NEW OPTICAL TESTS OF SPECIAL RELATIVITY

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We report on a test of Lorentz invariance performed by comparing the resonance frequencies of two orthogonal cryogenic optical resonators subject to Earth's rotation over ~ 1 year. For a possible anisotropy of the speed of light c, we obtain $\Delta_\theta c/c_0 = (2.6 \pm 1.7) \cdot 10^{-15}$. Within the Robertson-Mansouri-Sexl test theory, this implies an isotropy violation parameter $B = (2.2 \pm 1.5) \cdot 10^{-9}$, about three times lower than the best previous result. Within the general extension of the standard model of particle physics, we extract limits on 7 parameters at accuracies down to 10^{-15}, improving the best previous result by about two orders of magnitude.

Special Relativity (SR) is a fundamental theory that underlies all established models of the forces of nature, from the gravitational and electromagnetic to the weak and strong nuclear forces. Violations of SR, however, seem to be a common feature of many proposed models of quantum gravity, like string theory and loop gravity. It is therefore of great interest to verify SR in experiments of increasing accuracy. Here, we present a new Michelson-Morley (MM) experiment[1,2] that places stringent limits on several parameters of the general standard model extension (SME), which describes violations of SR arising from quantum gravity.[3]

The basic principle of a MM-experiment is to compare the velocities c_x and c_y of light propagating in two orthogonal directions — in our setup (Fig. 1) by measuring the frequencies of two Nd:YAG lasers at 1064 nm stabilized ("locked") to the resonance frequencies $\nu_{x,y} = mc_{x,y}/(2L)$ of cryogenic optical resonators (COREs), where L is the resonator length and m the integer mode number. A variation of $\nu_x - \nu_y$ induced by a rotation of the setup implies a violation of the isotropy of the speed of light c, in contrast to the prediction of SR.

The high stability of COREs made from crystalline sapphire (current upper lim-

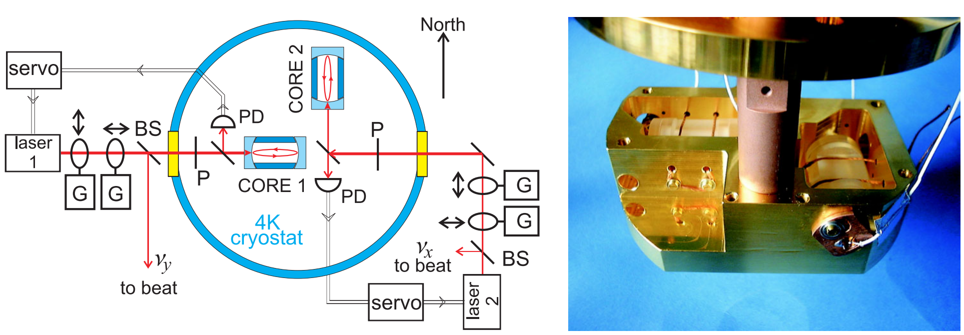

Figure 1. Schematic of the MM-experiment and photograph of the COREs inside holder.

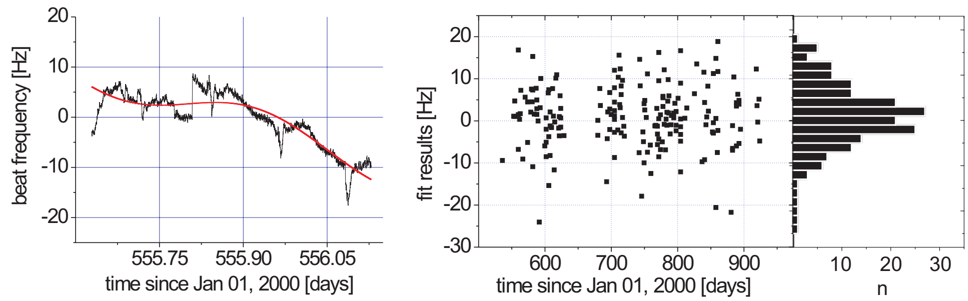

Figure 2. Left: A typical 12 h data set fitted with an offset, a linear drift, and the amplitude and phase of a hypothetical 12 h sinusoidal Lorentz violation signal predicted by the test theories. Right: Statistics over 199 such measurements.

its on the drift rates are 2 kHz/6 months from a comparison to an iodine frequency standard, and 0.1 Hz/h in CORE-CORE comparisons) makes them a valuable tool for high precision measurements of this type. For the MM-experiment, it allows us to use solely Earth's rotation; previous experiments[5] had to use a rotating turntable to overcome the drift rates (10 kHz/day) of room temperature cavities.

The COREs are operated inside a 4 K liquid helium cryostat with optical access. The advanced laser frequency stabilization scheme uses automatic beam positioning to compensate for cryostat movements caused by refills of coolants and an automatic offset compensation system[6] to find the middle of the 100 kHz wide resonator lines to about 1 Hz accuracy. A total of 3461 hours of usable data was acquired over a period of 390 days starting on June 19, 2001. This data was analyzed for sinusoidal Lorentz violation signals at six different frequencies predicted by the SME (Fig. 2).

Within the Maxwell sector of the SME, violations of boost invariance and isotropy of c are described by 3×3 matrices $\tilde{\kappa}_{e-}$ (symmetric) and $\tilde{\kappa}_{o+}$ (antisymmetric). Non-zero values of them lead to a modified c as well as a (usually negligible) modification[7] of L — and thus to a characteristic time dependency of $\nu_x - \nu_y$ on Earth's rotation and its orbital motion around the sun. From our MM-experiment, we obtain the bounds

$$\tilde{\kappa}_{e-} = \begin{pmatrix} a & 1.7 \pm 2.6 & -6.3 \pm 12.4 \\ 1.7 \pm 2.6 & b & 3.6 \pm 9.0 \\ -6.3 \pm 12.4 & 3.6 \pm 9.0 & -(a+b) \end{pmatrix} \cdot 10^{-15}$$

with $a - b = 8.9 \pm 4.9$ (expressed within the sun–centered celestial equatorial reference frame[3]). Likewise,

$$\tilde{\kappa}_{o+} = \begin{pmatrix} 0 & 14 \pm 14 & -1.2 \pm 2.6 \\ -14 \pm 14 & 0 & 0.1 \pm 2.7 \\ 1.2 \pm 2.6 & -0.1 \pm 2.7 & 0 \end{pmatrix} \cdot 10^{-11}$$

for the antisymmetric matrix, which enters the experiment suppressed by $\beta_\oplus = v_{\rm orbit}/c \sim 10^{-4}$. Compared to the best previous experiment[4] this represents an improvement by about two orders of magnitude. Furthermore, the > 1 year span

Table 1. Fitted signal amplitudes A_i^S, A_i^C of the sine and cosine components, respectively, of a hypothetical Lorentz violation signal. $\omega_\oplus \approx 2\pi/(23\text{h}56\text{min})$ and $\Omega_\oplus = 2\pi/1\,\text{year}$ denote the angular frequencies of Earth's sidereal rotation and orbit. The fit results actually used to determine limits on SME parameters are set in bold face.

ω_i	A_i^S (Hz)	A_i^C (Hz)
$\omega_\oplus - \Omega_\oplus$	$\mathbf{1.82 \pm 1.91}$	0.67 ± 1.58
$\omega_\oplus$	$\mathbf{-0.51 \pm 1.26}$	$\mathbf{0.89 \pm 1.74}$
$\omega_\oplus + \Omega_\oplus$	-0.43 ± 1.68	1.83 ± 1.83
$2\omega_\oplus - \Omega_\oplus$	$\mathbf{-0.01 \pm 0.57}$	$\mathbf{0.25 \pm 0.55}$
$2\omega_\oplus$	$\mathbf{0.37 \pm 0.56}$	$\mathbf{0.97 \pm 0.53}$
$2\omega_\oplus + \Omega_\oplus$	0.50 ± 0.55	0.75 ± 0.58

of our data allows us to set bounds on individual elements of $\tilde{\kappa}_{o+}$, and not only on special linear combinations.

Alternatively, following the example of other authors,[5,8,9] we may analyze our data within the classical kinematical framework by Robertson as well as Mansouri and Sexl (RMS). Here, one assumes a preferred frame Σ with a constant velocity of light c_0. In a frame moving with a velocity v (usually, the cosmic microwave background is taken for Σ, so $v = 369\,\text{km/s}$), the speed of light is given by $c(v,\theta)/c_0 = 1 + (A + B\sin^2\theta)\, v^2/c_0^2$, where θ is the angle between $\vec{v}$ and $\vec{c}$. If SR is valid, the coefficients A (boost invariance) and B (isotropy) vanish.

In a previous (Kennedy-Thorndike) experiment[8] comparing a CORE-stabilized laser and an iodine standard, we already determined $A = (1.9 \pm 2.1) \cdot 10^{-5}$ (meanwhile improved[9] to $A = (3.1 \pm 6.9) \cdot 10^{-9}$). From our MM-experiment we now obtain $\delta\nu/\nu = (0.73 \pm 0.48)\,\text{Hz}$, which implies a new limit on the isotropy parameter $B = (2.2 \pm 1.5) \cdot 10^{-9}$, with an uncertainty about three times lower than the best previous limit.[5]

Future versions of the experiment will employ a turntable to provide active rotation at an optimized rate. The use of fiber coupling and specially designed monolithic COREs are further promising options. Together, this should ultimately lead to an improvement by another two orders of magnitude or more.

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