Limits on oscillating fundamental constants from laser spectroscopy of molecular ensembles

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DM and oscillating fundamental constants

- DM may consist of light bosons. These form a classical field $\Phi$, which coherently oscillates at their Compton frequency $f_C = m_\Phi c^2/h$.

- $\Phi$ may have scalar interactions with the SM fields.
- The fundamental constants (FC) may be expectation values of SM fields.
- The coupling of $\Phi$ to SM fields may lead to oscillating fundamental constants.

Low-energy effective lagrangian with linear coupling:

$$\mathcal{L}_{\text{eff}} \supset \frac{\phi}{M_{Pl}} \left( \sum_{f=e, u, d, s} d_{m_f} m_f \bar{f} f + \frac{d_\alpha \alpha}{4} F F + \frac{d_\beta (g_s)}{2g_s} G G \right)$$

- $F$: electromagnetic field tensor
- $G$: gluon field tensor
- $f$: fermion fields (electron, up-quark, down-quark, strange quark)
- $d$: dimensionless coupling constants to the DM field $\Phi$
- $\alpha$: fine-structure constant
- $\beta$: beta function, describes the running of the coupling constant with energy $\alpha_s = g_s^2/4\pi$; strong force coupling constant; for 3 massless quarks, $\beta/2g_s = -9\alpha_s/8\pi$
DM and oscillating fundamental constants

\[ m_f(\phi) = m_f \left[ 1 + d_m \frac{\phi}{M_{Pl}} \right], \quad \alpha(\phi) \simeq \alpha \left[ 1 - d_\alpha \frac{\phi}{M_{Pl}} \right], \quad \alpha_s(\phi) \simeq \alpha_s \left[ 1 - \frac{2 d_g \beta(g_s)}{g_s} \frac{\phi}{M_{Pl}} \right] \]

\[ \frac{\partial \ln \Lambda_{QCD}}{\partial \phi} = - \frac{g_s}{2 \beta(g_s)} \frac{\partial \ln \alpha_s}{\partial \phi} = \frac{d_g}{M_{Pl}} \]

\[ \frac{\delta M_{nuc}}{M_{nuc}} = \frac{\delta \Lambda_{QCD}}{\Lambda_{QCD}} + 0.093 \frac{\delta \hat{m}}{\hat{m}} + 0.043 \frac{\delta m_s}{m_s}, \]

\[ \hat{m} = (m_u + m_d)/2 \]

- Observables of light scalar DM may come from FC oscillations
- A series of experiments on oscillating FC has already been performed [1]
- Also: Equivalence-Principle (EP)-violating/5th force accelerations searches for non-SM fields. Experiments have already set tight bounds [2]

for a list of references
see also M. Tobar, this workshop

An open search

Which fundamental constants?

All?

Magnitude?

Period?

Make an encompassing search

→ All constants

→ All frequencies
Approach

Frequency metrology

- Transition frequency $f$ between internal levels of a quantum system

- Transition frequency between levels of a spin in an external magnetic field

- Mode frequency of an electromagnetic resonator

- Mode frequency of a mechanical resonator

The frequency ratio of two dissimilar oscillators is measured as a function of time

**High quality factor of the transitions/modes lead to:**

- **High sensitivity**

**but**

- **Slow reaction – low bandwidth**

Trade-off
Some dependencies

- **Optical transition frequency**
  \[ f \propto m_e c^2 \alpha^2 H(\alpha) \]

- **Hyperfine transition frequency**
  \[ f \propto m_e c^2 \alpha^4 F(\alpha) \left( \frac{m_e}{m_p} \right) \mu_{nuc} \]

- **Molecular vibrational transition frequency**
  \[ f \propto m_e c^2 \alpha^2 \left( \frac{m_e}{M_{nuc}} \right)^{\frac{1}{2}} G \left( \frac{m_e}{M_{nuc}} \right) \]

- **Electromagnetic cavity mode frequency (empty cavity)**
  \[ f \propto m_e c^2 \alpha \]

- **Mechanical mode frequency**
  \[ f \propto m_e c^2 \alpha^2 \left( \frac{m_e}{M_{nuc}} \right)^{\frac{1}{2}} \]

\[ \frac{\delta M_{nuc}}{M_{nuc}} = \frac{\delta \Lambda_{QCD}}{\Lambda_{QCD}} + 0.093 \frac{\delta \hat{m}}{\hat{m}} + 0.043 \frac{\delta m_s}{m_s}, \quad \hat{m} = \left( m_u + m_d \right)/2 \]

\( \mu_{nuc} \) has a small/modest dependence on \( m_s \) (~0.01) and on \( \hat{m} \) (~0.1)
## Classes of systems and their performance

<table>
<thead>
<tr>
<th>System Type</th>
<th>Type</th>
<th>Fractional Accuracy/Stability</th>
<th>$f_{\text{max}}$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atomic clocks</strong></td>
<td>Optical transitions (electronic)</td>
<td>$10^{-18}/10^{-18}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Microwave transitions (hyperfine)</td>
<td>$10^{-16}/10^{-16}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Optical transitions (electronic)</td>
<td>$10^{-14}/10^{-14}$</td>
<td>$10^7$</td>
</tr>
<tr>
<td></td>
<td>Microwave (hyperfine)</td>
<td>$10^{-14}/10^{-14}$</td>
<td>$10^3$</td>
</tr>
<tr>
<td><strong>Molecular standards/spectroscopy</strong></td>
<td>Optical transitions (electronic)</td>
<td>$10^{-14}/10^{-15}$</td>
<td>$10^7$</td>
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<tr>
<td></td>
<td>Mid-infrared transitions (vibrational)</td>
<td>$10^{-15}/10^{-15}$</td>
<td>$10^6$</td>
</tr>
<tr>
<td></td>
<td>THz transitions (rotational)</td>
<td>$10^{-11}/10^{-11}$</td>
<td>$10^4$</td>
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<tr>
<td><strong>Other</strong></td>
<td>Mass spectrometers (mass ratios)</td>
<td>$10^{-11}$</td>
<td>0.1</td>
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<tr>
<td></td>
<td>Atom interferometers (h/mass)</td>
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</tr>
<tr>
<td></td>
<td>g-factors of electron, positron, nuclei</td>
<td>$10^{-12}$</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Electromagnetic resonators</strong></td>
<td>Microwave resonators</td>
<td>--/10^{-16}</td>
<td>$10^4$</td>
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<tr>
<td></td>
<td>Optical resonators</td>
<td>--/10^{-17}</td>
<td>$10^4$</td>
</tr>
<tr>
<td><strong>Mechanical resonators</strong></td>
<td>Quartz crystals</td>
<td>--/10^{-13}</td>
<td>$10^3$</td>
</tr>
</tbody>
</table>

*Note: rough estimates*
Opportunity

*Experiments so far have not addressed:*

Oscillations of nuclear mass with frequencies > 1 Hz

Optical spectroscopy is well suited for this purpose!

*Proposal:*

D. Antypas et al.

„*Probing fast oscillating scalar dark matter with atoms and molecules*”

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Optical transitions in molecules

Rotational and vibrational levels in two different electronic states of a diatomic molecule

Electronic transition: contribution from vibration to transition frequency is small (~ 0.1)

Vibrational transition: full contribution from vibration

From: W. Demtröder
Atoms, Molecules and Photons
Experimental setups

Experiment A  Saturation spectroscopy

Experiment B  Absorption spectroscopy

100 Hz < f < 0.1 MHz

0.1 MHz < f < 100 MHz

\[
\frac{\delta (f_{\text{mol}} - f_L)}{f_{\text{mol}}} = \begin{cases} 
\frac{\delta \alpha}{\alpha} + \frac{f_{\text{vib}}}{2f_{\text{mol}}} \frac{\delta m_e}{m_e} - \frac{f_{\text{vib}}}{2f_{\text{mol}}} \frac{\delta M_{\text{nuc}}}{M_{\text{nuc}}}, & f \leq f_{\text{cut}} \\
2 \frac{\delta \alpha}{\alpha} + \left(1 + \frac{f_{\text{vib}}}{2f_{\text{mol}}} \right) \frac{\delta m_e}{m_e} - \frac{f_{\text{vib}}}{2f_{\text{mol}}} \frac{\delta M_{\text{nuc}}}{M_{\text{nuc}}}, & f \geq f_{\text{cut}}
\end{cases}
\]

Experiment is sensitive to 6 fundamental constants!
Iodine transition lines

Experiment A

Experiment B

FWHM = 3.6 MHz

Detuning from hyperfine resonance (MHz)

Balanced detector output (V)

Laser frequency - 413 366 720 (MHz)

Data

Lorentzian fit

on-resonance experiment

off-resonance experiment

FWHM = 970 MHz
Experimental limits

- No evidence for oscillations
- Analysis takes axion lineshape into account
- Results are limited by technical noise

Experiment A
19 h of data

Experiment B
60 h of data
Analysis

Effectively:

\[
\frac{\delta |f_{\text{mol}} - f_L|}{f_{\text{mol}}} = \frac{f_{\text{vib}}}{2f_{\text{mol}}} \frac{\delta M_{\text{nuc}}}{M_{\text{nuc}}}.
\]

\[
\frac{\delta M_{\text{nuc}}}{M_{\text{nuc}}} = \frac{\delta \Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}} + 0.093 \frac{\delta \hat{m}}{\hat{m}} + 0.043 \frac{\delta m_s}{m_s},
\]

Dependence of nuclear mass on the DM field:

\[
\frac{\delta M_{\text{nuc}}}{M_{\text{nuc}}} = \left( d_g + 0.093d_{\hat{m}} + 0.043d_{m_s} \right) \frac{\langle \Phi \rangle}{M_{\text{Pl}}}
\]

\[
\langle \Phi \rangle = \frac{\sqrt{2}\rho_{\text{DM}}}{m_{\Phi}} \cos 2\pi f_C t
\]
Bounds

Solar halo limits: based on model 2007.11016; extended

(*) accidental

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Summary and conclusion

- A search for oscillating nuclear mass is feasible in a wide spectrum using standard molecular spectroscopy of gas: sub-kHz to 100 MHz
- Experimental bounds on modulation of molecular transition frequency are at several $\times 10^{-15}$
- We set bounds on the coupling of light DM scalar field to gluons and quark masses at level $10^6$ (Galactic halo model)
- Improvement of bounds by several orders appears feasible, with effort
1-loop result

$$\Lambda_{QCD} \sim \mu e^{2\pi/(\beta_0 \alpha_s(\mu^2, \Phi))}$$

$\mu$: renormalization-running-energy scale
$\beta_0$: leading-order beta function
$\alpha_s$: strong force coupling constant;
   here it also depends on $\Phi$ due to the inner coupling added to the $GG$ term
These do not depend on Φ having a background value or being DM.

Because Φ is light it mediates a long-range force between two SM objects that couple to Φ

the force can be tested via 5th-force-EP-type experiments.

Example: \( m_Φ = 1 \) neV \( \rightarrow f = 240 \) kHz, \( \Lambda = 1.2 \) km

\[
\mathcal{L} \subset y_{nuc} \frac{Φ}{M_{Pl}} m_{nuc} \overline{N} N \\
F(r) = y_{nuc}^2 \frac{m_{nuc}^2}{M_{Pl}^2} e^{-r/\Lambda} \frac{1}{4\pi r} \\
y_{nuc}: \text{Effective coupling constant} \\
N: \text{nucleon field} \\
\Lambda: \text{Compton wavelength } h/m_Φc \\
F: \text{nucleon-nucleon 5th force}
\]
Models of ultra-light DM:

- [1405.2925](https://arxiv.org/abs/1405.2925) the DM is the dilaton (the Goldstone boson of scale invariance)
- [1810.01889](https://arxiv.org/abs/1810.01889) (the DM is ALP and due to spontaneous breaking of CP mixes with the Higgs)