Precision microwave oscillators and Interferometers to test Lorentz Invariance in Electrodynamics

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Content

1. Rotating Cryogenic Sapphire Oscillators (Even Parity Test)

2. Odd Parity Tests of Lorentz Invariance
Tests of Lorentz Invariance

Standard Model

Gravity

Unification Theories

Planck-scale Lorentz Violations? Describe by SME

Standard Model Extension (SME)

Mathematical framework for analysing experiments

Incorporates Lorentz and CPT violations into existing Standard Model of Physics

Colladay and Kostelecky PRD 55(11) 6760, 1997
The Photon Sector of the SME

Electromagnetic Tests $\Rightarrow$ Photon Sector $\Rightarrow$ Modified Maxwell Equations

\[
\begin{bmatrix}
 D \\
 H
\end{bmatrix} = \begin{pmatrix}
 \varepsilon_0 (\varepsilon_r + \kappa_{DE}) & \sqrt{\frac{\varepsilon_0}{\mu_0}} K_{DB} \\
 \sqrt{\frac{\varepsilon_0}{\mu_0}} K_{HE} & \mu_0^{-1} (\mu_r^{-1} + \kappa_{HB})
\end{pmatrix} \begin{bmatrix}
 E \\
 B
\end{bmatrix}
\]

Linear combinations:

$K_{e+}^{jk}$, $K_{e-}^{jk}$, $K_{o+}^{jk}$, $K_{o-}^{jk}$, $\kappa_{\text{trace}} = 1/3 \text{Tr}(\kappa_{DE})$

Existing Limits in sun-centred frame:

$K_{e+}^{jk}$, $K_{o-}^{jk} < 2 \times 10^{-37}$

$K_{e-}^{jk} < 10^{-15}$, $K_{o+}^{jk} < 10^{-11}$
Introduction: Michelson-Morley Experiments

- MM experiments generally compare the speed of light in orthogonal directions using an interferometer (phase) or cavities (frequency) (For cavities, $f \sim c / L$)

- Rotation of the experiment, using either the Earth’s rotation or active rotation, modulates a putative Lorentz violating effect

(A. Michelson and E.W. Morley, Am. J. Sci. 34, 1887)
UWA Sapphire Clock:

Most Accurate clock to measure 0.1 seconds to a few hours

- Single crystal Sapphire at cryogenic temperature (4~10K):
- Supporting whispering gallery (WG) modes

Single crystal Sapphire Resonator (top view)
Putting Einstein to the Test

Light speed results could rewrite physics laws

Dr Peter Wolf, Associate Professor Michael Tobier, honours student Mohammed Saquil and PhD student Paul Stanwick are putting the sapphire clocks in motion here to test the theories of the world’s greatest physicists.

Einstein’s theories underpin all of modern day physics.

But was he right?

Researchers in the Frequency Standards and Metrology (FSM) group in the School of Physics are collaborating with a French group at the Paris of the University such as the School of Music,” Mr Beveridge said. “Traditionally, it’s the areas such as medicine, engineering and science that generate most of the commercial potential for universities, though OII is seeing a diversification of its commercialisation projects from right across the spectrum. Initial reaction to the TuneCollector product has been positive, and we are hopeful that this will translate into commercial success.”

One of Dr Leong’s challenges with TuneCollector was to develop an e-commerce platform that interfaced with UWA’s financial systems. This challenge was addressed by one of UWA’s graduates, Yoon-Li Chung, managing director of iPlaceSpace. The IT company provided the expertise to design and implement TuneCollector’s e-commerce system, so it could be sold over the Internet.

Mr Chung said that many people with a product ideally suited to sale via the web were being stopped by a combination of trepidation and a lack of the necessary information.

Observatory to see if Einstein’s theories will hold up under testing of much greater precision than was possible when he developed his theory of relativity in 1905.

Einstein’s theory explained the results recorded by Michelson and Morley in 1887 who failed to obtain evidence for any variation of the speed of light regardless of their measurements relative to the Earth’s motion.

Just prior to Einstein publishing his theory of relativity, Dutch physicist Hendrick Lorentz cemented one of the cornerstones of relativity: that the laws of physics remain constant irrespective of the frame of reference. This became known as the Lorentz invariance and is one of the fundamental postulates of relativity.

A violation of the Lorentz invariance is what Associate Professor Michael Tobier, his French colleague Dr Peter Wolf and the FSM research group is hoping for.

Dr Wolf is on leave from the International Bureau of Weights and Measures in Paris to the Paris Observatory, where they are conducting experiments using a sapphire clock developed at UWA to measure light velocity with respect to an atomic clock. The experiment examines the effect of the Earth’s motion on the speed of light with exquisite accuracy. The French-Australian collaboration already maintains a precision 70 times greater than results from previous experiments anywhere in the world. It took 560 days for its team to collect enough data to work with, because the experiment was reliant on the Earth’s rotation once every 24 hours.

At UWA, the experiment will be carried out using two sapphire clocks placed at right angles and rotated inside a specifically designed piece of equipment once every ten seconds. It could mean the Perth partners will get some results more quickly than their French counterparts. But it could take months – even years – to get the desired outcome.

“We are experimentalists: if we get a result, we hope that a physics theorist will come along and work out how we got it, as Einstein did for Michelson and Morley,” Professor Tobier said.

“All theories that try to unify all fundamental forces of nature suggest that Lorentz invariance may be broken due to high energy processes in the early universe just after the Big Bang, and these experiments are amongst the most promising for detecting such violations.”

Dr Wolf said that any local experiment was independent of velocity. It was like bouncing a ball or smoking a cigarette in a moving train. The ball still bounces up when it hits the floor and the cigarette smoke rises up, regardless of whether the train is moving forwards or backwards, slowly or fast. According to Lorentz invariance, a local experiment cannot tell you if you have a constant velocity in relation to the universe. In this local experiment, we will be measuring the speed of light in two different directions, to search for an effect of our motion through the universe which would violate Lorentz invariance.”

Einstein Goes Under the Microscope

Perth researchers are putting Einstein to the test in a series of experiments that could rewrite the laws of physics and provide answers to how the universe began.

Investigators from the University of Western Australia’s Frequency Standards and Metrology group in the School of Physics have joined forces with a French group at the Paris Observatory to test Albert Einstein’s theory of relativity.

The two teams are using advanced techniques to see if Einstein’s theory holds up under testing of much greater precision than was available to the world’s greatest physicist in 1905. Their experiments use a modern version of the famous Kennedy-Thorndike and Michelson-Morley techniques, to examine the effect of the Earth’s motion on the speed of light with exquisite accuracy.

The French-Australian testing is already reporting results that are 70 times more precise than previous experiments conducted in the world – and the equipment is expected to continue to improve in the near future. The experiments are being conducted at the University of WA, led by Associate Professor Michael Tobier, and in Paris by Dr Peter Wolf.

In Perth, the tests are done using two sapphire clocks developed at UWA to measure light velocity. The clocks are set at right angles and placed inside a specifically designed platform that rotates every ten seconds.

At the Paris Observatory, just one sapphire clock is being used.

The researchers are hoping their experiments will reveal a violation in one of the cornerstones of relativity, which says that the laws of physics remain constant irrespective of the frame of reference. Known as the Lorentz invariance, named after Dutch physicist Hendrick Lorentz who made the discovery, it is one of the fundamentals of physics.

“Thеories that try to unify all fundamental forces of nature suggest that Lorentz invariance may be broken by high energy processes in the early universe, like that caused by the Big Bang,” Associate Professor Tobier said.

“These experiments are amongst the most promising for detecting violations like that.”

The researchers are prepared for a long task ahead – it could take years to get the results they are after, and the work doesn’t stop there.

Once the data comes through, the job of trying to explain the results begins. Associate Professor Tobier said when Einstein developed the theory of relativity, he was explaining the results recorded by physicists Michelson and Morley, who failed to obtain evidence for any variation of the speed of light, regardless of their movements relative to the Earth’s motion.

“He was crossing his fingers something similar would happen with the research he was involved in. ‘We are experimentalists. If we get a result, we hope that a physics theorist will come along and work out how we got it,’ he said.

The researchers said it was possible their work could eventually shed more light on how nature behaves and may be another step in understanding how the universe began.

For more information about UWA: http://www.uwa.edu.au
Theory:
Frequencies of interest
Experiment: Resonators

Cylindrical Sapphire crystal

Superconducting Niobium Cavity

Operate the E8,1,1 mode
Frequency $\sim 10$GHz
$Q \sim 1 \times 10^8$
Experiment: Rotation system
Experiment: Overview
The University of Western Australia Experiment
Experiment: Fractional frequency instability
Results:
Analysis 2

\[ \frac{\Delta f(t)}{f} = A + Bt + C(t) \cos(2\omega_R t) + S(t) \sin(2\omega_R t) \]

\[ S(t) = S_0 + \sum_i S_{S,i} \cos(\omega_i t) + S_{C,i} \sin(\omega_i t) \]

(and similarly for cosine)

Demodulate (sine\cosine)
In blocks of 100 rotations

\[ C_{C,2\omega_\Theta+\Omega_\Theta} \sim \frac{1}{2} \kappa_{\nu\xi}^2 (3 + \cos(2\chi)) \sin\left[ \frac{\eta}{2} \right]^2 \beta_{\Theta \Theta} \]

\[ C_{S,\omega_\Theta+\Omega_\Theta} \sim \sin\left[ \frac{\eta}{2} \right] \left( \kappa_{\nu\xi}^2 \cos\left[ \frac{\eta}{2} \right] + \kappa_{\nu\xi}^2 \sin\left[ \frac{\eta}{2} \right] \right) \sin(2\chi) \beta_{\Theta \Theta} \]
Results:
Standard Model Extension

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{e^-}^{XY}$</td>
<td>2.9 (2.3)</td>
<td>-57 (23)</td>
<td>-3.1 (2.5)</td>
</tr>
<tr>
<td>$\kappa_{e^-}^{XZ}$</td>
<td>-6.9 (2.2)</td>
<td>-32 (13)</td>
<td>-1.9 (3.7)</td>
</tr>
<tr>
<td>$\kappa_{e^-}^{YZ}$</td>
<td>2.1 (2.1)</td>
<td>-5 (13)</td>
<td>-4.5 (3.7)</td>
</tr>
<tr>
<td>$\kappa_{e^-}^{XX} - \kappa_{e^-}^{YY}$</td>
<td>-5.0 (4.7)</td>
<td>-32 (46)</td>
<td>5.4 (4.8)</td>
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<tr>
<td>$\kappa_{e^-}^{ZZ}$</td>
<td>143 (179)</td>
<td>.....</td>
<td>-19 (52)</td>
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<tr>
<td>$K_{o^+}^{XY}$</td>
<td>-0.9 (2.6)</td>
<td>18 (15)</td>
<td>2.0 (2.1)</td>
</tr>
<tr>
<td>$K_{o^+}^{XZ}$</td>
<td>-4.4 (2.5)</td>
<td>-14 (23)</td>
<td>-3.6 (2.7)</td>
</tr>
<tr>
<td>$K_{o^+}^{YZ}$</td>
<td>-3.2 (2.3)</td>
<td>27 (22)</td>
<td>2.9 (2.8)</td>
</tr>
</tbody>
</table>

Analysis assumes no cancellation

Results:
RMS

- Our experiment is inherently insensitive to the boost term $P_{KT} = \beta - a - 1$ so there is no benefit from a full year analysis.
- Take a weighted average of $P_{MM}$ determined from each data set.

Eg.

$$C_{2\omega_R+2\omega_\Theta} = P_{MM} [4.6 \times 10^{-7} - 1.4 \times 10^{-8} \cos(\Phi_0) - 7.1 \times 10^{-8} \sin(\Phi_0)]$$

($\Phi_0$ is the annular phase of the earth’s orbit)

<table>
<thead>
<tr>
<th>RMS Parameter</th>
<th>This work [1]</th>
<th>Previous Best Result [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{MM} = \frac{1}{2} - \beta + \delta$</td>
<td>$9.4 (8.1)$</td>
</tr>
</tbody>
</table>

Stanwix, Tobar et. al. PHYSICAL REVIEW D 74, 081101(R) (2006)

Hartnett et. al. Applied Physics Letters (Vol.89, No.20)

Future

Stanwix, Tobar et. al. 2005, PRL
Herrmann et. al. 2005
Antonini et. al. 2005
Sapphire Resonator

WGE and WGH modes are spatially orthogonal

Crystal Diameter: 51mm

Whispering Gallery Modes excited in crystal near dielectric vacuum interface
Stability

UWA CSOs
Paris SYRTE
Toulouse
CNES
Sydney NMI
Tokyo NICT
Odd Parity Tests

Even-parity cavity tests are symmetric

10^{-4} suppressed sensitivity to $\kappa_{o+}^{ik}$ (v/c)

10^{-8} suppressed sensitivity to $\kappa_{tr}$ (v/c)^2

Odd-parity test must be asymmetric

direct sensitivity to $\kappa_{o+}^{ik}$

10^{-4} suppressed sensitivity to $\kappa_{tr}$ (v/c)

($\kappa_{tr}$ is rotation invariant)


One-way speed of light experiments (Ives-Stilwell):

- Tobar M. et al., PRD 71, 025004 (2005) $\Rightarrow$ upper limit on $\kappa_{tr}$

Hohensee et. al. Phys. Rev. D 75, 049902(E) (2007). 2.2 \times 10^{-7}
Frequencies of Interest

For odd-parity tests:

\[ \omega_\oplus - \Omega_\oplus \quad \omega_\oplus \quad \omega_\oplus + \Omega_\oplus \]

\[ K_{tr} \quad K_{o+} \quad K_{tr} \]

\[ 11 \mu Hz \]

Rotation in Lab:

\[ \Omega_\oplus \]

\[ \omega_s - \omega_\oplus \quad \omega_s \quad \omega_s + \omega_\oplus \]

\[ 0.1 Hz \]

\[ v_\oplus / c \sim 10^{-4} \]
Asymmetric Interferometer

\[ \Delta \theta \]

\[ \Delta \theta_{\text{odd}} \approx \frac{2\pi L}{\lambda_0} \left( \mu_r^a - \mu_r^b \right) \left\{ \frac{K_0}{10^{-4}K_{tr}} \right\} \]

Direction dependent \(\Rightarrow\) Standing waves cancel
Ferrite Waveguide

**Arm a**: YIG (Yttrium Iron Garnet): $\mu_r^a=0.88$ at 9GHz

**Arm b**: Coaxial cable / Passive Components: $\mu_r^b=1$

$\varepsilon_r=15.1$, Insertion Loss $\sim 6$dB at 9GHz

Cross section $4.225\times 10.475$mm (WR42)
\[ \delta u_{\text{out}} = \delta u_{\text{SOURCE}} + \delta u_{\text{READOUT}} + S_{PD}(\delta \phi_{\text{DUT}} + \Delta \theta_{\text{odd}}) \]
Phase Noise Floor

Measured with 50 Ohm termination at LNA input

Time domain measurements =>
White for $f > 0.03\text{Hz}$
- **190 dBc/Hz achievable at 0.1 Hz**

<table>
<thead>
<tr>
<th>SME parameter</th>
<th>Current Upper Limit</th>
<th>Our Sensitivity (24 hours of data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odd $\kappa_o^{jk}$</td>
<td>$\sim 2-3 \times 10^{-12}$ (&lt;1 year of data)</td>
<td>$\sim 10^{-12}$</td>
</tr>
<tr>
<td>Scalar $\kappa_{tr}$</td>
<td>$2 \times 10^{-7}$ (72 hrs of data)</td>
<td>$\sim 10^{-8}$</td>
</tr>
</tbody>
</table>

i.e. most sensitive experiment to measure these parameters
