TESTS OF LORENTZ INVARIANCE USING A MICROWAVE RESONATOR: AN UPDATE P. Wolf

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Abstract - The frequencies of a cryogenic sapphire oscillator and a hydrogen maser are compared to set
new constraints on a possible violation of Lorentz invariance. We determine the variation of the oscillator
frequency as a function of its orientation (Michelson-Morley test) and of its velocity (Kennedy-Thorndike
test) with respect to a preferred frame candidate. We constrain the corresponding parameters of the Mansouri
and Sexl test theory to $\delta + \beta + \frac{1}{2} \leq 3.4 \times 10^{-9}$ and $\beta - \alpha - 1 \leq 4.1 \times 10^{-7}$ which is of the same order as
the best previous result for the former and represents a 50 fold improvement for the latter. These results
result correspond to an improvement of our previously published limits [Wolf P. et al., Phys. Rev. Lett. 90,
60402, (2003)] by about a factor 2. We describe the changes of the experiment, and show the new data
that lead to that improvement.

The Einstein equivalence principle (EEP) is at the heart of special and general relativity Will and
a cornerstone of modern physics. One of the constituent elements of EEP is Local Lorentz invariance
(LLI) which, loosely stated, postulates that the outcome of any local test experiment is independent of
the velocity of the freely falling apparatus (the fundamental hypothesis of special relativity). The central
importance of this postulate in modern physics has motivated tremendous work to experimentally test LLI
Will. Additionally, nearly all unification theories (in particular string theory) violate the EEP at some level
Damour1 which further motivates experimental searches for such violations of the universality of free fall
Damour2 and of Lorentz invariance Kosto1,Kosto2.

The vast majority of modern experiments that test LLI rely essentially on the stability of atomic clocks
and macroscopic resonators Brillet,KT,Hils,Schiller,Wolf, therefore improvements in oscillator technology
have gone hand in hand with improved tests of LLI. Our experiment is no exception, the large improvement
being a direct result of the excellent stability of our cryogenic sapphire oscillator. Additionally its operation
at a microwave frequency allows a direct comparison to a hydrogen maser which provides a highly stable
and reliable reference frequency.

Numerous test theories that allow the modeling and interpretation of experiments that test LLI have
been developed. Kinematical frameworks Robertson,MaS postulate a simple parametrisation of the Lorentz
transformations with experiments setting limits on the deviation of those parameters from their special
relativistic values. A more fundamental approach is offered by theories that parametrise the coupling between
gravitational and non-gravitational fields (TH$\epsilon$µ LightLee,Will,Blanchet or χ$g$ Ni formalisms) which allow
the comparison of experiments that test different aspects of the EEP. Finally, formalisms based on string
theory Damour1,Damour2,Kosto1 have the advantage of being well motivated by theories of physics that
are at present the only candidates for a unification of gravity and the other fundamental forces of nature.

Owing to their simplicity the kinematical frameworks of Robertson,MaS have been widely used to model
and interpret many previous experiments testing LLI Brillet,Hils,Schiller,Riis,WP. In order to compare our
results to those experiments we will follow this route in the present work (an analysis of our experiment
in the light of other test theories being relegated to a future publication). Those frameworks postulate
generalized transformations between a preferred frame candidate $\Sigma(T,X)$ and a moving frame $S(t,x)$ where
it is assumed that in both frames coordinates are realized by identical standards (e.g. hydrogen masers
for the time coordinates and sapphire rods for the length coordinates in our case). We start from the
transformations of MaS (in differential form) for the case where the velocity of S as measured in $\Sigma$ is along
the positive X-axis, and assuming Einstein synchronization in S (we will be concerned with signal travel
times around closed loops so the choice of synchronization convention can play no role):

eqnarray
dT = 1a(dt + vx \xi c^2) \\
\text{eqnarray}
dt = dl[c(1 - (\beta - \alpha - 1) \xi^2)]
\end{eqnarray}
Michelson-Morley type experiments MM, Brillet determine the coefficient \( P_{MM} = (1/2 - \beta + \delta) \) of the direction dependent term. For many years the most stringent limit on that parameter was \( |P_{MM}| \leq 5 \times 10^{-9} \) determined over 23 years ago in an outstanding experiment Brillet. Our experiment confirms that result with roughly equivalent uncertainty \((3.4 \times 10^{-9})\). Recently an improvement to \( |P_{MM}| \leq 1.3 \times 10^{-9} \) has been reported Muller. Kennedy-Thorndike experiments KT, Hils, Schiller measure the coefficient \( P_{KT} = (\beta - \alpha - 1) \) of the velocity dependent term. The most stringent limit Schiller on \( |P_{KT}| \) has been recently improved from Hils by a factor 3 to \( |P_{KT}| \leq 2.1 \times 10^{-5} \). We improve this result by a factor of 50 to \( |P_{KT}| \leq 4.1 \times 10^{-7} \). Finally clock comparison and Doppler experiments Riis, Grieser, WP measure \( \alpha \), currently limiting it to \( |\alpha + 1/2| \leq 8 \times 10^{-7} \). The three types of experiments taken together then completely characterize any deviation from Lorentz invariance in this particular test theory.

Our cryogenic oscillator consists of a sapphire crystal of cylindrical shape operating in a whispering gallery mode (see fig. 1 for a schematic drawing and Chang, Mann for a detailed description).

figure[htb] [height=6.5cm, width=8.5cm] MMKTfig1.eps Typical relative frequency stability of the CSO - H-maser difference after removal of a linear frequency drift. The inset is a schematic drawing of the cylindrical sapphire oscillator with the Poynting vector \( \mathbf{P} \) in the whispering gallery (WG) mode, the velocity \( \mathbf{v}(t) \) of the cylinder with respect to the CMB, and the relevant angles for a photon in the WG mode. fig:clocks