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Comment

Comment on: The quantum vacuum as the origin of the speed of light

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Abstract. In a recent paper, Urban et al. [Eur. Phys. J. D **67**, 58 (2013)] propose a model of the vacuum that predicts a fluctuating speed of light. Here, it is pointed out that under certain assumptions, past experiments strongly constrain the strength of such fluctuations, to a level smaller by approximately 8 orders compared with the estimate given in the paper.

1 Introduction

Urban et al. [1] propose a model that predicts fluctuations of the speed of light in vacuum. Their numerical estimate, equation (37) states that the statistical uncertainty in the propagation time T for covering a distance L is given by:

$$\sigma_T(L) \approx 5 \times 10^{-2}\,\text{fs}\,\sqrt{L/(1\,\text{m})}\,. \tag{1}$$

Alternatively, using $T = L/c$, this may be written as a relative uncertainty,

$$\sigma_T(L)/T \approx 1.5 \times 10^{-8}/\sqrt{L/(1\,\text{m})}\,. \tag{2}$$

This is a rather large relative uncertainty if L is of laboratory-type magnitude ($L = O(1\,\text{m})$), and thus the question arises whether already performed laboratory experiments may provide useful bounds to the hypothetical speed-of-light fluctuations.

For an accurate comparison with experiment, at least three more features of the model need to be known. First, the spectral density of the fluctuations: in models of space-time fluctuations, certain spectral densities are suggested, but in the work discussed here, none is given. Second, the correlation length of the fluctuations: is the fluctuation of the propagation time for a path $\overline{AB}$ correlated to that of a path $\overline{A'B'}$ that is parallel to AB and located at a certain distance d? Does the correlation change if the paths are orthogonal? The scaling of σ_T with $\sqrt{L}$ suggests no correlation. Third, do the fluctuations only affect the one-way propagation time, or do they also hold for back-and-forth propagation?

Optical (or microwave) resonators are devices that are extremely sensitive to variations of the speed of light, and have been used extensively for tests of Lorentz Invariance and also to search for space-time fluctuations. They are also essential tools for optical atomic clocks and precision laser spectroscopy. The frequency of a mode of a standing-wave optical resonator of length L may be written as:

$$\nu(L) = m\,c/(2\,L)\,, \tag{3}$$

where m is an integer mode number. Combining equations (1) and (3) leads to the prediction

$$\sigma_\nu(L)/\nu = \sigma_T(L)/T\,, \tag{4}$$

where we assume that there is no cancellation in the course of the back-and-forth propagation. If this were the case, one could consider a ring resonator in which the electromagnetic mode is made to propagate along each leg in one direction only; an expression similar to equation (4) would still hold. Thus, the model predicts fluctuations of the resonance frequency of a resonator.

In experiments with optical resonators, a laser wave is coupled into the resonator and usually the frequency of the laser source is constantly adjusted to be in resonance with one particular mode m, by means of an electronic controller. The laser wave is also available for diagnostics measurements; for example, it can be heterodyned with another laser wave stabilized to an atomic transition, or to another resonator. Here, the first unknown feature is relevant: if the fluctuations of the speed of light would be of very high frequency, the response of the cavity (given by the decay time of the wave) may not be able to follow them, and their effects would be strongly suppressed in the frequency of the resonator-stabilized laser. If they are not, one would expect a broadening of the spectral linewidth $\delta\nu$ of the laser wave and a frequency instability increased compared to the level due to other causes.

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Spectral linewidths of lasers stabilized to cavities and their frequency instabilities are routinely measured in many metrology laboratories. One quantity characterizing frequency instability is the Allan deviation $\sigma_y(\tau)$, where τ is the integration time, usually taken to be in the range 1 s to several hours. It is not identical to the r.m.s. uncertainty appearing in equation (4), but is nevertheless a quantity that would be influenced by (slow) speed of light fluctuations. Experimentally, according to the conventional interpretation, the fluctuations of the frequency of a stabilized laser are at present limited by thermal noise of the resonator structure [2], if other noise sources, such as vibrational noise, have been sufficiently reduced.

Among the many experiments performed, we point out the following two. The relative linewidth of a laser stabilized to a standing-wave resonator ($L \simeq 0.2\,\mathrm{m}$), and compared to another one located at a distance of $7\,\mathrm{m}$ was $\delta\nu/\nu \simeq 2 \times 10^{-16}$ [3]. The integration time for this measurement was on the order of 10 s. A relative Allan deviation of $\sigma_y(\tau = 0.4\,\mathrm{s})/\nu \simeq 1 \times 10^{-16}$ and $\sigma_y(\tau = 10\,\mathrm{s})/\nu \simeq 3 \times 10^{-16}$ was reported. In another study, the frequency fluctuations of resonator-stabilized lasers occurring over long integration times have been analyzed and interpreted as upper limits for the strength of space-time fluctuations [4]. A relative Allan deviation of 3×10^{-15} for integration times $\tau = 10^4\,\mathrm{s}$ was reported. The distance between the resonators was 2.5 m. In many experiments, determinations of the linewidth averaged over short integration times, $\tau < 1\,\mathrm{s}$, typically show values limited by the time-bandwidth uncertainty, approximately $\delta\nu/\nu \approx 1 \times 10^{-15}/\tau$, but this small-$\tau$ regime has not received much attention yet.

These values are up to 8 orders smaller than what is predicted by equation (4), under the stated assumptions, and they cover a wide averaging time range.

A complete test of the fluctuation model is only possible if the above-mentioned features are worked out. Experimental setups (e.g. ring resonator instead of standing-wave resonator, comparison of a resonator with an atomic clock instead of with a second resonator) could be devised so as to be sensitive to model features different from the ones assumed here.

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