha} - 0.025 \frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})}
\]

\[
\frac{\frac{d}{dt}(v^{(Hg)}_{opt}/v^{(Cs)}_{\|})}{(v^{(Hg)}_{opt}/v^{(Cs)}_{\|})} = (3.7 \pm 3.9) \times 10^{-16} \text{ yr}^{-1} = -6.03 \frac{\frac{d}{dt} \alpha}{\alpha} + 0.039 \frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} - \frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}
\]

\[
\frac{\frac{d}{dt}(v^{(Yb)}_{opt}/v^{(Cs)}_{\|})}{(v^{(Yb)}_{opt}/v^{(Cs)}_{\|})} = (-7.8 \pm 14) \times 10^{-16} \text{ yr}^{-1} = -1.95 \frac{\frac{d}{dt} \alpha}{\alpha} + 0.039 \frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} - \frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}
\]

\[
\frac{\frac{d}{dt}(v^{(H)}_{opt}/v^{(Cs)}_{\|})}{(v^{(H)}_{opt}/v^{(Cs)}_{\|})} = (-32 \pm 63) \times 10^{-16} \text{ yr}^{-1} = -2.83 \frac{\frac{d}{dt} \alpha}{\alpha} + 0.039 \frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} - \frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}
\]

Using a weighted least squares fit:

\[
\frac{d}{dt} \alpha = (-3.1 \pm 3.5) \times 10^{-16}
\]

\[
\frac{d}{dt}(m_q/\Lambda_{QCD}) = (80 \pm 220) \times 10^{-16}
\]

\[
\frac{d}{dt}(m_e/\Lambda_{QCD}) = (18 \pm 25) \times 10^{-16}
\]

LNE-SYRTE, JPB (2004)

NIST, PRL (2007)


MPQ + LNE-SYRTE

PRL (2004)

Limit on \(\alpha\) variation is becoming competitive with Oklo \((\sim 10^{-17} \text{yr}^{-1})\) and “excludes” Quasar limits (assuming linear change)

- however, still difficult to decorrelate variations of the different constants (correlation coefficients = 0.3, 0.9, 0.6).
- more accurate, and more diverse measurements are required!!
- analysis for annual terms allows search for variation from scalar fields with local sources \((\propto \text{GM/r})\).
A mission to explore long range Gravity using Quantum technology
• Gravity is well explored at small (laboratory) to medium (Moon, inner planets) distances.
• At very large distances (galaxies, supernovae, cosmology) some puzzles remain.
• The largest distances explored by man-made artefacts are of the size of the outer solar system. For example, Pioneer satellites show a still unexplained anomalous Doppler rate ($a_p \sim 8.7 \times 10^{-10} \text{ m/s}^2$, with smaller annual and diurnal terms on top).

• Ideally, a future mission should:
  ⇒ Measure as many “facets” of large scale gravity as possible, as precisely as possible.
  
  ⇒ Mission with three different observation types (ranging, local acceleration, time) rather than just one (Doppler) in the case of Pioneer.

• Whatever the outcome, it will be essential for fundamental physics, deep space navigation, solar system science, astronomy, cosmology, etc…
• We will use the Pioneer anomaly and some of the proposed “conventional” and “new physics” hypotheses to evaluate the possibilities of such a mission.
1. Cold atom absolute accelerometer, 3 axis measurement of local acceleration. Uncertainty $\leq 5 \times 10^{-12} \text{ m/s}^2$ for integration times $\geq 10$ days.

2. Optical atomic clock with an uncertainty $\leq 10^{-17}$ in relative frequency for integration times $\geq 10$ days.

3. Laser ranging and two-way time transfer, with time stability $\leq 10 \text{ ps}$ for integration times $\geq 10$ days for time transfer, and ranging uncertainty $\leq 1 \text{ ns}$ (30 cm).

Range = up + down
Synchro = up - down
Pioneer example:
Some conventional and “new physics” hypotheses
(non exhaustive)

C1: Non-gravitational acceleration (drag, thermal, etc...)
C2: Additional Newtonian potential (Kuiper belt, etc...)
C3: Effect on Pioneer Doppler (DSN, ionosphere, troposphere, etc...) that also effects SAGAS ranging (sum of up and down link) but not the time transfer (difference of up and down link).
C4: Effect on Pioneer Doppler that has no effect on SAGAS ranging or time transfer (eg. ionosphere $\propto 1/f^2$)

P1: Generalised metric theory (Jaekel & Reynaud), first sector.
P2: Generalised metric theory (Jaekel & Reynaud), second sector.
Orders of magnitude for sensitivity with 1 year of data, satellite on radial trajectory, $v \sim 12$ km/s, $r \sim 50$ AU, $a_p \sim 8.7 \times 10^{-10}$ m/s$^2$:

<table>
<thead>
<tr>
<th></th>
<th>Acc.</th>
<th>Clock</th>
<th>Ranging</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>$6 \times 10^{-3}$</td>
<td>$3 \times 10^{-3}$</td>
<td>$7 \times 10^{-7}$</td>
</tr>
<tr>
<td>C2</td>
<td>-</td>
<td>$1 \times 10^{-4}$</td>
<td>$7 \times 10^{-7}$</td>
</tr>
<tr>
<td>C3</td>
<td>-</td>
<td>$&lt; 3 \times 10^{-3}$</td>
<td>$&lt; 7 \times 10^{-7}$</td>
</tr>
<tr>
<td>C4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P1</td>
<td>-</td>
<td>$1 \times 10^{-4}$</td>
<td>$7 \times 10^{-7}$</td>
</tr>
<tr>
<td>P2</td>
<td>-</td>
<td>$3 \times 10^{-5}$</td>
<td>$7 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Uncertainties on measurement of anomaly effect

“-” = no anomaly effect

• All instruments show sensitivity better than 1% $\Rightarrow$ measurement of “fine structure” and evolution with $r$ and $t$, i.e. rich testing ground for theories.
• Complementary instruments allow good discrimination between hypotheses
• C2 and P1 are phenomenologically identical (identical modification of Newtonian part of metric in $g_{00}$) but precise measurement will allow “fine tuning”
• Longer data acquisition will improve most numbers
Secondary objectives

- Measurement of gravitational redshift
- Tests of Post Newtonian gravity (light-bending, Shapiro, …)
- Search for variation of fundamental constants (LPI tests)
- Tests of Lorentz invariance (Ives-Stilwell, Kennedy-Thorndike, and Michelson-Morley, type experiments)
- Search for very low frequency ($10^{-5}$ Hz) gravitational waves
- Technology demonstrator for cold atom metrology in space, solar system timing, time/frequency transfer, navigation, ….  
- First phase: use for terrestrial T/F transfer, geodesy, etc…  
- …

To be defined more precisely depending on final mission design, which should be optimised for primary objective.
The People who make it possible:


+ ...